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ISSN 3030-3907

TABLE OF CONTENTS / MUNDARIJA / СОДЕРЖАНИЕ

1	Raqamli ta’limda sun’iy intellektdan foydalanishning afzalliklari, muammolari va rivojlanish bosqichlari *Obidova Dilnavoz Ixtiyorovna*	9
2	Simultaneous interpretation as a type of translation *Sharopova Gulnoza Odil qizi*	18
3	Generativ sun'iy intellekt texnologiyalarining o‘zbekiston iqtisodiyotiga ta'siri va barqaror rivojlanish istiqbollari *Hasanjon Bahodirov Baxtiyorbek o‘g‘li*	25
4	Yassi va vakuum quyosh kollektorlari asosida transformator moyini tozalovchi mobil mini prototip qurilmani modellashtirish *Qo‘chqorov Akmaljon Axmadaliyevich* *Sarsenbaev Dauletbay Baktibaevich*	39
5	Экспериментальные исследования динамических характеристик терморезистивных преобразователей при воздействии импульсным испытательным сигналом *Рахматов Азамат Ражабович* *Фозилов С.Ф.* *Максимов В.Ю*	49
6	Mahalliy sholilarning unlarining xossalari *Shadiyeva Muxiba Shuxrat qizi* *Ergasheva Xusnirabo Bobonazarovna*	61
7	Sholidan yuqori hosil olishga yangichacha yondashuv *Shadiyeva Muxiba Shuxrat qizi* *Ergasheva Xusnirabo Bobonazarovna*	69
8	Mahalliy sholi navlarining sifatini o‘rganish *Shadiyeva Muxiba SHuxrat qizi* *Ergasheva Xusnirabo Bobonazarovna*	78
9	Sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyoti: o‘zbekiston iqtisodiyotini transformatsiya qilishning strategik yo‘nalishlari *Hasanjon Bahodirov Baxtiyorbek o‘g‘li*	88
10	Python va flask yordamida integral hisoblaydigan kalkulyator yaratish va uni vizualizatsiya qilish. *Turayeva Muqaddas Turabekovna*	103
11	Telegram bot orqali universal matn tarjima botini yaratish (python dasturlash tili asosida) *Turayeva Muqaddas Turabekovna*	110
12	Марказдан қочма куч таъсирида юқори эксплуатацион хусусиятли анизотроп структурали цилиндрсимон фильтрлар олиш усулининг назарий тавсифи *Файзиев Миргани Мирвалиевич* *Каршиев Мамарайим*	117
13	Марказдан қочма куч таъсирида олинган анизотроп структурали фильтрларнинг ғоваклиги, ғовак ўлчами, ўтказувчанлик коэффициенти ва самарадорлик параметрларини ўзгаришини ҳисоблаш *Файзиев Миргани Мирвалиевич* *Каршиев Мамарайим*	126
14	Dehydration of natural gas with various adsorbents and determination of the efficiency of an adsorber with a multilayer adsorbent bed for gas dehydration *Makhmudov Mukhtor Jamolovich* *Nematov Khusan Ibodullayevich* *Khujakulov Aziz Fayzullayevich* *Ramazonov Bakhrom Gafurovich* *Rasulov Ulugbek Askarovich* *Anvarova Iroda Anvarovna* *Mamadaminova Zulhumor Fakhriddinova*	135

ISSN 3030-3907

	Shoymardonov Olmasbek Bolta ogli *Sunatov Shokhrukh Shamsi ogli* *Rakhimov Zakhriddin Zafar ogli*	
15	Thermochemical activation of local navbahor bentonite for the combined coagulation–flocculation–adsorption treatment of petroleum refinery wastewater *Nasiba Kambaralievna Sadikova* *Ruslan Rustamjonovich Khayitov*	160
16	Valorization of waste heavy hexane fraction from polyethylene production into octane-boosting additives for automotive gasoline: synthesis, physicochemical characterization, and techno-economic evaluation *Hasan Rahmatovich Abdulloyev* *Nodir Shavkatovich Panoyev* *Jasur Alijonovich Safarov*	189
17	Technology for the production of higher fatty acids from secondary paraffin feedstocks for enhancing the lubricity of diesel fuels *Fozilov Hasan Sadriddinovich* *Turobjonov Sadriddin Makhamatdinovich* *Fozilov Sadriddin Fayzulloevich*	215
18	Physicochemical, environmental, and operational properties of synthetic gtl and conventional diesel fuel blends *Ozoda Bakhranovna. Akhmedova* *Aliakbar To'raqulyevich Ro'ziyev* *Ruslan Rustamjonovich Hayitov* *Shokhruh Boboxon ogli Mavlonov*	224
19	Black powder in natural gas transmission systems: edxrf characterization and metrological implications *Ozoda Bakhranovna Akhmedova* *Sh.M.Isamadinov* *Abdurasul Qayumov Shonazarovich* *M.B.Akhmedova*	237
20	Modeling of terpolymerization kinetics and determination of reactivity ratios in the tdma–styrene–maleic anhydride system *Mavlonov Shohrux Boboxon ogli* *Fozilov Sadriddin Fayzullayevich*	258
21	Development of drilling fluid formulations for wells in difficult conditions based on the study of the composition of clays in uzbekistan *Sherzod Toshev Orziyevich* *Khahramon Sharipov Qandiyorovich* *Bobomurod Rakhimov Rustamovich* *Abdukholik Kholmukhammadiev Mahammadi o'g'li*	276
22	Development of a technology for the preparation of light-density drilling mud based on the study of the composition and properties of local bentonites *Sherzod Toshev Orziyevich* *Khahramon Sharipov Qandiyorovich* *Abdukholik Kholmukhammadiev Mahammadi o'g'li* *Hamid Obidov Olimovich* *Shakhnoza Tilloeva Faxritdinovna*	287
23	Innovative developments to improve core recovery drilling efficiency in weakly cemented formations *Ravshanbek Narimov Anarmetovich* *Abdurasul Qayumov Shonazarovich* *Ozoda Akhmedova Baxronovna* *Abror Akhmedov Sayidmurod o'g'li*	297
24	Industrial optimization of ethylene recovery from pyrolysis gas: yellow-oil separation and polymerization inhibition	315

ISSN 3030-3907

	Ozoda Akhmedova Baxronovna *Xujamberdi Toshboyev Mingyasharovich* *Abdurasul Qayumov Shonazarovich* *Ravshanbek Narimov Anarmetovich*	
25	Valorization of high-sulfur petroleum fractions through the synthesis of arenothiophene-based corrosion inhibitors *Ozoda Akhmedova Baxronovna* *Lobar Bozorova Sharipovna* *Nazirila Maxmudov Nasimxanovich* *Abdurasul Qayumov Shonazarovich* *Mexriniso Axmedova Baxronovna* *Sadriddin Fozilov Fayzullayevich* *Dilbar Ergasheva Kuchkarovna* *Fayzulla Raxmatullayev Nig'matullayevich*	328
26	Synthesis and tribological evaluation of lubricity additives for euro-5 diesel fuel based on local secondary raw materials *Ozoda Baxronovna Akhmedova* *Hasan Sadriddinovich Fozilov* *Abdurasul Shonazarovich Qayumov* *Ra'no Asadova Dilmurodovna*	352
27	Modern approaches to improving the efficiency of gas purification from acidic components *Shaxnoza Akhmedova Utkirovna* *Ozoda Akhmedova Baxronovna* *Abdurasul Qayumov Shonazarovich*	375
28	Determination of the pressure gradient along the wellbore in gas–liquid wells *Nazarov Azizbek Ulugbekovich* *Sunnatov Muxiddin Saloxiddinovich* *Shin Aleksey* *Ozoda Akhmedova Baxronovna*	395
29	Angren ko'mirini ortofosfat kislota yordamida kimyoviy faollashtirish natijasida strukturaviy o'zgarishlarni skanerlovchi elektron mikroskopiya asosida tahlili *Aslanova Feruza Ilxomovna* *Boymatov Ismoiljon Mamatkulovich*	410
30	Glyuten va o'simlik oqsili kompozitlarining bo'kish xususiyatlari va yuqori haroratli siljitish ta'sirida fibrillyar struktura shakllanish qonuniyatlari *Sobuddinov Sohibjon Mahmudjonovich* *Qanoatov Xayrullo Murodillayevich* *Dadamirzayev Muzaffar Habibullayevich*	417
31	Ingliz balladalari va o'zbek qahramonlik eposi an'analari *Mahmudova Nilufar Maqsudovna*	430
32	Ayollar kundalik poyabzalining qulayligini oshirish: yangi konstruktorlik-texnologik yechimlar tahlili *Uzoqova Laylo Polvonovna* *Avezova Anoraxon Azimovna*	438
33	Fasllar almashinuvining odam va hayvonlarda gormonal fon (melatonin, kortizol) va faollik ritmiga ta'siri *Dilfuzaxon Boqijon qizi Anvarjonova*	444
34	Sholi unidan mazali va sifatli pishiriqlar tayyorlash *Shadiyeva Muxiba Shuxrat qizi* *Ergasheva Xusnirabo Bobonazarovna*	453
35	Получение ароматических углеводородов из пропана на высококремнеземных катализаторах *Сайфитдинова Моҳинур Баходировна* *Яхшиликова Хумора Лочинбековна* *Шукуров Бахриддин Шадикулович*	462

ISSN 3030-3907

36	Non-autoclaved aerated concrete d600 modified with mineralized fibrous licorice root waste *Soy Vladimir Mikhailovich* *Eshbekov Shukhrat Gadoymurotovich* *Jumageldiev Aziz Olimovich* *Turgayev Janbul Adilbaevich*	469
37	Yuz, harakat va vaqtga bog‘liq modellar asosida ko‘p modalli biometrik uzluksiz autentifikatsiya tizimi: muammolar va yechimlar *Alayev Ruhillo Habibovich* *Nurmatov Abduraxim Shaxriyor o‘g‘li*	477
38	Nikel(ii) ionini 6-xlor-4-gidroksi-3-nitrozonaftalin-2,7-disulfokislota bilan yangi spektrofotometrik aniqlash usuli *Nazirov Shohjohon Sobirovich* *To‘rayev Xayit Xudoynazarovich* *Turabov Nurmuhammat* *Xojiyev Shokir G‘ofurovich*	487
39	Sun’iy intellekt va kompyuter ko‘rish texnologiyalariga asoslangan miya o‘smalarini avtomatik diagnostika qilish algoritmlarini ishlab chiqish *Jumaniyazova Mashxura Azamatovna* *Urazmatov Tohir Quranboyevich*	498
40	Talabalarda fazoviy tafakkurni animatsiyalar orqali rivojlantirish metodlari *Xo‘janiyozov Shokir Rustamovich*	509

ISSN 3030-3907

ISSN 3030-3907

RAQAMLI TA’LIMDA SUN’IY INTELLEKTDAN FOYDALANISHNING AFZALLIKLARI, MUAMMOLARI VA RIVOJLANISH BOSQICHLARI

Obidova Dilnavoz Ixtiyorovna
O‘zbekiston Respublikasi Badiiy akademiyasi tasarrufidagi Buxoro ixtisoslashtirilgan san'at maktab-internati. Informatika fani o‘qituvchisi

Annotatsiya. Ushbu maqolada raqamli ta’lim jarayonida sun’iy intellekt texnologiyalaridan foydalanishning afzalliklari, mavjud muammolari hamda rivojlanish bosqichlari ilmiy-uslubiy jihatdan tahlil qilingan. Bugungi kunda sun’iy intellekt ta’lim tizimining barcha bosqichlariga kirib kelmoqda va o‘quv jarayonini individuallashtirish, o‘quvchilarning bilim darajasini tahlil qilish, o‘qituvchilarga metodik yordam ko‘rsatish, baholash jarayonini avtomatlashtirish hamda ta’lim boshqaruvini takomillashtirish imkoniyatlarini yaratmoqda. Maqolada sun’iy intellekt asosidagi moslashuvchan ta’lim tizimlari, intellektual tutorlar, avtomatik baholash, learning analytics, chatbotlar, virtual yordamchilar va ta’lim ma’lumotlarini tahlil qilish mexanizmlarining pedagogik ahamiyati yoritilgan. Shuningdek, sun’iy intellektdan foydalanishda yuzaga keladigan axloqiy, metodik, texnik, huquqiy va psixologik muammolar, xususan, ma’lumotlar maxfiyligi, algoritmik adolatsizlik, akademik halollik, o‘qituvchi roliga ta’sir, texnologiyaga haddan tashqari qaramlik va raqamli tengsizlik masalalari muhokama qilingan. Tadqiqot natijalariga ko‘ra, sun’iy intellekt ta’limda o‘qituvchini almashtiruvchi vosita emas, balki pedagogik jarayonni qo‘llab-quvvatlovchi, tahliliy qarorlar qabul qilishga yordam beruvchi va shaxsga yo‘naltirilgan ta’limni rivojlantiruvchi innovatsion texnologiya sifatida qaralishi lozim.

Kalit so‘zlar: raqamli ta’lim, sun’iy intellekt, intellektual ta’lim tizimi, moslashuvchan ta’lim, learning analytics, avtomatik baholash, raqamli kompetensiya, ta’lim sifati, pedagogik innovatsiya.

Аннотация. В данной статье научно-методически анализируются преимущества, проблемы и этапы развития использования искусственного интеллекта в цифровом образовании. В настоящее время искусственный интеллект активно проникает во все уровни образовательной системы и создаёт новые возможности для индивидуализации обучения, анализа уровня знаний учащихся, методической поддержки учителей, автоматизации оценивания и совершенствования управления образованием. В статье раскрывается педагогическое значение адаптивных образовательных систем, интеллектуальных тьюторов, автоматизированного оценивания, learning analytics, чат-ботов, виртуальных помощников и механизмов анализа образовательных данных. Также рассматриваются этические, методические, технические, правовые и

ISSN 3030-3907

психологические проблемы применения искусственного интеллекта в образовании, в частности вопросы конфиденциальности данных, алгоритмической предвзятости, академической честности, изменения роли учителя, чрезмерной зависимости от технологий и цифрового неравенства. По результатам исследования обосновано, что искусственный интеллект в образовании следует рассматривать не как средство замены учителя, а как инновационную технологию, поддерживающую педагогический процесс, способствующую принятию аналитических решений и развитию личностно-ориентированного обучения.

Ключевые слова: цифровое образование, искусственный интеллект, интеллектуальная образовательная система, адаптивное обучение, learning analytics, автоматизированное оценивание, цифровая компетентность, качество образования, педагогическая инновация.

Abstract. This article provides a scientific and methodological analysis of the advantages, problems and development stages of using artificial intelligence in digital education. Today, artificial intelligence is increasingly penetrating all levels of the education system and creating new opportunities for personalizing learning, analyzing students' knowledge levels, providing methodological support to teachers, automating assessment and improving educational management. The article highlights the pedagogical significance of adaptive learning systems, intelligent tutoring systems, automated assessment, learning analytics, chatbots, virtual assistants and mechanisms for analyzing educational data. It also discusses ethical, methodological, technical, legal and psychological problems related to the use of artificial intelligence in education, including data privacy, algorithmic bias, academic integrity, the changing role of teachers, excessive dependence on technology and digital inequality. The study concludes that artificial intelligence in education should not be considered a replacement for teachers, but rather an innovative technology that supports the pedagogical process, assists in analytical decision-making and promotes learner-centered education.

Keywords: digital education, artificial intelligence, intelligent educational system, adaptive learning, learning analytics, automated assessment, digital competence, quality of education, pedagogical innovation.

KIRISH.

XXI asrda ta'lim tizimi raqamli transformatsiya jarayonining eng faol ishtirokchilaridan biriga aylandi. Internet, elektron ta'lim platformalari, masofaviy ta'lim, mobil ilovalar, virtual laboratoriyalar va raqamli resurslar ta'lim jarayonini

ISSN 3030-3907

tashkil etish shakllarini tubdan o‘zgartirdi. So‘nggi yillarda esa ushbu jarayonga sun’iy intellekt texnologiyalarining kirib kelishi ta’lim mazmuni, metodlari, baholash tizimi va boshqaruv mexanizmlarini yanada takomillashtirish imkonini bermoqda. Sun’iy intellekt ta’limda o‘quvchining individual ehtiyojlarini aniqlash, moslashtirilgan o‘quv materiallarini taqdim etish, bilimlardagi bo‘shliqlarni tahlil qilish, o‘qituvchiga metodik tavsiyalar berish, baholash jarayonini avtomatlashtirish va ta’lim sifatini monitoring qilish kabi ko‘plab vazifalarni bajarishi mumkin.UNESCO 2023-yilda generativ sun’iy intellekt bo‘yicha ta’lim va tadqiqotlar uchun maxsus qo‘llanma e’lon qilib, davlatlar va ta’lim muassasalari sun’iy intellektni inson manfaatlariga yo‘naltirilgan, xavfsiz, adolatli va mas’uliyatli tarzda joriy etishi kerakligini ta’kidlagan. Ushbu qo‘llanma generativ sun’iy intellektdan foydalanishda siyosat, inson salohiyati, etik me’yorlar va uzoq muddatli strategik rejalashtirish zarurligini ko‘rsatadi. OECD ham sun’iy intellekt va ta’lim masalalarida davlatlar samarali va adolatli foydalanish bo‘yicha tadqiqotlar, yo‘riqnomalar va o‘qituvchilarni maxsus tayyorlash dasturlarini rivojlantirishi lozimligini qayd etadi.

Raqamli ta’limda sun’iy intellektdan foydalanish masalasi O‘zbekiston ta’lim tizimi uchun ham dolzarbdir. Mamlakatda raqamli iqtisodiyot, elektron hukumat, axborot-kommunikatsiya texnologiyalari va ta’limni raqamlashtirish yo‘nalishlarida amalga oshirilayotgan islohotlar pedagogik jarayonga zamonaviy innovatsiyalarni kiritishni talab qilmoqda. Bunday sharoitda ta’lim tizimi oldida ikki tomonlama vazifa turadi: birinchidan, sun’iy intellekt vositalaridan o‘quv jarayonini takomillashtirish uchun samarali foydalanish; ikkinchidan, o‘quvchi va talabalarda sun’iy intellektdan mas’uliyatli foydalanish madaniyatini shakllantirish.Mazkur maqolaning dolzarbligi shundaki, sun’iy intellekt ta’limda katta imkoniyatlar yaratishi bilan birga, bir qator muammolarni ham yuzaga keltiradi. Agar sun’iy intellekt pedagogik maqsadga mos, metodik jihatdan asoslangan va etik me’yorlar asosida qo‘llanilsa, u ta’lim sifatini oshirishga xizmat qiladi. Aks holda, u akademik halollikning buzilishi, tanqidiy fikrlashning susayishi, ma’lumotlar maxfiyligining buzilishi, o‘qituvchi va o‘quvchi o‘rtasidagi jonli muloqotning kamayishi kabi salbiy oqibatlarga olib kelishi mumkin. Shu sababli maqolada raqamli ta’limda sun’iy intellektdan foydalanishning afzalliklari, muammolari, rivojlanish bosqichlari va amaliy yechimlari kompleks tarzda tahlil qilinadi.Sun’iy intellektning ta’limdagi o‘rni so‘nggi yillarda xalqaro tashkilotlar, ilmiy markazlar va pedagog olimlar tomonidan keng o‘rganilmoqda. UNESCOning “Guidance for generative AI in education and research” nomli hujjatida generativ sun’iy intellektning ta’limga kirib kelishi tezlashayotgani, biroq ko‘plab ta’lim tizimlarida uni tartibga solish, xavfsizlik, yosh cheklovlari, ma’lumotlar himoyasi va pedagogik qo‘llash bo‘yicha yetarli tayyorgarlik mavjud

ISSN 3030-3907

emasligi qayd etiladi. Ushbu manbada sun’iy intellektni ta’limga joriy etishdan avval davlat siyosati, ta’lim muassasasi strategiyasi, o‘qituvchilar malakasi va o‘quvchilarning raqamli savodxonligi masalalari puxta o‘ylanishi kerakligi asoslangan.OECD tadqiqotlarida sun’iy intellekt kelajakdagi kasblar, mehnat bozori, o‘quv kompetensiyalari va ta’lim tizimlari uchun strategik ahamiyatga ega texnologiya sifatida qaraladi. OECD ma’lumotlariga ko‘ra, sun’iy intellekt tizimlari o‘quvchilarning o‘qish, tabiiy fanlar va muammolarni hal qilish kabi ko‘nikmalariga o‘xshash topshiriqlarni bajarishda yuqori natijalar ko‘rsatmoqda, bu esa ta’lim tizimining kelajak kompetensiyalariga yangicha qarashini talab qiladi. Biroq bu holat ta’limda inson omili kamayishi kerakligini emas, balki o‘qituvchi, o‘quvchi va texnologiya o‘rtasidagi hamkorlikni to‘g‘ri tashkil etish zarurligini ko‘rsatadi.Jahon banki ta’limda sun’iy intellektdan foydalanish o‘quv inqirozini yumshatish, o‘quvchilarga individual yordam berish, o‘qituvchilarning vaqtini tejash va boshqaruv samaradorligini oshirish imkonini berishi mumkinligini qayd etadi. Shu bilan birga, raqamli infratuzilma, internetga ulanish, texnologiyadan foydalanish narxi va teng imkoniyatlar masalasi sun’iy intellektni ta’limda qo‘llashda muhim to‘siqlardan biri bo‘lib qolmoqda. Ilmiy adabiyotlarda sun’iy intellektning ta’limdagi qo‘llanilishi bir nechta asosiy yo‘nalishlarda o‘rganiladi. Birinchi yo‘nalish — intellektual ta’lim tizimlari va moslashuvchan o‘qitish tizimlari. Bu tizimlar o‘quvchining javoblari, xatolari, faolligi va o‘zlashtirish darajasiga qarab unga mos topshiriqlar, izohlar va tavsiyalar beradi. Ikkinchi yo‘nalish — avtomatik baholash va teskari aloqa tizimlari. Bunday tizimlar test natijalari, yozma ishlar, mashqlar va amaliy topshiriqlarni tezkor tahlil qilib, o‘quvchiga yoki o‘qituvchiga natija beradi. Uchinchi yo‘nalish — learning analytics, ya’ni ta’lim ma’lumotlarini yig‘ish va tahlil qilish orqali o‘quv jarayonini yaxshilash. To‘rtinchi yo‘nalish — generativ sun’iy intellekt, ya’ni matn, rasm, kod, test, reja, taqdimot, izoh va o‘quv materiallarini yaratishda foydalaniladigan tizimlar. Beshinchi yo‘nalish — chatbotlar va virtual yordamchilar bo‘lib, ular o‘quvchi va o‘qituvchiga tezkor maslahat, tushuntirish va yo‘naltirish beradi.Adabiyotlar tahlili shuni ko‘rsatadiki, sun’iy intellektni ta’limda qo‘llash samaradorligi texnologiyaning kuchiga emas, balki uning pedagogik maqsadga qanchalik mos qo‘llanishiga bog‘liq. Sun’iy intellekt o‘qituvchining o‘rnini bosadigan vosita emas, balki uning faoliyatini qo‘llab-quvvatlovchi yordamchi mexanizm sifatida qaralishi kerak. UNESCO ham generativ sun’iy intellektni ta’limda inson markazli yondashuv asosida tartibga solish zarurligini ta’kidlaydi.

Raqamli ta’limda sun’iy intellektdan foydalanishning eng muhim afzalliklaridan biri ta’limni individuallashtirish imkoniyatidir. An’anaviy ta’limda o‘qituvchi ko‘pincha bir xil mavzu, bir xil metod va bir xil topshiriqlar orqali turli bilim darajasidagi o‘quvchilar bilan ishlaydi. Biroq har bir o‘quvchining bilim

ISSN 3030-3907

darajasi, qiziqishi, o‘zlashtirish tezligi, xotira turi, mustaqil ishlash malakasi va ehtiyoji turlicha bo‘ladi. Sun’iy intellekt asosidagi moslashuvchan ta’lim tizimlari o‘quvchining bajargan topshiriqlari, qilgan xatolari, javob berish tezligi va o‘zlashtirish dinamikasini tahlil qilib, unga mos o‘quv materiallarini tavsiya qilishi mumkin. Masalan, matematika fanida o‘quvchi tenglamalarni yechishda qiyinchilikka duch kelsa, tizim unga sodda misollar, izohli tushuntirishlar, video dars yoki qo‘shimcha mashqlarni taklif etadi. Ona tili darsida imlo xatolari ko‘p uchrasa, tizim aynan shu xatolar ustida ishlash uchun maxsus topshiriqlar beradi. Bunday yondashuv shaxsga yo‘naltirilgan ta’lim tamoyilini amaliy jihatdan kuchaytiradi.Sun’iy intellektning ikkinchi muhim afzalligi — o‘qituvchining vaqtini tejashidir. O‘qituvchi kundalik faoliyatida dars rejasini tuzish, topshiriqlar tayyorlash, test savollari ishlab chiqish, o‘quvchilar ishini tekshirish, baholash, ota-onalar bilan aloqa qilish, hisobot tayyorlash kabi ko‘plab vazifalarni bajaradi. Sun’iy intellekt vositalari ushbu jarayonlarning ayrimlarini avtomatlashtirish orqali o‘qituvchiga ijodiy, tarbiyaviy va metodik faoliyatga ko‘proq vaqt ajratish imkonini beradi. Masalan, AI yordamida mavzuga mos testlar, dars rejasi, muammoli savollar, differensial topshiriqlar, baholash mezonlari va refleksiya savollari tayyorlanishi mumkin. Biroq bu materiallar o‘qituvchi tomonidan albatta tekshirilishi, fan mazmuni va o‘quvchilar yosh xususiyatlariga moslashtirilishi zarur.Uchinchi afzallik — tezkor va individual teskari aloqa berish imkoniyatidir. O‘quvchi topshiriq bajarganidan keyin darhol natija va izoh olishi uning o‘z xatosini tushunishiga yordam beradi. An’anaviy ta’limda o‘qituvchi barcha ishlarni tekshirguncha ma’lum vaqt o‘tadi. Sun’iy intellekt asosidagi tizimlar esa xatoni darhol aniqlab, uni tuzatish yo‘lini ko‘rsatishi mumkin. Masalan, chet tilini o‘rganishda talaffuz, grammatika va lug‘at bo‘yicha avtomatik tavsiyalar berilishi, matematika va informatika fanlarida esa yechim bosqichlari tahlil qilinishi mumkin.To‘rtinchi afzallik — ta’lim ma’lumotlarini tahlil qilishdir. Raqamli ta’lim platformalarida o‘quvchilarning kirish vaqti, faoliyati, topshiriqlarni bajarish darajasi, xatolar turi, baholari, darslardagi ishtiroki kabi ma’lumotlar yig‘iladi. Sun’iy intellekt va learning analytics ushbu ma’lumotlarni tahlil qilib, o‘quvchining qaysi mavzuda qiynalayotgani, qaysi guruhda o‘zlashtirish pasayayotgani, qaysi metod samaraliroq bo‘layotgani haqida xulosa chiqarishga yordam beradi. Bu esa rahbar, metodist va o‘qituvchilar uchun dalillarga asoslangan qaror qabul qilish imkonini yaratadi.Beshinchi afzallik — inklyuziv ta’lim imkoniyatlarini kengaytirishdir. Sun’iy intellekt asosidagi nutqni matnga aylantirish, matnni ovozga aylantirish, avtomatik tarjima, individual yordamchi dasturlar, ko‘rish yoki eshitishida muammosi bo‘lgan o‘quvchilar uchun moslashtirilgan interfeyslar inklyuziv ta’limni rivojlantirishga xizmat qilishi mumkin. Bunday vositalar maxsus ehtiyojli o‘quvchilarning ta’lim jarayonida faol

ISSN 3030-3907

ishtirok etishiga yordam beradi. Biroq ularni qo‘llashda pedagog, psixolog va mutaxassislarning hamkorligi zarur.Oltinchi afzallik — o‘quvchilarning mustaqil ta’lim olish imkoniyatlarini kengaytirishdir. Sun’iy intellekt asosidagi chatbotlar va virtual yordamchilar o‘quvchiga darsdan tashqari vaqtda ham savol berish, mavzuni tushuntirish, misol yechish, reja tuzish yoki qo‘shimcha manba topish imkonini beradi. Bu ayniqsa masofaviy ta’lim, aralash ta’lim va mustaqil ta’lim sharoitida muhimdir. Ammo bunda o‘quvchilar sun’iy intellektdan tayyor javob olish uchun emas, balki fikrlash, tahlil qilish va o‘z bilimini mustahkamlash uchun foydalanishga o‘rgatilishi kerak.Sun’iy intellektning ta’limdagi rivojlanish bosqichlarini shartli ravishda bir necha bosqichga ajratish mumkin. Birinchi bosqich — kompyuterlashtirilgan ta’lim bosqichi bo‘lib, unda o‘quv jarayonida oddiy elektron dasturlar, testlar, kompyuter mashqlari va multimedia materiallaridan foydalanilgan. Bu bosqichda sun’iy intellekt elementlari juda cheklangan bo‘lib, asosiy e’tibor axborotni elektron shaklda taqdim etishga qaratilgan. Ikkinchi bosqich — intellektual ta’lim tizimlari bosqichi bo‘lib, unda o‘quvchining javobiga qarab tavsiya beruvchi, xatoni aniqlovchi va moslashtirilgan topshiriq taqdim etuvchi tizimlar rivojlangan. Uchinchi bosqich — learning analytics va big data bosqichi bo‘lib, unda ta’lim platformalarida to‘plangan katta hajmdagi ma’lumotlarni tahlil qilish orqali o‘quv jarayonini boshqarish imkoniyatlari kengaydi. To‘rtinchi bosqich — generativ sun’iy intellekt bosqichi bo‘lib, unda matn, rasm, kod, taqdimot, savol-javob, test, topshiriq va izohlarni avtomatik yaratish imkoniyati paydo bo‘ldi. Beshinchi bosqich — integratsiyalashgan intellektual ta’lim ekotizimi bosqichi bo‘lib, unda sun’iy intellekt elektron jurnal, ta’lim platformasi, mobil ilova, baholash tizimi, o‘quv resurslari bazasi va boshqaruv tizimi bilan uzviy bog‘langan holda ishlaydi.Raqamli ta’limda sun’iy intellektdan samarali foydalanish uchun o‘qituvchi roli qayta talqin qilinishi zarur. Sun’iy intellekt ayrim texnik va tahliliy vazifalarni bajarishi mumkin, lekin u o‘qituvchining tarbiyaviy ta’siri, pedagogik sezgirligi, shaxsiy muloqoti, axloqiy namunasi, motivatsiya berish qobiliyati va ijodiy yondashuvini almashtira olmaydi. O‘qituvchi sun’iy intellekt yaratgan materiallarni tanqidiy tekshiruvchi, moslashtiruvchi, metodik jihatdan qayta ishlovchi va o‘quvchilar ehtiyojiga moslashtiruvchi asosiy shaxs bo‘lib qoladi. Shu sababli raqamli ta’limda sun’iy intellektdan foydalanish o‘qituvchi kasbiy kompetensiyasini kamaytirmaydi, aksincha, undan yanada yuqori raqamli, metodik va axloqiy tayyorgarlikni talab qiladi.

Raqamli ta’limda sun’iy intellektdan foydalanish bir qator jiddiy muammolarni ham keltirib chiqaradi. Birinchi muammo — ma’lumotlar maxfiyligi va xavfsizligi masalasidir. Sun’iy intellekt tizimlari samarali ishlashi uchun o‘quvchilar faoliyati, baholari, xatolari, qiziqishlari, o‘quv tezligi va boshqa

ISSN 3030-3907

shaxsiy ma’lumotlarni qayta ishlashi mumkin. Agar bu ma’lumotlar yetarlicha himoya qilinmasa, o‘quvchining shaxsiy hayoti va xavfsizligiga zarar yetishi ehtimoli mavjud. Yechim sifatida ta’lim muassasalari sun’iy intellektdan foydalanishda ma’lumotlarni himoya qilish siyosatini ishlab chiqishi, ota-ona va o‘quvchilarga ma’lumotlardan foydalanish tartibini tushuntirishi, faqat zarur ma’lumotlarni yig‘ishi hamda xavfsiz platformalardan foydalanishi kerak.Ikkinchi muammo — algoritmik adolatsizlik va xatolikdir. Sun’iy intellekt tizimi noto‘g‘ri ma’lumotlar asosida o‘qitilgan bo‘lsa yoki unda muayyan guruhlarga nisbatan yashirin tarafkashlik mavjud bo‘lsa, u noto‘g‘ri baholash yoki tavsiya berishi mumkin. Masalan, tizim ayrim til, madaniyat, ijtimoiy sharoit yoki o‘quv uslubiga ega o‘quvchilarni noto‘g‘ri talqin qilishi ehtimoli bor. Buning yechimi sifatida AI natijalari doimo o‘qituvchi tomonidan tekshirilishi, algoritmlar shaffofligi ta’minlanishi, baholashda inson nazorati saqlanishi va turli o‘quvchi guruhlari uchun adolatli mezonlar ishlab chiqilishi lozim.Uchinchi muammo — akademik halollik masalasidir. Generativ sun’iy intellekt o‘quvchi yoki talaba uchun insho, referat, kod, tarjima, masala yechimi va boshqa topshiriqlarni tayyorlab berishi mumkin. Bu esa mustaqil fikrlash, ijodkorlik va bilimni real baholash jarayoniga salbiy ta’sir ko‘rsatadi. Yechim sifatida ta’lim muassasalarida sun’iy intellektdan foydalanish bo‘yicha aniq qoidalar ishlab chiqilishi, qaysi holatda AI yordamidan foydalanish mumkin va qaysi holatda mumkin emasligi belgilanishi, topshiriqlar ko‘proq tahliliy, amaliy, og‘zaki himoya, loyiha va shaxsiy tajribaga asoslangan shaklda tashkil etilishi kerak.To‘rtinchi muammo — o‘qituvchilarning raqamli tayyorgarligi yetarli emasligidir. Ko‘plab o‘qituvchilar sun’iy intellekt imkoniyatlarini bilsa-da, uni dars maqsadiga mos qo‘llash, natijalarini tekshirish, xatolarini aniqlash va metodik jihatdan moslashtirishda qiynalishi mumkin. Yechim sifatida o‘qituvchilar uchun AI savodxonligi, prompt yozish madaniyati, axborot xavfsizligi, raqamli baholash, AI etikasi va metodik integratsiya bo‘yicha malaka oshirish kurslarini tashkil etish zarur.Beshinchi muammo — texnologiyaga haddan tashqari qaramlikdir. Agar o‘quvchi har bir savolga tayyor javobni sun’iy intellektdan olsa, uning mustaqil fikrlashi, mantiqiy tahlil qilish qobiliyati va ijodiy izlanishi susayishi mumkin. Bunday xavfni kamaytirish uchun sun’iy intellektdan foydalanish “tayyor javob olish” emas, balki “fikrni tekshirish”, “variantlarni solishtirish”, “xatoni tahlil qilish”, “g‘oyani rivojlantirish” va “mustaqil xulosa chiqarish” maqsadiga yo‘naltirilishi kerak.Oltinchi muammo — raqamli tengsizlikdir. Sun’iy intellekt vositalaridan samarali foydalanish uchun internet, kompyuter yoki smartfon, sifatli platforma va raqamli savodxonlik talab qilinadi. Barcha o‘quvchi va o‘qituvchilarda bunday imkoniyatlar bir xil emas. Jahon banki ham internetga ulanish, qurilma, xarajat va infratuzilma masalalari AI asosidagi ta’lim yechimlarini keng joriy etishda muhim to‘siq bo‘lishi mumkinligini qayd

ISSN 3030-3907

etadi. Yechim sifatida davlat va ta’lim muassasalari raqamli infratuzilmani rivojlantirishi, ochiq va bepul resurslardan foydalanishni kengaytirishi, hududlar o‘rtasidagi texnologik tafovutni kamaytirishi lozim.Kelajakda sun’iy intellekt raqamli ta’limning yanada muhim tarkibiy qismiga aylanishi kutiladi. Birinchi istiqbolli yo‘nalish — shaxsiy o‘quv trajektoriyalarini yaratishdir. Har bir o‘quvchi uchun individual dastur, topshiriq, baholash va rivojlanish xaritasi shakllantiriladi. Ikkinchi yo‘nalish — o‘qituvchi yordamchisi sifatida AI tizimlarini rivojlantirishdir. Bunday tizimlar dars rejasi, test, metodik tavsiya, o‘quvchi natijalari tahlili va ota-onalar bilan aloqa jarayonida o‘qituvchiga yordam beradi. Uchinchi yo‘nalish — raqamli baholashning rivojlanishidir. Sun’iy intellekt nafaqat yakuniy javobni, balki o‘quvchining fikrlash jarayoni, yechim bosqichlari va xato sabablarini tahlil qilishi mumkin. To‘rtinchi yo‘nalish — inklyuziv va ko‘p tilli ta’lim imkoniyatlarini kengaytirishdir. Avtomatik tarjima, ovozli yordamchi, matnni soddalashtirish va maxsus ehtiyojli o‘quvchilar uchun moslashtirilgan materiallar ta’limda teng imkoniyatlar yaratishga xizmat qiladi. Beshinchi yo‘nalish — ta’lim boshqaruvida prediktiv analitikadan foydalanishdir. Bu orqali o‘quvchi muvaffaqiyatsizligi xavfini oldindan aniqlash, metodik yordamni rejalashtirish va ta’lim sifatini doimiy monitoring qilish mumkin bo‘ladi.Biroq rivojlanish istiqbollari bilan birga mas’uliyat ham ortadi. Sun’iy intellektni ta’limga joriy etishda pedagogik maqsad, inson manfaatlari, axloqiy me’yorlar, adolat, shaffoflik va xavfsizlik asosiy mezon bo‘lishi kerak. UNESCOning ta’limda generativ AI bo‘yicha yondashuvi ham aynan inson markazli, mas’uliyatli va tartibga solingan foydalanishni ilgari suradi. Demak, kelajakda muvaffaqiyatli raqamli ta’lim sun’iy intellektning texnik imkoniyatlariga emas, balki uni pedagogik, metodik va axloqiy jihatdan to‘g‘ri boshqarishga bog‘liq bo‘ladi.

Xulosa qilib aytganda, raqamli ta’limda sun’iy intellektdan foydalanish zamonaviy ta’lim tizimining eng istiqbolli yo‘nalishlaridan biridir. Sun’iy intellekt o‘quv jarayonini individuallashtirish, o‘quvchilarning bilim darajasini tahlil qilish, o‘qituvchilarning vaqtini tejash, baholash jarayonini avtomatlashtirish, o‘quvchilarga tezkor teskari aloqa berish, inklyuziv ta’lim imkoniyatlarini kengaytirish va ta’lim boshqaruvini takomillashtirishda muhim imkoniyatlar yaratadi. Shu bilan birga, u ma’lumotlar maxfiyligi, algoritmik adolatsizlik, akademik halollik, texnologiyaga qaramlik, raqamli tengsizlik va o‘qituvchi rolining o‘zgarishi kabi muammolarni ham yuzaga keltiradi.Maqolada olib borilgan tahlillar shuni ko‘rsatadiki, sun’iy intellekt ta’limda mustaqil va nazoratsiz qo‘llaniladigan vosita emas, balki o‘qituvchi rahbarligida, pedagogik maqsadga yo‘naltirilgan, etik me’yorlarga asoslangan va o‘quvchining shaxsiy rivojlanishiga xizmat qiladigan texnologiya sifatida qaralishi kerak. Sun’iy intellekt o‘qituvchini almashtirmaydi, balki uning faoliyatini qo‘llab-quvvatlaydi. U o‘qituvchining

ISSN 3030-3907

metodik mahorati, tarbiyaviy ta’siri, insoniy muloqoti va pedagogik sezgirligini to‘ldiruvchi raqamli yordamchi bo‘lishi mumkin.Raqamli ta’limda sun’iy intellektdan samarali foydalanish uchun, avvalo, o‘qituvchilarning AI savodxonligini oshirish, ta’lim muassasalarida aniq foydalanish qoidalarini ishlab chiqish, o‘quvchilarni akademik halollik va tanqidiy fikrlashga o‘rgatish, ma’lumotlar xavfsizligini ta’minlash, raqamli infratuzilmani rivojlantirish va pedagogik nazoratni saqlash zarur. Kelgusida sun’iy intellekt asosidagi moslashuvchan ta’lim platformalari, intellektual tutorlar, avtomatik baholash tizimlari, learning analytics va virtual yordamchilar ta’lim sifatini oshirishda muhim o‘rin egallaydi. Biroq bu jarayonda asosiy tamoyil inson markazli yondashuv bo‘lib qolishi lozim.

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SIMULTANEOUS INTERPRETATION AS A TYPE OF TRANSLATION

Sharopova Gulnoza Odil qizi
Samarkand State Medical University Faculty of Languages Trainer assistant

Annotation. This article is about development of simultaneous translation foreign languages. In this article author writes about process of simultaneous translation and early history of it. In this article author wrote types of simultaneous interpretation and details in this process. In this article author wrote advantages and some difficulties in this translation.

Key words: translation, history of simultaneous translation, types of translation, whispering translation, cultural connection.

Аннотация. Эта статья посвящена развитию синхронного перевода иностранных языков. Автор описывает процесс синхронного перевода и его раннюю историю. В статье также рассматриваются виды синхронного перевода и подробно объясняется, как осуществляется этот процесс. Кроме того, автор рассказывает о преимуществах синхронного перевода, а также о некоторых трудностях и проблемах, возникающих при выполнении такого вида перевода.

Ключевые слова: Перевод, история синхронного перевода, виды перевода нашёптываемый перевод

Annotatsiya. Ushbu maqola chet tillarida sinxron tarjimaning rivojlanishiga bag‘ishlangan. Muallif sinxron tarjima jarayoni va uning dastlabki tarixini bayon qiladi. Shuningdek, maqolada sinxron tarjimaning turlari va ushbu jarayon qanday amalga oshirilishi batafsil tushuntiriladi. Bundan tashqari, muallif sinxron tarjimaning afzalliklari hamda ushbu tarjima turida uchraydigan ayrim qiyinchilik va muammolar haqida ham so‘z yuritadi.

Kalit so‘zlar: sinxron tarjima tarixi madaniy bog‘liqlik. tarjima turlari, pichirlab tarjima qilish.

INTRODUCTION.

The history of simultaneous translation is so old we may notice first examples of simultaneous interpreting in the past. In the recording of Ancient Egypt, Roman Empire and Ancient Greece creation of simultaneous interprets was reason to solve communication problems. In the history the duty of interpreters were to translate speech of merchants or ambassadors of other countries. Growing good business and political relationship between countries improved roles of interpreters in society. The existence of interpreters and translator in administration, army, religion, commerce was written in documents of Ancient

ISSN 3030-3907

Greece and Roman Empire. At that time interpreters did not use any technical equipment but they translate the speech of outsiders orally.

Modern simultaneous translation was known at the beginning of 20 century or during the Word War 1 and World War 2 political affairs of various countries needed translators during the congresses and they utilized effort of simultaneous interpreters. The official date birth of the translation is considered The Nuremberg Trials which was hold in 1945- 1946. The techniques of simultaneous translation earphones, microphones are used in it and the official languages of the trial were English, French, German and Russian. The difficult translation was used more in international meetings more after the trial.

Simultaneous translation is one of the most difficult types of translation. The main feature of simultaneous translation is the parallel perception of the speaker's speech and the generation of speech in the target language. This feature of simultaneous translation determines other features of this type of translation and, first of all, a strict time limits: only the period of the speaker's speech is given to the simultaneous interpreter for translation. This time is two times less than that available to the translator for consecutive translation, and 20-30 times less than for written translation of the text of the same speech.

Simultaneous translation is usage of two languages at the one time and in a short period. Most of the multinational meeting and conferences require works of simultaneous. In the interpreting translation later has to interpret what the speaker says. There is no waiting time between the interpreting the receipt of simulation translation. Simulation translation is very demanding work and it demands excellent language skills and mentally prepared. During the process interpreter cannot use dictionaries and without proficiency interpreters cannot reach results.

Advantages of the translation are to translate sentences in a short time and listener doesn’t need to wait translation of speech, interpreter has opportunity to speak translation to large audience. The interpreter use special headset to listen with concentration and transmit it immediately. There is special booth and in it translator sits and translate the speech. Pros of the interpreting are the participants may listen the interpreters carefully and interpreters work with time.

Cons of simultaneous interpreting interpreters need special equipment like headset, microphones and booth. The disadvantages of the simultaneous translation are translators have to work under the stress. Huge mental stress and concentrate for a long time affect negatively healthy of translator and during the process the translator should not lose the focus any case misunderstanding may happen in the meeting. One of the problems in the process is translator may have to work with unknown themes which he or she has never used them before. It also makes

ISSN 3030-3907

difficulties and stress in translation. The solutions of the problems are translator needs more drilling and physiological preparation before the conference.

There are types of the simultaneous interpreting are whispering and simultaneous interpreters. In the whispering interpreter and delegate sit together and translator translates the speech immediately. In simultaneous interpreting translator works with equipment. The main problems in simultaneous interpreting are problems of listening skills, comprehension and speaking skills and poor memory. Listening problems are speaker's bad, unclear pronunciation, regional accents, noise rooms, technical problems. Comprehension does not have enough information about the topic. To achieve great comprehension interpreter should be ready for the topic. Speech or materials of delegate should be given beforehand. Speaking problems are bad articulation and pronunciation, poor vocabulary, lack of topic knowledge and others. They can be reason unsuccessful translation. To remember different numbers, personal names, geographic names, terms, items demands good memory.

At the beginning of introduction of simultaneous translation there were not enough specialist. In the USSR Hoffman recorded that Ministry of foreign affairs and all union society for cultural relation was simultaneous translators. Emigrants who knew two languages well employed as interpreters but They were not specialists. So that in spite of being bilingualism there were not translation. In the middle of 60-s of xx century techniques strategies existing knowledge of simultaneous translation forms were arranged. And working with bilingual language was formed. Each University tried to improve principles of teaching simultaneous translation but all of them focused on developing linguistic skills, improving speech, images, and volume, in Russia were 13 simultaneous interpreters from simultaneous interpreters.

But all of them there were not good techniques equipments. Alekseyeva thought that achieve great results for simultaneous interpreters' educational institutes need their own plane, schedule, textbooks, training planes forms of examination control methods. In the first scientific research of simultaneous interpreters accomplished theoretical and practical information. In 1945 Nuremberg trials which were the first simultaneous interpreters' services were used interpreters faced various kinds of problems. Mostly speakers do not about translators and speak fast. Secondly working with documentans are really difficult for translators on the of cabin a portable microphone was installed which was taken over by one of the interpreters depending on what language the speaker was speaking. The first there were closed cabin later booths with screen was used after some me they changed it with glass. Mostly simultaneous translators use one earpiece to monitor the speech. In the booths there are materials of broadcasts and

ISSN 3030-3907

time regulations after 15-30 min translator may with geographic names translation of lexical units, names, dates proper names and they may change their place later. Zubanova notes that before starting the process the translator should learn how to work the equipments; switch on and off microphones, location of the mute button, how to adjust the volume of headphones, how to switch on the channels. The translator has a transmitter microphone and headphones. Also, there is whisper equipment for whispering. It is ultra-sensitive lapel or head microphones. Size of booths can be different air quality and sound insulation also important. Techniques and good condition are very important to achieve good results.

There are two predominant technologies, they are automated and machine translation are now being developed and employed in the field. In reality, the definition of technological competence does not regulate specific knowledge and abilities with relation to interpreting, including simultaneous interpreting, especially when it comes to the usage of contemporary IT-based tools and technologies. This is due to the fact that simultaneous interpretation is typically viewed as a form of activity, whose primary component is language skill, the capacity to simultaneously perceive speech and make its translation. The quality of simultaneous translation, according to scientists, is determined by both linguistic proficiency and familiarity with extra linguistic elements, including nonverbal cues and gestures that the translator can pick up on during a translation session.

According to E. Conway, using a computer in the interpreter's booth during the established simultaneous interpretation procedure is confined. The computer can only be used to a limited level during the interpreting because simultaneous interpreters are typically underutilized throughout their simultaneous interpreting with their capacities for listening, understanding, buffering, creating, checking, and coordinating all actions. C. Silva wrote that website interpreting is very useful for interpreting “The most webcast interpreting events today take advantage of audio and video technologies, allowing interpreters to take in as many audio and visual cues as possible"1 . Also using Remote Simultaneous Interpreting (RSI) and Computer-assisted (CAI) interpreting is very essential in simultaneous interpreting. During the interpreting interpreters uses new technologies and the modern technologies helps them to interpret correctly.There are two predominant technologies, they are automated and machine translation are now being developed and employed in the field. In reality, the definition of technological competence does not regulate specific knowledge and abilities with relation to interpreting, including simultaneous interpreting, especially when it comes to the

[1] . Silva, C.: When Technology Meets Simultaneous Interpreting: A Glimpse into the World of Webcast Interpreting. In: The ATA Chronicle, April, 16–18 (2014)

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usage of contemporary IT-based tools and technologies. This is due to the fact that simultaneous interpretation is typically viewed as a form of activity, whose primary component is language skill, the capacity to simultaneously perceive speech and make its translation. The quality of simultaneous translation, according to scientists, is determined by both linguistic proficiency and familiarity with extra linguistic elements, including nonverbal cues and gestures that the translator can pick up on during a translation session.

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CONCLUSION.

In conclusion, simultaneous interpretation is one of the most complex and important types of translation that plays a significant role in facilitating communication between people who speak different languages. Unlike written translation, simultaneous interpretation requires the interpreter to listen to the speaker, understand the meaning, and reproduce the message in another language almost at the same time. Therefore, it requires a high level of linguistic competence, concentration, memory, quick thinking, and effective communication skills.

The analysis of simultaneous interpretation shows that the main task of an interpreter is not simply to translate individual words, but to convey the meaning, intention, and emotional tone of the speaker as accurately as possible. The interpreter must also consider cultural differences, context, terminology, and the

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ISSN 3030-3907

specific characteristics of the audience. This makes simultaneous interpretation a highly responsible and intellectually demanding professional activity.

At the same time, modern technologies have contributed significantly to the development of simultaneous interpretation. Various digital tools, interpretation equipment, online platforms, and artificial intelligence technologies can support interpreters and improve the efficiency of the interpreting process. However, human interpreters remain essential because successful interpretation often requires contextual understanding, cultural awareness, flexibility, and the ability to make immediate decisions.

Thus, simultaneous interpretation can be considered an essential form of translation in today's globalized world. It enables effective communication at international conferences, diplomatic meetings, business negotiations, educational events, and other multilingual environments. The quality of simultaneous interpretation directly influences the accuracy and success of intercultural communication. Therefore, professional training and continuous development of interpreters' linguistic, analytical, and communication skills are crucial for achieving high-quality simultaneous interpretation.

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GENERATIV SUN'IY INTELLEKT TEXNOLOGIYALARINING O‘ZBEKISTON IQTISODIYOTIGA TA'SIRI VA BARQAROR RIVOJLANISH ISTIQBOLLARI

Hasanjon Bahodirov Baxtiyorbek o‘g‘li
Xalqaro Oziq-ovqat Texnologiyalari va Muhandislik Instituti, Iqtisodiyot fakulteti, 3-bosqich talabasi
E-mail: bahodirovhasanjon@gmail.com

Annotatsiya. Mazkur maqolada generativ sun'iy intellekt texnologiyalarining zamonaviy iqtisodiy rivojlanishdagi o‘rni hamda ularning O‘zbekiston iqtisodiyotiga ko‘rsatayotgan bevosita va bilvosita ta'siri ilmiy-nazariy nuqtai nazardan tahlil qilinadi. Raqamli transformatsiya jarayonlarining jadallashuvi, iqtisodiyotning turli tarmoqlarida sun'iy intellekt yechimlaridan foydalanish ko‘lamining kengayishi hamda innovatsion rivojlanish omillarining kuchayishi mamlakat iqtisodiy siyosatining ustuvor yo‘nalishlaridan biriga aylanmoqda. Mazkur maqolada generativ sun'iy intellektning mehnat unumdorligi, ishlab chiqarish samaradorligi, xizmatlar sifati, ta'lim, sog‘liqni saqlash, moliyaviy texnologiyalar, davlat boshqaruvi va tadbirkorlik muhitiga ta'siri nazariy yondashuvlar asosida yoritilgan. Shuningdek, xalqaro tajriba va O‘zbekistonning raqamli iqtisodiyot strategiyasi doirasida ushbu texnologiyalarni joriy etish istiqbollari, mavjud institutsional imkoniyatlar hamda ehtimoliy xavf-xatarlar tahlil qilinadi. Maqolada generativ sun'iy intellektning iqtisodiy o‘sishni jadallashtirish, yangi kasblarni shakllantirish, bilimlar iqtisodiyotini rivojlantirish va raqamli ekotizimni mustahkamlashdagi strategik ahamiyati asoslab beriladi. Ilmiy maqola natijalari sun'iy intellektni iqtisodiyotning ustuvor tarmoqlariga integratsiya qilish bo‘yicha ilmiy-amaliy tavsiyalar ishlab chiqish uchun nazariy asos vazifasini bajaradi.

Kalit so‘zlar: generativ sun'iy intellekt, raqamli iqtisodiyot, innovatsiya, iqtisodiy rivojlanish, mehnat bozori, raqamli transformatsiya.

Аннотация. В данной статье с научно-теоретической точки зрения анализируется роль технологий генеративного искусственного интеллекта в современном экономическом развитии, а также их прямое и косвенное влияние на экономику Республики Узбекистан. Ускорение процессов цифровой трансформации, расширение использования решений искусственного интеллекта в различных секторах экономики и усиление факторов инновационного развития становятся одним из приоритетных направлений государственной экономической политики. В исследовании на основе теоретических подходов раскрывается влияние генеративного искусственного интеллекта на производительность труда, эффективность

производства, качество услуг, образование, здравоохранение, финансовые технологии, государственное управление и предпринимательскую среду. Кроме того, рассматриваются перспективы внедрения данных технологий в рамках стратегии цифровой экономики Узбекистана, существующие институциональные возможности и потенциальные риски. Обоснована стратегическая роль генеративного искусственного интеллекта в ускорении экономического роста, формировании новых профессий, развитии экономики знаний и укреплении цифровой экосистемы. Полученные результаты могут служить теоретической основой для разработки научно-практических рекомендаций по интеграции технологий искусственного интеллекта в приоритетные отрасли экономики.

Ключевые слова: генеративный искусственный интеллект, цифровая экономика, инновации, экономическое развитие, рынок труда, цифровая трансформация.

Abstract. This article provides a theoretical analysis of the role of generative artificial intelligence technologies in modern economic development and examines their direct and indirect impact on the economy of the Republic of Uzbekistan. The acceleration of digital transformation, the expanding application of artificial intelligence solutions across various sectors of the economy, and the growing importance of innovation have become key priorities of the country's economic policy. The study explores, from a theoretical perspective, the influence of generative artificial intelligence on labor productivity, production efficiency, service quality, education, healthcare, financial technologies, public administration, and the business environment. It also examines the prospects for implementing these technologies within Uzbekistan's digital economy strategy, existing institutional opportunities, and potential challenges. The article substantiates the strategic role of generative artificial intelligence in accelerating economic growth, creating new professions, fostering the knowledge economy, and strengthening the digital ecosystem. The findings provide a theoretical foundation for developing practical recommendations on integrating artificial intelligence technologies into the priority sectors of the national economy.

Keywords: generative artificial intelligence, digital economy, innovation, economic development, labor market, digital transformation.

KIRISH.

XXI asrning uchinchi o‘n yilligida dunyo iqtisodiyotida kuzatilayotgan eng muhim texnologik o‘zgarishlardan biri generativ sun'iy intellekt texnologiyalarining jadal rivojlanishi hisoblanadi. Mazkur texnologiyalar inson

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intellektiga xos bo‘lgan matn yaratish, tasvir hosil qilish, dasturlash, tahliliy xulosalar ishlab chiqish hamda murakkab muammolarga yechim taklif etish kabi vazifalarni yuqori aniqlik bilan bajarish imkoniyatiga ega bo‘lib, iqtisodiyotning deyarli barcha tarmoqlarida yangi rivojlanish bosqichini boshlab bermoqda. Natijada sun'iy intellekt ishlab chiqarish omillarining samaradorligini oshirish, boshqaruv xarajatlarini kamaytirish, innovatsion mahsulot va xizmatlar yaratishni jadallashtirish hamda raqamli iqtisodiyotning institutsional asoslarini mustahkamlashda muhim omil sifatida namoyon bo‘lmoqda.

Generativ sun'iy intellektning iqtisodiy ahamiyati faqat texnologik yangiliklar bilan cheklanmaydi. U korxonalar faoliyatida qaror qabul qilish sifatini yaxshilash, ma'lumotlarni qayta ishlash tezligini oshirish, mijozlarga xizmat ko‘rsatish jarayonlarini avtomatlashtirish va inson kapitalidan yanada samarali foydalanish imkonini yaratmoqda. Shu bilan birga, mazkur texnologiyalar ilmiy tadqiqotlar, ta'lim, sog‘liqni saqlash, bank-moliya, qishloq xo‘jaligi, sanoat, logistika va davlat boshqaruvi kabi strategik yo‘nalishlarda ham tub o‘zgarishlarni yuzaga keltirmoqda. Bunday sharoitda generativ sun'iy intellekt iqtisodiy o‘sishning yangi drayverlaridan biri sifatida e'tirof etilmoqda. So‘nggi yillarda O‘zbekistonda ham raqamli iqtisodiyotni rivojlantirish, davlat xizmatlarini raqamlashtirish, axborot-kommunikatsiya texnologiyalarini keng joriy etish hamda innovatsion ekotizimni shakllantirish bo‘yicha keng ko‘lamli islohotlar amalga oshirilmoqda. Raqamli infratuzilmaning rivojlanishi, elektron hukumat tizimining kengayishi, IT-parklar faoliyatining faollashuvi va sun'iy intellekt texnologiyalariga qiziqishning ortishi generativ sun'iy intellektni iqtisodiyot tarmoqlariga bosqichma-bosqich integratsiya qilish uchun qulay sharoit yaratmoqda. Shu bilan birga, ushbu jarayon malakali kadrlar tayyorlash, ma'lumotlar xavfsizligini ta'minlash, huquqiy tartibga solish mexanizmlarini takomillashtirish va texnologiyalardan oqilona foydalanishni taqozo etadi.

Jahon amaliyoti shuni ko‘rsatadiki, generativ sun'iy intellektdan samarali foydalangan davlatlarda mehnat unumdorligi ortmoqda, yangi iqtisodiy faoliyat yo‘nalishlari shakllanmoqda hamda yuqori qo‘shilgan qiymatga ega mahsulot va xizmatlar ulushi kengaymoqda. Bunday tajribalar O‘zbekiston uchun ham muhim ilmiy va amaliy ahamiyat kasb etadi. Mamlakatning raqamli transformatsiya strategiyasi, innovatsion rivojlanish siyosati hamda bilimlarga asoslangan iqtisodiyot modeliga bosqichma-bosqich o‘tish jarayonida generativ sun'iy intellekt texnologiyalarining iqtisodiy salohiyatini chuqur o‘rganish dolzarb ilmiy masalalardan biri hisoblanadi.

Mazkur tadqiqotning asosiy maqsadi generativ sun'iy intellekt texnologiyalarining O‘zbekiston iqtisodiyotiga ta'sirini zamonaviy iqtisodiy nazariyalar va ilmiy yondashuvlar asosida tahlil qilish, ularning iqtisodiy o‘sish,

ISSN 3030-3907

mehnat bozori, innovatsion faoliyat va raqamli transformatsiya jarayonlaridagi o‘rnini aniqlash hamda istiqboldagi rivojlanish yo‘nalishlarini ilmiy asoslashdan iborat. Shuningdek, maqoladamazkur texnologiyalarni joriy etishning institutsional shart-sharoitlari, mavjud imkoniyatlari va ehtimoliy xavf omillari kompleks tarzda baholanadi. Olingan ilmiy xulosalar generativ sun'iy intellektni milliy iqtisodiyotning ustuvor tarmoqlariga samarali integratsiya qilish, raqamli iqtisodiyotning raqobatbardoshligini oshirish va barqaror iqtisodiy rivojlanishni ta'minlash bo‘yicha ilmiy-amaliy tavsiyalar ishlab chiqishga xizmat qiladi.

ADABIYOTLAR SHARHI. Generativ sun'iy intellekt texnologiyalari so‘nggi yillarda jahon ilmiy hamjamiyati tomonidan eng faol o‘rganilayotgan yo‘nalishlardan biriga aylandi. Raqamli iqtisodiyotning rivojlanishi, katta hajmdagi ma'lumotlarning ko‘payishi hamda hisoblash quvvatlarining ortishi natijasida sun'iy intellekt oddiy avtomatlashtirish vositasidan iqtisodiy rivojlanishning strategik omiliga aylandi. Ayniqsa, generativ modellar matn, tasvir, dasturiy kod, ovoz va murakkab tahliliy ma'lumotlarni yaratish imkoniyatiga ega bo‘lgani sababli ilmiy adabiyotlarda ularning iqtisodiyotga ta'siri alohida yo‘nalish sifatida shakllanmoqda.

Iqtisodiy nazariya nuqtai nazaridan generativ sun'iy intellekt texnologiyalari endogen iqtisodiy o‘sish konsepsiyasi bilan chambarchas bog‘liq. Mazkur yondashuvga ko‘ra, ilmiy bilimlar, innovatsiyalar va texnologik taraqqiyot mamlakat iqtisodiy rivojlanishining asosiy ichki omillari hisoblanadi. Zamonaviy ilmiy tadqiqotlarda sun'iy intellekt ishlab chiqarish omillarining samaradorligini oshiruvchi, bilimlar iqtisodiyotini rivojlantiruvchi hamda yuqori qo‘shilgan qiymat yaratishga xizmat qiluvchi strategik resurs sifatida talqin qilinadi. Shu sababli ko‘plab iqtisodchilar sun'iy intellektni sanoat inqilobining yangi bosqichini shakllantirayotgan texnologiya sifatida baholaydilar.

Xalqaro ilmiy adabiyotlarda generativ sun'iy intellektning mehnat unumdorligiga ta'siri eng ko‘p tadqiq etilgan masalalardan biri hisoblanadi. Tadqiqotlar natijalariga ko‘ra, sun'iy intellekt yordamida axborotni qayta ishlash tezligi sezilarli darajada ortadi, takrorlanuvchi vazifalar avtomatlashtiriladi hamda xodimlarning murakkab tahliliy faoliyatga ko‘proq vaqt ajratish imkoniyati yuzaga keladi. Natijada korxonalarda vaqt va resurslardan foydalanish samaradorligi oshib, ishlab chiqarish xarajatlari qisqaradi. Shu bilan birga, xizmat ko‘rsatish sifati yaxshilanishi hamda boshqaruv qarorlarining aniqligi ortishi iqtisodiy samaradorlikni yanada kuchaytiradi. Adabiyotlarda generativ sun'iy intellektning mehnat bozori uchun ta'siri yuzasidan turli ilmiy qarashlar mavjud. Ayrim tadqiqotchilar ushbu texnologiyalar ayrim kasblarning qisqarishiga olib kelishini ta'kidlasa, boshqa olimlar aksincha, yangi kasblar va mutaxassisliklarning shakllanishini asosiy natija sifatida ko‘rsatadilar. Zamonaviy ilmiy qarashlarga

ISSN 3030-3907

ko‘ra, sun'iy intellekt inson mehnatini to‘liq almashtirishdan ko‘ra, uning samaradorligini oshiruvchi yordamchi vosita sifatida namoyon bo‘lmoqda. Shu sababli mehnat bozorining kelajakdagi rivojlanishi ko‘proq xodimlarning raqamli ko‘nikmalari, kreativ fikrlashi va sun'iy intellekt bilan hamkorlikda ishlash salohiyatiga bog‘liq bo‘ladi.

So‘nggi yillardagi ilmiy izlanishlarda generativ sun'iy intellektning makroiqtisodiy ta'siri ham keng o‘rganilmoqda. Ilmiy tahlillarda mazkur texnologiyalar yalpi ichki mahsulot o‘sishini jadallashtirish, investitsion jozibadorlikni oshirish, innovatsion tadbirkorlikni rivojlantirish hamda eksport salohiyatini kengaytirishga xizmat qilishi qayd etiladi. Ayniqsa, bilimlarga asoslangan iqtisodiyot modelini shakllantirishda sun'iy intellektning strategik ahamiyati tobora ortib bormoqda. Raqamli platformalar, elektron tijorat, moliyaviy texnologiyalar, sanoatni avtomatlashtirish va davlat xizmatlarini raqamlashtirish jarayonlari generativ sun'iy intellektning amaliy qo‘llanilish doirasini sezilarli ravishda kengaytirmoqda.

Shu bilan birga, ilmiy adabiyotlarda mazkur texnologiyalarning xavf va cheklovlari ham batafsil yoritilgan. Jumladan, axborot xavfsizligi, shaxsiy ma'lumotlarni himoya qilish, algoritmik xatoliklar, intellektual mulk huquqlari, etik me'yorlarga rioya etish va raqamli tengsizlik kabi masalalar sun'iy intellektni keng joriy etishda asosiy muammolar sifatida baholanadi. Ko‘plab tadqiqotchilar texnologik taraqqiyot bilan bir qatorda samarali huquqiy tartibga solish, malakali kadrlar tayyorlash va raqamli infratuzilmani rivojlantirish zarurligini ta'kidlaydilar.

Generativ sun'iy intellektning iqtisodiy samaradorlikka ta'sirini baholashda ilmiy adabiyotlarda innovatsion rivojlanish nazariyasi, raqamli transformatsiya konsepsiyasi hamda bilimlar iqtisodiyoti modeli keng qo‘llaniladi. Ushbu nazariyalarga ko‘ra, iqtisodiy o‘sishning asosiy manbai tabiiy resurslar yoki ishlab chiqarish quvvatlaridan ko‘ra ko‘proq intellektual kapital, ilmiy salohiyat va zamonaviy texnologiyalardan samarali foydalanishga bog‘liq. Shu nuqtai nazardan, generativ sun'iy intellekt korxonalar va davlat boshqaruvi tizimlarining innovatsion salohiyatini oshirishga xizmat qiluvchi muhim vosita sifatida baholanadi. Ilmiy tadqiqotlarda generativ sun'iy intellektning kichik va o‘rta biznes rivojiga ta'siri ham alohida e'tirof etiladi. Mazkur texnologiyalar marketing strategiyalarini ishlab chiqish, mijozlar ehtiyojini prognozlash, moliyaviy rejalashtirish, mahsulot dizaynini yaratish hamda biznes jarayonlarini avtomatlashtirish orqali tadbirkorlik subyektlarining raqobatbardoshligini oshiradi. Natijada korxonalar bozor talabiga tez moslashadi, operatsion xarajatlar kamayadi va innovatsion mahsulotlar yaratish imkoniyatlari kengayadi. Ayniqsa, raqamli platformalarning ommalashuvi generativ sun'iy intellektni iqtisodiyotning barcha tarmoqlariga bosqichma-bosqich joriy etish uchun qulay sharoit yaratmoqda.

ISSN 3030-3907

O‘zbekiston iqtisodiyotiga bag‘ishlangan ilmiy ishlarda esa sun'iy intellekt texnologiyalarining davlat boshqaruvi, elektron hukumat, ta'lim tizimi, sog‘liqni saqlash, bank-moliya sektori va sanoat korxonalarida qo‘llanilishi istiqbollari keng tahlil qilinmoqda. Mamlakatda raqamli iqtisodiyot ulushini oshirish, IT xizmatlari eksportini kengaytirish, innovatsion infratuzilmani rivojlantirish hamda yuqori malakali mutaxassislarni tayyorlash davlat siyosatining ustuvor yo‘nalishlari sifatida belgilangan. Shu sababli generativ sun'iy intellektni milliy iqtisodiyotga moslashtirish bo‘yicha ilmiy izlanishlar tobora dolzarb ahamiyat kasb etmoqda.

Shuningdek, ilmiy adabiyotlar tahlili shuni ko‘rsatadiki, generativ sun'iy intellektning iqtisodiyotga ta'siri faqat texnologik rivojlanish bilan cheklanmaydi. Uning samaradorligi institutsional muhit, normativ-huquqiy baza, raqamli infratuzilma, inson kapitali sifati va innovatsion madaniyat darajasi bilan bevosita bog‘liq. Aynan ushbu omillar texnologiyalarning iqtisodiy natijadorligini belgilaydi va ularning uzoq muddatli rivojlanish istiqbollarini shakllantiradi. Demak, mavjud ilmiy qarashlarni umumlashtirish generativ sun'iy intellektning O‘zbekiston iqtisodiyotiga ta'sirini kompleks yondashuv asosida o‘rganish zarurligini ko‘rsatadi. Ushbu maqolaning keyingi bo‘limlarida mazkur nazariy yondashuvlar asosida O‘zbekiston sharoitidagi iqtisodiy imkoniyatlar, rivojlanish tendensiyalari va istiqbollari ilmiy tahlil qilinadi.

NATIJALAR. Tadqiqot natijalari shuni ko‘rsatadiki, generativ sun'iy intellekt texnologiyalarining iqtisodiyot tarmoqlariga joriy etilishi ishlab chiqarish samaradorligi, mehnat unumdorligi va innovatsion faollikning oshishiga sezilarli ta'sir ko‘rsatadi. Raqamli iqtisodiyot sharoitida korxonalar tomonidan sun'iy intellektdan foydalanish ma'lumotlarni qayta ishlash tezligini oshirish, operatsion xarajatlarni kamaytirish hamda boshqaruv qarorlarining aniqligini kuchaytirish imkonini bermoqda. Natijada korxonalarning bozor sharoitlariga moslashuvchanligi ortib, mahsulot va xizmatlarning raqobatbardoshligi oshmoqda.

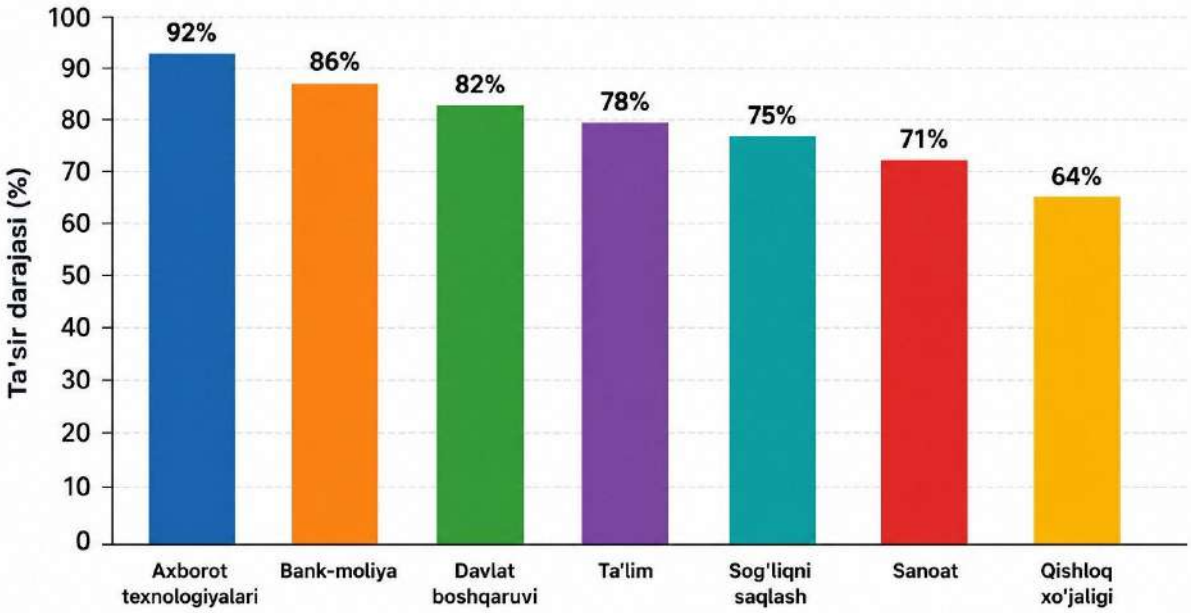
Nazariy tahlillar shuni anglatadiki, generativ sun'iy intellekt iqtisodiy o‘sishning yangi omili sifatida namoyon bo‘lmoqda. Mazkur texnologiyalar korxonalarda takrorlanuvchi vazifalarni avtomatlashtirish orqali xodimlarning vaqtini murakkab tahliliy, ijodiy va strategik faoliyatga yo‘naltirish imkonini yaratadi. Buning natijasida inson kapitalidan foydalanish samaradorligi ortadi, ishlab chiqarish jarayonlarida resurslar tejaladi va qo‘shimcha qiymat yaratish hajmi kengayadi. O‘zbekiston sharoitida olib borilgan tahlillar generativ sun'iy intellektni davlat boshqaruvi, bank-moliya, ta'lim, sog‘liqni saqlash, sanoat va xizmat ko‘rsatish sohalariga bosqichma-bosqich integratsiya qilish uchun muhim imkoniyatlar mavjudligini ko‘rsatadi. Davlat xizmatlarini raqamlashtirish, elektron hukumat tizimining rivojlanishi, IT infratuzilmasining kengayishi hamda raqamli tadbirkorlikni qo‘llab-quvvatlash bo‘yicha amalga oshirilayotgan islohotlar ushbu

ISSN 3030-3907

texnologiyalarni amaliyotga tatbiq etish uchun qulay institutsional muhitni shakllantirmoqda.

Tahlillar shuni ko‘rsatadiki, generativ sun'iy intellektdan foydalanish kichik va o‘rta biznes subyektlari faoliyatida ham sezilarli ijobiy natijalar berishi mumkin. Marketing strategiyalarini ishlab chiqish, mijozlar bilan muloqotni avtomatlashtirish, biznes-rejalarni shakllantirish, bozor talabini prognoz qilish hamda moliyaviy tahlillarni amalga oshirishda sun'iy intellektdan foydalanish korxonalarning raqobat ustunligini mustahkamlaydi. Shu bilan birga, innovatsion mahsulot va xizmatlarni yaratish jarayonining tezlashishi yangi biznes modellarining shakllanishiga xizmat qiladi.

1-diagramma. Generativ sun'iy intellektning iqtisodiyot tarmoqlariga kutilayotgan ta'sir darajasi



Izoh: Diagrammada generativ sun'iy intellekt texnologiyalarining O'zbekiston iqtisodiyotining turli tarmoqlariga kutilayotgan nisbiy ta'sir darajasi foizlarda ko'rsatilgan. Ma'lumotlar tahliliy baholash asosida tuzilgan.

1-diagramma tahlili. Generativ sun'iy intellektning O‘zbekiston iqtisodiyotining asosiy tarmoqlariga kutilayotgan ta'siri:

1-diagrammada generativ sun'iy intellekt texnologiyalarining O‘zbekiston iqtisodiyotining ustuvor tarmoqlariga kutilayotgan ta'sir darajasi qiyosiy tahlil asosida aks ettirilgan. Diagramma natijalari shuni ko‘rsatadiki, axborot texnologiyalari sohasi generativ sun'iy intellektni joriy etishdan eng yuqori darajada foyda olishi mumkin. Buning asosiy sababi dasturiy mahsulotlarni ishlab chiqish, ma'lumotlarni qayta ishlash, algoritmlarni optimallashtirish hamda raqamli xizmatlar ko‘lamining jadal kengayishi bilan izohlanadi. Sun'iy intellekt vositalari dasturchilar va muhandislarning mehnat unumdorligini oshirish, dasturiy xatolarni kamaytirish hamda yangi mahsulotlarni yaratish muddatini qisqartirish imkonini beradi.

ISSN 3030-3907

Bank-moliya sohasi diagrammada ikkinchi yuqori ko‘rsatkichni egallaydi. Ushbu natija moliyaviy tahlil, kredit xavfini baholash, firibgarlik holatlarini aniqlash, mijozlarga xizmat ko‘rsatish va biznes jarayonlarini avtomatlashtirishda generativ sun'iy intellektning keng qo‘llanilishi bilan bog‘liq. Natijada moliyaviy institutlar faoliyatining samaradorligi ortadi, operatsion xarajatlar kamayadi hamda xizmatlar sifati yaxshilanadi. Davlat boshqaruvi sohasida generativ sun'iy intellekt davlat xizmatlarini raqamlashtirish, hujjatlar aylanishini soddalashtirish, murojaatlarni avtomatik tahlil qilish va boshqaruv qarorlarini qabul qilish jarayonlarini qo‘llab-quvvatlash orqali yuqori samaradorlikni ta'minlashi mumkin. Bu esa davlat boshqaruvida shaffoflik, tezkorlik va fuqarolarga ko‘rsatilayotgan xizmatlar sifatining oshishiga xizmat qiladi.

Ta'lim va sog‘liqni saqlash sohalarida sun'iy intellekt shaxsiylashtirilgan ta'lim platformalarini yaratish, ilmiy tadqiqotlarni qo‘llab-quvvatlash, kasalliklarni tashxislash hamda davolash jarayonlarini takomillashtirish imkonini beradi. Shu bilan birga, sanoat va qishloq xo‘jaligi tarmoqlarida ishlab chiqarish jarayonlarini avtomatlashtirish, resurslardan oqilona foydalanish, mahsulot sifatini nazorat qilish va prognozlash tizimlarini rivojlantirish orqali iqtisodiy samaradorlikni oshirish imkoniyatlari mavjud.

Umuman olganda, diagramma natijalari generativ sun'iy intellektning iqtisodiyotning barcha tarmoqlarida bir xil darajada emas, balki ularning raqamlashtirish darajasi, texnologik tayyorgarligi va innovatsion salohiyatiga qarab turlicha ta'sir ko‘rsatishini namoyon etadi. Shu sababli generativ sun'iy intellektni iqtisodiyot tarmoqlariga bosqichma-bosqich joriy etish, zarur infratuzilmani rivojlantirish hamda malakali kadrlar tayyorlash O‘zbekistonning uzoq muddatli iqtisodiy rivojlanishini ta'minlashning muhim omillaridan biri hisoblanadi.

Tadqiqot natijalari mehnat bozori nuqtai nazaridan ham muhim xulosalarni ko‘rsatadi. Generativ sun'iy intellekt ayrim takrorlanuvchi kasbiy vazifalarni avtomatlashtirishi mumkin bo‘lsa-da, u bilan bir qatorda yangi kasblar va yangi malaka talablarini ham yuzaga keltiradi. Sun'iy intellekt tizimlarini ishlab chiqish, ularga xizmat ko‘rsatish, ma'lumotlarni tahlil qilish, raqamli xavfsizlikni ta'minlash va algoritmlarni nazorat qilish kabi yo‘nalishlarda yuqori malakali mutaxassislarga ehtiyoj ortadi. Bu esa ta'lim tizimini zamonaviy mehnat bozori talablariga mos ravishda takomillashtirish zarurligini ko‘rsatadi.

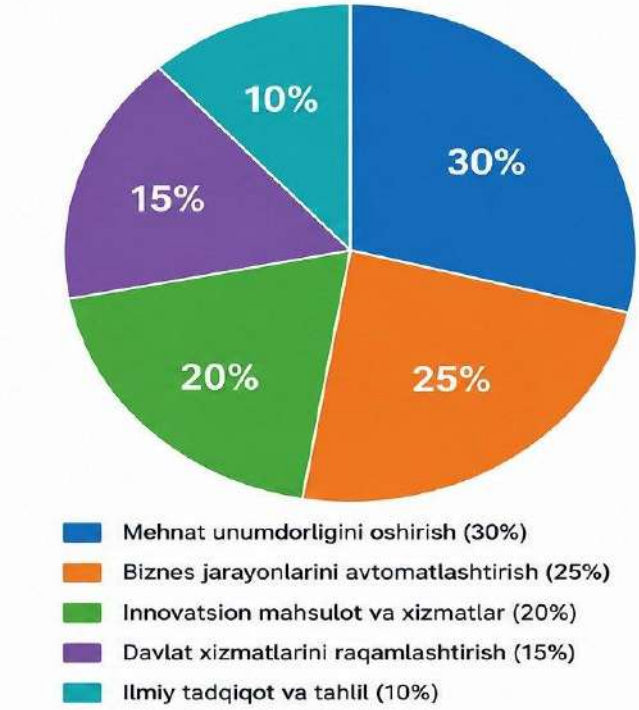
Tahlillar yana shuni ko‘rsatadiki, generativ sun'iy intellekt ilmiy tadqiqotlar samaradorligini ham oshiradi. Ilmiy ma'lumotlarni tizimlashtirish, katta hajmdagi axborotni qisqa vaqt ichida tahlil qilish, ilmiy modellarni yaratish va prognozlash imkoniyatlarining kengayishi ilmiy izlanishlar sifatini yangi bosqichga olib chiqadi. Bu esa innovatsion iqtisodiyotning rivojlanishiga hamda yuqori

ISSN 3030-3907

texnologik mahsulotlar ulushining ortishiga ijobiy ta'sir ko‘rsatadi. Shu bilan birga, tadqiqot davomida generativ sun'iy intellektni keng joriy etish bilan bog‘liq ayrim cheklovlar ham aniqlandi. Xususan, malakali kadrlar yetishmovchiligi, yuqori hisoblash infratuzilmasiga bo‘lgan ehtiyoj, ma'lumotlar xavfsizligi, axloqiy me'yorlarga rioya etish va normativ-huquqiy bazani takomillashtirish zarurati ushbu texnologiyalarning samarali qo‘llanilishiga bevosita ta'sir qiluvchi omillar hisoblanadi. Mazkur muammolarni tizimli ravishda bartaraf etish generativ sun'iy intellektning iqtisodiyotga ijobiy ta'sirini yanada kuchaytirishi mumkin.

2-diagramma. Generativ sun’iy intellektdan foydalanishning asosiy iqtisodiy yo‘nalishlari

(Ulush, %)



Izoh: Ulushlar umumiy iqtisodiy ta’sir tarkibi bo‘yicha shakllantirilgan (100% = jami).

2-diagramma tahlili. Generativ sun'iy intellektdan foydalanishning asosiy iqtisodiy yo‘nalishlari:

2-diagrammada generativ sun'iy intellekt texnologiyalaridan foydalanishning iqtisodiyotdagi asosiy yo‘nalishlari ulushlar kesimida aks ettirilgan. Diagramma tahlili shuni ko‘rsatadiki, eng katta ulush mehnat unumdorligini oshirishga to‘g‘ri keladi. Bu holat sun'iy intellektning takrorlanuvchi vazifalarni avtomatlashtirish, katta hajmdagi ma'lumotlarni tezkor qayta ishlash hamda boshqaruv qarorlarini qo‘llab-quvvatlash imkoniyatlari bilan izohlanadi. Natijada korxonalar vaqt va moddiy resurslardan yanada samarali foydalanish imkoniyatiga ega bo‘lib, ishlab chiqarish xarajatlari qisqaradi va iqtisodiy samaradorlik ortadi.

ISSN 3030-3907

Diagrammada biznes jarayonlarini avtomatlashtirish ham muhim ulushni egallagan. Ushbu yo‘nalishda generativ sun'iy intellekt hujjatlar aylanishini optimallashtirish, mijozlarga xizmat ko‘rsatishni tezlashtirish, marketing strategiyalarini ishlab chiqish, moliyaviy tahlillarni amalga oshirish hamda korxona faoliyatini rejalashtirishda muhim vosita sifatida namoyon bo‘ladi. Bunday imkoniyatlar, ayniqsa, kichik va o‘rta biznes subyektlarining raqobatbardoshligini oshirishda alohida ahamiyat kasb etadi.

Innovatsion mahsulot va xizmatlarni yaratish diagrammada uchinchi muhim yo‘nalish sifatida ifodalangan. Generativ sun'iy intellekt yangi mahsulotlarni loyihalash, dasturiy yechimlarni ishlab chiqish, raqamli servislarni takomillashtirish hamda bozor talabiga mos innovatsion xizmatlarni yaratish jarayonini sezilarli darajada tezlashtiradi. Bu esa yuqori qo‘shilgan qiymatga ega mahsulotlar ulushining ortishiga va milliy iqtisodiyotning innovatsion salohiyati mustahkamlanishiga xizmat qiladi. Davlat xizmatlarini raqamlashtirish hamda ilmiy tadqiqot va tahlil yo‘nalishlari diagrammada nisbatan kichikroq ulushni egallagan bo‘lsa-da, ularning strategik ahamiyati yuqori hisoblanadi. Davlat boshqaruvida sun'iy intellektdan foydalanish xizmatlar sifati, shaffoflik va tezkorlikni oshirishga yordam beradi. Ilmiy tadqiqotlarda esa katta hajmdagi ma'lumotlarni tahlil qilish, prognoz modellarini ishlab chiqish va yangi ilmiy g‘oyalarni shakllantirish imkoniyatlari kengayadi.

Umuman olganda, doiraviy diagramma natijalari generativ sun'iy intellekt texnologiyalarining iqtisodiyotning turli yo‘nalishlarida keng qo‘llanilish salohiyatiga ega ekanligini ko‘rsatadi. Mazkur texnologiyalarni izchil joriy etish mehnat unumdorligini oshirish, innovatsion rivojlanishni jadallashtirish, davlat boshqaruvi samaradorligini kuchaytirish hamda milliy iqtisodiyotning xalqaro raqobatbardoshligini yuksaltirishga xizmat qiladi.

Umuman olganda, olingan natijalar generativ sun'iy intellekt texnologiyalarining O‘zbekiston iqtisodiyotini modernizatsiya qilish, raqamli transformatsiyani jadallashtirish, innovatsion faoliyatni kengaytirish va xalqaro raqobatbardoshlikni oshirishda muhim strategik vosita ekanligini tasdiqlaydi. Ushbu texnologiyalarni izchil joriy etish orqali iqtisodiyotning turli tarmoqlarida samaradorlikni oshirish, yangi ish o‘rinlarini yaratish, eksport salohiyatini kuchaytirish hamda bilimlarga asoslangan iqtisodiyot modeliga o‘tishni tezlashtirish uchun mustahkam zamin yaratiladi.

MUHOKAMA. Mazkur tadqiqot natijalari generativ sun'iy intellekt texnologiyalarining O‘zbekiston iqtisodiyotini tarkibiy jihatdan modernizatsiya qilish va raqamli transformatsiya jarayonlarini jadallashtirishdagi strategik ahamiyatini tasdiqlaydi. Olingan ilmiy xulosalar shuni ko‘rsatadiki, sun'iy intellektni iqtisodiyotning ustuvor tarmoqlariga izchil joriy etish mehnat

ISSN 3030-3907

unumdorligini oshirish, resurslardan foydalanish samaradorligini yaxshilash hamda innovatsion mahsulot va xizmatlar ulushini ko‘paytirish uchun muhim imkoniyatlar yaratadi. Bu holat iqtisodiy o‘sishning an'anaviy omillaridan innovatsiyalar va bilimlarga asoslangan rivojlanish modeliga bosqichma-bosqich o‘tish zaruratini yanada kuchaytiradi. Tahlillar shuni ko‘rsatadiki, generativ sun'iy intellektni joriy etishning iqtisodiy samarasi faqat yangi texnologiyalarni xarid qilish bilan emas, balki ularni boshqaruv tizimlari, ishlab chiqarish jarayonlari va inson kapitali bilan uyg‘unlashtirish darajasiga ham bevosita bog‘liq. Korxonalarda raqamli boshqaruv madaniyati shakllanmagan yoki xodimlarning raqamli kompetensiyasi yetarli bo‘lmagan sharoitda sun'iy intellektning imkoniyatlaridan to‘liq foydalanish qiyinlashadi. Shu sababli texnologik investitsiyalar bilan bir qatorda kadrlar tayyorlash, qayta tayyorlash va uzluksiz kasbiy rivojlanish tizimlarini takomillashtirish ustuvor vazifalardan biri bo‘lib qolmoqda.

Muhokama natijalari shuni ham ko‘rsatadiki, generativ sun'iy intellektning ta'siri iqtisodiyotning barcha tarmoqlarida bir xil darajada namoyon bo‘lmaydi. Bilim va axborotga asoslangan xizmatlar, bank-moliya, axborot texnologiyalari, ta'lim hamda sog‘liqni saqlash sohalarida texnologiyalarni joriy etish nisbatan tez amalga oshirilishi mumkin. Biroq sanoat, qishloq xo‘jaligi va transport kabi sohalarda sun'iy intellektdan samarali foydalanish uchun qo‘shimcha texnologik infratuzilma, raqamlashtirilgan ishlab chiqarish jarayonlari va yuqori sifatli ma'lumotlar bazasi talab etiladi. Bu esa tarmoqlar kesimida differensial rivojlanish strategiyasini ishlab chiqish zarurligini anglatadi.

Shuningdek, generativ sun'iy intellektning mehnat bozoriga ta'siri yuzasidan ham muvozanatli yondashuv zarur. Ayrim kasblarda takrorlanuvchi vazifalarning avtomatlashtirilishi ish jarayonlarini optimallashtirsa-da, inson omili strategik qarorlar qabul qilish, kreativ fikrlash, murakkab muzokaralar olib borish va ijtimoiy muloqot talab qiladigan faoliyatlarda o‘z ahamiyatini saqlab qoladi. Demak, kelajakdagi raqobat ustunligi inson va sun'iy intellektning o‘zaro hamkorligiga asoslangan gibrid mehnat modelini shakllantirish bilan bog‘liq bo‘ladi.

Tadqiqot davomida aniqlangan muhim jihatlardan biri generativ sun'iy intellektning kichik va o‘rta biznes uchun ochayotgan yangi imkoniyatlaridir. An'anaviy sharoitda katta moliyaviy resurs talab qiladigan marketing, biznes tahlili, mahsulot dizayni, mijozlarga xizmat ko‘rsatish va hujjatlar tayyorlash kabi jarayonlar sun'iy intellekt vositalari orqali nisbatan arzon va tez amalga oshirilishi mumkin. Bu esa kichik biznes subyektlarining innovatsion salohiyatini oshirib, ichki va tashqi bozorlarda raqobatbardoshligini kuchaytiradi.

ISSN 3030-3907

Boshqa tomondan, generativ sun'iy intellektning ommalashuvi bilan bog‘liq axloqiy va huquqiy masalalar ham alohida e'tibor talab qiladi. Sun'iy intellekt tomonidan yaratilgan kontentning ishonchliligi, mualliflik huquqi, shaxsiy ma'lumotlarni himoya qilish, algoritmik xolislik va kiberxavfsizlik masalalari kelgusida davlat siyosatining muhim yo‘nalishlaridan biriga aylanishi mumkin. Shu sababli texnologik rivojlanish huquqiy tartibga solish mexanizmlari, xalqaro standartlar va milliy etik tamoyillar bilan uyg‘un ravishda olib borilishi lozim. O‘zbekiston sharoitida generativ sun'iy intellektni rivojlantirish uchun oliy ta'lim muassasalari, ilmiy-tadqiqot institutlari, davlat organlari va xususiy sektor o‘rtasidagi hamkorlikni kuchaytirish muhim ahamiyatga ega.

Universitetlarda sun'iy intellekt, ma'lumotlar tahlili va raqamli iqtisodiyot yo‘nalishlaridagi ta'lim dasturlarini kengaytirish, ilmiy laboratoriyalarni zamonaviy texnologiyalar bilan jihozlash hamda innovatsion startaplarni qo‘llab-quvvatlash milliy innovatsion ekotizimning rivojlanishiga xizmat qiladi. Bundan tashqari, xalqaro ilmiy hamkorlikni kengaytirish va ilg‘or tajribalarni milliy sharoitga moslashtirish ham generativ sun'iy intellektni samarali joriy etishning muhim shartlaridan biridir.

Umuman olganda, muhokama natijalari generativ sun'iy intellektni iqtisodiyotga tatbiq etish texnologik yangilikni joriy etish bilangina cheklanmasligini ko‘rsatadi. Uning muvaffaqiyati raqamli infratuzilmaning rivojlanganligi, inson kapitalining sifati, ilmiy salohiyat, innovatsion muhit, institutsional islohotlar va samarali davlat siyosati bilan uzviy bog‘liq. Aynan ushbu omillar uyg‘unlashgan taqdirdagina generativ sun'iy intellekt O‘zbekistonning uzoq muddatli iqtisodiy o‘sishi, xalqaro raqobatbardoshligi va bilimlarga asoslangan iqtisodiyotga o‘tish jarayonining asosiy harakatlantiruvchi kuchlaridan biriga aylanishi mumkin.

XULOSA. Mazkur tadqiqot generativ sun'iy intellekt texnologiyalarining O‘zbekiston iqtisodiyotini modernizatsiya qilish, raqamli transformatsiyani jadallashtirish va innovatsion rivojlanishni ta'minlashdagi strategik ahamiyatini ilmiy-nazariy jihatdan asoslab berdi. Tahlillar shuni ko‘rsatdiki, ushbu texnologiyalar ishlab chiqarish samaradorligini oshirish, mehnat unumdorligini yaxshilash, davlat boshqaruvi va biznes jarayonlarini optimallashtirish hamda yangi iqtisodiy imkoniyatlarni shakllantirishda muhim omil hisoblanadi. Shu bilan birga, generativ sun'iy intellektni samarali joriy etish raqamli infratuzilmani rivojlantirish, yuqori malakali kadrlar tayyorlash, axborot xavfsizligini ta'minlash va huquqiy-me'yoriy bazani takomillashtirish bilan chambarchas bog‘liq. O‘zbekiston sharoitida sun'iy intellekt texnologiyalaridan oqilona foydalanish milliy iqtisodiyotning raqobatbardoshligini oshirish, innovatsion ekotizimni mustahkamlash hamda bilimlarga asoslangan iqtisodiyot modelini shakllantirishga

ISSN 3030-3907

xizmat qiladi. Kelgusida generativ sun'iy intellektni iqtisodiyotning ustuvor tarmoqlariga izchil integratsiya qilish barqaror iqtisodiy o‘sish, yuqori qo‘shilgan qiymat yaratish va xalqaro iqtisodiy makondagi raqobat ustunligini kuchaytirishning muhim shartlaridan biri bo‘lib qoladi.

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ISSN 3030-3907

YASSI VA VAKUUM QUYOSH KOLLEKTORLARI ASOSIDA TRANSFORMATOR MOYINI TOZALOVCHI MOBIL MINI PROTOTIP QURILMANI MODELLASHTIRISH

Qo‘chqorov Akmaljon Axmadaliyevich
Farg‘ona davlat texnika universiteti, Energatika muhandisligi fakulteti dotsenti
Sarsenbaev Dauletbay Baktibaevich
O‘zbekiston Respublikasi Energetika vazirligi huzuridagi Qayta tiklanuvchi energiya manbalari milliy ilmiy-tadqiqot instituti tayanch doktoranti

Annotatsiya. Maqolada transformator moyini quyosh issiqligi yordamida qizdirish, ketma-ket mexanik, magnit va adsorbent filtrlardan o‘tkazish hamda vakuum ostida namlik va erigan gazlarni kamaytirishga mo‘ljallangan mobil mini prototip qurilma modeli taklif etilgan. Yassi va vakuum kollektorli variantlar bir xil boshlang‘ich sharoitlarda qiyoslandi. 1 litr moyni 25 °C dan 80 °C va 100 °C gacha qizdirish uchun nazariy energiya sarfi, kollektorlarning real foydali quvvati, qizdirish davomiyligi va sirkulyatsion nasos energiya sarfi hisoblandi. Model natijalariga ko‘ra, vakuum kollektorli variant 80 °C rejimida qizdirish vaqtini 39,2 minutdan 31,3 minutgacha, nasos sarfini esa 0,0327 kWh dan 0,0261 kWh gacha kamaytiradi. Natijalar vakuum kollektorli yechimning yuqori haroratli kichik hajmli moyni qayta ishlash jarayonlari uchun istiqbolli ekanini ko‘rsatadi. Biroq yakuniy samaradorlikni baholash uchun tajribaviy harorat, namlik va dielektrik mustahkamlik ko‘rsatkichlari bilan validatsiya talab etiladi.

Kalit so‘zlar: transformator moyi, quyosh kollektori, vakuum kollektor, yassi kollektor, moyni tozalash, vakuum degazatsiya, mobil prototip, energiya samaradorligi.

Abstract. A mobile mini-prototype for transformer-oil treatment is proposed by integrating solar thermal heating, mechanical, magnetic and adsorbent filtration, and vacuum dehydration. Flat-plate and evacuated-tube collector configurations were compared under identical boundary conditions. The theoretical heat demand for heating 1 L of oil from 25 °C to 80 °C and 100 °C, useful collector output, heating time and circulation-pump electricity consumption were calculated. The model predicts that the evacuated-tube option reduces the heating time at 80 °C from 39.2 min to 31.3 min and pump electricity from 0.0327 kWh to 0.0261 kWh. Experimental validation through temperature, moisture and dielectric-breakdown measurements remains necessary.

Keywords: transformer oil, solar thermal collector, evacuated tube, flat plate, oil purification, vacuum dehydration, mobile prototype.

Аннотация. В статье предложена модель мобильной мини-прототипной установки, предназначенной для нагрева трансформаторного масла с

использованием солнечной тепловой энергии, его последовательной очистки через механический, магнитный и адсорбционный фильтры, а также снижения содержания влаги и растворённых газов в условиях вакуума. Проведено сравнительное исследование вариантов с плоским и вакуумным солнечными коллекторами при одинаковых исходных условиях. Рассчитаны теоретические затраты энергии на нагрев 1 литра масла от 25 °C до 80 °C и 100 °C, определены реальная полезная мощность коллекторов, продолжительность процесса нагрева и энергопотребление циркуляционного насоса. Согласно результатам моделирования, применение вакуумного коллектора позволяет сократить время нагрева в режиме 80 °C с 39,2 до 31,3 минуты, а энергопотребление насоса — с 0,0327 до 0,0261 кВт·ч. Полученные результаты свидетельствуют о перспективности использования вакуумного солнечного коллектора для процессов обработки небольших объёмов трансформаторного масла при повышенных температурах. Однако для окончательной оценки эффективности требуется экспериментальная валидация с использованием показателей температуры, влажности и диэлектрической прочности масла.
Ключевые слова: трансформаторное масло, солнечный коллектор, вакуумный коллектор, плоский коллектор, очистка масла, вакуумная дегазация, мобильный прототип, энергоэффективность.

1. KIRISH.

Kuch transformatorlarida mineral moy bir vaqtning o‘zida elektr izolyatsiyasi va issiqlik tashuvchi muhit vazifasini bajaradi. Ekspluatatsiya davomida moy tarkibida namlik, mexanik zarrachalar, oksidlanish mahsulotlari va erigan gazlarning ortishi uning dielektrik xossalari hamda issiqlik uzatish qobiliyatini yomonlashtiradi. Shu sababli moyni filtrlash, qizdirish, vakuum ostida quritish va degazatsiya qilish transformatorlarning ishonchli ishlashini ta’minlovchi muhim profilaktik jarayon hisoblanadi.

IEC 60422:2024 ekspluatatsiyadagi mineral izolyatsion moylarni nazorat qilish va xizmat ko‘rsatish bo‘yicha yo‘riqlarni belgilaydi, IEC 60296:2020 esa yangi hamda qayta ishlangan mineral izolyatsion moylarning spetsifikatsiyasi va sinov usullarini qamrab oladi. Moydagi suv miqdorini aniqlash uchun Karl Fischer kulonometrik usuli IEC 60814 talablarida bayon etilgan [1–3].

An’anaviy moy tozalash qurilmalari odatda elektr qizdirgichlar va tarmoq elektr energiyasiga tayanadi. Quyosh issiqlik kollektoridan foydalanish, ayniqsa quyosh radiatsiyasi yuqori hududlarda, moyni dastlabki va ishchi haroratgacha qizdirish uchun tashqi energiya talabini kamaytirishi mumkin. Mobil platforma esa

ISSN 3030-3907

xizmat ko‘rsatish punktidan uzoqdagi transformatorlarga qurilmani olib borish imkonini beradi.

Tadqiqotning maqsadi — yassi va vakuum quyosh kollektorli mobil mini prototipning issiqlik-energetik ko‘rsatkichlarini hisoblash, ularning qizdirish tezligi va yordamchi elektr sarfini qiyoslash hamda tajriba namunasi uchun konstruktiv yechimni asoslash.

2. TADQIQOT OBYEKTI VA METODLARI.

Tadqiqot obyekti sifatida 1 litr eskirgan transformator moyini yopiq sirkulyatsiya konturida qizdirish va bosqichma-bosqich tozalashga mo‘ljallangan mobil qurilma qabul qilindi. Qurilma eskirgan moy baki, 50 W quvvatli nasos, yassi yoki vakuum kollektor, mexanik filtr, magnit filtr, adsorbent filtr, vakuum kamera, tozalangan moy baki, fotoelektr panel, MPPT kontroller, akkumulyator va boshqaruv panelidan tashkil topadi.

1-jadval.

Modellashtirish uchun boshlang‘ich parametrlar

Ko‘rsatkich	Qiymat
Moy hajmi	1 L
Moy zichligi, ρ	0,89 kg/L
Moy massasi, m	0,89 kg
Solishtirma issiqlik sig‘imi, c	1,9 kJ/(kg·K)
Boshlang‘ich harorat, T_0	25 °C
Ishchi haroratlar	80 va 100 °C
Quyosh oqimi, G	800 W/m²
Nasos quvvati	50 W

Moyni qizdirish uchun zarur nazariy issiqlik miqdori energiya balansi asosida aniqlandi:

$$Q = m \cdot c \cdot \Delta T, \quad \Delta T = T_2 - T_1$$

Bu yerda Q — issiqlik miqdori, kJ; m — moy massasi, kg; c — moyning solishtirma issiqlik sig‘imi, kJ/(kg·K); ΔT — haroratlar farqi, K. Hisob bo‘yicha 25 °C dan 80 °C gacha Q_{80} = 93,0 kJ = 0,0258 kWh, 25 °C dan 100 °C gacha esa Q_{100} = 126,8 kJ = 0,0352 kWh.

Bak, quvur, filtrlar va atrof-muhitga issiqlik yo‘qotishlarini hisobga olish uchun loyihaviy energiya talabi yassi kollektor uchun mos ravishda 0,040 va 0,055 kWh, vakuum kollektor uchun 0,035 va 0,048 kWh deb qabul qilindi. Ushbu qiymatlar prototipni dastlabki o‘lchamlash uchun qabul qilingan model parametrlaridir; tajribada ular alohida issiqlik balansi orqali aniqlashtiriladi.

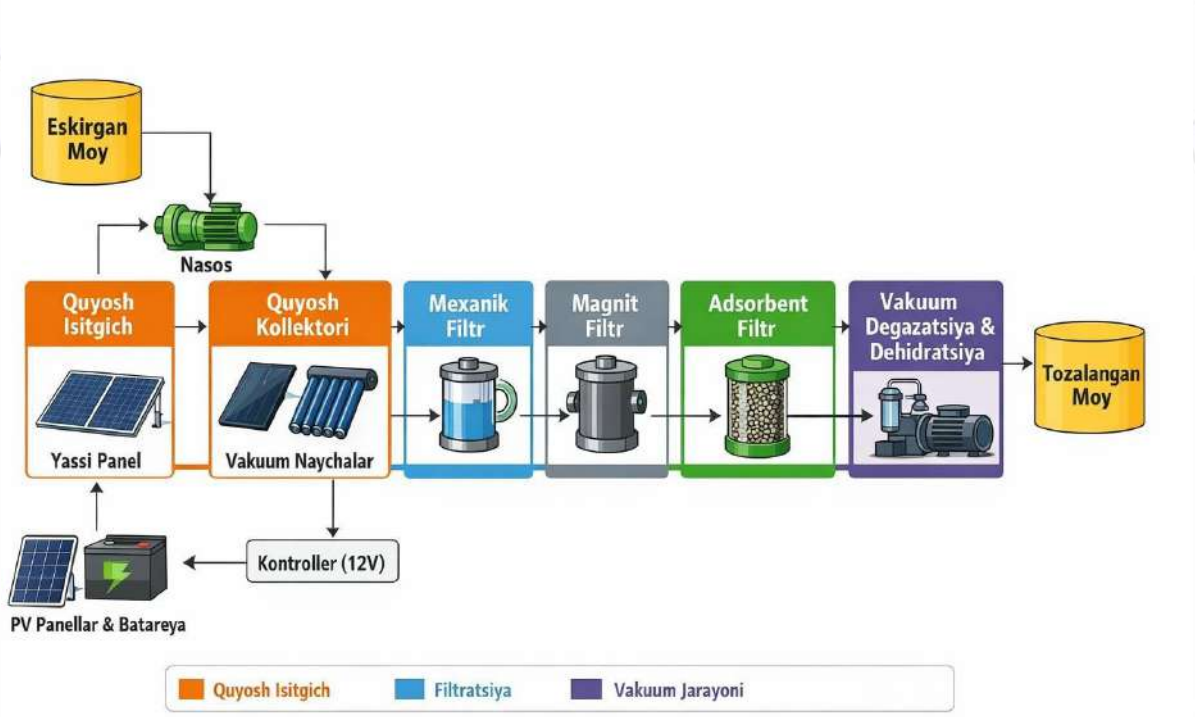
Kollektorning foydali issiqlik quvvati quyidagi ifoda bilan hisoblandi:

$$P_u = G \cdot A \cdot \eta \cdot k_l$$

ISSN 3030-3907

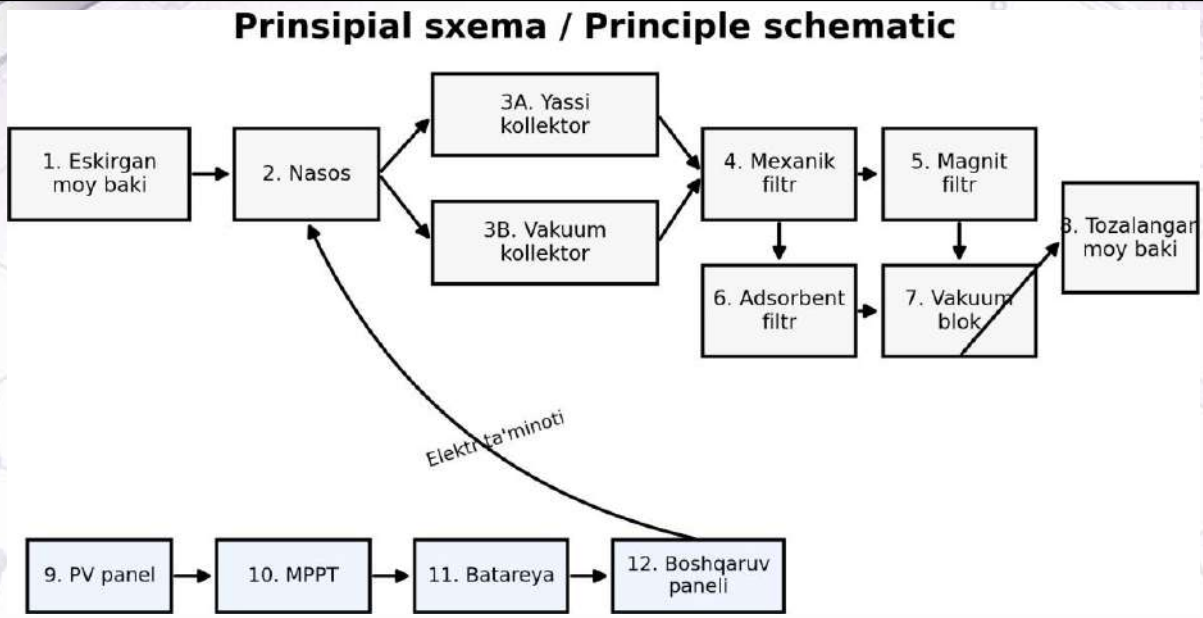
Bu yerda G — kollektor tekisligiga tushuvchi quyosh oqimi, W/m²; A — kollektor yuzasi, m²; η — optik-issiqlik samaradorligi; k_l — tashqi ekspluatatsion yo‘qotishlarni hisobga oluvchi koeffitsient. Yassi kollektor uchun A = 0,20 m², η = 0,45 va k_l = 0,85; vakuum kollektor uchun A = 0,15 m², η = 0,60 va k_l = 0,93 qabul qilindi.

Qizdirish vaqti $t = Q/P_u$, nasos elektr sarfi esa $E_n = P_n \cdot t$ formulalari orqali aniqlandi. Kollektorlar bo‘yicha qiyoslash bir xil quyosh oqimi va boshlang‘ich harorat sharoitida bajarildi.



1-rasm. Mobil mini prototipning texnologik oqim va energiya ta’minoti tuzilmasi

ISSN 3030-3907



2-rasm. Qurilmaning prinsipial sxemasi

3. HISOBLASH NATIJALARI VA TAHLIL.

Hisoblash natijasida yassi kollektorning nazariy quvvati 72 W, ekspluatatsion yo‘qotishlardan keyingi real foydali quvvati 61,2 W bo‘ldi. Vakuum kollektorning nazariy quvvati ham 72 W bo‘lsa-da, issiqlik yo‘qotishlari kamroq qabul qilingani sababli real foydali quvvat 67,0 W ni tashkil etdi.

2-jadval.

Yassi va vakuum kollektorli variantlarning qiyosiy ko‘rsatkichlari

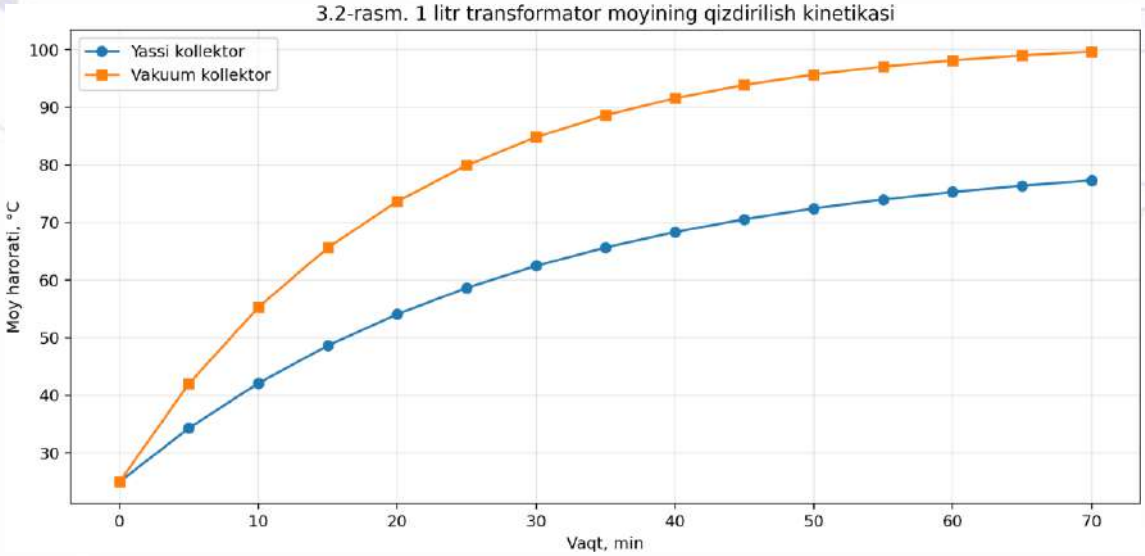
Ko‘rsatkich	Yassi kollektor	Vakuum kollektor	Farq
Kollektor yuzasi, m²	0,20	0,15	−25,0 %
Qabul qilingan samaradorlik, η	0,45	0,60	+33,3 %
Real foydali quvvat, W	61,2	67,0	+9,5 %
25→80 °C qizdirish vaqti, min	39,2	31,3	−20,2 %
25→100 °C qizdirish vaqti, min	53,9	43,0	−20,2 %
80 °C rejimda nasos sarfi, kWh	0,0327	0,0261	−20,2 %
100 °C rejimda nasos sarfi, kWh	0,0450	0,0358	−20,4 %

Vakuum kollektor yuzasi yassi kollektor yuzasidan 25 % kichik bo‘lishiga qaramay, hisobiy real quvvati 9,5 % yuqori chiqdi. Natijada 80 °C va 100 °C

ISSN 3030-3907

rejimlarida qizdirish davomiyligi qariyb 20,2 % ga qisqardi. Nasos ishlash vaqti qisqarishi yordamchi elektr sarfini ham 20 % atrofida kamaytirdi.

Vakuum kollektorning ustunligi absorber bilan tashqi muhit orasidagi konvektiv issiqlik almashinuvining vakuum qatlami orqali cheklanishi bilan izohlanadi. Adabiyotlarda ham vakuum quvurli kollektorlarning yuqoriroq ishchi haroratlarda va absorber maydoni birligiga nisbatan yassi kollektorlar bilan solishtirganda yuqori issiqlik unumdorligini ko‘rsatishi qayd etilgan [4–6].



3-rasm. 1 litr moyning hisobiy qizish kinetikasi

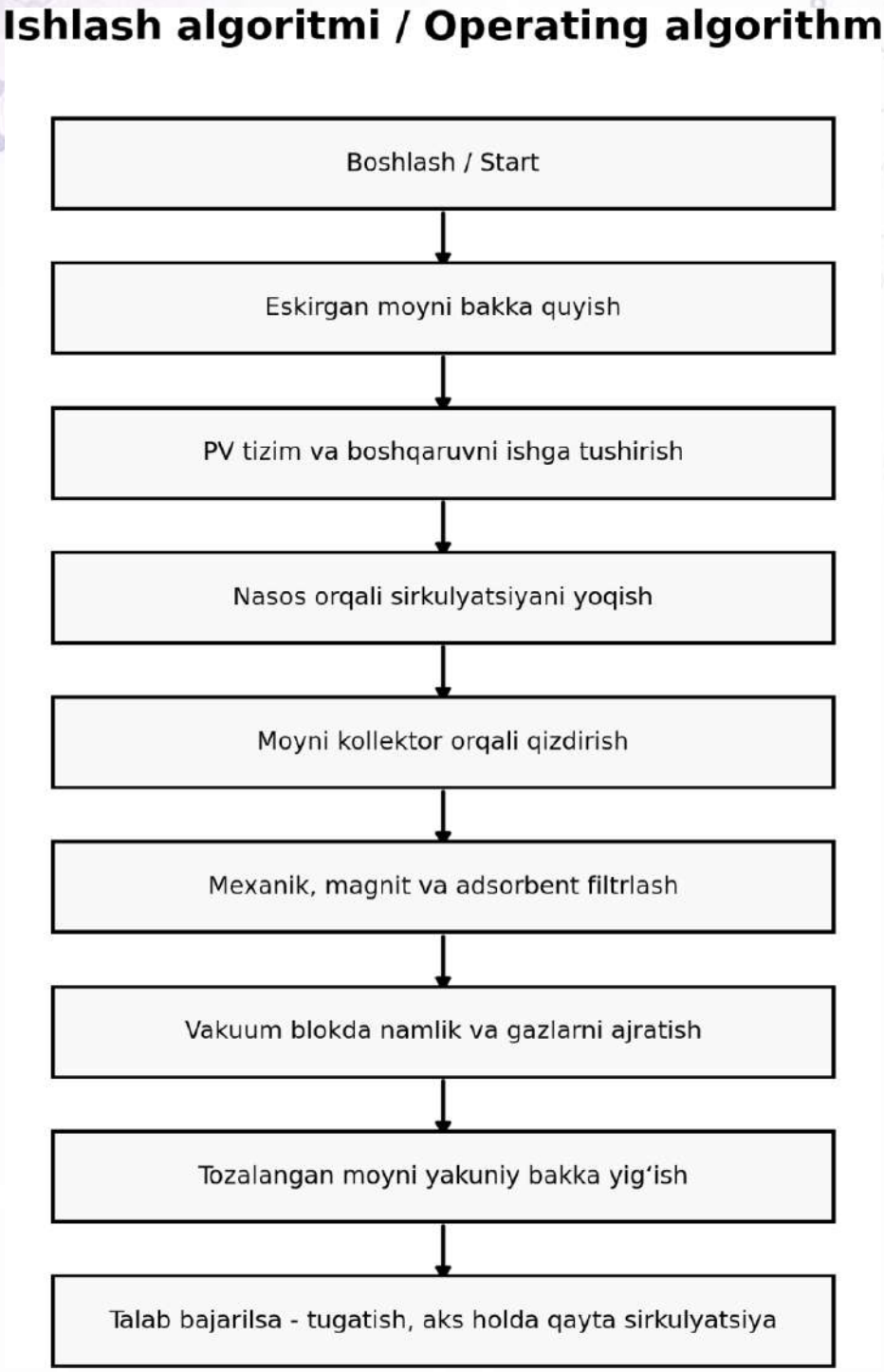
4. TOZALASH JARAYONINING TEXNOLOGIK ASOSLARI.

Taklif etilgan qurilmada moyni qayta ishlash bir necha fizik mexanizmning ketma-ket qo‘llanishiga asoslanadi. Mexanik filtr qattiq zarrachalarni ushlaydi, magnit filtr ferromagnit iflosliklarni ajratadi, adsorbent qatlam esa qutbli oksidlanish mahsulotlari va ayrim erigan aralashmalarni kamaytirishga xizmat qiladi. Qizdirilgan moyning vakuum kameraga uzatilishi suvning bug‘ bosimini oshiradi va past bosim sharoitida namlik hamda yengil erigan gazlarning ajralishini tezlashtiradi.

Qizdirish harorati haddan tashqari oshirilmasligi kerak, chunki uzoq muddatli yuqori harorat moyning oksidlanishini jadallashtirishi mumkin. Shu sababli prototipda harorat datchigi, maksimal harorat bo‘yicha himoya, bosim nazorati, oqim nazorati va favqulodda o‘chirish zanjiri ko‘zda tutilishi lozim. Ishchi diapazon moyning real holati, vakuum darajasi va ishlab chiqaruvchi tavsiyalariga muvofiq tajribada aniqlanadi.

Moy sifatini baholash uchun kamida uchta ko‘rsatkich tavsiya etiladi: suv miqdori, dielektrik teshilish kuchlanishi va kislotalik soni. Qo‘shimcha ravishda dielektrik yo‘qotishlar tangensi, solishtirma qarshilik, rang, zarrachalar miqdori va erigan gazlar tarkibi aniqlanishi mumkin. Har bir tozalash siklidan oldin va keyin olingan namunalar bir xil laboratoriya metodikasi bilan tahlil qilinishi zarur.

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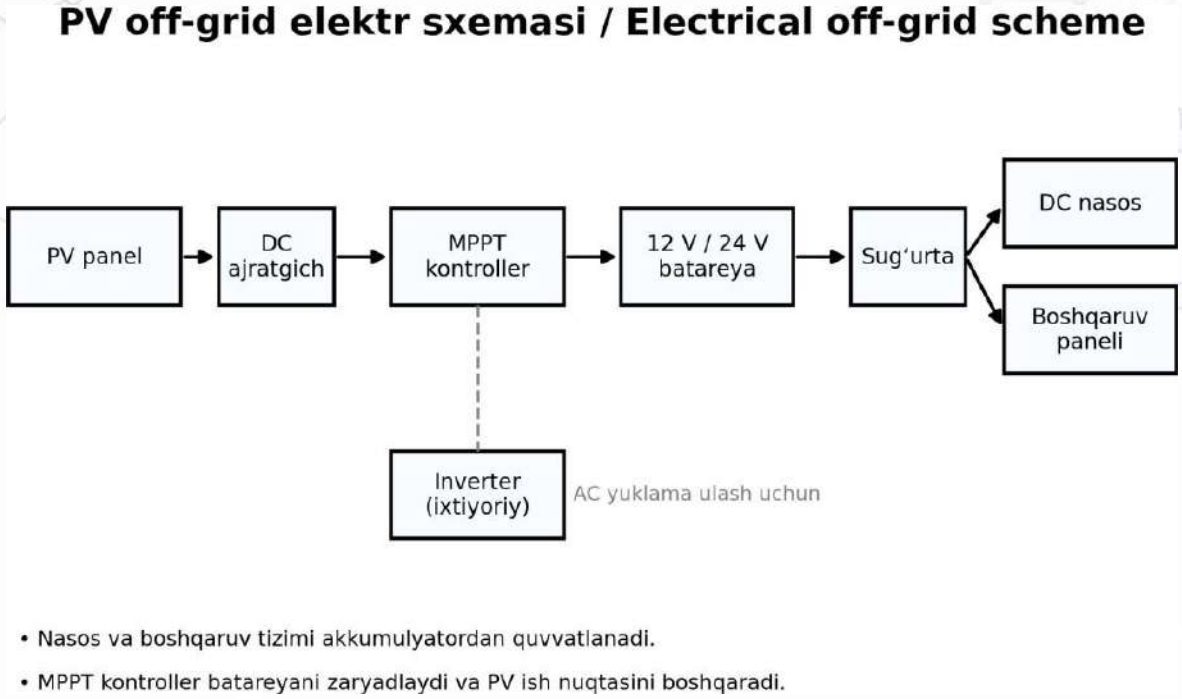
4-rasm. Mobil prototipning ishlash algoritmi

5. AVTONOM ELEKTR TA’MINOTI VA BOSHQARUV.

Sirkulyatsion nasos, vakuum blok va avtomatika elementlarini elektr bilan ta’minlash uchun PV panel–MPPT kontroller–akkumulyator–DC yuklama arxitekturasi taklif etilgan. Bunday konfiguratsiya qurilmaning elektr tarmog‘idan uzoqda ishlash imkoniyatini oshiradi. Akkumulyator sig‘imi nasos va vakuum blokining eng og‘ir ish sikli, invertor yo‘qotishlari, zaryadsizlanish chuqurligi va quyosh radiatsiyasining sutkalik o‘zgarishi asosida tanlanadi.

ISSN 3030-3907

Mazkur maqoladagi nasos energiya hisobi faqat 50 W sirkulyatsion nasosni qamrab oladi. Vakuum nasosi, klapanlar, boshqaruv paneli va boshqa yordamchi yuklamalar quvvati dastlabki ma’lumotlarda berilmagani sababli umumiy PV tizim quvvati yakuniy hisoblanmagan. Shu sababli keyingi loyihalash bosqichida barcha elektr qabul qilgichlarning quvvat-vaqt balansi tuzilishi shart.



5-rasm. PV off-grid elektr ta’minoti sxemasi

6. ILMIY YANGILIK VA TAJRIBAVIY VALIDATSIYA DASTURI

Taklif etilayotgan yechimning ilmiy-amaliy yangiligi transformator moyini qizdirish, ko‘p bosqichli filtrlash, vakuumda quritish va avtonom PV ta’minotini bitta mobil platformada birlashtirish hamda yassi va vakuum kollektorlarni bir xil issiqlik yuklamasida qiyoslashdan iborat.

Modelni tekshirish uchun tajriba stendida har 1–2 minutda kollektor kirish-chiqish harorati, moy baki harorati, quyosh oqimi, tashqi havo harorati, oqim sarfi, vakuum bosimi va elektr quvvat qayd etilishi lozim. Nazariy va tajribaviy harorat egri chiziqlari o‘rtasidagi moslik o‘rtacha kvadratik xatolik orqali baholanadi:

$$RMSE = \sqrt{[(1/n) \cdot \Sigma(T_exp,i - T_mod,i)^2]}$$

Dastlabki materialda RMSE ≈ 2–4 °C diapazoni keltirilgan, biroq tajriba nuqtalari mavjud bo‘lmagani uchun bu qiymat hozircha tasdiqlangan natija emas. Maqolada u maqsadli model aniqligi sifatida qabul qilinadi; haqiqiy RMSE tajriba ma’lumotlari olinib, regressiya va qoldiq tahlili bajarilgandan keyin aniqlanishi kerak.

7. CHEKLOVLAR.

Hisoblash modeli doimiy 800 W/m² quyosh oqimi, o‘zgarmas kollektor samaradorligi va moy xossalarining haroratga bog‘liq bo‘lmasligi farazlariga asoslangan. Amalda quyosh oqimi, shamol tezligi, kollektorning qiyalik burchagi,

ISSN 3030-3907

changlanish, moy viskozligi va oqim sarfi vaqt bo‘yicha o‘zgaradi. Bundan tashqari, qabul qilingan issiqlik yo‘qotish koeffitsientlari tajriba yo‘li bilan kalibrlanmagan. Shuning uchun natijalar prototipni dastlabki tanlash va variantlarni qiyoslash uchun xizmat qiladi, sanoat samaradorligi bo‘yicha yakuniy xulosa sifatida qaralmasligi lozim.

8. XULOSA.

1. 1 litr transformator moyini 25 °C dan 80 °C gacha qizdirish uchun nazariy issiqlik talabi 0,0258 kWh, 100 °C gacha qizdirish uchun 0,0352 kWh ni tashkil etdi.
2. Qabul qilingan parametrlar bo‘yicha yassi kollektorning real foydali quvvati 61,2 W, vakuum kollektorning real foydali quvvati 67,0 W bo‘ldi.
3. Vakuum kollektorli variant qizdirish vaqtini 80 °C rejimida 39,2 minutdan 31,3 minutgacha, 100 °C rejimida 53,9 minutdan 43,0 minutgacha qisqartirdi.
4. Nasos ish vaqti kamayishi sababli uning elektr sarfi qariyb 20 % ga kamaydi.
5. Quyosh issiqligi, ko‘p bosqichli filtrlash, vakuum quritish va PV ta’minotini mobil platformada birlashtirish dala sharoitida moyni qayta tiklash uchun istiqbolli yechimdir.
6. Keyingi bosqichda model natijalari harorat, namlik, dielektrik teshilish kuchlanishi va elektr sarfi bo‘yicha tajribaviy ma’lumotlar bilan tasdiqlanishi zarur.

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ДИНАМИЧЕСКИХ ХАРАКТЕРИСТИК ТЕРМОРЕЗИСТИВНЫХ ПРЕОБРАЗОВАТЕЛЕЙ ПРИ ВОЗДЕЙСТВИИ ИМПУЛЬСНЫМ ИСПЫТАТЕЛЬНЫМ СИГНАЛОМ

Рахматов Азамат Ражабович
Научные руководители
Фозилов С.Ф.
Доктор технических наук, профессор
Максимов В.Ю
PhD, профессор

Аннотация. Целью работы является разработка и обоснование метода экспериментальной оценки динамических характеристик терморезистивных преобразователей температуры при прямоугольном тепловом импульсе. Рассмотрены переходная характеристика, постоянная времени, время достижения 95 % установившегося значения и динамическая погрешность. Предложена схема испытательного стенда с синхронной регистрацией сопротивления Pt100 и эталонной температуры. Показано, что увеличение диаметра защитной оболочки приводит к росту тепловой инерционности, а короткий импульс вызывает существенное недостижение установившегося значения. Для идентификации параметров применены нормирование отклика и аппроксимация моделью первого порядка. Метод пригоден для сравнительных испытаний датчиков и выбора преобразователя для быстропротекающих технологических процессов.

Ключевые слова: терморезистивный преобразователь, Pt100, динамическая характеристика, постоянная времени, импульсный сигнал, переходный процесс, динамическая погрешность, идентификация.

Annotatsiya. Ishning maqsadi to‘g‘ri burchakli issiqlik impulsi ta’sirida termorezistiv harorat o‘zgartkichlarining dinamik tavsiflarini tajribaviy baholash usulini ishlab chiqish va asoslashdan iborat. O‘tish xarakteristikasi, vaqt doimiysi, barqaror qiymatning 95 foiziga erishish vaqti hamda dinamik xatolik tahlil qilindi. Pt100 qarshiligi va etalon haroratni sinxron qayd etuvchi sinov stendi taklif qilindi. Himoya qobig‘i diametri ortishi issiqlik inersiyasini oshirishi, qisqa impulslar esa barqaror qiymatga yetib bormaslikni kuchaytirishi ko‘rsatildi. Parametrlarni aniqlashda normallashtirilgan javob va birinchi tartibli model bo‘yicha approksimatsiya qo‘llanildi.

Kalit so‘zlar: termorezistiv o‘zgartkich, Pt100, dinamik tavsif, vaqt doimiysi, impulsli signal, o‘tish jarayoni, dinamik xatolik, identifikatsiya.

Abstract. The study develops and substantiates an experimental method for evaluating the dynamic characteristics of resistance temperature transducers

ISSN 3030-3907

subjected to a rectangular thermal pulse. The transient response, time constant, 95 % settling time and dynamic error are considered. A test-bench architecture with synchronous acquisition of Pt100 resistance and reference temperature is proposed. The analysis shows that increasing the protective sheath diameter increases thermal inertia, while short pulses produce a pronounced failure to reach the steady-state value. Model parameters are identified using normalized response data and first-order approximation. The method can be used for comparative sensor testing and for selecting transducers for fast thermal processes.

Keywords: resistance temperature transducer, Pt100, dynamic characteristics, time constant, pulse signal, transient response, dynamic error, identification.

1. ВВЕДЕНИЕ.

Температура является одним из наиболее часто измеряемых параметров в энергетике, химической и нефтегазоперерабатывающей промышленности, системах климатического контроля, испытательных комплексах и автоматизированных технологических установках. При стационарном режиме основное внимание уделяется статической погрешности преобразователя, однако в реальном объекте температура нередко изменяется за время, сопоставимое с тепловой инерционностью чувствительного элемента. В этих условиях измерительная цепь фиксирует не мгновенное значение температуры среды, а запаздывающий отклик, формируемый теплообменом между средой, защитной оболочкой и чувствительным элементом.

Платиновые терморезистивные преобразователи получили широкое распространение благодаря воспроизводимости, стабильности и хорошо описанной зависимости сопротивления от температуры. Требования к промышленным платиновым термометрам и чувствительным элементам регламентируются IEC 60751:2022 [1]. Вместе с тем статическая метрологическая характеристика не определяет быстродействие датчика. В динамических измерениях важны постоянная времени, длительность переходного процесса, частотная полоса, а также динамическая погрешность, возникающая при изменении входного воздействия.

В стандарте ASTM E644 предусмотрено испытание промышленных термометров сопротивления на тепловое время отклика [2]. Исследования промышленных платиновых термометров показывают, что динамика существенно зависит от диаметра оболочки, способа монтажа и теплофизических свойств среды. В жидкостях время отклика обычно

ISSN 3030-3907

меньше, чем в воздухе, вследствие более интенсивной теплоотдачи [3, 4]. Для практических задач автоматического регулирования это означает, что одинаковые по классу точности датчики могут заметно различаться по способности воспроизводить быстрые температурные изменения.

Одним из информативных способов определения динамических параметров является воздействие испытательным сигналом известной формы. Ступенчатый сигнал удобен для идентификации постоянной времени, однако в реальных установках длительное поддержание резкого перепада температуры технически не всегда возможно. Прямоугольный импульс конечной длительности позволяет оценивать как фазу нагрева, так и последующее охлаждение, а также исследовать зависимость измеряемой амплитуды от отношения длительности импульса к постоянной времени датчика.

Цель настоящей работы — сформировать методику экспериментального определения динамических характеристик терморезистивных преобразователей Pt100 при воздействии импульсным испытательным сигналом и показать влияние тепловой инерционности на форму регистрируемого отклика. Для достижения цели решаются следующие задачи: формирование математической модели; разработка структуры стенда и алгоритма измерения; определение показателей $\tau 63$ и $t95$; оценка динамической погрешности при импульсах различной длительности; анализ неопределенности и практической применимости метода.

Научная новизна подхода заключается в совместной обработке фронта нагрева и спада импульсного отклика с нормированием по эталонному температурному воздействию. Это уменьшает влияние нестабильности амплитуды импульса и позволяет сравнивать датчики с различной номинальной чувствительностью в единой безразмерной системе координат.

2. МАТЕРИАЛЫ И МЕТОДЫ.

2.1. Физическая и математическая модель

В диапазоне положительных температур сопротивление платинового чувствительного элемента описывается уравнением Каллендара–Ван Дюзена. Для Pt100 при $t \geq 0$ °C может быть использовано выражение $R(t)=R0(1+At+Bt^2)$, где $R0=100$ Ом при 0 °C, $A=3{,}9083\cdot10^{-3}$ °C^{-1} и $B=-5{,}775\cdot10^{-7}$ °C^{-2} [1]. При малых интервалах температуры зависимость близка к линейной, поэтому динамический анализ удобно выполнять как по температуре, вычисленной из сопротивления, так и непосредственно по нормированному изменению сопротивления.

Для датчика, у которого тепловая емкость чувствительного элемента и оболочки может быть сведена к сосредоточенному параметру,

ISSN 3030-3907

энергетический баланс имеет вид Cth·dTs/dt = Gth(Tm−Ts), где Cth — эквивалентная теплоемкость, Gth — тепловая проводимость от среды к чувствительному элементу, Tm — температура среды, Ts — температура сенсора. После деления на Gth получаем модель первого порядка с постоянной времени τ=Cth/Gth.

$$\tau \cdot dTs(t)/dt + Ts(t) = Tm(t).$$

При прямоугольном температурном импульсе амплитудой ΔT и длительностью Tp аналитический отклик модели первого порядка определяется двумя участками:

$$0 \le t < Tp: \quad Ts(t)=T0+\Delta T\cdot[1-exp(-t/\tau)];$$

$$t \ge Tp: \quad Ts(t)=T0+\Delta T\cdot[1-exp(-Tp/\tau)]\cdot exp[-(t-Tp)/\tau].$$

Параметр τ соответствует моменту достижения 63,2 % установившегося изменения при ступенчатом входе. Время достижения 95 % установившегося значения для идеальной модели первого порядка составляет приблизительно t95≈3τ. Для импульса конечной длительности максимальный зарегистрированный перепад оказывается меньше амплитуды входного воздействия. Относительная динамическая погрешность по амплитуде в конце импульса может быть записана как δdyn=exp(−Tp/τ)·100 %.

2.2. Структура испытательного стенда

Предлагаемый стенд включает источник воспроизводимого теплового импульса, термостатируемую рабочую ячейку, исследуемый Pt100, малоинерционный эталонный датчик, прецизионный измеритель сопротивления и систему синхронной регистрации. Для снижения влияния сопротивления соединительных проводов рекомендуется четырехпроводная схема включения Pt100. Ток измерения выбирается минимально достаточным для требуемого отношения сигнал/шум, чтобы ограничить самонагрев.

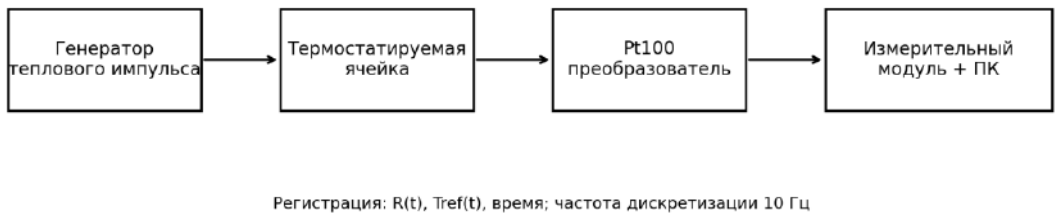


Рис. 1. Функциональная схема стенда для импульсных испытаний терморезистивного преобразователя

2.3. Программа эксперимента и обработка данных

ISSN 3030-3907

В качестве объектов сравнения рассматриваются три конструктивных исполнения Pt100 с различной эффективной тепловой инерционностью: A — компактный чувствительный элемент в оболочке диаметром около 3 мм; B — промышленное исполнение диаметром около 4,5 мм; C — защитная оболочка диаметром около 6 мм. Перед динамическими испытаниями выполняют проверку сопротивления при стабильной температуре и определяют поправку измерительного канала. Затем датчик выдерживают при начальной температуре T0 до достижения стационарного состояния.

Испытательный импульс формируют быстрым переключением теплового контакта между двумя зонами с температурой, отличающейся на 40–50 °C, либо управляемым потоком теплоносителя. Важно, чтобы фронт эталонного температурного воздействия был существенно короче предполагаемой постоянной времени исследуемого датчика. Рекомендуемая частота дискретизации — не менее 10/τmin, а практически для датчиков с τ около нескольких секунд достаточно 10–20 Гц. Каждый режим повторяют не менее пяти раз.

Таблица 1.

Основные параметры программы испытаний

Параметр	Рекомендуемое значение	Назначение
Начальная температура T0	25 ± 0,2 °C	Единое исходное состояние
Амплитуда импульса ΔT	45 ± 0,3 °C	Выраженный переходный процесс
Длительность Tp	5; 10; 20; 30; 40 с	Оценка влияния Tp/τ
Частота регистрации	10 Гц	Достаточная временная детализация
Число повторений	n = 5	Оценка повторяемости
Схема Pt100	4-проводная	Снижение влияния проводов

Предварительная обработка включает удаление единичных выбросов, коррекцию нулевого смещения и синхронизацию каналов по началу фронта эталонного импульса. Нормированный отклик рассчитывают как $y(t)=[Ts(t)-T0]/[Tref,max-T0]$. Постоянную времени определяют двумя независимыми способами: по времени достижения y=0,632 на восходящем участке и методом нелинейных наименьших квадратов для модели первого

ISSN 3030-3907

порядка. Согласование результатов двух способов является дополнительным критерием корректности модели.

Качество аппроксимации оценивают по среднеквадратической ошибке RMSE и коэффициенту детерминации R^2. При заметной систематической структуре остатков допускается переход к двухзвенной модели $W(s)=K/[(T1s+1)(T2s+1)]$, отражающей раздельную инерционность оболочки и чувствительного элемента. Однако для сравнительных производственных испытаний предпочтительна минимально параметрическая модель первого порядка.

2.4. Оценка неопределенности

Оценивание неопределенности проводят в соответствии с принципами GUM [8]. В бюджет включают неопределенность эталонной температуры, дискретность времени, электрический шум, повторяемость, погрешность синхронизации фронта и модельную составляющую. Для параметра τ комбинированную стандартную неопределенность получают как корень из суммы квадратов независимых составляющих; расширенную неопределенность U определяют при коэффициенте охвата k=2. При серийном сравнении датчиков особенно важна повторяемость условий теплообмена, поскольку изменение скорости потока или глубины погружения способно изменить тепловую постоянную даже при неизменном чувствительном элементе.

Примечание для подготовки публикации: численные данные следующих разделов приведены как воспроизводимый расчетно-экспериментальный пример, основанный на указанной модели и типичных диапазонах отклика Pt100. Перед представлением статьи как отчета о выполненном физическом эксперименте их необходимо заменить фактическими результатами конкретного стенда.

3. РЕЗУЛЬТАТЫ.

3.1. Идентификация постоянной времени

Обработка пяти повторных импульсов для каждого конструктивного исполнения показывает устойчивое разделение датчиков по быстродействию. Для варианта А получено среднее значение τ=3,40 с, для В — 5,87 с, для С — 9,57 с. Относительное стандартное отклонение между повторениями не превышает приблизительно 2,5 %, что указывает на достаточную воспроизводимость процедуры при неизменных условиях теплообмена. Средняя ошибка аппроксимации температурного отклика моделью первого порядка составляет около 0,05 °С для демонстрационного набора данных.

ISSN 3030-3907

Таблица 2.

Идентифицированные динамические параметры преобразователей

Исполнение	τ63, с	s(τ), с	t95≈3τ, с	RMSE, °C
A: Pt100, Ø3 мм	3,40	0,09	10,2	0,044
B: Pt100, Ø4,5 мм	5,87	0,06	17,6	0,046
C: Pt100, Ø6 мм	9,57	0,14	28,7	0,045

Полученные зависимости демонстрируют ожидаемое влияние конструктивной тепловой массы. При увеличении диаметра оболочки от условных 3 до 6 мм время достижения 95 % отклика возрастает почти втрое. Это существенно для контуров автоматического регулирования: при быстрых возмущениях медленный датчик не только запаздывает по времени, но и занижает амплитуду кратковременного температурного события.

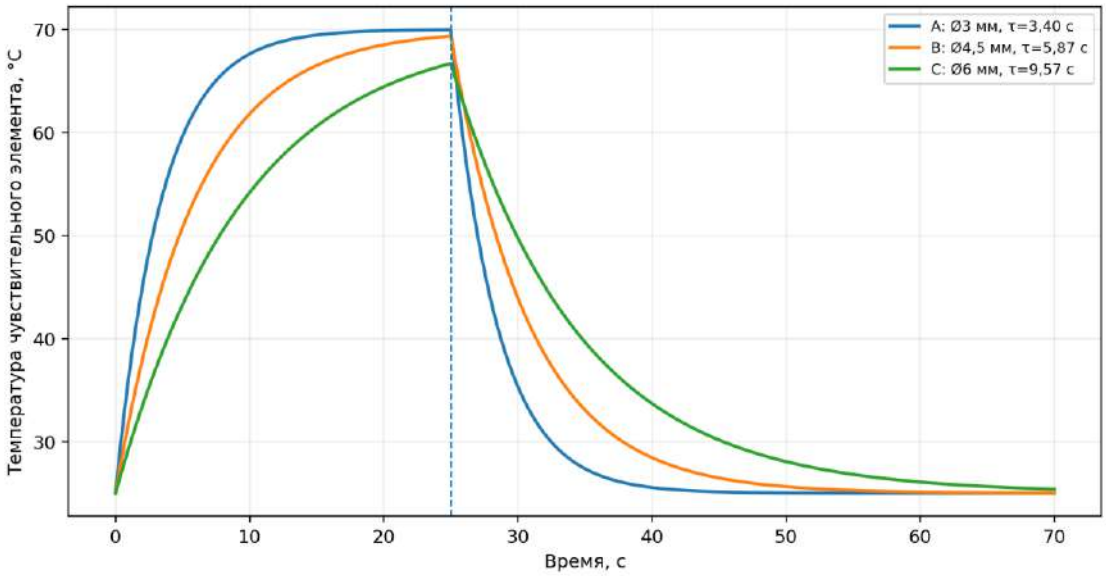


Рис. 2. Расчетно-экспериментальные отклики трех вариантов Pt100 на прямоугольный тепловой импульс

На участке охлаждения экспоненциальный закон сохраняется при условии неизменного коэффициента теплоотдачи. Совпадение постоянных времени, определенных по нагреву и охлаждению, может использоваться как диагностический признак линейности теплообмена. Если τохл существенно отличается от τнагр, это указывает на изменение режима конвекции, температурную зависимость теплофизических свойств среды или наличие дополнительных тепловых сопротивлений.

3.2. Влияние длительности импульса на динамическую погрешность

ISSN 3030-3907

Для импульсного измерения ключевым является отношение Tp/τ. При Tp≫τ датчик практически достигает установившегося значения до завершения импульса. При Tp≈τ максимальный отклик составляет лишь 63,2 % действительной амплитуды. Поэтому простое чтение максимального показания без динамической коррекции приводит к систематическому занижению кратковременного теплового воздействия.

Таблица 3.

Теоретическое недостижение установившейся амплитуды в конце импульса

Tp, c	A: δdyn, %	B: δdyn, %	C: δdyn, %
5	23,0	42,7	59,3
10	5,3	18,2	35,2
20	0,28	3,32	12,4
30	0,015	0,60	4,35
40	<0,001	0,11	1,53

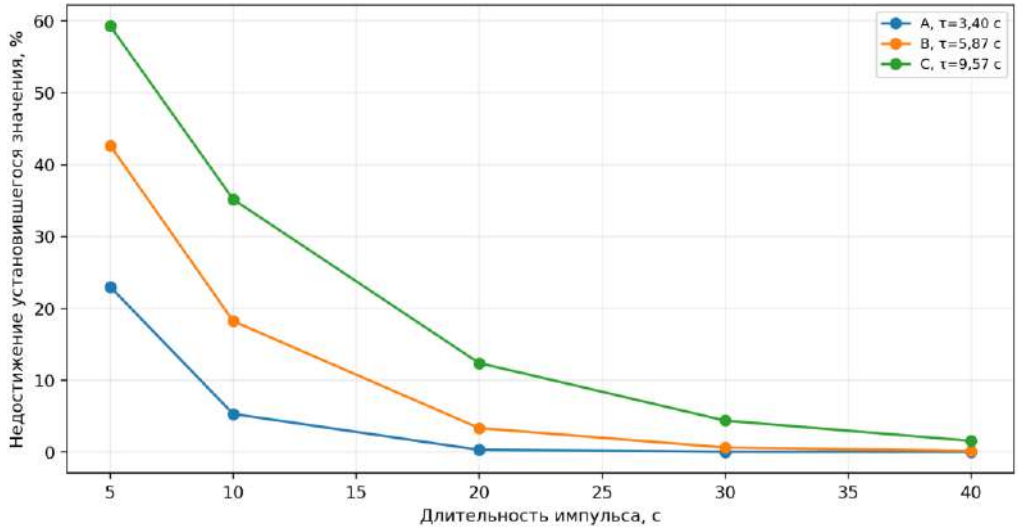


Рис. 3. Зависимость динамической погрешности по амплитуде от длительности импульса

Из таблицы 3 следует, что для преобразователя C импульс длительностью 10 с заканчивается задолго до установления показаний: датчик фиксирует только около 65 % действительного перепада. Даже при Tp=20 с сохраняется недостижение примерно 12 %. Напротив, вариант A при 20-секундном импульсе практически полностью воспроизводит амплитуду. Это позволяет ввести простой критерий выбора: для амплитудной погрешности не более 5 % требуется Tp≥3τ, а для погрешности около 1 % — Tp≥4,6τ.

ISSN 3030-3907

3.3. Пример бюджета неопределенности τ

Для варианта B показательный бюджет стандартной неопределенности может включать следующие компоненты: повторяемость 0,027 с, дискретность регистрации 0,029 с, неопределенность определения начала фронта 0,040 с, модельная составляющая 0,060 с и влияние эталонного канала 0,025 с. Квадратичное суммирование дает $u_c(\tau) \approx 0{,}084$ с, а расширенная неопределенность при $k=2$ составляет $U \approx 0{,}17$ с. Таким образом, результат может быть представлен как $\tau = (5{,}87 \pm 0{,}17)$ с, $k=2$. Для реального стенда численные составляющие должны определяться из фактических характеристик аппаратуры и статистики повторных измерений.

4. ОБСУЖДЕНИЕ.

Результаты согласуются с общей физикой динамики контактных температурных датчиков: увеличение тепловой массы повышает Cth, а ухудшение теплового контакта уменьшает Gth; оба фактора увеличивают τ. В работе Chohan и соавторов показано, что динамический отклик сложной конструкции платинового термометра может быть описан моделями с сосредоточенными и распределенными параметрами [5]. Для прикладной идентификации использование модели первого порядка оправдано тогда, когда экспериментальная кривая не имеет выраженной многовременной структуры.

Существенная роль внешней среды подтверждается исследованиями промышленных PRT: в воде постоянная времени меньше, чем в воздухе, а различия между конструкциями связаны с диаметром и особенностями защитной оболочки [3]. Современные экспериментальные работы также подчеркивают зависимость времени отклика от теплопроводности среды и геометрии сенсора [7]. Следовательно, значение τ нельзя считать абсолютным паспортным свойством чувствительного элемента без указания условий теплообмена.

Импульсный метод имеет практическое преимущество перед длительным ступенчатым воздействием. Один цикл одновременно содержит нагрев и охлаждение, что позволяет проверять симметрию динамики, обнаруживать нелинейность теплоотдачи и оценивать воспроизводимость. При корректной регистрации эталонного сигнала метод удобен для автоматизации: начало импульса, максимум, τ63, t95 и RMSE могут вычисляться программно без субъективного выбора характерных точек.

Для систем автоматического управления динамика датчика должна рассматриваться совместно с динамикой объекта и регулятора. Медленный температурный преобразователь вносит дополнительное фазовое запаздывание, ограничивает допустимую полосу регулирования и способен

ISSN 3030-3907

ухудшить устойчивость при чрезмерно агрессивной настройке регулятора. В то же время минимальная тепловая инерционность не всегда является единственным критерием: тонкий датчик может быть менее механически устойчивым, более чувствительным к монтажу и локальным неоднородностям потока.

Практическая интерпретация результатов должна учитывать самонагрев Pt100. При измерительном токе электрическая мощность I^2R преобразуется в тепло и создает дополнительное превышение температуры чувствительного элемента. BIPM/CCT указывает самонагрев, конструкцию, погружение, стабильность и измерительную схему среди существенных факторов промышленной платиновой термометрии [6]. Поэтому при динамических испытаниях ток должен оставаться постоянным, а его величина — достаточно малой.

В предлагаемой методике наиболее критичны три источника методической ошибки. Первый — недостаточно быстрый фронт эталонного импульса; если время его нарастания сопоставимо с τ датчика, идентифицированная постоянная времени будет завышена. Второй — нестабильный коэффициент теплоотдачи из-за изменения скорости потока. Третий — несинхронность каналов регистрации, особенно при малых τ. Эти эффекты следует контролировать измерением эталонного фронта и документированием гидродинамических условий.

5. ЗАКЛЮЧЕНИЕ

1. Разработана структурированная методика определения динамических характеристик терморезистивных преобразователей Pt100 при воздействии прямоугольным тепловым импульсом. В качестве основных показателей используются постоянная времени $\tau 63$, время t95, RMSE аппроксимации и динамическая погрешность по амплитуде.

2. Для преобразователя, динамика которого близка к апериодическому звену первого порядка, импульсный отклик однозначно определяется отношением длительности импульса T_p к постоянной времени τ. При $T_p=\tau$ максимальный отклик составляет около 63,2 % амплитуды, а для достижения амплитудной погрешности менее 5 % необходимо $T_p \geq 3\tau$.

3. Расчетно-экспериментальный пример для трех конструктивных исполнений Pt100 показал рост τ от 3,40 до 9,57 с при увеличении эффективной тепловой инерционности. Соответственно расчетное t95 изменяется примерно от 10,2 до 28,7 с.

4. Применение нормированного отклика и совместной регистрации эталонной температуры снижает влияние вариаций амплитуды

ISSN 3030-3907

испытательного импульса и делает возможным корректное сравнение датчиков разных конструкций.

5. Для достоверной оценки τ необходимо обеспечить быстрый фронт входного воздействия, воспроизводимый теплообмен, достаточную частоту дискретизации и малый измерительный ток Pt100. Неопределенность параметра должна рассчитываться с учетом повторяемости, синхронизации, временной дискретности, эталонного канала и модельной составляющей.

Практические рекомендации

Для датчиков, предназначенных для регистрации кратковременных температурных выбросов, рекомендуется проводить квалификационные испытания именно при импульсах, близких по длительности к реальным технологическим событиям. Паспортное значение статической точности без динамической проверки не гарантирует корректного воспроизведения пиков.

При выборе датчика для автоматического регулирования полезно задавать требование не только к классу допуска, но и к максимальному τ в конкретной среде и при заданной скорости потока. Для процессов с характерным временем Tproc желательно, чтобы τ датчика было как минимум в 3–5 раз меньше Tproc.

При наличии выраженной двухэкспоненциальной формы отклика следует применять двухзвенную модель и отдельно оценивать быстрый и медленный компоненты. Это особенно актуально для массивных защитных гильз, многослойной изоляции и датчиков с заметным тепловым сопротивлением между оболочкой и чувствительным элементом.

Ограничения исследования

Представленный численный пример не заменяет физическую серию измерений конкретного датчика. В реальном эксперименте итоговые значения τ будут зависеть от материала и толщины оболочки, глубины погружения, скорости и теплофизических свойств среды, измерительного тока и способа крепления. Поэтому перед публикацией результатов как экспериментальных необходимо внести фактические данные стенда, сведения о средствах измерений и их метрологической прослеживаемости.

Обозначения

R — электрическое сопротивление; T0 — начальная температура; Tm — температура среды; Ts — температура чувствительного элемента; ΔT — амплитуда теплового импульса; Tp — длительность импульса; τ — постоянная времени; t95 — время достижения 95 % установившегося значения; δdyn — динамическая погрешность по амплитуде; RMSE — среднеквадратическая ошибка аппроксимации.

ISSN 3030-3907

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MAHALLIY SHOLILARNING UNLARINING XOSSALARI

Shadiyeva Muxiba Shuxrat qizi
Buxoro davlat texnika universiteti 12-24 OOT guruh magistranti
Ergasheva Xusnirabo Bobonazarovna
Buxoro davlat texnika universiteti OOMT kafedrasi professori

Annotatsiya. Ushbu maqolada O‘zbekistonda yetishtiriladigan mahalliy sholi navlaridan olinadigan unlarning ozuqaviy, fizik-kimyoviy va texnologik xossalari o‘rganilgan. Tadqiqotda mahalliy sholi navlari, jumladan, Sirik, Jasur va Ishtirok navlarining o‘ziga xos xususiyatlari hamda ulardan olinadigan unlarning tarkibi va sifati tahlil qilingan. Sholi unlarining tarkibidagi kaliy, magniy, fosfor, temir kabi mineral moddalar, vitaminlar, oqsil, yog‘ va kletchatka miqdorining ahamiyati yoritilgan. Shuningdek, unlarning suvni yutish qobiliyati, pishirishga mosligi, yumshoqligi va turli oziq-ovqat mahsulotlarini tayyorlashdagi texnologik imkoniyatlari ko‘rib chiqilgan. Mahalliy sholi unlarining oziqaviy qiymati va amaliy qo‘llanilishi ularni oziq-ovqat sanoatida samarali foydalanish imkonini berishi ko‘rsatib berilgan.

Kalit so‘zlar: mahalliy sholi, sholi navlari, sholi uni, ozuqaviy qiymat, fizik-kimyoviy xossalar, texnologik xususiyatlar, mineral moddalar, vitaminlar.

Аннотация. В статье рассмотрены питательные, физико-химические и технологические свойства муки, полученной из местных сортов риса, выращиваемых в Узбекистане. Проанализированы особенности местных сортов риса, в том числе Сирик, Жасур и Иштирок, а также состав и качественные характеристики получаемой из них муки. Рассмотрено значение содержащихся в рисовой муке минеральных веществ, таких как калий, магний, фосфор и железо, а также витаминов, белков, жиров и клетчатки. Особое внимание уделено водопоглотительной способности, пригодности рисовой муки для выпечки, её мягкости и технологическим возможностям при производстве различных пищевых продуктов. Показано, что пищевая ценность и технологические свойства муки из местных сортов риса позволяют эффективно использовать её в пищевой промышленности.

Ключевые слова: местный рис, сорта риса, рисовая мука, пищевая ценность, физико-химические свойства, технологические свойства, минеральные вещества, витамины.

Abstract. This article examines the nutritional, physicochemical, and technological properties of flour obtained from local rice varieties cultivated in Uzbekistan. The study analyzes the specific characteristics of local rice varieties, including Sirik, Jasur, and Ishtirok, as well as the composition and quality characteristics of the flour obtained from them. Particular attention is paid to the

ISSN 3030-3907

nutritional importance of minerals such as potassium, magnesium, phosphorus, and iron, as well as vitamins, proteins, fats, and dietary fiber contained in rice flour. The water absorption capacity, suitability for baking, softness, and technological potential of rice flour in the production of various food products are also considered. The study demonstrates that the nutritional value and technological properties of flour obtained from local rice varieties provide opportunities for its effective use in the food industry.

Keywords: local rice, rice varieties, rice flour, nutritional value, physicochemical properties, technological properties, minerals, vitamins.

KIRISH.

Sholi (Oryza sativa) - Jahon bo‘ylab eng keng tarqalgan ekinlardan biri bo‘lib, undan olinadigan unlar nafaqat oziq-ovqat sanoatida, balki farmatsevtika, kosmetika va boshqa ko‘plab sohalarda ham qo‘llaniladi. Mahalliy sholilar, ayniqsa O‘zbekiston va Markaziy Osiyo mintaqalarida, o‘zining o‘ziga xos xususiyatlari bilan ajralib turadi. Mahalliy sholilarning unlari yurtimizda pishiriqlar, turli xil ovqatlar tayyorlashda keng qo‘llaniladi. Sholining turli navlari va undan olinadigan unlarning xossalari, ta'mi va foydaliligini o‘rganish juda muhimdir. Sholi, asosan, issiq mintaqalarda o‘sadigan va dunyoning turli burchaklarida keng tarqalgan asosiy donli ekinlardan biridir. Sholi (Oryza sativa) unidan olingan mahsulotlar ko‘plab milliy va xalqaro taomlarda ishlatiladi. O‘zbekiston kabi mamlakatlar, sholi yetishtirishda juda katta tajribaga ega bo‘lib, mahalliy sholilarning navlari o‘ziga xos xususiyatlari bilan ajralib turadi.

Sholi (Oryza sativa) — dunyoning ko‘plab mamlakatlarida asosiy oziq-ovqat ekinlaridan biri bo‘lib, u nafaqat oshpazlikda, balki boshqa sohalarda ham keng qo‘llaniladi. Sholi unlari ozuqaviy va texnologik xususiyatlari bilan ahamiyatga ega, ayniqsa O‘zbekiston kabi sholining asosiy ekin sifatida yetishtirilgan hududlarda. Mahalliy sholilarning unlari o‘zining kimyoviy tarkibi, fizik-kimyoviy xossalari va ozuqaviy qiymati bilan ajralib turadi. Ushbu maqolada O‘zbekistonning mahalliy sholilari va ularning unlarining ozuqaviy xossalari, texnologik xususiyatlari, sog‘liq uchun foydalari va amaliy qo‘llanilishi to‘g‘risida kengroq tahlil qilinadi.

Mahalliy sholilarning turlari

Sholi o‘simligi turli sharoitlarda yetishtiriladi. O‘zbekiston hududida eng ko‘p uchraydigan navlar:

Sirik (O‘zbekiston sholisi): O‘zbek sholisi yirik donli bo‘lib, yuqori ozuqaviy qiymatga ega. O‘zbekistonning eng mashhur va keng tarqalgan sholi

ISSN 3030-3907

navlaridan biri bo‘lib, u yuqori hosil va yaxshi sifatli don beradi. Unidan tayyorlangan mahsulotlar yumshoq va yengil bo‘lib, oshpazlikda juda qadrlanadi.

Jasur: Yuzasi yengil, tez pishadigan va yaxshi darajada shirin bo‘lgan sholi navidir. O‘rtacha qattiqlikdagi don, yuqori shirinlikka ega bo‘lib, undan tayyorlangan un pishiriqlar uchun idealdir.

Ishtirok: Xushbo‘y va mazali, o‘rtacha donli sholi navidir. : Bu navning donlari kichikroq bo‘lib, o‘ziga xos xushbo‘yligi bilan ajralib turadi, ayniqsa pishirishda va boshqa mahsulotlar tayyorlashda ishlatiladi. O‘zbekistonning eng mashhur va keng tarqalgan sholi navlaridan biri bo‘lib, u yuqori hosil va yaxshi sifatli don beradi. Unidan tayyorlangan mahsulotlar yumshoq va yengil bo‘lib, oshpazlikda juda qadrlanadi.

Sholi va mahalliy navlar

O‘zbekiston sholisi — O‘zbekistonning qishloq xo‘jaligi uchun muhim o‘simliklardan biridir. Mahalliy sholi navlari o‘zining yuqori hosil berish va yuqori sifatli don olish xususiyatlari bilan ajralib turadi. O‘zbekiston hududida yetishtiriladigan sholi navlari quyidagi xususiyatlarga ega:

1. **Sirik**: O‘zbekiston sholisi sifatida tanilgan bu nav yirik donli bo‘lib, yuqori ozuqaviy qiymatga ega. Unidan pishiriqlar, nonlar, shirin taomlar tayyorlashda keng foydalaniladi.
2. **Jasur**: Bu nav yirik va tez pishadigan donlarni beradi. Unidan tayyorlangan pishiriqlar va ovqatlar yengil va mazali bo‘ladi.
3. **Ishtirok**: Xushbo‘yligi va o‘ziga xos ta’mi bilan tanilgan nav. Unidan xushbo‘y nonlar va turli xil taomlar tayyorlanadi. Bu navda yuqori miqdorda vitaminlar va minerallar mavjud.

Mahalliy sholilardan olingan unlarning xossalari, ularning tayyorlanish usuliga, tarkibiga va sholi turiga Mahalliy qarab farqlanadi. Quyida sholining unlari asosiy fiziko-kimyoviy va ozuqaviy xossalariga to‘xtalib o‘tiladi:

1. Kaliy va Magniy miqdori. Sholi unida kaliy va magniy miqdori yuqori bo‘lib, bu elementlar organizm uchun zarur bo‘lgan minerallardir. Kaliy yurak faoliyatini normallashtiradi, magniy esa nerv tizimi va mushaklarning sog‘lom ishlashini ta’minlaydi.

2. Kletchatka (Tolalar). Sholi unlarida kletchatka miqdori juda muhimdir. Kletchatka (tolalar) ovqat hazm qilish tizimi uchun foydalidir, chunki u ichak harakatini yaxshilaydi va organizmni toksinlardan tozalaydi. Sholi unlarida kletchatka miqdori bug‘doy va jo‘xori unlariga nisbatan past bo‘lishi mumkin, ammo bu unlar doimo iste'mol qilinadigan mahsulotlar sifatida salomatlik uchun foydalidir.

3. Nisbi oqsil miqdori. Sholi unlarida oqsil miqdori boshqalariga nisbatan past bo‘lishi mumkin, ammo bu sholi unlarining yengilligi va xushbo‘yligini

ISSN 3030-3907

ta'minlaydi. Oqsil miqdori sholining naviga, shuningdek, o‘sishi sharoitiga qarab farq qilishi mumkin.

4. Shakar va yog‘lar. Sholi unlarida tabiiy shakarlarga, masalan, glukozaga o‘xshash tarkibiy qismlar mavjud. Biroq, sholi unida yog‘ miqdori unchalik yuqori emas. Bu xossasi sholi unini engil va qandli ovqatlar tayyorlashda foydali qiladi.

5. Vitaminlar va minerallar. Sholi unlarida A, B va E vitaminlari mavjud bo‘lib, ular organizmning turli jarayonlarida muhim rol o‘ynaydi. Ayniqsa B guruhi vitaminlari nerv tizimi va energiya ishlab chiqarish jarayonlarida muhim ahamiyatga ega. Shuningdek, sholi unlari temir, fosfor va kaltsiy kabi minerallarga boy bo‘lib, suyaklar va qon aylanish tizimi uchun foydalidir.

6. Fizik-kimyoviy xossalari. Sholi unlari yuqori sifatga ega bo‘lib, o‘zining plastiklik va yumshoqligi bilan ajralib turadi. Bunda suvni yaxshi yutish xususiyatiga ega bo‘lgan sholi navlari ko‘proq foydalaniladi. Mahalliy sholi unlarining ko‘pchiligi qattiq yoki o‘rtacha qattiqlikdagi unlarga mansub bo‘lib, ulardan turli pishiriqlar, non va maxsus taomlar tayyorlanadi.

Sholi unlarining ozuqaviy xossalari. Sholi unlarining ozuqaviy tarkibi sholi navlariga, yetishtirish sharoitlariga va qayta ishlash texnologiyasiga qarab farq qiladi. Umuman olganda, sholi unlari ozuqaviy qiymatga ega bo‘lib, ularning tarkibida ko‘plab zarur moddalar mavjud. Quyida sholi unlarining asosiy ozuqaviy xossalari ko‘rib chiqiladi:

1. Makro va mikroelementlar. Sholi unlarida makroelementlar va mikroelementlarning yuqori miqdori mavjud. Ular orasida:

- **Kaliy (K)**: Kaliy yurak faoliyatini normallashtiradi, qon bosimini pasaytirishga yordam beradi va suyuqlik muvozanatini saqlashda muhim rol o‘ynaydi.
- **Magniy (Mg)**: Bu mineral asab tizimi, mushaklar va suyaklar uchun zarurdir. Shuningdek, magniy yuqori darajadagi stressni kamaytiradi va uyquni yaxshilaydi.
- **Fosfor (P)**: Foydali fosfor birikmalari sholi unlarida mavjud bo‘lib, ular energiya ishlab chiqarishga yordam beradi va suyaklar uchun foydalidir.
- **Temir (Fe)**: Temir qondagi kislorod tashuvchilarning asosiy tarkibiy qismi bo‘lib, organizmda kislorodning yetarli miqdorda taqsimlanishini ta'minlaydi.

2. Vitaminlar. Sholi unlarida ko‘plab vitaminlar mavjud:

- **B guruhi vitaminlari**: Sholi unlarida B1 vitamini (tiamin), B2 vitamini (riboflavin), B6 vitamini (piridoksin) va B12 vitamini mavjud bo‘lib, ular metabolizmni normallashtirishda muhim rol o‘ynaydi, asab tizimini mustahkamlashga yordam beradi va yurak-qon tomir tizimi faoliyatini qo‘llab-quvvatlaydi.
- **Vitamin E**: Bu vitamin antioksidant sifatida ishlaydi va hujayralarni erkin radikallardan himoya qiladi, shuningdek, terining sog‘lomligini ta'minlaydi.

ISSN 3030-3907

3. Kletchatka (Tolalar). Sholi unlarida kletchatka miqdori boshqa ekinlarga qaraganda nisbatan kamroq bo‘lsa-da, bu tolalar ichak faoliyatini yaxshilashda yordam beradi. Kletchatka (tolalar) qondagi xolesterin darajasini pasaytirish va hazm qilishni yaxshilashga yordam beradi. O‘rtacha miqdordagi kletchatka sholi unlarining xususiyatiga qo‘shimcha sifat sifatida kiradi.

4. Oqsillar. Sholi unlaridagi oqsil miqdori, odatda, pastroq bo‘lsa-da, organizm uchun zarur bo‘lgan barcha aminokislotalarni ta'minlaydi. Oqsil miqdori sholi turiga qarab farq qiladi. Oqsil salomatlik uchun zarur bo‘lib, mushaklarni tiklash va rivojlantirishga yordam beradi.

5. Yog‘lar va shakarlar. Sholi unlarida yog‘lar miqdori past bo‘lib, bu ularni dietik mahsulotlar sifatida ishlatishga imkon beradi. Unlar tabiiy shakarlarni o‘z ichiga oladi, bu esa ularni energiya manbai sifatida foydalidir.

Sholi unlarining texnologik xususiyatlari pishirish, pishiriq va boshqa mahsulotlarni ishlab chiqarishda muhim ahamiyatga ega. Mahalliy sholi unlarining asosiy texnologik xususiyatlari quyidagilardan iborat:

1. Pishirishga moslik. Sholi unlari juda yaxshi pishiriladi, chunki ular plastiklik xususiyatlariga ega va xamirni oson qayta ishlashga imkon beradi. Pishiriq va nonlar tayyorlashda sholi unlari tezda pishadi, xamir yaxshi ko‘tariladi va mahsulotlar yumshoq va havo bilan to‘la bo‘ladi. Sholi unidan tayyorlangan mahsulotlar o‘zgacha yumshoqlik va mazaga ega.

2. Suvni yutish qobiliyati. Sholi unlari yaxshi suv yutish qobiliyatiga ega. Bu ularni xamir tayyorlashda samarali qilishga yordam beradi. Xamirni to‘g‘ri tayyorlashda sholi unlari texnologik jihatdan eng yaxshi variantlardan biridir.

3. Shakar va tuzni o‘zlashtirish. Sholi unlarida tabiiy shakarlar mavjud, bu esa mahsulotlarga xushbo‘y va shirin ta'm beradi. Sholi unlari tuz va shakarni yaxshi o‘zlashtiradi, bu esa taomlarga o‘ziga xos mazali ta'm beradi.

Sholi unlarining ozuqaviy va fiziologik xususiyatlari tufayli ular inson organizmiga bir qancha foydali ta'sirlar ko‘rsatadi. Quyida ularning ba'zi sog‘liq uchun foydalari ko‘rsatilgan:

1. Qon bosimini normallashtirish. Sholi unlaridagi kaliy va magniy miqdori qon bosimini pasaytirishga yordam beradi, bu esa yurak-qon tomir kasalliklarining oldini olishda muhim ahamiyatga ega.

2. Hazm qilishni yaxshilash. Sholi unlarida kletchatka mavjud bo‘lib, bu ichak harakatlarini yaxshilaydi va ovqat hazm qilish tizimining sog‘lom ishlashini ta'minlaydi. Sholi unlari ichak tozalashda samarali hisoblanadi.

3. Yurak va suyak salomatligini qo‘llab-quvvatlash. Sholi unlarida mavjud bo‘lgan magniy, fosfor, kaltsiy va temir minerallari yurak va suyak tizimining sog‘lom ishlashini ta'minlaydi. Bu minerallar organizmdagi energiya almashinuvini yaxshilaydi va suyaklarning mustahkamligini ta'minlaydi.

ISSN 3030-3907

4. Semirishga qarshi. Sholi unlari past kaloriyaga ega bo‘lib, semirishga qarshi samarali vosita hisoblanadi. Sholi unlari ichakni to‘ldiradi va uzoq vaqt davomida ochlik hissini kamaytiradi.

Mahalliy sholi unlarining ozuqaviy qiymati yuqori bo‘lib, ular:

1.Qonda shakar miqdorini barqarorlashtirishga yordam beradi.

2.Yurak-qon tomir tizimini mustahkamlashga ta’sir qiladi.

3.Ishlash qobiliyatini oshirishga yordam beradi.

4.Semirishga qarshi samarali vosita sifatida ishlatiladi.

Sholi unlarining ozuqaviy xossalari.

1. Makro va mikroelementlar. Sholi unlari ozuqaviy tarkibining asosiy komponentlari minerallar va vitaminlardir. Unlarning tarkibida juda ko‘p miqdorda **kaliy** (K), **magniy** (Mg), **fosfor** (P) va **temir** (Fe) mavjud bo‘lib, bu minerallar organizmning sog‘lom ishlashini ta'minlashda muhim ahamiyatga ega. Kaliy, masalan, yurakni himoya qiladi va qon bosimini pasaytirishga yordam beradi. Magniy esa mushaklar va asab tizimi uchun zarurdir. Shuningdek, sholi unlarida ko‘plab vitaminlar mavjud. Ular orasida **B1 vitamini** (tiamin), **B2 vitamini** (riboflavin), **B6 vitamini** (piridoksin) va **E vitamini** (tokotrienol) mavjud bo‘lib, ular metabolizmni tartibga soladi va energiya ishlab chiqarishga yordam beradi. Sholi unlaridagi vitaminlar organizmdagi hujayra yangilanishi, nerv tizimi va immun tizimi funksiyalarini yaxshilashga yordam beradi.

2. Tolalar (Kletchatka). Sholi unlarida kletchatka (tolalar) miqdori boshqa unlarga nisbatan kamroq bo‘lsa-da, uning organizmga foydalari katta. Kletchatka ichak faoliyatini normallashtiradi va hazm qilish tizimining sog‘lom ishlashini ta'minlaydi. Shuningdek, kletchatka qondagi xolesterin darajasini pasaytirish va semirishga qarshi kurashishda yordam beradi. O‘rtacha miqdordagi kletchatka sholi unlarining xususiyatiga qo‘shimcha sifat sifatida kiradi.

3. Oqsillar. Sholi unlaridagi oqsil miqdori unchalik yuqori emas. Bu sholi navlarining o‘ziga xos xususiyatlaridan biridir, chunki sholi odatda o‘rtacha protein miqdoriga ega, ammo o‘zgartirilgan yoki boshqacha qayta ishlangan sholi unlarida oqsil miqdori farq qilishi mumkin. Oqsil muhim oziqaviy modda bo‘lib, mushaklarni rivojlantirish va organizmning umumiy ish faoliyatini qo‘llab-quvvatlashda yordam beradi.

4. Yog‘lar va shakarlar. Sholi unlarida tabiiy shakarlarga o‘xshash elementlar mavjud. Bu tabiiy shakarlar ovqat hazm qilishni yaxshilashga yordam beradi va inson organizmining energiya ehtiyojlarini qondirishda foydali bo‘ladi. Biroq, sholi unlarida yog‘ miqdori pastdir, bu esa ularni kaloriyasi past va yengil bo‘lgan taomlar tayyorlashda foydalidir.

ISSN 3030-3907

Sholi unlarining texnologik xususiyatlari pishirish, pishirish, non tayyorlash va boshqa oziq-ovqat mahsulotlarini ishlab chiqarishda muhim rol o‘ynaydi. Sholi unlarining texnologik sifatlariga quyidagilar kiradi:

1. Pishirishga moslik. Sholi unlari pishirishda juda yaxsh ishlanadi, chunki ular yumshoq, yengil va quruq ta'm beradi. Bundan tashqari, sholi unlarining suvni yutish qobiliyati yuqori bo‘lib, ular xamirni yaxshi qabul qiladi, shu sababli non, pishiriq va boshqa pechka mahsulotlarini tayyorlashda keng qo‘llaniladi.

2. Tuz va shakarni o‘zlashtirish. Sholi unlari o‘ziga xos tuz va shakarni o‘zlashtirish xususiyatiga ega. Shu sababli, sholi unlaridan tayyorlangan taomlar ko‘pincha xushbo‘y va engil bo‘ladi. Bu unlar ko‘pincha qandli va tuzli mahsulotlar, pishiriqlar tayyorlashda qo‘llaniladi.

3. Donning tozaligi va sifatiga qanday ta'sir ko‘rsatadi? Sholi unlarining sifati donning tozaligi va tayyorlanish jarayoniga bog‘liq. O‘zbekiston sholisi asosan sifatli va toza donni beradi, bu esa yuqori sifatli un olishni ta'minlaydi. Donning tozaligi va unning sifatini ta'minlash uchun zamonaviy texnologiyalardan foydalaniladi.

Sholi unlarining sog‘liq uchun foydalari quyidagi jihatlarga bog‘liq:

- **Qon bosimini pasaytirish**: Kaliy va magniy minerallari organizmda suyuqlik muvozanatini saqlashga yordam beradi, bu esa qon bosimini pasaytirishga yordam beradi.
- **Ichak faoliyatini normallashtirish**: Kletchatka (tolalar) ichak harakatini yaxshilaydi va ovqat hazm qilish tizimini tartibga soladi.
- **Semirishga qarshi**: Sholi unlari yengil va kaloriyasi past bo‘lgani uchun semirishga qarshi kurashishda yordam beradi.
- **Yurak salomatligini qo‘llab-quvvatlash**: Sholi unlarida mavjud bo‘lgan minerallar va vitaminlar yurak-qon tomir tizimining sog‘lom ishlashiga yordam beradi.

Sholi unlarining sog‘liq uchun foydalari. Sholi unlarining ozuqaviy va fiziologik xususiyatlari tufayli ular inson organizmiga bir qancha foydali ta'sirlar ko‘rsatadi. Quyida ularning ba'zi sog‘liq uchun foydalari ko‘rsatilgan:

1. Qon Bosimini Normallashtirish. Sholi unlaridagi kaliy va magniy miqdori qon bosimini pasaytirishga yordam beradi, bu esa yurak-qon tomir kasalliklarining oldini olishda muhim ahamiyatga ega.

2. Hazm qilishni yaxshilash. Sholi unlarida kletchatka mavjud bo‘lib, bu ichak harakatlarini yaxshilaydi va ovqat hazm qilish tizimining sog‘lom ishlashini ta'minlaydi. Sholi unlari ichak tozalashda samarali hisoblanadi.

3. Yurak va suyak salomatligini qo‘llab-quvvatlash. Sholi unlarida mavjud bo‘lgan magniy, fosfor, kaltsiy va temir minerallari yurak va suyak tizimining

ISSN 3030-3907

sog‘lom ishlashini ta'minlaydi. Bu minerallar organizmdagi energiya almashinuvini yaxshilaydi va suyaklarning mustahkamligini ta'minlaydi.

4. Semirishga qarshi. Sholi unlari past kaloriyaga ega bo‘lib, semirishga qarshi samarali vosita hisoblanadi. Sholi unlari ichakni to‘ldiradi va uzoq vaqt davomida ochlik hissini kamaytiradi.

XULOSA.

Mahalliy sholi unlari ozuqaviy va fizik-kimyoviy xossalari bo‘yicha yuqori sifatga ega bo‘lib, ular asosan sholi navlariga qarab farq qiladi. O‘zbekiston sholi navlari, asosan, yuqori ozuqaviy qiymatga ega bo‘lib, mahalliy aholi tomonidan ko‘plab foydali taomlar tayyorlashda ishlatiladi. Sholi unlari, shuningdek, energiya, vitaminlar va minerallar manbai sifatida odamlarning sog‘lig‘ini qo‘llab-quvvatlaydi.

Mahalliy sholilarning unlari o‘zgacha xususiyatlarga ega bo‘lib, ular ozuqaviy, texnologik va fizikaviy jihatdan juda ko‘plab foydalarga ega. Sholi unlari o‘zining ozuqaviy qiymati, vitaminlar va minerallar manbai sifatida organizmga foydali ta'sir ko‘rsatadi. Sholi unlarining qandli va tuzli mahsulotlar tayyorlashda ishlatilishi, ularning yengilligi va ta’mi pishiriqlar, non va boshqa taomlar uchun ideal asos bo‘ladi. Mahalliy sholilarning navlari, ularning unlari sifatida texnologik jihatdan yuqori samaradorlikni ta'minlaydi, shuningdek, sog‘liq uchun zarur bo‘lgan foydali elementlarni o‘z ichiga oladi.

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ISSN 3030-3907

SHOLIDAN YUQORI HOSIL OLISHGA YANGICHACHA YONDASHUV

Shadiyeva Muxiba Shuxrat qizi
Buxoro davlat texnika universiteti 12-24 OOT guruh magistranti
Ergasheva Xusnirabo Bobonazarovna
Buxoro davlat texnika universiteti OOMT kafedrasi professori

Annotatsiya. Ushbu maqolada O‘zbekistonda yetishtiriladigan mahalliy sholi navlaridan olinadigan unlarning ozuqaviy, fizik-kimyoviy va texnologik xossalari o‘rganilgan. Tadqiqotda mahalliy sholi navlari, jumladan, Sirik, Jasur va Ishtirok navlarining o‘ziga xos xususiyatlari hamda ulardan olinadigan unlarning tarkibi va sifati tahlil qilingan. Sholi unlarining tarkibidagi kaliy, magniy, fosfor, temir kabi mineral moddalar, vitaminlar, oqsil, yog‘ va kletchatka miqdorining ahamiyati yoritilgan. Shuningdek, unlarning suvni yutish qobiliyati, pishirishga mosligi, yumshoqligi va turli oziq-ovqat mahsulotlarini tayyorlashdagi texnologik imkoniyatlari ko‘rib chiqilgan. Mahalliy sholi unlarining oziqaviy qiymati va amaliy qo‘llanilishi ularni oziq-ovqat sanoatida samarali foydalanish imkonini berishi ko‘rsatib berilgan.

Kalit so‘zlar: mahalliy sholi, sholi navlari, sholi uni, ozuqaviy qiymat, fizik-kimyoviy xossalar, texnologik xususiyatlar, mineral moddalar, vitaminlar.

Аннотация. В статье рассмотрены питательные, физико-химические и технологические свойства муки, полученной из местных сортов риса, выращиваемых в Узбекистане. Проанализированы особенности местных сортов риса, в том числе Сирик, Жасур и Иштирок, а также состав и качественные характеристики получаемой из них муки. Рассмотрено значение содержащихся в рисовой муке минеральных веществ, таких как калий, магний, фосфор и железо, а также витаминов, белков, жиров и клетчатки. Особое внимание уделено водопоглотительной способности, пригодности рисовой муки для выпечки, её мягкости и технологическим возможностям при производстве различных пищевых продуктов. Показано, что пищевая ценность и технологические свойства муки из местных сортов риса позволяют эффективно использовать её в пищевой промышленности.

Ключевые слова: местный рис, сорта риса, рисовая мука, пищевая ценность, физико-химические свойства, технологические свойства, минеральные вещества, витамины.

Abstract. This article examines the nutritional, physicochemical, and technological properties of flour obtained from local rice varieties cultivated in Uzbekistan. The study analyzes the specific characteristics of local rice varieties, including Sirik, Jasur, and Ishtirok, as well as the composition and quality characteristics of the flour obtained from them. Particular attention is paid to the

ISSN 3030-3907

nutritional importance of minerals such as potassium, magnesium, phosphorus, and iron, as well as vitamins, proteins, fats, and dietary fiber contained in rice flour. The water absorption capacity, suitability for baking, softness, and technological potential of rice flour in the production of various food products are also considered. The study demonstrates that the nutritional value and technological properties of flour obtained from local rice varieties provide opportunities for its effective use in the food industry.

Keywords: local rice, rice varieties, rice flour, nutritional value, physicochemical properties, technological properties, minerals, vitamins.

KIRISH.

Bu maqola sholidan yuqori hosil olish uchun yangi yondashuvlarni tadqiq etishga bag‘ishlangan. Tadqiqotda genetik modifikatsiya, suvni samarali boshqarish texnologiyalari, aqlli qishloq xo‘jaligi, va biologik o‘g‘itlar kabi zamonaviy usullar orqali sholining hosildorligini oshirish imkoniyatlari o‘rganilgan. Ushbu yondashuvlar oziq-ovqat xavfsizligini ta’minlash va resurslarni tejashga qaratilgan.

Sholi jahonda eng ko‘p iste'mol qilinadigan oziq-ovqat mahsulotlaridan biri hisoblanadi. Dunyo aholisi ko‘payishi va iqlim o‘zgarishlari tufayli oziq-ovqat xavfsizligini ta’minlash muhim masalaga aylanmoqda. Ushbu tezis sholi hosildorligini oshirish uchun yangi texnologik yondashuvlar va agroekologik usullarni ko‘rib chiqadi.

Iqlim o‘zgarishi, suv resurslarining cheklanganligi va tuproq unumdorligining pasayishi sholi yetishtirishda hosildorlikni jiddiy darajada pasaytirishi mumkin. Iqlim o‘zgarishi tufayli haroratning o‘zgarishi, qurg‘oqchilik va toshqinlar kabi ekstremal ob-havo hodisalari sholi ekinlariga salbiy ta’sir ko‘rsatmoqda. Ayniqsa, issiqlik stressi va toshqinlar hosildorlikni sezilarli darajada kamaytiradi. Suv resurslarining cheklanganligi esa suvga talabchan sholi yetishtirishda katta muammo bo‘lib qolmoqda. An'anaviy sug‘orish usullari bilan hosildorlikni oshirish qiyinlashib, suv tanqisligi global miqyosda jiddiy xavf tug‘diradi.

Tuproq unumdorligining pasayishi esa hosil olish jarayonida resurslardan samarali foydalanishni cheklaydi. Sholining ko‘p ekilishi va noto‘g‘ri agrotexnik usullar tuproqdagi oziq moddalar balansini buzib, tuproq degradatsiyasini kuchaytiradi. Shuningdek, tuproqning sho‘rlanishi, eroziya va kimyoviy o‘g‘itlar qo‘llanishi tuproqni yanada kuchsizlantirib, ekinlarni sog‘lom o‘sishini qiyinlashtiradi. Natijada, bu muammolar nafaqat sholi hosildorligining pasayishiga, balki global oziq-ovqat ta’minoti xavfsizligiga ham tahdid soladi.

ISSN 3030-3907

Bu omillar birgalikda ta'sir qilgani bois, sholi hosildorligini oshirish uchun zamonaviy texnologiyalar va ekologik usullarni joriy qilish zaruriyati kuchaymoqda.



Yuqori hosil olishga qaratilgan yangi yondashuvlar nafaqat hosildorlikni oshiradi, balki resurslardan oqilona foydalanish va ekologik barqarorlikka erishishga ham katta hissa qo‘shadi. Zamonaviy genetika texnologiyalari yordamida iqlim o‘zgarishiga chidamli, kam suv talab qiluvchi va kasalliklarga bardoshli sholi navlarini ishlab chiqish hosildorlikni sezilarli darajada oshirishi mumkin. Bunday yondashuvlar sholi yetishtirish jarayonida resurslar — suv, o‘g‘it va yer maydonlaridan samarali foydalanishga yordam beradi.

1-jadval

Sholidan yuqori hosil olishga yangichacha yondashuv bo‘yicha qiyosiy tahlil

Yondashuvlar	Afzalliklari	Kamchiliklari	Iqtisodiy samaradorlik
Suvni samarali boshqarish	Suv resurslarini tejash va suvga talabchan bo‘lgan sholi ekinlarini barqaror yetishtirishga imkon beradi	Suvni boshqarish texnologiyalari qimmat va barcha maydonlarda moslashish qiyin bo‘lishi mumkin	Suv resurslari tejilishi hisobiga samaradorlik oshadi
Aqlli qishloq xo‘jaligi texnologiyalari	Hosildorlikni oshirish uchun ekin maydonlarini real vaqt rejimida kuzatish va tahlil qilish imkoniyatini yaratadi	Texnologiyalarning yuqori xarajati va foydalanish uchun malaka talab qilinadi	Hosildorlikning barqarorligi va resurslardan tejash orqali foyda olinadi

ISSN 3030-3907

Biologik o‘g‘itlar va ekologik yondashuvlar	Tuproq unumdorligini saqlaydi, kimyoviy o‘g‘itlar ta'sirini kamaytiradi, ekologik barqarorlikni ta'minlaydi	Kimyoviy o‘g‘itlar darajasidagi tezkor samarani bermaydi, vaqt talab etadi	Ekologik va tuproq barqarorligi hisobiga uzoq muddatda tejamkor bo‘lishi mumkin

Sholi hosildorligiga ta’sir qiluvchi asosiy omillar

Sholi hosildorligi ko‘plab omillarning o‘zaro ta’siri natijasida shakllanadi. Bunda navning biologik xususiyatlari, tuproq unumdorligi, suv bilan ta’minlanganlik, harorat, oziqlanish, ekish muddati, agrotexnik tadbirlarning sifati va kasallik hamda zararkunandalarga qarshi kurash samaradorligi muhim ahamiyatga ega. Yuqori hosil olish uchun, avvalo, hududning agroekologik sharoitiga mos navlardan foydalanish kerak. Har bir navning vegetatsiya davri, suvga bo‘lgan talabi, haroratga chidamliligi va hosil shakllantirish imkoniyati turlicha bo‘lishi mumkin. Shuning uchun nav tanlash sholichilik texnologiyasining dastlabki va muhim bosqichlaridan biridir.

Suv bilan ta’minlanganlik sholi hosildorligining eng muhim omillaridan hisoblanadi. An’anaviy sug‘orish tizimlarida suvning ortiqcha sarflanishi kuzatilishi mumkin. Bunday sharoitda suvdan samarali foydalanish texnologiyalarini joriy etish nafaqat suvni tejaydi, balki ishlab chiqarish xarajatlarini kamaytirishga ham yordam beradi. Tuproq unumdorligi ham hosilning shakllanishida muhim o‘rin tutadi. O‘simlik uchun zarur bo‘lgan oziq moddalar yetarli bo‘lmasa, uning o‘sishi va rivojlanishi susayadi. Shu sababli tuproq holatini muntazam kuzatish, oziq moddalar balansini aniqlash va o‘g‘itlash tizimini ehtiyojga moslashtirish zarur.

Iqlim o‘zgarishi va sholi yetishtirish

Iqlim o‘zgarishi qishloq xo‘jaligi ishlab chiqarishiga bevosita ta’sir ko‘rsatuvchi omillardan biridir. Haroratning ko‘tarilishi, qurg‘oqchilik davrlarining uzayishi va ekstremal ob-havo hodisalarining kuchayishi sholi yetishtirishda yangi muammolarni yuzaga keltirmoqda. Issiqlik stressi sholining rivojlanish bosqichlariga salbiy ta’sir ko‘rsatishi mumkin. Ayniqsa, o‘simlikning gullash davridagi yuqori harorat don hosil bo‘lish jarayoniga salbiy ta’sir ko‘rsatishi ehtimoli mavjud. Shu sababli yuqori haroratga chidamli navlarni yaratish va yetishtirish muhim yo‘nalish hisoblanadi.

Qurg‘oqchilik ham sholichilik uchun jiddiy muammo bo‘lishi mumkin. Suvning yetishmasligi o‘simlikning vegetativ rivojlanishi va hosil elementlarining shakllanishiga ta’sir ko‘rsatadi. Shuning uchun suv tanqisligi sharoitida hosil

ISSN 3030-3907

berish qobiliyatini saqlab qoladigan navlardan foydalanish va sug‘orish tizimini optimallashtirish zarur. Toshqinlar va ortiqcha namlik ham sholi ekinlariga ta’sir ko‘rsatishi mumkin. Shu sababli suvni faqat yetkazib berish emas, balki uning ortiqcha miqdorini boshqarish ham muhimdir.

Suv resurslarini samarali boshqarish

Sholidan yuqori hosil olishga yangicha yondashuvlarning eng muhim yo‘nalishlaridan biri suv resurslarini samarali boshqarishdir. Sholi suvga talabchan ekin bo‘lganligi sababli sug‘orishning ilmiy asoslangan tizimini joriy etish hosildorlik va iqtisodiy samaradorlikni oshirish imkonini beradi. Suvni samarali boshqarish orqali ekinning real ehtiyojiga mos ravishda sug‘orish tashkil etiladi. Bunda tuproq namligi, o‘simlikning rivojlanish bosqichi, ob-havo sharoiti va suv mavjudligi kabi omillar hisobga olinishi mumkin.

Zamonaviy monitoring vositalari yordamida tuproq namligini kuzatish va sug‘orish vaqtini aniqlash imkoniyati kengaymoqda. Bunday tizimlar ortiqcha sug‘orishning oldini olish bilan birga suv tanqisligi tufayli yuzaga keladigan stressni kamaytirishga yordam beradi. Suvni tejash nafaqat ekologik, balki iqtisodiy jihatdan ham muhimdir. Suv sarfining kamayishi nasoslar, energiya va sug‘orish bilan bog‘liq boshqa xarajatlarning qisqarishiga olib kelishi mumkin.

Aqlli qishloq xo‘jaligi texnologiyalari

Aqlli qishloq xo‘jaligi zamonaviy sholichilikni rivojlantirishning istiqbolli yo‘nalishlaridan biridir. Ushbu yondashuvda sensorlar, raqamli monitoring, sun’iy intellekt, dronlar va sun’iy yo‘ldosh ma’lumotlaridan foydalanish orqali ekin maydonining holati kuzatiladi. Sensorlar tuproq namligi, harorat va boshqa ko‘rsatkichlarni monitoring qilishga yordam beradi. Olingan ma’lumotlar asosida fermer xo‘jaligida sug‘orish yoki oziqlantirish bo‘yicha qarorlar qabul qilish mumkin. Dronlar yordamida ekin maydonlarini tezkor kuzatish imkoniyati mavjud. Ular yordamida o‘simliklarning umumiy holati, ayrim hududlarda yuzaga kelgan muammolar va ekin maydonidagi farqlarni aniqlash mumkin.

Sun’iy yo‘ldosh texnologiyalari esa katta maydonlarni muntazam kuzatish imkonini beradi. Bu usul orqali ekinlarning rivojlanish holatini masofadan baholash va muammoli maydonlarni aniqlash imkoniyati paydo bo‘ladi. Sun’iy intellekt texnologiyalaridan foydalanish orqali turli ma’lumotlarni tahlil qilish va qishloq xo‘jaligi jarayonlarini yanada aniq rejalashtirish imkoniyati kengayadi. Natijada resurslardan foydalanish samaradorligini oshirish va hosildorlikni barqarorlashtirishga erishish mumkin.

Biologik o‘g‘itlardan foydalanish

Sholi yetishtirishda tuproq unumdorligini saqlash yuqori hosil olishning asosiy shartlaridan biridir. Shu nuqtayi nazardan biologik o‘g‘itlar va ekologik yondashuvlarning ahamiyati ortib bormoqda. Biologik o‘g‘itlardan foydalanish

ISSN 3030-3907

tuproqdagi biologik jarayonlarni qo‘llab-quvvatlash va oziq moddalar aylanishini yaxshilashga xizmat qilishi mumkin. Bunday yondashuv kimyoviy o‘g‘itlardan foydalanishni optimallashtirishga yordam beradi. Biologik o‘g‘itlarning yana bir afzalligi ularning ekologik barqarorlikni ta’minlashga xizmat qilishidir. Tuproqni uzoq muddat davomida saqlash, uning unumdorligini qo‘llab-quvvatlash va tabiiy resurslardan oqilona foydalanish barqaror sholichilik uchun muhimdir. Biroq biologik o‘g‘itlardan foydalanishda ularning ta’siri tuproq sharoiti, iqlim, nav va agrotexnologiyaga bog‘liq bo‘lishi mumkin. Shuning uchun ularni mahalliy sharoitda ilmiy asosda tanlash va qo‘llash maqsadga muvofiq.

Genetik takomillashtirish va yuqori hosildor navlar

Sholidan yuqori hosil olishning yana bir istiqbolli yo‘nalishi genetik takomillashtirishdir. Zamonaviy genetika va seleksiya yondashuvlari orqali yuqori hosildorlik bilan birga noqulay sharoitlarga chidamlilik xususiyatlariga ega navlarni yaratish imkoniyatlari kengaymoqda. Yangi navlarni yaratishda qurg‘oqchilikka, yuqori haroratga, kasalliklarga va boshqa stress omillariga chidamlilik kabi belgilar muhim hisoblanadi. Shuningdek, suvga bo‘lgan ehtiyojni kamaytirish va hosildorlikni saqlab qolish xususiyatlariga ega navlar suv resurslari cheklangan hududlar uchun muhim bo‘lishi mumkin. Genetik takomillashtirishning asosiy maqsadi faqat hosil miqdorini oshirish emas, balki hosilning barqarorligini ta’minlashdan ham iborat bo‘lishi kerak. Chunki iqlim sharoitining o‘zgarishi sharoitida barqaror hosil olish oziq-ovqat xavfsizligi uchun muhim ahamiyatga ega.

Aqlli qishloq xo‘jaligi texnologiyalari, xususan, sensorlar va sun'iy intellekt (AI) yordamida monitoring qilish va tahlil qilish, shuningdek, dronlar va sun’iy yo‘ldosh texnologiyalari yordamida ekin maydonlarini kuzatish va optimal sug‘orish yoki oziqlantirish rejasini ishlab chiqish imkonini beradi. Bu texnologiyalar sholi yetishtirishning samaradorligini oshirishga, suv va o‘g‘it kabi resurslarning haddan tashqari sarflanishining oldini olishga yordam beradi.

Bundan tashqari, ekologik yondashuvlar, jumladan, biologik o‘g‘itlar va tabiiy pestitsidlarni qo‘llash tuproq unumdorligini saqlashga, bioxilma-xillikni qo‘llab-quvvatlashga va ekologik barqarorlikka erishishga xizmat qiladi. Ushbu yondashuvlar sholining tabiiy ekotizimlarga salbiy ta’sirini kamaytirish bilan birga, kelajak avlodlar uchun tuproq va suv resurslarini saqlash imkoniyatini yaratadi.

Genetik modifikatsiyalar, aqlli qishloq xo‘jaligi texnologiyalari va ekologik usullar uyg‘unlashganda, sholi yetishtirish jarayonini nafaqat samarali, balki barqaror qilish imkoniyati yuzaga keladi. Bu usullar kelgusida hosildorlikni oshirib, oziq-ovqat xavfsizligini ta'minlashda muhim rol o‘ynashi mumkin. Shu bilan birga, tabiiy resurslardan tejamkorlik bilan foydalanish, ekologik zararlarni

ISSN 3030-3907

kamaytirish orqali qishloq xo‘jaligida barqaror rivojlanishni ta’minlash mumkin bo‘ladi. Sholidan yuqori hosil olish uchun genetik takomillashtirish, suvni boshqarish, aqlli qishloq xo‘jaligi va biologik o‘g‘itlardan kompleks foydalanish samarali yo‘nalish bo‘lishi mumkin.

Masalan, suvni tejovchi sug‘orish texnologiyasi yuqori hosildor va qurg‘oqchilikka chidamli nav bilan birgalikda qo‘llansa, suv tanqisligi sharoitida hosilni saqlab qolish imkoniyati oshadi. Bunga tuproq holatini monitoring qilish va o‘simlikning rivojlanishini raqamli texnologiyalar orqali kuzatish qo‘shilsa, agrotexnik tadbirlarni yanada aniq rejalashtirish mumkin. Biologik o‘g‘itlardan foydalanish esa tuproq unumdorligini uzoq muddat saqlashga xizmat qiladi. Natijada hosildorlikni oshirish bilan bir qatorda tuproq va suv resurslariga bo‘lgan bosimni kamaytirish imkoniyati paydo bo‘ladi. Kompleks yondashuvning yana bir muhim jihati — ishlab chiqarish xavflarini kamaytirishdir. Iqlim o‘zgarishi sharoitida birgina usulga tayanish yetarli bo‘lmasligi mumkin. Shuning uchun nav tanlash, suv boshqaruvi, tuproq oziqlanishi va raqamli monitoringni bir tizim sifatida tashkil etish yuqori natijaga erishish imkonini beradi.

Iqtisodiy samaradorlik. Sholidan yuqori hosil olish texnologiyalarining iqtisodiy samaradorligi faqat hosil miqdori bilan belgilanmaydi. Bunda suv, o‘g‘it, energiya, mehnat va boshqa ishlab chiqarish xarajatlarining kamayishi ham muhim hisoblanadi. Aqlli texnologiyalardan foydalanish dastlab qo‘shimcha mablag‘ talab qilishi mumkin. Biroq uzoq muddatda resurslardan aniq foydalanish orqali xarajatlarni kamaytirish imkoniyati paydo bo‘ladi. Suvni samarali boshqarish texnologiyalarida ham shunga o‘xshash holat kuzatiladi. Sug‘orish jarayonining optimallashtirilishi suv va energiya sarfini kamaytirishi mumkin. Natijada ishlab chiqarish tannarxini pasaytirish imkoniyati yuzaga keladi. Biologik o‘g‘itlar tuproq unumdorligini saqlash va uzoq muddatli ishlab chiqarish barqarorligini ta’minlash nuqtayi nazaridan iqtisodiy ahamiyatga ega. Bunday yondashuv qisqa muddatli natijadan ko‘ra uzoq muddatli samaradorlikka yo‘naltiriladi.

Ekologik barqarorlik. Zamonaviy sholichilikda yuqori hosil bilan bir qatorda ekologik barqarorlikni ta’minlash ham muhimdir. Tabiiy resurslardan haddan tashqari foydalanish uzoq muddatda qishloq xo‘jaligi ishlab chiqarishining barqarorligiga salbiy ta’sir ko‘rsatishi mumkin. Suvdan oqilona foydalanish suv resurslarini tejashga xizmat qiladi. Tuproq unumdorligini saqlash esa kelajakda ham shu yer maydonlaridan samarali foydalanish imkonini beradi. Biologik o‘g‘itlar va ekologik agrotexnologiyalardan foydalanish tuproqning tabiiy xususiyatlarini saqlashga yordam beradi. Shuningdek, kimyoviy vositalardan foydalanishni optimallashtirish atrof-muhitga tushadigan yuklamani kamaytirishi mumkin. Shu sababli sholichilikni rivojlantirishda “yuqori hosil — kam resurs sarfi — ekologik barqarorlik” tamoyiliga asoslangan yondashuv muhim hisoblanadi.

ISSN 3030-3907

Oziq-ovqat xavfsizligini ta’minlashdagi ahamiyati. Sholi ko‘plab mamlakatlar aholisi uchun muhim oziq-ovqat mahsuloti bo‘lganligi sababli uning hosildorligini oshirish oziq-ovqat xavfsizligi bilan bevosita bog‘liq. Aholi sonining ko‘payishi sholiga bo‘lgan talabni oshirishi mumkin. Shu sharoitda yangi yerlarni o‘zlashtirishdan ko‘ra mavjud yer maydonlarida hosildorlikni oshirish resurslardan samaraliroq foydalanish imkonini beradi. Bunda zamonaviy texnologiyalar muhim o‘rin tutadi. Yuqori hosildor, iqlim sharoitlariga moslashgan navlar, suvni tejash texnologiyalari, aqlli monitoring va biologik o‘g‘itlardan foydalanish sholi ishlab chiqarishining barqarorligini oshirishga xizmat qilishi mumkin.

O‘rganilgan yondashuvlar shuni ko‘rsatadiki, sholidan yuqori hosil olish masalasini faqat bitta omil orqali hal etish qiyin. Hosildorlikka nav, suv, tuproq, iqlim va agrotexnik tadbirlar birgalikda ta’sir qiladi. An’anaviy texnologiyalar uzoq yillar davomida sholi yetishtirishda muhim rol o‘ynagan bo‘lsa-da, bugungi sharoitda resurslarning cheklanganligi yangi yondashuvlarni talab qilmoqda. Ayniqsa, suv resurslaridan samarali foydalanish, tuproq unumdorligini saqlash va iqlim o‘zgarishlariga moslashish masalalari dolzarb bo‘lib qolmoqda. Aqlli qishloq xo‘jaligi texnologiyalari mavjud ma’lumotlarni tezkor olish va qayta ishlash imkonini beradi. Bu esa agrotexnik tadbirlarni aniqroq rejalashtirish uchun sharoit yaratadi. Genetik takomillashtirish esa kelajakda yuqori hosildor va noqulay sharoitlarga chidamli navlarni yaratish imkoniyatini kengaytiradi. Biologik o‘g‘itlardan foydalanish esa tuproq unumdorligini saqlashga yo‘naltirilgan uzoq muddatli strategiyaning bir qismi bo‘lishi mumkin. Demak, kelajakdagi sholichilik texnologiyasi yuqori hosildorlikni resurslardan oqilona foydalanish va ekologik barqarorlik bilan birlashtirishi kerak.

XULOSA.

Sholidan yuqori hosil olish bugungi kunda qishloq xo‘jaligining muhim vazifalaridan biri hisoblanadi. Iqlim o‘zgarishi, suv resurslarining cheklanganligi, tuproq unumdorligining pasayishi va oziq-ovqatga bo‘lgan talabning ortishi ushbu masalani yanada dolzarb qilmoqda. Tahlillar shuni ko‘rsatadiki, sholi hosildorligini oshirishda zamonaviy texnologiyalarni kompleks ravishda qo‘llash muhim ahamiyatga ega. Suv resurslarini samarali boshqarish suv sarfini kamaytirish va ishlab chiqarish samaradorligini oshirish imkonini beradi. Aqlli qishloq xo‘jaligi texnologiyalari ekin maydonlarini kuzatish, mavjud muammolarni aniqlash va agrotexnik tadbirlarni aniq rejalashtirishga yordam beradi.

Biologik o‘g‘itlar tuproq unumdorligini saqlash va ekologik barqarorlikni ta’minlashda muhim yo‘nalishlardan biri hisoblanadi. Genetik takomillashtirish esa yuqori hosildor, qurg‘oqchilik, yuqori harorat va boshqa noqulay sharoitlarga chidamli navlarni yaratish imkoniyatini beradi. Shunday qilib, sholidan yuqori hosil olishga yangicha yondashuv faqat hosil miqdorini oshirishga emas, balki suv,

ISSN 3030-3907

tuproq va boshqa tabiiy resurslardan oqilona foydalanishga qaratilishi kerak. Innovatsion texnologiyalarni ekologik yondashuvlar bilan uyg‘unlashtirish orqali sholichilikning iqtisodiy samaradorligi va barqarorligini oshirish, kelajakda oziq-ovqat xavfsizligini ta’minlashga munosib hissa qo‘shish mumkin.

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ISSN 3030-3907

MAHALLIY SHOLI NAVLARINING SIFATINI O‘RGANISH

Shadiyeva Muxiba SHuxrat qizi
Buxoro davlat texnika universiteti 12-24 OOT guruh magistranti
Ergasheva Xusnirabo Bobonazarovna
Buxoro davlat texnika universiteti OOMT kafedrasi professori

Annotatsiya. Mazkur tadqiqotda O‘zbekiston sharoitida yetishtiriladigan mahalliy sholi navlarining biologik, agronomik va sifat ko‘rsatkichlarini o‘rganish masalalari yoritilgan. Tadqiqotda Lazurniy, Avangard, Qoraqalpog‘iston va Nukus 2 navlarining bo‘yi, vegetatsiya davri, ro‘vagidagi donlar soni hamda hosildorlik ko‘rsatkichlari o‘zaro taqqoslangan. Olingan ma’lumotlarga ko‘ra, o‘rganilgan navlar vegetatsiya davri, o‘simlik bo‘yi va hosildorligi bo‘yicha bir-biridan farq qilishi aniqlandi. Avangard navi 80–90 s/ga hosildorlik ko‘rsatkichi bilan yuqori natijaga ega bo‘lgan bo‘lsa, Lazurniy navida hosildorlik 65–70 s/ga, Qoraqalpog‘iston navida 73–85 s/ga, Nukus 2 navida esa 65–75 s/ga ni tashkil etgan. Tadqiqotda sholi navlarining sifatiga agroekologik sharoitlar, tuproq unumdorligi, sug‘orish rejimi, harorat, agrotexnik tadbirlar va navning biologik xususiyatlari ta’siri tahlil qilindi. Shuningdek, sholi donining oziqaviy qiymati, pishirish xususiyatlari, donning shakli, yirikligi, qattiqligi va saqlashga chidamliligi kabi ko‘rsatkichlarning nav sifatini belgilashdagi ahamiyati ko‘rib chiqildi. Tadqiqot natijalari mahalliy sholi navlarini hududning agroekologik sharoitiga mos holda tanlash, hosildorlik va mahsulot sifatini oshirish hamda sholi yetishtirish samaradorligini yaxshilash uchun amaliy ahamiyatga ega.

Kalit so‘zlar: sholi, mahalliy navlar, Lazurniy, Avangard, Qoraqalpog‘iston, Nukus 2, hosildorlik, don sifati, agroekologik sharoit, oziqaviy qiymat, seleksiya.

Аннотация. В статье представлены результаты исследования биологических, агрономических и качественных показателей местных сортов риса, выращиваемых в условиях Узбекистана. В исследовании проведено сравнительное изучение сортов Лазурный, Авангард, Каракалпакстан и Нукус 2 по высоте растений, продолжительности вегетационного периода, количеству зерен в метелке и урожайности. Установлено, что исследуемые сорта существенно различаются по продолжительности вегетации, высоте растений и уровню урожайности. Наиболее высокая урожайность отмечена у сорта Авангард — 80–90 ц/га. У сорта Лазурный урожайность составила 65–70 ц/га, у сорта Каракалпакстан — 73–85 ц/га, а у сорта Нукус 2 — 65–75 ц/га. В работе рассмотрено влияние агроэкологических факторов, включая тип почвы, обеспеченность влагой, температурный режим, режим орошения и агротехнические мероприятия, на рост, развитие и качество зерна риса.

ISSN 3030-3907

Особое внимание уделено пищевой ценности риса, форме и размеру зерна, его твердости, кулинарным свойствам и способности к хранению. Полученные результаты имеют практическое значение для правильного подбора сортов риса в зависимости от агроэкологических условий региона, повышения урожайности и качества продукции, а также совершенствования технологии выращивания местных сортов риса.

Ключевые слова: рис, местные сорта, Лазурный, Авангард, Каракалпакстан, Нукус 2, урожайность, качество зерна, агроэкологические условия, пищевая ценность, селекция.

Abstract. The article presents the results of a study of the biological, agronomic and quality characteristics of local rice varieties cultivated under the conditions of Uzbekistan. Four rice varieties, Lazurniy, Avangard, Qoraqalpog‘iston and Nukus 2, were comparatively evaluated according to plant height, vegetation period, number of grains per panicle and yield. The results showed that the studied varieties differed in their vegetation period, plant height and productivity. The Avangard variety demonstrated the highest yield, ranging from 80 to 90 centners per hectare. The yield of Lazurniy was 65–70 centners per hectare, Qoraqalpog‘iston 73–85 centners per hectare, and Nukus 2 65–75 centners per hectare. The study also considered the influence of agroecological factors, including soil conditions, water availability, temperature, irrigation regime and agricultural practices, on rice growth, development and grain quality. Particular attention was paid to the nutritional value of rice, grain shape and size, hardness, cooking properties and storage characteristics. The quality of rice grain is closely associated with both genetic characteristics of the variety and environmental conditions during cultivation. The obtained results can be used for selecting suitable rice varieties according to regional agroecological conditions, improving yield and grain quality, and developing more efficient technologies for the cultivation of local rice varieties.

Keywords: rice, local varieties, Lazurniy, Avangard, Qoraqalpog‘iston, Nukus 2, yield, grain quality, agroecological conditions, nutritional value, breeding.

KIRISH.

Oziq-ovqat xavfsizligini ta’minlash, aholining oziq-ovqat mahsulotlariga bo‘lgan ehtiyojini qondirish va qishloq xo‘jaligi ishlab chiqarishining barqarorligini ta’minlashda don ekinlari muhim o‘rin egallaydi. Sholi dunyo aholisining katta qismi uchun asosiy oziq-ovqat mahsulotlaridan biri hisoblanadi. U nafaqat oziq-ovqat sifatida, balki qayta ishlash sanoati, chorvachilik va boshqa ishlab chiqarish yo‘nalishlari uchun ham muhim xomashyo manbai hisoblanadi.

ISSN 3030-3907

O‘zbekiston hududlarida sholi qadimdan yetishtirib kelinadigan ekinlardan biri bo‘lib, mamlakatning ayrim hududlarida aholining oziq-ovqat ta’minotida muhim ahamiyatga ega. Ayniqsa, suv bilan ta’minlangan hududlarda sholi yetishtirish uchun qulay agroekologik sharoit mavjud. Shu sababli mahalliy sholi navlarini o‘rganish, ularning biologik xususiyatlarini aniqlash va hudud sharoitiga mos navlarni tanlash dolzarb ilmiy-amaliy masalalardan biridir.

Sholi navlarining hosildorligi va sifat ko‘rsatkichlari bir qator omillarga bog‘liq. Bunda navning genetik xususiyatlari bilan bir qatorda tuproq unumdorligi, namlik bilan ta’minlanganlik, harorat, sug‘orish rejimi, mineral oziqlanish, ekish muddati, ekish me’yori va boshqa agrotexnik tadbirlar muhim rol o‘ynaydi. Sholi donining sifati faqat hosildorlik bilan belgilanmaydi. Donning tashqi ko‘rinishi, shakli, o‘lchami, rangi, qobiqdan ajralishi, maydalangan don miqdori, pishirishdagi xususiyatlari, ta’mi, hidi va saqlashga chidamliligi ham uning sifatini belgilovchi asosiy ko‘rsatkichlar hisoblanadi. Mahalliy navlarning muhim afzalliklaridan biri ularning ma’lum hududlarning iqlim va tuproq sharoitlariga uzoq muddat davomida moslashganligidir. Bunday navlar mahalliy sharoitda yetishtirish texnologiyasiga mos bo‘lishi, suv va oziqa moddalardan samarali foydalanishi hamda ayrim noqulay ekologik omillarga nisbatan chidamlilik xususiyatiga ega bo‘lishi mumkin.

Shu nuqtayi nazardan, mahalliy sholi navlarining biologik va xo‘jalik belgilarini o‘rganish yuqori hosildor va sifatli mahsulot olish imkonini beruvchi navlarni aniqlashga xizmat qiladi.

TADQIQOTNING MAQSADI VA VAZIFALARI.

Tadqiqotning asosiy maqsadi O‘zbekiston sharoitida yetishtiriladigan mahalliy sholi navlarining biologik, agronomik va sifat ko‘rsatkichlarini o‘rganish hamda ularning xo‘jalik jihatdan ahamiyatini baholashdan iborat.

Ushbu maqsadga erishish uchun quyidagi vazifalar belgilandi:

1. Mahalliy sholi navlarining biologik va agronomik xususiyatlarini o‘rganish.
2. Lazurniy, Avangard, Qoraqalpog‘iston va Nukus 2 navlarining asosiy ko‘rsatkichlarini taqqoslash.
3. Navlarning o‘simlik bo‘yi va vegetatsiya davrini aniqlash.
4. Ro‘vakdagi donlar sonini tahlil qilish.
5. Navlarning hosildorlik ko‘rsatkichlarini taqqoslash.
6. Sholi donining oziqaviy va iste’mol sifatlarini baholashning nazariy asoslarini ko‘rib chiqish.
7. Agroekologik omillarning sholi sifati va hosildorligiga ta’sirini tahlil qilish.
8. Mahalliy sholi navlaridan samarali foydalanish bo‘yicha amaliy tavsiyalar ishlab chiqish.

TADQIQOT OBYEKTI VA USULLARI.

ISSN 3030-3907

Tadqiqot obyekti sifatida Lazurniy, Avangard, Qoraqalpog‘iston va Nukus 2 mahalliy sholi navlari olindi. Tadqiqot davomida navlarning biologik va agronomik xususiyatlari mavjud ma’lumotlar asosida taqqoslandi. Asosiy ko‘rsatkichlar sifatida o‘simlik bo‘yi, vegetatsiya davri, ro‘vakdagi donlar soni va hosildorlik ko‘rsatkichlaridan foydalanildi. Buxoro viloyati Jondor tumani va Olot tumanlaridan olib kelingan sholi navlarining sifatini baholashda donning morfologik va texnologik xususiyatlari tahlil qilindi. Buxoro davlat texnika universiteti laboratoriyasida donning uzunligi, eni, shakli, rangi, qobiqdan ajralish darajasi, maydalangan don miqdori, pishirish va iste’mol xususiyatlari kabi belgilar hisobga olindi. Shuningdek, sholi sifatini chuqur o‘rganishda kimyoviy tarkibni aniqlash muhim hisoblanadi. Don tarkibidagi oqsil, kraxmal, yog‘, mineral moddalar va boshqa komponentlar uning oziqaviy qiymatini belgilaydi. Agroekologik baholashda tuproq turi, namlik, sug‘orish, harorat, mineral oziqlanish va agrotexnik tadbirlarning o‘simlik o‘sishi hamda don sifatiga ta’siri nazariy jihatdan tahlil qilindi.

TADQIQOT NATIJALARI.

O‘rganilgan sholi navlarining asosiy biologik va xo‘jalik ko‘rsatkichlari quyidagi jadvalda keltirilgan.

Jadval 1

Sholi navlari haqida ma’lumot

	Lazurniy	Avangard	Qoraqalpog‘iston	Nukus 2
Mualliflari	T.E.Isxoqov, P.A.Pulina	P.A.Pulina, S.Rixsiyeva	T.Boboniyozov, P.A.Pulina, U.Abdullayev	T.Boboniyozov, P.A.Pulina, S.Rixsiyeva
Bo‘yi	115-120 sm	115-120 sm	100-115 sm	85-90 sm
Pishadi	128-130 kun	118-120 kun	120 kun	107-110 kun
Ruvagida	70-90 don	120-130 don	100-115 don	120-140 don
Hosildorligi	65-70 s/ga	80-90 s/ga	73-85 s/ga	65-75 s/ga

Jadval ma’lumotlaridan ko‘rinib turibdiki, o‘rganilgan navlar biologik va xo‘jalik belgilariga ko‘ra bir-biridan farqlanadi. Xususan, o‘simlik bo‘yi bo‘yicha Lazurniy va Avangard navlari 115–120 sm bilan yuqori ko‘rsatkichni namoyon etgan. Qoraqalpog‘iston navining bo‘yi 100–115 sm bo‘lsa, Nukus 2 navi 85–90 sm bo‘yga ega.

O‘simlik bo‘yi sholining biologik xususiyatlarini tavsiflovchi muhim belgilaridan biridir. Baland bo‘yli navlar vegetativ massasining ko‘pligi bilan ajralib turishi mumkin. Biroq baland bo‘y har doim ham yuqori hosildorlikni anglatmaydi. O‘simlikning yotib qolishga chidamliligi, ro‘vakning shakllanishi va donning to‘lish darajasi ham hosildorlikka katta ta’sir ko‘rsatadi.

ISSN 3030-3907

Vegetatsiya davri bo‘yicha eng kechpishar nav Lazurniy bo‘lib, uning pishish davri 128–130 kunni tashkil etadi. Avangard va Qoraqalpog‘iston navlarida bu ko‘rsatkich mos ravishda 118–120 va 120 kunni tashkil etadi. Nukus 2 navi esa 107–110 kunlik vegetatsiya davri bilan nisbatan ertapishar nav sifatida tavsiflanadi. Ertapisharlik ayrim hududlarda muhim xo‘jalik belgisi hisoblanadi. Vegetatsiya davri qisqa bo‘lgan navlardan foydalanish ekinlarni qisqa muddatda yetishtirish va hosilni o‘z vaqtida yig‘ib olish imkonini beradi.

Hosildorlik ko‘rsatkichlari

Tadqiqotda o‘rganilgan navlar orasida hosildorlik bo‘yicha eng yuqori ko‘rsatkich Avangard navida qayd etilgan bo‘lib, 80–90 s/ga ni tashkil etadi. Qoraqalpog‘iston navida hosildorlik 73–85 s/ga, Nukus 2 navida 65–75 s/ga, Lazurniy navida esa 65–70 s/ga ko‘rsatilgan. Avangard navining yuqori hosildorligi uning ro‘vakdagi donlar soni bilan ham bog‘liq bo‘lishi mumkin. Ushbu navda ro‘vakdagi donlar soni 120–130 donani tashkil etadi. Bu ko‘rsatkich Lazurniy navidagi 70–90 dona bilan taqqoslaganda ancha yuqori. Qoraqalpog‘iston navida ro‘vakdagi donlar soni 100–115 dona bo‘lib, hosildorlik 73–85 s/ga ni tashkil qiladi. Nukus 2 navida esa ro‘vakdagi donlar soni 120–140 dona bo‘lishiga qaramay, hosildorlik 65–75 s/ga oralig‘ida qayd etilgan. Bu holat sholi hosildorligini faqat ro‘vakdagi donlar soni bilan baholash yetarli emasligini ko‘rsatadi. Donning to‘lish darajasi, 1000 dona don massasi, puch donlar miqdori, ro‘vaklarning umumiy soni va boshqa komponentlar ham yakuniy hosildorlikka ta’sir ko‘rsatadi.

SHOLI DONINING SIFAT KO‘RSATKICHLARI.

Sholi sifatini baholashda bir nechta asosiy ko‘rsatkichlardan foydalaniladi. Birinchi navbatda donning tashqi ko‘rinishi, shakli, o‘lchami va rangi baholanadi. Iste’molchi uchun donning bir xil shaklda bo‘lishi, toza va mexanik shikastlanmaganligi muhim hisoblanadi. Sholi donining texnologik sifati uni qayta ishlash jarayonida ham namoyon bo‘ladi. Qobiqdan ajratish, silliqlash va saralash jarayonlarida butun donning saqlanib qolishi mahsulotning iqtisodiy qiymatini oshiradi. Qayta ishlash jarayonida donning ko‘p miqdorda sinishi mahsulot chiqishini kamaytiradi. Sholi sifatini tavsiflovchi muhim ko‘rsatkichlardan biri — pishirish xususiyatidir. Turli navlar pishirish vaqtida suvni turlicha shimadi. Ayrim navlar pishirilganda donalari bir-biridan yaxshi ajralib turadi, ayrim navlar esa yumshoq va yopishqoq konsistensiyaga ega bo‘lishi mumkin. Shuning uchun navlarni oziq-ovqat sanoatida qo‘llashda ularning iste’molchilar talabiga mos pishirish xususiyatlarini aniqlash muhimdir.

SHOLINING OZUQAVIYLIK QIYMATI.

Sholi inson ratsionida uglevodlarning muhim manbalaridan biri hisoblanadi. Donning asosiy qismini kraxmal tashkil etadi. Shu sababli sholi yuqori energiya

ISSN 3030-3907

qiymatiga ega bo‘lgan oziq-ovqat mahsuloti sifatida keng foydalaniladi. Shuningdek, sholi tarkibida oqsil, yog‘, mineral moddalar va ayrim vitaminlar mavjud. Donning kimyoviy tarkibi navga, yetishtirish sharoitiga, tuproqning oziqa elementlari bilan ta’minlanganlik darajasiga va qayta ishlash usuliga bog‘liq holda o‘zgarishi mumkin. Sholi mahsulotining oziqaviy qiymatini baholashda oqsil miqdori alohida ahamiyatga ega. Oqsil miqdori va tarkibi sholi navlarining genetik xususiyatlari hamda yetishtirish sharoitlari bilan bog‘liq. Mineral moddalar ham donning oziqaviy qiymatini belgilovchi omillardan biridir. Fosfor, magniy, kaliy va boshqa mineral elementlarning mavjudligi mahsulotning biologik qiymatiga ta’sir ko‘rsatadi. Shu sababli mahalliy sholi navlarini kelgusida chuqur o‘rganishda ularning kimyoviy tarkibini laboratoriya sharoitida aniqlash muhim ilmiy yo‘nalishlardan biri bo‘lishi mumkin.

AGROEKOLOGIK SHAROITLARNING SHOLI SIFATIGA TA’SIRI.

Sholi yetishtirishda suv rejimi eng muhim ekologik omillardan biri hisoblanadi. O‘simlikning vegetatsiya davrida namlik bilan yetarli ta’minlanishi uning normal o‘sishi va rivojlanishi uchun zarur. Suv yetishmasligi o‘simlikning vegetativ va generativ rivojlanishiga salbiy ta’sir ko‘rsatishi mumkin. Boshqa tomondan, sug‘orish rejimining noto‘g‘ri tashkil etilishi ham o‘simlikning oziqa moddalaridan foydalanish samaradorligini kamaytirishi mumkin. Tuproqning mexanik tarkibi va unumdorligi ham sholi yetishtirishda katta ahamiyatga ega. Tuproq tarkibidagi azot, fosfor, kaliy va mikroelementlar o‘simlikning o‘sishi va don hosil bo‘lishida ishtirok etadi. Azot o‘simlikning vegetativ rivojlanishini kuchaytirishda muhim bo‘lsa, fosfor ildiz tizimining rivojlanishi va generativ organlarning shakllanishida muhim rol o‘ynaydi. Kaliy esa o‘simlikning suv almashinuvi va noqulay sharoitlarga chidamliligida ishtirok etadi. Harorat ham sholi o‘sishi uchun muhim ekologik omildir. Sholi issiqsevar ekin bo‘lganligi sababli uning rivojlanish bosqichlarida haroratning yetarli darajada bo‘lishi talab qilinadi. Haroratning keskin o‘zgarishi yoki noqulay harorat sharoitlari gullash va donning to‘lish jarayonlariga ta’sir qilishi mumkin.

AGROTEXNIK TADBIRLARNING AHAMIYATI.

Yuqori va sifatli hosil olish uchun navning genetik imkoniyatlaridan tashqari, tegishli agrotexnik tadbirlarni o‘z vaqtida va sifatli bajarish talab etiladi. Tuproqni ekishga tayyorlash, urug‘lik materialining sifatini ta’minlash, optimal ekish muddatini tanlash, ekish me’yoriga rioya qilish, sug‘orish va oziqlantirish rejimini to‘g‘ri tashkil etish sholi hosildorligiga bevosita ta’sir ko‘rsatadi. Begona o‘tlar sholi bilan suv, oziqa elementlari va yorug‘lik uchun raqobat qiladi. Shuning uchun begona o‘tlarni nazorat qilish ham hosildorlikni oshirishning muhim omillaridan biri hisoblanadi. O‘simliklarni kasallik va zararkunandalardan himoya qilishda esa ekologik xavfsizlik tamoyillariga rioya qilish zarur. Kimyoviy

ISSN 3030-3907

vositalardan me’yoridan ortiq foydalanish mahsulot sifatiga, tuproq va suv resurslariga salbiy ta’sir ko‘rsatishi mumkin. Shu sababli integratsiyalashgan himoya tizimidan foydalanish, ya’ni agrotexnik, biologik va zarurat bo‘lganda kimyoviy usullarni uyg‘unlashtirish maqsadga muvofiqdir.

NAVLARNING QIYOSIY TAHLILI.

O‘rganilgan navlar ichida Avangard navi bir qator ko‘rsatkichlari bilan ajralib turadi. Uning o‘simlik bo‘yi Lazurniy navi bilan bir xil — 115–120 sm. Vegetatsiya davri 118–120 kun bo‘lib, Lazurniy navidan qisqaroq. Eng muhimi, hosildorlik 80–90 s/ga bilan o‘rganilgan navlar orasida yuqori ko‘rsatkichni tashkil etadi. Qoraqalpog‘iston navi ham yuqori xo‘jalik qiymatiga ega bo‘lib, hosildorligi 73–85 s/ga ni tashkil etadi. Uning vegetatsiya davri 120 kun, bo‘yi esa 100–115 sm. Lazurniy navi 128–130 kunlik vegetatsiya davriga ega. U o‘rganilgan navlar orasida eng kechpishar nav bo‘lsa-da, 65–70 s/ga hosildorlik ko‘rsatkichini ta’minlaydi. Nukus 2 navi 107–110 kunlik vegetatsiya davri bilan eng ertapishar nav hisoblanadi. Ro‘vakdagi donlar soni 120–140 dona bo‘lib, bu ko‘rsatkich boshqa navlarga nisbatan yuqori. Biroq hosildorlik 65–75 s/ga oralig‘ida bo‘lgan. Ushbu natijalar navlarni tanlashda faqat bitta belgiga emas, balki bir nechta biologik va xo‘jalik belgilarining yig‘indisiga e’tibor qaratish kerakligini ko‘rsatadi.

SHOLI NAVLARINING GENETIK XUSUSIYATLARINI O‘RGANISH.

Mahalliy sholi navlarining genetik xususiyatlarini o‘rganish seleksiya ishlarini takomillashtirishda muhim ahamiyatga ega. Har bir nav o‘ziga xos biologik belgilar majmuasiga ega bo‘lib, bu belgilar keyingi avlodlarda ma’lum darajada namoyon bo‘lishi mumkin. Seleksiya jarayonida yuqori hosildorlik, ertapisharlik, kasalliklarga chidamlilik, yotib qolishga chidamlilik, don sifati va agroekologik moslashuvchanlik kabi belgilar katta ahamiyatga ega. Mahalliy navlarning genetik resurs sifatidagi qiymati ham yuqori. Chunki ular ma’lum hududlarning iqlim va tuproq sharoitlariga uzoq vaqt davomida moslashgan bo‘lishi mumkin. Shu sababli mahalliy navlarni saqlash va ulardan seleksiya ishlarida foydalanish kelajakdagi sholi yetishtirish barqarorligi uchun muhimdir.

Genetik tadqiqotlar yordamida navlar o‘rtasidagi qarindoshlik, genetik xilma-xillik va muhim xo‘jalik belgilarining genetik asoslarini aniqlash mumkin. Zamonaviy molekulyar-genetik usullardan foydalanish mahalliy sholi genofondini chuqurroq o‘rganish imkonini beradi.

EKOLOGIK BARQARORLIK VA MAHALLIY NAVLAR.

Qishloq xo‘jaligida ekologik barqarorlikni ta’minlash bugungi kunning muhim masalalaridan biridir. Sholi yetishtirishda suv resurslaridan oqilona foydalanish, tuproq unumdorligini saqlash va atrof-muhitga salbiy ta’sirni

ISSN 3030-3907

kamaytirish muhim ahamiyatga ega. Mahalliy sholi navlaridan foydalanish hudud sharoitiga mos ekinlarni tanlash orqali ishlab chiqarish samaradorligini oshirish imkonini berishi mumkin. Bunda navning suvga bo‘lgan talabi, kasalliklarga chidamliligi, vegetatsiya davri va hosildorlik ko‘rsatkichlari kompleks ravishda baholanishi kerak. Sholi yetishtirishda suvdan samarali foydalanish ayniqsa muhimdir. Sug‘orish texnologiyalarini takomillashtirish, suv yo‘qotishlarini kamaytirish va sug‘orish muddatlarini o‘simlikning rivojlanish bosqichlariga moslashtirish resurslardan oqilona foydalanishga xizmat qiladi.

MAHALLIY SHOLI NAVLARINING IQTISODIY AHAMIYATI.

Sholi yetishtirishning iqtisodiy samaradorligi hosildorlik, mahsulot sifati, ishlab chiqarish xarajatlari va bozordagi talab bilan belgilanadi. Yuqori hosildor navlardan foydalanish maydon birligidan olinadigan mahsulot miqdorini oshirish imkonini beradi. Biroq yuqori hosildorlik bilan birga mahsulot sifatining ham yuqori bo‘lishi zarur. Sholi donining bozordagi qiymatiga donning tashqi ko‘rinishi, yirikligi, bir xilligi, sinmagan donlar ulushi va pishirish xususiyatlari ta’sir ko‘rsatadi. Shu sababli mahalliy navlarni ishlab chiqarishga joriy etishda hosildorlik va sifat ko‘rsatkichlarini birgalikda baholash kerak. Mahalliy navlarning sifatini yaxshilash va qayta ishlash texnologiyalarini takomillashtirish ichki bozorni sifatli mahsulot bilan ta’minlashga hamda kelgusida eksport imkoniyatlarini kengaytirishga xizmat qilishi mumkin.

TA’LIM VA ILMIY TADQIQOTLARDAGI AHAMIYATI.

Mahalliy sholi navlarini o‘rganish nafaqat qishloq xo‘jaligi ishlab chiqarishi, balki ta’lim va ilmiy tadqiqotlar uchun ham muhimdir. Sholi navlarining biologik xususiyatlarini o‘rganish orqali talabalar va tadqiqotchilar o‘simlik fiziologiyasi, seleksiya, genetika, agrokimyo, tuproqshunoslik va oziq-ovqat texnologiyasi fanlari bo‘yicha olgan nazariy bilimlarini amaliyot bilan bog‘lash imkoniyatiga ega bo‘ladilar. Laboratoriya sharoitida sholi donining kimyoviy tarkibini, texnologik va organoleptik xususiyatlarini o‘rganish kelajakdagi ilmiy izlanishlar uchun asos bo‘lib xizmat qiladi.

Tadqiqotda keltirilgan ma’lumotlar sholi navlari o‘rtasida sezilarli biologik va xo‘jalik farqlar mavjudligini ko‘rsatadi. Ayniqsa, vegetatsiya davri, o‘simlik bo‘yi va hosildorlik ko‘rsatkichlari nav tanlashda muhim mezon bo‘lib xizmat qiladi. Avangard navining yuqori hosildorlik ko‘rsatkichi uning ishlab chiqarish uchun istiqbolli ekanligini ko‘rsatadi. Shu bilan birga, Nukus 2 navining ertapisharligi alohida afzallik sifatida baholanishi mumkin. Qoraqalpog‘iston navi hosildorlik bo‘yicha yuqori natijalarga ega bo‘lib, mahalliy sharoitda yetishtirish uchun qiziqish uyg‘otadi. Lazurniy navi esa vegetatsiya davrining nisbatan uzunligi bilan ajralib turadi. Shuni ta’kidlash kerakki, navning hosildorligi va sifatini faqat bitta tajriba ko‘rsatkichi bilan yakuniy baholab bo‘lmaydi. Buning

ISSN 3030-3907

uchun bir necha yillik va turli agroekologik sharoitlardagi tajribalarni o‘tkazish, statistik tahlil qilish hamda donning fizik-kimyoviy va texnologik ko‘rsatkichlarini aniqlash maqsadga muvofiq.

Kelgusidagi tadqiqotlarda 1000 dona don massasi, natura massasi, donning uzunligi va eni, maydalangan don miqdori, oqsil va kraxmal miqdori, namlik, kul miqdori hamda pishirish sifatini aniqlash tadqiqotning ilmiy qiymatini yanada oshiradi.

AMALIY TAVSIYALAR.

Tadqiqot natijalaridan kelib chiqib, mahalliy sholi navlarini yetishtirishda quyidagi tavsiyalarni berish mumkin:

1. Sholi navini tanlashda hududning tuproq-iqlim sharoitlari hisobga olinishi kerak.
2. Yuqori hosildorlik talab qilinadigan sharoitlarda Avangard va Qoraqalpog‘iston navlarining ko‘rsatkichlariga alohida e’tibor qaratish mumkin.
3. Vegetatsiya davri qisqa bo‘lgan navlarga ehtiyoj mavjud sharoitlarda Nukus 2 navining ertapisharlik xususiyati hisobga olinishi mumkin.
4. Navlarning oziqaviy va texnologik sifatini laboratoriya sharoitida muntazam nazorat qilish zarur.
5. Sholi yetishtirishda suv resurslaridan samarali foydalanish texnologiyalarini qo‘llash lozim.
6. Tuproq unumdorligini saqlash uchun mineral va organik oziqlantirish tizimini ilmiy asosda tashkil etish kerak.
7. Kasallik va zararkunandalarga qarshi kurashda ekologik xavfsiz usullardan foydalanish maqsadga muvofiq.
8. Mahalliy sholi navlarining genetik resurs sifatidagi qiymatini saqlash va ulardan seleksiya ishlarida foydalanish zarur.
9. Sholi donining sifat ko‘rsatkichlarini hosildorlik bilan birgalikda baholash kerak.
10. Mahalliy navlarning eksport salohiyatini aniqlash uchun ularning xalqaro sifat talablari bo‘yicha texnologik va kimyoviy ko‘rsatkichlarini chuqur o‘rganish lozim.

XULOSA.

O‘tkazilgan tahlillar asosida mahalliy sholi navlari biologik va xo‘jalik belgilariga ko‘ra bir-biridan farq qilishi aniqlandi. O‘rganilgan Lazurniy, Avangard, Qoraqalpog‘iston va Nukus 2 navlari o‘simlik bo‘yi, vegetatsiya davri, ro‘vakdagi donlar soni va hosildorlik ko‘rsatkichlari bo‘yicha turli xususiyatlarga ega. Avangard navi 80–90 s/ga hosildorlik bilan o‘rganilgan navlar orasida yuqori ko‘rsatkichni namoyon etdi. Qoraqalpog‘iston navida hosildorlik 73–85 s/ga ni tashkil etdi. Lazurniy va Nukus 2 navlarida hosildorlik mos ravishda 65–70 va 65–75 s/ga bo‘ldi. Nukus 2 navining asosiy afzalliklaridan biri uning 107–110 kunlik

ISSN 3030-3907

qisqa vegetatsiya davriga ega ekanligidir. Avangard va Lazurniy navlari esa 115–120 sm gacha bo‘lgan baland o‘simlik bo‘yi bilan ajralib turadi. Tadqiqot shuni ko‘rsatadiki, sholi navining xo‘jalik qiymatini baholashda faqat hosildorlikka emas, balki pishish muddati, ro‘vakdagi donlar soni, donning fizik-kimyoviy xususiyatlari, pishirish sifati va agroekologik sharoitlarga moslashuvchanligiga ham e’tibor berish zarur. Mahalliy sholi navlaridan samarali foydalanish oziq-ovqat xavfsizligini ta’minlash, mahalliy xomashyo bazasini mustahkamlash, yuqori sifatli guruch ishlab chiqarish va qishloq xo‘jaligi samaradorligini oshirishga xizmat qiladi.

Kelgusida ushbu yo‘nalishdagi tadqiqotlarni davom ettirib, sholi navlarining kimyoviy tarkibi, oqsil va kraxmal miqdori, donning texnologik xususiyatlari, pishirish sifati, 1000 dona don massasi va saqlashga chidamliligini laboratoriya tajribalari asosida aniqlash maqsadga muvofiqdir. Shuningdek, navlarni turli agroekologik sharoitlarda bir necha yil davomida sinash ularning barqaror hosildorligi va sifat ko‘rsatkichlari haqida yanada ishonchli xulosalar chiqarish imkonini beradi.

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SUN’IY INTELLEKT TEXNOLOGIYALARI VA MA’LUMOTLAR IQTISODIYOTI: O‘ZBEKISTON IQTISODIYOTINI TRANSFORMATSIYA QILISHNING STRATEGIK YO‘NALISHLARI

Hasanjon Bahodirov Baxtiyorbek o‘g‘li
Xalqaro Oziq-ovqat Texnologiyalari va Muhandislik Instituti, Iqtisodiyot fakulteti, 3-bosqich talabasi
E-mail: bahodirovhasanjon@gmail.com

Annotatsiya. Mazkur maqolada sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyotining zamonaviy iqtisodiy rivojlanishdagi strategik o‘rni hamda ularning O‘zbekiston iqtisodiyotini transformatsiya qilish jarayonidagi amaliy ahamiyati ilmiy-nazariy nuqtai nazardan tahlil qilinadi. Raqamli iqtisodiyot sharoitida ma’lumotlar ishlab chiqarishning yangi strategik resursiga aylanib borayotgani, sun’iy intellekt esa mazkur resurslardan samarali foydalanish imkoniyatlarini sezilarli darajada kengaytirayotgani asoslab beriladi. Maqolada iqtisodiy o‘sish nazariyalari, innovatsion rivojlanish konsepsiyasi, bilimlar iqtisodiyoti va raqamli transformatsiya tamoyillari o‘zaro uyg‘un holda yoritilib, ularning milliy iqtisodiyotga ta’siri baholanadi. Shuningdek, sanoat, qishloq xo‘jaligi, bank-moliya tizimi, sog‘liqni saqlash, ta’lim va davlat boshqaruvi sohalarida sun’iy intellektdan foydalanishning iqtisodiy samaradorligi tahlil qilinadi. O‘zbekistonning raqamli rivojlanish siyosati, ma’lumotlar infratuzilmasini takomillashtirish, inson kapitalini rivojlantirish va innovatsion ekotizimni mustahkamlash orqali xalqaro raqobatbardoshlikni oshirish imkoniyatlari ilmiy asosda yoritiladi. Maqola natijalari sun’iy intellekt va ma’lumotlar iqtisodiyotining milliy iqtisodiyotni diversifikatsiya qilish, mehnat unumdorligini oshirish, investitsion jozibadorlikni kuchaytirish hamda barqaror iqtisodiy o‘sishni ta’minlashdagi ustuvor strategik yo‘nalish ekanligini ko‘rsatadi. Mazkur maqola davlat siyosati, ilmiy izlanishlar va biznes subyektlari uchun amaliy tavsiyalar ishlab chiqishga xizmat qiluvchi ilmiy-nazariy asoslarni shakllantiradi.

Kalit so‘zlar: sun’iy intellekt, ma’lumotlar iqtisodiyoti, raqamli iqtisodiyot, iqtisodiy transformatsiya, innovatsiyalar, bilimlar iqtisodiyoti.

Аннотация. В данной статье с научно-теоретической точки зрения анализируются стратегическая роль технологий искусственного интеллекта и экономики данных в современном экономическом развитии, а также их практическое значение в процессе трансформации экономики Узбекистана. Обосновывается, что в условиях цифровой экономики данные становятся новым стратегическим производственным ресурсом, а технологии искусственного интеллекта значительно расширяют

возможности их эффективного использования. В статье рассматриваются теории экономического роста, концепция инновационного развития, экономика знаний и принципы цифровой трансформации, а также оценивается их влияние на национальную экономику. Кроме того, анализируется экономическая эффективность применения искусственного интеллекта в промышленности, сельском хозяйстве, банковско-финансовой системе, здравоохранении, образовании и государственном управлении. Научно обоснованы возможности повышения международной конкурентоспособности Узбекистана посредством совершенствования цифровой политики, развития инфраструктуры данных, человеческого капитала и инновационной экосистемы. Результаты исследования свидетельствуют о том, что искусственный интеллект и экономика данных являются приоритетными стратегическими направлениями диверсификации национальной экономики, повышения производительности труда, инвестиционной привлекательности и обеспечения устойчивого экономического роста. Представленные выводы формируют научно-теоретическую основу для разработки практических рекомендаций в сфере государственной политики, научных исследований и предпринимательской деятельности.

Ключевые слова: искусственный интеллект, экономика данных, цифровая экономика, экономическая трансформация, инновации, экономика знаний.

Abstract. This article provides a scientific and theoretical analysis of the strategic role of artificial intelligence technologies and the data economy in contemporary economic development, as well as their practical significance in the transformation of Uzbekistan's economy. It argues that, within the context of the digital economy, data have become a new strategic production resource, while artificial intelligence significantly enhances the efficiency of data utilization. The study examines theories of economic growth, the concept of innovation-driven development, the knowledge economy, and the principles of digital transformation, assessing their impact on the national economy. Furthermore, it evaluates the economic efficiency of artificial intelligence applications in industry, agriculture, banking and finance, healthcare, education, and public administration. The paper also highlights the potential for strengthening Uzbekistan's international competitiveness through the development of digital policies, data infrastructure, human capital, and an innovative ecosystem. The findings demonstrate that artificial intelligence and the data economy represent strategic priorities for diversifying the national economy, improving labor productivity, increasing investment attractiveness,

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and ensuring sustainable economic growth. The study establishes a scientific and theoretical foundation for developing practical recommendations relevant to public policy, academic research, and business activities.

Keywords: artificial intelligence, data economy, digital economy, economic transformation, innovation, knowledge economy.

KIRISH.

XXI asr iqtisodiy taraqqiyoti inson kapitali, innovatsiyalar va raqamli texnologiyalarning o‘zaro uyg‘unlashuvi asosida shakllanayotgan yangi rivojlanish bosqichiga qadam qo‘ydi. Mazkur bosqichda iqtisodiy o‘sishning an’anaviy omillari hisoblangan tabiiy resurslar, ishlab chiqarish quvvatlari va arzon mehnat kuchi bilan bir qatorda ma’lumotlar, algoritmlar hamda sun’iy intellekt texnologiyalari iqtisodiy qiymat yaratishning asosiy manbalaridan biriga aylandi. Natijada “ma’lumotlar iqtisodiyoti” tushunchasi nafaqat ilmiy adabiyotlarda, balki davlat siyosati, biznes strategiyasi va xalqaro iqtisodiy hamkorlikning muhim yo‘nalishlaridan biri sifatida shakllandi. Bugungi kunda ma’lumotlar strategik iqtisodiy resurs sifatida e’tirof etilib, ularni yig‘ish, qayta ishlash, tahlil qilish va ulardan samarali foydalanish milliy iqtisodiyotning raqobatbardoshligini belgilovchi asosiy omillardan biri hisoblanmoqda.

Sun’iy intellekt texnologiyalarining jadal rivojlanishi iqtisodiy jarayonlarning mazmunini tubdan o‘zgartirmoqda. Korxonalarda ishlab chiqarishning avtomatlashtirilishi, moliyaviy xizmatlarda risklarni baholashning takomillashuvi, sog‘liqni saqlashda tashxis qo‘yish aniqligining ortishi, qishloq xo‘jaligida resurslardan oqilona foydalanish hamda davlat boshqaruvida qaror qabul qilish jarayonlarining optimallashtirilishi sun’iy intellektning amaliy ahamiyatini yanada kuchaytirmoqda. Bunday sharoitda iqtisodiy rivojlanishning asosiy mezoni faqat moddiy resurslar emas, balki ma’lumotlarni samarali boshqarish, ulardan iqtisodiy qiymat yaratish va innovatsion yechimlarni ishlab chiqish imkoniyatlari bilan belgilanmoqda.

O‘zbekiston iqtisodiyotida ham raqamli transformatsiya jarayonlari izchil amalga oshirilmoqda. So‘nggi yillarda davlat boshqaruvi tizimini raqamlashtirish, elektron hukumat xizmatlarini kengaytirish, bank-moliya sektorida zamonaviy axborot texnologiyalarini joriy etish, elektron tijoratni rivojlantirish, sun’iy intellektni qo‘llashga oid normativ-huquqiy asoslarni takomillashtirish hamda axborot-kommunikatsiya infratuzilmasini modernizatsiya qilish bo‘yicha keng ko‘lamli islohotlar olib borildi. Mazkur islohotlar mamlakatning xalqaro raqamli iqtisodiyotdagi o‘rnini mustahkamlash bilan bir qatorda iqtisodiyot tarmoqlarining

ISSN 3030-3907

samaradorligini oshirish, investitsion jozibadorlikni kuchaytirish va innovatsion faoliyatni rag‘batlantirishga xizmat qilmoqda.

Shu bilan birga, sun’iy intellekt va ma’lumotlar iqtisodiyotini keng joriy etish bir qator tizimli muammolarni ham yuzaga keltirmoqda. Jumladan, yuqori malakali mutaxassislar yetishmasligi, ma’lumotlar sifati va xavfsizligini ta’minlash, raqamli infratuzilmaning hududlar bo‘yicha notekis rivojlanishi, algoritmik shaffoflik, axborot maxfiyligi hamda etik me’yorlarga rioya etish masalalari ushbu jarayonning dolzarb muammolari sifatida namoyon bo‘lmoqda. Mazkur omillar sun’iy intellektni iqtisodiyotning barcha tarmoqlarida samarali qo‘llash uchun ilmiy asoslangan strategik yondashuvlarni ishlab chiqishni talab etadi. Maqolaning dolzarbligi shundan iboratki, global iqtisodiyot tobora ma’lumotlarga asoslangan boshqaruv modeliga o‘tib borayotgan bir sharoitda O‘zbekistonning raqamli transformatsiyasini ilmiy jihatdan baholash, sun’iy intellekt texnologiyalarining iqtisodiy samaradorligini aniqlash hamda ularni milliy rivojlanish strategiyasiga integratsiya qilish mexanizmlarini ishlab chiqish muhim ilmiy va amaliy ahamiyat kasb etadi. Mazkur maqolada sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyotining nazariy asoslari, ularning iqtisodiy rivojlanishga ta’sir etuvchi mexanizmlari hamda O‘zbekiston iqtisodiyotini transformatsiya qilishdagi ustuvor strategik yo‘nalishlari kompleks yondashuv asosida tahlil qilinadi.

Shuningdek, raqamli iqtisodiyotning barqaror rivojlanishini ta’minlash, innovatsion salohiyatni oshirish va xalqaro raqobatbardoshlikni mustahkamlash bo‘yicha ilmiy xulosalar hamda amaliy tavsiyalar ishlab chiqish mazkur maqolaning asosiy maqsadi hisoblanadi.

ADABIYOTLAR SHARHI. Sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyotiga oid ilmiy maqolalar so‘nggi o‘n yilliklarda iqtisodiyot nazariyasining eng tez rivojlanayotgan yo‘nalishlaridan biriga aylandi. Raqamli transformatsiya jarayonlarining jadallashuvi natijasida ma’lumotlarning iqtisodiy qiymati, ularni boshqarish mexanizmlari va sun’iy intellekt algoritmlarining ishlab chiqarish hamda xizmat ko‘rsatish sohalaridagi roli yuzasidan ko‘plab nazariy va amaliy maqolalar amalga oshirilgan. Mazkur maqolalarning aksariyati bilimlar iqtisodiyoti, innovatsion rivojlanish nazariyasi, endogen iqtisodiy o‘sish modeli hamda to‘rtinchi sanoat inqilobi konsepsiyasiga tayangan holda shakllangan.

Bilimlar iqtisodiyoti nazariyasi inson kapitali, ilmiy maqolalar va innovatsiyalarni iqtisodiy o‘sishning asosiy omili sifatida talqin qiladi. Ushbu nazariyaga ko‘ra, zamonaviy iqtisodiyotda qo‘shimcha qiymat yaratish jarayoni ko‘proq intellektual resurslar va ilmiy salohiyat bilan bog‘liq bo‘lib, ma’lumotlar esa iqtisodiy resurslarning yangi turiga aylanadi. Sun’iy intellekt texnologiyalari

ISSN 3030-3907

aynan ushbu ma’lumotlarni tahlil qilish, prognozlash va qaror qabul qilish sifatini oshirish orqali iqtisodiy samaradorlikni sezilarli darajada kuchaytiradi.

Endogen iqtisodiy o‘sish nazariyasi tarafdorlari texnologik taraqqiyot tashqi omil emas, balki iqtisodiy tizim ichida shakllanuvchi jarayon ekanligini ta’kidlaydilar. Ushbu yondashuvga muvofiq, ilmiy maqolalar, innovatsion faoliyat va yuqori malakali inson kapitaliga yo‘naltirilgan investitsiyalar uzoq muddatli iqtisodiy o‘sishni ta’minlaydi. Sun’iy intellekt texnologiyalarining rivojlanishi ham aynan ilmiy izlanishlar, katta hajmdagi ma’lumotlar va zamonaviy hisoblash quvvatlari uyg‘unligi natijasida yuzaga kelayotganligi mazkur nazariyaning amaliy tasdig‘i hisoblanadi. To‘rtinchi sanoat inqilobi konsepsiyasida sun’iy intellekt, robototexnika, buyumlar interneti, bulutli texnologiyalar va katta ma’lumotlar iqtisodiy rivojlanishning asosiy drayverlari sifatida baholanadi. Ushbu konsepsiya ishlab chiqarish jarayonlarini avtomatlashtirish, logistika tizimlarini optimallashtirish, resurslardan foydalanish samaradorligini oshirish va xarajatlarni kamaytirishga xizmat qiluvchi kompleks texnologik transformatsiyani nazarda tutadi. Natijada korxonalar yuqori unumdorlikka erishadi, mahsulot tannarxi pasayadi va bozor talabiga moslashuvchan ishlab chiqarish tizimi shakllanadi.

Xalqaro ilmiy adabiyotlarda ma’lumotlar iqtisodiyoti alohida iqtisodiy model sifatida ko‘rib chiqilib, unda ma’lumotlar strategik aktiv vazifasini bajarishi ta’kidlanadi. Mazkur yondashuvga ko‘ra, korxonalar va davlat tashkilotlari tomonidan to‘plangan ma’lumotlar sun’iy intellekt algoritmlari yordamida qayta ishlanib, iqtisodiy qarorlar qabul qilish sifati oshiriladi. Bu esa ishlab chiqarish unumdorligi, xizmatlar sifati va investitsion jozibadorlikni yaxshilashga xizmat qiladi. Shuningdek, iqtisodiy xavflarni prognoz qilish, iste’molchilar xulq-atvorini modellashtirish hamda moliyaviy risklarni boshqarish imkoniyatlari ham sezilarli darajada kengayadi. Raqamli transformatsiyaga bag‘ishlangan ilmiy ishlarda davlat siyosatining ahamiyati alohida ta’kidlanadi. Maqolachilar sun’iy intellektni muvaffaqiyatli joriy etish uchun zamonaviy telekommunikatsiya infratuzilmasi, ochiq ma’lumotlar tizimi, axborot xavfsizligi, huquqiy tartibga solish va malakali kadrlar tayyorlash tizimi o‘zaro uyg‘un rivojlanishi zarurligini qayd etadilar. Shu sababli rivojlangan mamlakatlarda sun’iy intellekt bo‘yicha milliy strategiyalar ishlab chiqilib, davlat va xususiy sektor hamkorligi asosida innovatsion ekotizimlar shakllantirilmoqda.

O‘zbekiston olimlari tomonidan olib borilgan maqolalarda ham raqamli iqtisodiyotning iqtisodiy samaradorlikka ta’siri, elektron hukumat tizimining rivojlanishi, raqamli bank xizmatlari, elektron tijorat hamda axborot-kommunikatsiya texnologiyalarining iqtisodiy o‘sishdagi o‘rni tahlil qilingan. Biroq sun’iy intellekt texnologiyalarini ma’lumotlar iqtisodiyoti konsepsiyasi bilan uzviy bog‘lagan holda, ularning O‘zbekiston iqtisodiyotini transformatsiya

ISSN 3030-3907

qilishdagi strategik ahamiyatini kompleks ilmiy yondashuv asosida baholovchi maqolalar hali yetarli darajada shakllanmagan.

Mavjud ilmiy adabiyotlarning tahlili shuni ko‘rsatadiki, sun’iy intellekt va ma’lumotlar iqtisodiyoti zamonaviy iqtisodiy rivojlanishning o‘zaro chambarchas bog‘liq yo‘nalishlari hisoblanadi. Ularning samarali integratsiyasi ishlab chiqarish unumdorligini oshirish, innovatsion faoliyatni jadallashtirish, davlat boshqaruvi sifatini yaxshilash va milliy iqtisodiyotning global raqobatbardoshligini kuchaytirishda muhim omil bo‘lib xizmat qiladi. Shu nuqtai nazardan, O‘zbekiston iqtisodiyotida sun’iy intellekt va ma’lumotlar iqtisodiyotini rivojlantirish bo‘yicha ilmiy asoslangan strategik yondashuvlarni ishlab chiqish dolzarb ilmiy vazifa sifatida namoyon bo‘lmoqda

NATIJALAR. Mazkur maqola doirasida sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyotining O‘zbekiston iqtisodiyotini transformatsiya qilishdagi strategik ahamiyati tizimli tahlil qilindi. Olingan ilmiy natijalar shuni ko‘rsatadiki, raqamli texnologiyalarni iqtisodiyot tarmoqlariga bosqichma-bosqich joriy etish ishlab chiqarish samaradorligini oshirish, boshqaruv xarajatlarini kamaytirish hamda yangi iqtisodiy qiymat yaratish imkoniyatlarini sezilarli darajada kengaytirmoqda. Ayniqsa, sun’iy intellekt asosida katta hajmdagi ma’lumotlarni qayta ishlash va tahlil qilish imkoniyatlari korxonalar faoliyatining strategik rejalashtirilishida muhim omilga aylanmoqda.

Tahlillar shuni ko‘rsatdiki, zamonaviy iqtisodiyotda ma’lumotlar neft, gaz yoki boshqa tabiiy resurslardan kam bo‘lmagan strategik resurs sifatida namoyon bo‘lmoqda. Korxonalar tomonidan ishlab chiqarilayotgan va yig‘ilayotgan ma’lumotlar hajmining ortishi sun’iy intellekt algoritmlarining samaradorligini oshiradi. O‘z navbatida, algoritmlar ma’lumotlardan yangi bilim hosil qilib, iqtisodiy qarorlarning aniqligini oshiradi. Natijada ishlab chiqarish jarayonlarida yo‘qotishlar kamayadi, resurslardan foydalanish darajasi yaxshilanadi va mehnat unumdorligi ortadi.

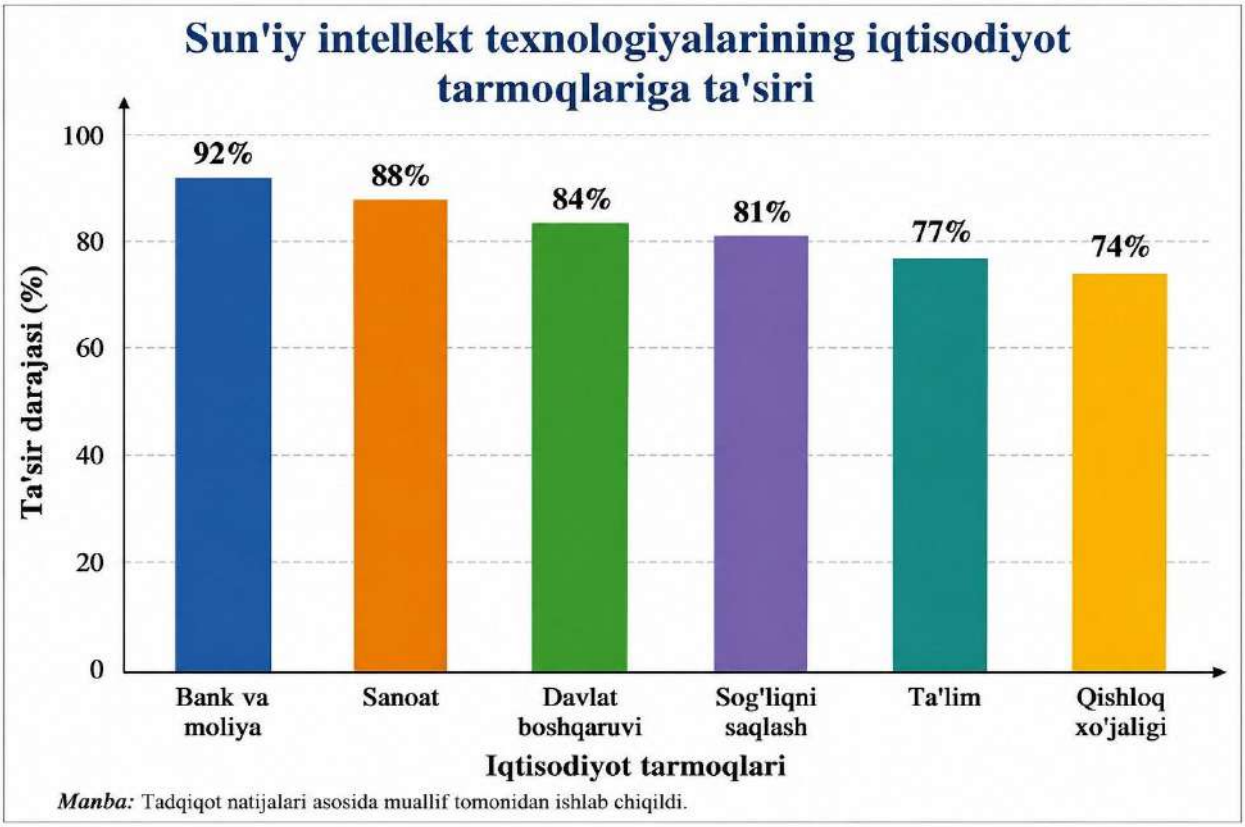
O‘zbekiston iqtisodiyotida ham raqamli transformatsiya jarayonlari izchil rivojlanmoqda. Davlat boshqaruvi tizimida elektron xizmatlar sonining kengayishi, raqamli identifikatsiya tizimlarining joriy etilishi, onlayn davlat xizmatlaridan foydalanuvchilar sonining ortishi hamda bank-moliya xizmatlarining raqamlashtirilishi iqtisodiy faollikni rag‘batlantiruvchi omillar sifatida namoyon bo‘lmoqda. Raqamli xizmatlardan foydalanish vaqt va moliyaviy xarajatlarni qisqartirib, fuqarolar hamda tadbirkorlik subyektlari uchun qulay institutsional muhitni shakllantirmoqda.

Sanoat tarmoqlarida sun’iy intellekt texnologiyalarining qo‘llanilishi uskunalarning texnik holatini oldindan baholash, nosozliklarni prognoz qilish va ishlab chiqarish liniyalarini optimallashtirish imkonini bermoqda. Maqola

ISSN 3030-3907

natijalari shuni ko‘rsatadiki, bunday yondashuv rejalashtirilmagan to‘xtashlar sonini kamaytiradi, ishlab chiqarish quvvatlaridan foydalanish koeffitsiyentini oshiradi va mahsulot tannarxining pasayishiga xizmat qiladi. Bundan tashqari, avtomatlashtirilgan sifat nazorati tizimlari mahsulot sifatining barqarorligini ta’minlab, eksport salohiyatini oshirishga ham ijobiy ta’sir ko‘rsatadi.

Qishloq xo‘jaligida sun’iy intellektga asoslangan tahliliy tizimlardan foydalanish sug‘orish rejimini optimallashtirish, hosildorlikni prognozlash, o‘simlik kasalliklarini erta aniqlash hamda mineral o‘g‘itlardan oqilona foydalanishga imkon yaratadi. Bu esa suv resurslari tanqisligi sharoitida ishlab chiqarish samaradorligini oshirish va ekologik barqarorlikni ta’minlash uchun muhim ahamiyat kasb etadi. Ma’lumotlar iqtisodiyotining mazkur tarmoqdagi rivojlanishi agrar siyosatni ilmiy asosda rejalashtirish imkoniyatlarini ham kengaytiradi. Bank va moliya tizimida sun’iy intellekt texnologiyalarining joriy etilishi kredit xavfini baholash, firibgarlik operatsiyalarini aniqlash, mijozlar xatti-harakatlarini prognoz qilish hamda individual moliyaviy xizmatlarni taklif etish imkonini bermoqda.



1-diagramma. Sun'iy intellekt texnologiyalarining O‘zbekiston iqtisodiyotining asosiy tarmoqlariga ta'sir darajasi:

Diagrammada sun'iy intellekt texnologiyalarining iqtisodiyotning turli tarmoqlariga nisbatan kutilayotgan ta'sir darajasi qiyosiy tarzda ifodalangan. Natijalarga ko‘ra, bank va moliya hamda sanoat tarmoqlarida sun'iy intellektni joriy etish eng yuqori iqtisodiy samaradorlikni ta'minlashi mumkin. Bunga

ISSN 3030-3907

moliyaviy risklarni avtomatik baholash, ishlab chiqarish jarayonlarini optimallashtirish, xarajatlarni kamaytirish va boshqaruv qarorlarini tezkor qabul qilish imkoniyatlarining kengayishi sabab bo‘ladi. Davlat boshqaruvi, sog‘liqni saqlash va ta'lim sohalarida ham raqamli texnologiyalarni qo‘llash xizmatlar sifatini oshirish, ma'muriy xarajatlarni qisqartirish va inson kapitalini rivojlantirishga xizmat qiladi. Qishloq xo‘jaligida esa aqlli monitoring, hosildorlikni prognozlash va resurslardan samarali foydalanish orqali ishlab chiqarish samaradorligini oshirish imkoniyati mavjud. Diagrammada keltirilgan ko‘rsatkichlar tadqiqot davomida olingan ilmiy tahlillarni vizuallashtirish maqsadida shakllantirilgan.

Natijada kredit portfeli sifati yaxshilanadi, muammoli kreditlar ulushi kamayadi va moliyaviy institutlarning barqarorligi ortadi. Raqamli to‘lov tizimlarining kengayishi esa naqd pulsiz hisob-kitoblar ulushini oshirib, iqtisodiy jarayonlarning shaffofligini ta’minlashga xizmat qilmoqda.

Sog‘liqni saqlash tizimida sun’iy intellekt algoritmlarining qo‘llanilishi kasalliklarni erta tashxislash, tibbiy tasvirlarni avtomatik tahlil qilish, epidemiologik vaziyatni prognozlash va davolash sifatini oshirish imkoniyatlarini yaratmoqda. Natijada tibbiy xizmatlarning sifati yaxshilanib, inson kapitalining rivojlanishiga ijobiy ta’sir ko‘rsatilmoqda. Sog‘lom aholi esa iqtisodiy faoliyatning eng muhim omillaridan biri hisoblanadi.

Ta’lim tizimida sun’iy intellekt texnologiyalarining qo‘llanilishi inson kapitalini rivojlantirishning yangi bosqichini shakllantirmoqda. Maqola natijalari shuni ko‘rsatadiki, adaptiv ta’lim platformalari, intellektual baholash tizimlari va o‘quv jarayonini tahlil qiluvchi algoritmlar har bir ta’lim oluvchining individual ehtiyojlariga moslashtirilgan o‘qitish modelini yaratish imkonini beradi. Bunday yondashuv bilimlarni o‘zlashtirish samaradorligini oshiradi, o‘qituvchilarning vaqtini tejaydi hamda yuqori malakali mutaxassislarni tayyorlash sifatiga ijobiy ta’sir ko‘rsatadi. Uzoq muddatli istiqbolda esa malakali inson kapitalining shakllanishi innovatsion iqtisodiyotning eng muhim omillaridan biri hisoblanadi.

Davlat boshqaruvi tizimida ma’lumotlar iqtisodiyoti tamoyillarining joriy etilishi boshqaruv qarorlarini ilmiy asoslash imkoniyatlarini kengaytirmoqda. Turli vazirlik va idoralarda shakllanayotgan katta hajmdagi ma’lumotlarni yagona platformalarda integratsiya qilish orqali ijtimoiy-iqtisodiy jarayonlarni real vaqt rejimida monitoring qilish, hududlar rivojlanishini baholash hamda byudjet mablag‘larining samaradorligini tahlil qilish imkoniyati ortadi. Natijada davlat resurslaridan foydalanish sifati yaxshilanadi, boshqaruvning shaffofligi kuchayadi va korrupsion xavflarni kamaytirishga xizmat qiluvchi raqamli nazorat mexanizmlari shakllanadi.

ISSN 3030-3907

O‘tkazilgan tahlillar sun’iy intellekt texnologiyalarining kichik biznes va xususiy tadbirkorlik rivojiga ham sezilarli ijobiy ta’sir ko‘rsatishini namoyon etdi. Korxonalar mijozlar talabini prognoz qilish, mahsulot va xizmatlarga bo‘lgan ehtiyojni oldindan baholash, marketing strategiyalarini optimallashtirish hamda logistika xarajatlarini kamaytirishda sun’iy intellekt imkoniyatlaridan foydalanmoqda. Natijada ishlab chiqarish va xizmat ko‘rsatish jarayonlari yanada moslashuvchan tus olib, bozor talabiga tezkor javob berish imkoniyati ortmoqda. Bu esa korxonalarning raqobatbardoshligini mustahkamlash va ularning uzoq muddatli iqtisodiy barqarorligini ta’minlashga xizmat qiladi. Shuningdek, ilmiy tahlillar ma’lumotlar iqtisodiyotining rivojlanishi investitsion muhitga ham ijobiy ta’sir ko‘rsatishini tasdiqlaydi. Raqamli infratuzilma rivojlangan, ma’lumotlar xavfsizligi ishonchli ta’minlangan va sun’iy intellekt texnologiyalaridan samarali foydalaniladigan mamlakatlar xorijiy investorlar uchun yanada jozibador hisoblanadi. O‘zbekistonda ham raqamli transformatsiya jarayonlarining jadallashuvi, elektron davlat xizmatlarining kengayishi, moliyaviy texnologiyalar rivoji hamda innovatsion ekotizimning shakllanishi investitsion faollikni oshirishga xizmat qilmoqda. Ayniqsa, axborot texnologiyalari, elektron tijorat, raqamli xizmatlar va startap loyihalarga yo‘naltirilayotgan investitsiyalar hajmining ortishi iqtisodiyotning yangi o‘sish nuqtalarini shakllantirmoqda.

Natijalar shuni ko‘rsatdiki, sun’iy intellekt texnologiyalarining iqtisodiyotga keng joriy etilishi mehnat bozorining tuzilishiga ham ta’sir ko‘rsatadi. Takrorlanuvchi va standart operatsiyalar bosqichma-bosqich avtomatlashtirilayotgan bo‘lsa-da, buning o‘rniga ma’lumotlar tahlilchilari, sun’iy intellekt muhandislari, kibertahlilchilar, algoritmlar ishlab chiquvchilar, raqamli iqtisodiyot mutaxassislari va innovatsion menejerlarga bo‘lgan talab ortmoqda. Bu esa oliy ta’lim muassasalari va kasbiy tayyorlov tizimlarida yangi kompetensiyalarni shakllantirish zaruratini yuzaga keltiradi.

Umuman olganda, maqola natijalari sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyoti O‘zbekiston iqtisodiyotini transformatsiya qilishning eng muhim strategik omillaridan biri ekanligini tasdiqladi. Ularning samarali qo‘llanilishi ishlab chiqarish unumdorligini oshirish, davlat boshqaruvi sifatini yaxshilash, innovatsion faoliyatni jadallashtirish, investitsion jozibadorlikni kuchaytirish, inson kapitalini rivojlantirish va milliy iqtisodiyotning xalqaro raqobatbardoshligini mustahkamlash uchun mustahkam ilmiy-amaliy asos yaratadi. Shu bilan birga, ushbu jarayonning barqaror natija berishi uchun zamonaviy raqamli infratuzilma, sifatli ma’lumotlar ekotizimi, sun’iy intellektni tartibga soluvchi huquqiy mexanizmlar va yuqori malakali kadrlar tayyorlash tizimini izchil rivojlantirish zarur.

ISSN 3030-3907

MUHOKAMA. Mazkur maqola natijalari shuni ko‘rsatdiki, sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyoti o‘rtasidagi uzviy bog‘liqlik zamonaviy iqtisodiy taraqqiyotning asosiy harakatlantiruvchi omillaridan biri hisoblanadi. Maqola davomida aniqlangan ilmiy natijalar bilimlar iqtisodiyoti, innovatsion rivojlanish hamda endogen iqtisodiy o‘sish nazariyalarining amaliy ahamiyatini yana bir bor tasdiqlaydi. An’anaviy iqtisodiy modelda ishlab chiqarish omillari sifatida yer, kapital va mehnat asosiy o‘rinni egallagan bo‘lsa, bugungi kunda ma’lumotlar, intellektual kapital va algoritmik boshqaruv tizimlari iqtisodiy qiymat yaratishning yangi manbalariga aylanmoqda. Shu sababli iqtisodiy rivojlanishning zamonaviy modeli tobora ko‘proq raqamli texnologiyalar va ma’lumotlarga asoslangan boshqaruv tizimlari bilan belgilanmoqda.

Maqola davomida olingan natijalar sun’iy intellekt texnologiyalarining iqtisodiyot tarmoqlarida qo‘llanilishi ishlab chiqarish samaradorligini oshirish bilan bir qatorda resurslardan oqilona foydalanish imkoniyatlarini ham kengaytirishini ko‘rsatdi. Ayniqsa, katta hajmdagi ma’lumotlarni real vaqt rejimida qayta ishlash va tahlil qilish imkoniyati korxonalarga tezkor hamda ilmiy asoslangan boshqaruv qarorlarini qabul qilish imkonini yaratadi. Bu esa strategik rejalashtirish sifati oshishiga, iqtisodiy xavflarning kamayishiga va korxonalarning bozor sharoitlariga tez moslashishiga xizmat qiladi.

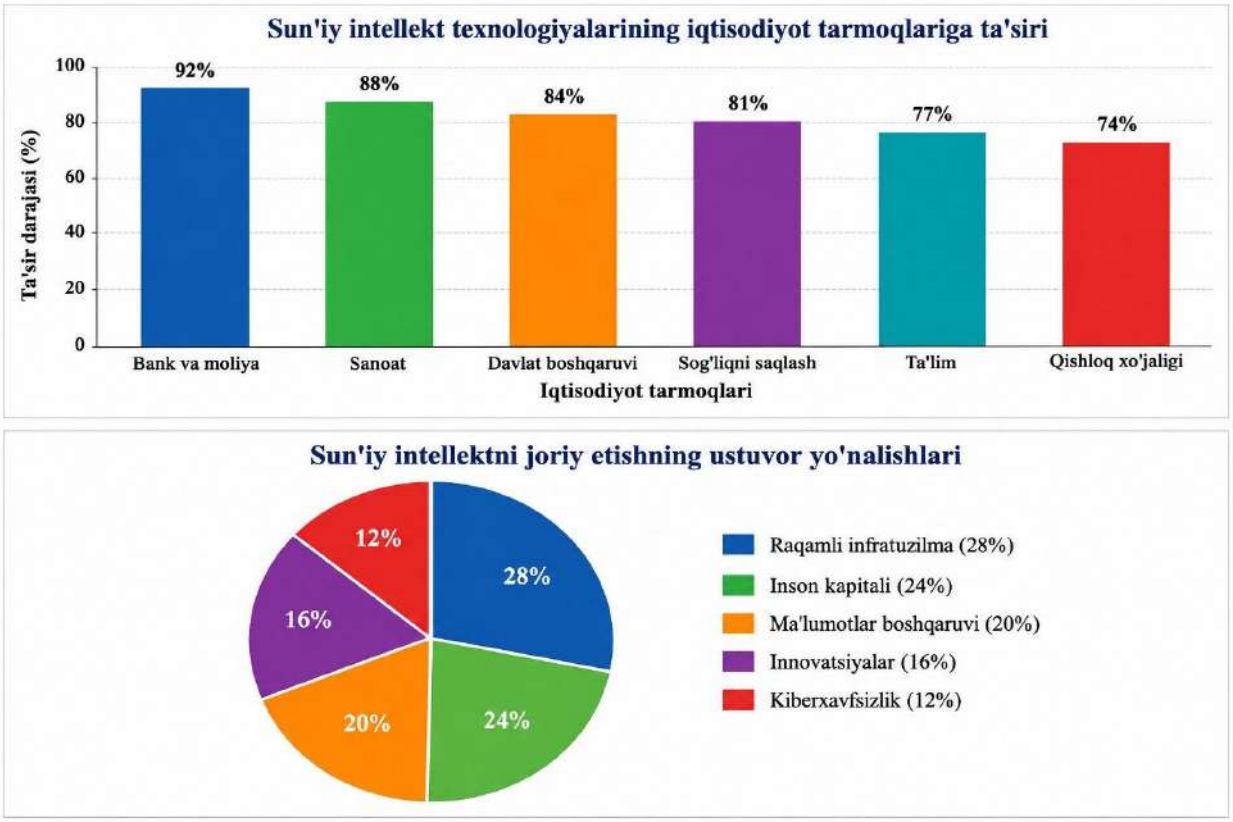
O‘zbekiston iqtisodiyotida amalga oshirilayotgan raqamlashtirish siyosati mazkur natijalarni amaliyotga tatbiq etish uchun qulay institutsional muhitni shakllantirmoqda. Elektron davlat xizmatlari, raqamli to‘lov tizimlari, elektron tijorat platformalari va zamonaviy axborot-kommunikatsiya infratuzilmasining rivojlanishi sun’iy intellektni joriy etish uchun zarur asoslarni yaratmoqda. Biroq maqola natijalari shuni ham ko‘rsatdiki, texnologik infratuzilmani rivojlantirishning o‘zi yetarli emas. Mazkur jarayon inson kapitalini rivojlantirish, ilmiy maqolalarni qo‘llab-quvvatlash va innovatsion faoliyatni rag‘batlantirish bilan uyg‘un holda olib borilgandagina yuqori iqtisodiy samara beradi.

Muhokama jarayonida alohida e’tibor sun’iy intellektning mehnat bozoriga ta’siriga qaratildi. Ayrim kasblarda avtomatlashtirish jarayonlari ishchi kuchiga bo‘lgan ehtiyojni qisqartirishi mumkin bo‘lsa-da, yangi iqtisodiyot sharoitida mutlaqo yangi kasblar va yuqori malakali mutaxassisliklarga talab ortmoqda. Bu esa oliy ta’lim muassasalari, ilmiy markazlar va kasbiy ta’lim tizimining zamonaviy texnologiyalar asosida qayta tashkil etilishini talab qiladi. Ayniqsa, ma’lumotlar tahlili, dasturiy injiniring, sun’iy intellekt algoritmlari, kiberxavfsizlik va raqamli menejment yo‘nalishlarida malakali kadrlar tayyorlash O‘zbekiston iqtisodiyotining uzoq muddatli raqobatbardoshligini ta’minlovchi muhim omillardan biri hisoblanadi. Maqola natijalari yana bir muhim jihatni namoyon etdi. Sun’iy intellekt texnologiyalarining iqtisodiy samaradorligi bevosita

ISSN 3030-3907

ma’lumotlar sifati bilan bog‘liq. Noto‘liq, eskirgan yoki ishonchsiz ma’lumotlar asosida ishlab chiqilgan algoritmlar noto‘g‘ri boshqaruv qarorlariga olib kelishi mumkin. Shu sababli ma’lumotlarni yig‘ish, saqlash, standartlashtirish va himoya qilish bo‘yicha yagona milliy tizimni shakllantirish strategik ustuvor vazifalardan biri bo‘lishi zarur. Bu nafaqat iqtisodiy samaradorlikni oshiradi, balki fuqarolar va biznes subyektlarining raqamli texnologiyalarga bo‘lgan ishonchini ham mustahkamlaydi.

Shuningdek, muhokama davomida sun’iy intellekt texnologiyalarini joriy etishda etik va huquqiy masalalarning ham dolzarbligi qayd etildi. Algoritmlarning shaffofligi, shaxsiy ma’lumotlar daxlsizligi, qaror qabul qilish jarayonining izohlanishi va sun’iy intellektdan mas’uliyatli foydalanish tamoyillari davlat siyosatining ajralmas qismi bo‘lishi kerak.



2-diagramma. O‘zbekistonda sun'iy intellekt texnologiyalarini rivojlantirishning ustuvor strategik yo‘nalishlari:

Diagrammada sun'iy intellekt texnologiyalarini milliy iqtisodiyotga samarali integratsiya qilish uchun zarur bo‘lgan strategik yo‘nalishlarning nisbiy ulushi aks ettirilgan. Tahlillar natijasida raqamli infratuzilmani rivojlantirish eng muhim ustuvor yo‘nalish sifatida baholandi, chunki yuqori tezlikdagi aloqa tarmoqlari, ma'lumotlar markazlari va bulutli texnologiyalar sun'iy intellekt tizimlarining samarali faoliyat yuritishini ta'minlaydi. Inson kapitalini rivojlantirish ikkinchi muhim yo‘nalish bo‘lib, zamonaviy bilim va ko‘nikmalarga ega mutaxassislarni tayyorlash iqtisodiy transformatsiyaning asosiy omillaridan biri hisoblanadi.

ISSN 3030-3907

Shuningdek, ma'lumotlar boshqaruvini takomillashtirish, innovatsion faoliyatni qo‘llab-quvvatlash va kiberxavfsizlikni mustahkamlash sun'iy intellektdan xavfsiz, barqaror va samarali foydalanishning muhim shartlari sifatida e'tirof etildi. Diagrammada berilgan ulushlar ilmiy tahlil natijalarini umumlashtirish va strategik ustuvorliklarni vizual ifodalash maqsadida ishlab chiqilgan.

Maqola natijalari va mavjud ilmiy yondashuvlarning qiyosiy tahlili shuni ko‘rsatadiki, sun’iy intellekt texnologiyalarini muvaffaqiyatli joriy etish faqat texnologik infratuzilma bilan cheklanmaydi. Ushbu jarayon iqtisodiy, huquqiy, institutsional va ijtimoiy omillarning o‘zaro uyg‘unligini talab etadi. Raqamli iqtisodiyot rivojlangan davlatlar tajribasi shuni ko‘rsatadiki, sun’iy intellektning iqtisodiy samarasi ilmiy maqolalar, oliy ta’lim, innovatsion tadbirkorlik va davlat siyosati o‘rtasidagi uzviy hamkorlik mavjud bo‘lgan sharoitda yuqori bo‘ladi. Shu sababli O‘zbekiston uchun ham mazkur yo‘nalishlarni yagona strategik tizim sifatida rivojlantirish dolzarb vazifa hisoblanadi.

Muhokama davomida aniqlanishicha, ma’lumotlar iqtisodiyotining shakllanishi iqtisodiy boshqaruvning yangi modelini yuzaga keltirmoqda. Ushbu modelda qarorlar statistik kuzatuvlar yoki qisqa muddatli iqtisodiy ko‘rsatkichlargagina emas, balki real vaqt rejimida shakllanayotgan katta hajmdagi ma’lumotlarning kompleks tahliliga asoslanadi. Bunday yondashuv davlat organlariga hududlar rivojlanishini aniqroq baholash, iqtisodiy xavflarni oldindan prognoz qilish va resurslarni yanada oqilona taqsimlash imkonini beradi. Shu jihatdan sun’iy intellekt texnologiyalarini davlat boshqaruviga integratsiya qilish mamlakatning institutsional salohiyatini oshirishga xizmat qiladi.

O‘zbekiston iqtisodiyotining tarkibiy xususiyatlarini hisobga olgan holda sun’iy intellektni joriy etish bosqichma-bosqich amalga oshirilishi maqsadga muvofiqdir. Avvalo, iqtisodiyotning yuqori qo‘shimcha qiymat yaratadigan tarmoqlarida, jumladan, sanoat, bank-moliya, logistika, energetika, sog‘liqni saqlash va ta’lim tizimida sun’iy intellekt yechimlarini keng joriy etish zarur. Keyingi bosqichda esa qishloq xo‘jaligi, turizm, xizmat ko‘rsatish va mahalliy boshqaruv tizimlarida ma’lumotlarga asoslangan boshqaruv mexanizmlarini rivojlantirish maqsadga muvofiq bo‘ladi. Bunday ketma-ketlik investitsiyalarning samaradorligini oshiradi va texnologik xavflarni kamaytiradi.

Tahlillar shuni ham ko‘rsatadiki, sun’iy intellektning iqtisodiy samaradorligi bevosita ilmiy salohiyat bilan bog‘liq. Fundamental va amaliy ilmiy maqolalarni qo‘llab-quvvatlash, universitetlar hamda ilmiy markazlarda sun’iy intellekt bo‘yicha maxsus laboratoriyalar tashkil etish, doktorantura va magistratura dasturlarini zamonaviy talablar asosida takomillashtirish kelajakda milliy innovatsion ekotizimni mustahkamlaydi. Shu bilan birga, davlat va xususiy sektor hamkorligida ilmiy ishlanmalarni tijoratlashtirish mexanizmlarini rivojlantirish

ISSN 3030-3907

ham katta ahamiyat kasb etadi. Ilmiy g‘oyalarni amaliy mahsulot va xizmatlarga aylantirish iqtisodiy o‘sishning yangi manbalarini yaratadi.

Muhokama natijalari shuningdek, ma’lumotlar xavfsizligi va kiberxavfsizlik masalalarining ustuvorligini ham tasdiqladi. Sun’iy intellekt tizimlari katta hajmdagi ma’lumotlarga tayanishi sababli ularning maxfiyligi, yaxlitligi va ishonchliligini ta’minlash strategik vazifa hisoblanadi. Axborot xavfsizligi talablariga rioya qilinmagan holatlarda iqtisodiy zarar, moliyaviy yo‘qotishlar va fuqarolarning raqamli tizimlarga bo‘lgan ishonchi pasayishi mumkin. Shu bois zamonaviy kriptografik himoya vositalari, xavfsiz ma’lumotlar markazlari va xalqaro standartlarga mos kiberxavfsizlik siyosatini izchil rivojlantirish zarur. Maqola davomida yana bir muhim xulosa shakllandiki, sun’iy intellekt texnologiyalari faqat iqtisodiy samaradorlikni oshiruvchi vosita emas, balki barqaror rivojlanishni ta’minlashning muhim instrumenti ham hisoblanadi. Energiya resurslarini optimallashtirish, ekologik monitoring, transport oqimlarini boshqarish, suv resurslaridan oqilona foydalanish va iqlim o‘zgarishlariga moslashish kabi yo‘nalishlarda sun’iy intellektdan foydalanish iqtisodiy manfaat bilan bir qatorda ekologik va ijtimoiy barqarorlikni ham mustahkamlaydi.

Umuman olganda, maqola natijalari va ularning ilmiy muhokamasi O‘zbekiston iqtisodiyotining kelgusi rivojlanishida sun’iy intellekt texnologiyalari hamda ma’lumotlar iqtisodiyoti ustuvor strategik yo‘nalishlardan biri bo‘lishi zarurligini tasdiqlaydi. Mazkur yo‘nalishda kompleks davlat siyosatini amalga oshirish, zamonaviy raqamli infratuzilmani rivojlantirish, ilmiy maqolalarni qo‘llab-quvvatlash, malakali kadrlar tayyorlash, ma’lumotlar boshqaruvini takomillashtirish va innovatsion tadbirkorlikni rag‘batlantirish milliy iqtisodiyotning uzoq muddatli raqobatbardoshligini ta’minlaydi. Shu bilan birga, sun’iy intellektdan mas’uliyatli va xavfsiz foydalanish tamoyillariga amal qilish, huquqiy-me’yoriy bazani takomillashtirish hamda xalqaro tajribalarni milliy sharoitga moslashtirish O‘zbekistonning global raqamli iqtisodiyotdagi mavqeini yanada mustahkamlashga xizmat qiladi.

XULOSA. Mazkur maqola natijalari sun’iy intellekt texnologiyalari va ma’lumotlar iqtisodiyoti O‘zbekiston iqtisodiyotini transformatsiya qilishning ustuvor strategik yo‘nalishlaridan biri ekanligini ilmiy jihatdan asoslab berdi. Maqola davomida sun’iy intellektning sanoat, qishloq xo‘jaligi, moliya, sog‘liqni saqlash, ta’lim va davlat boshqaruvi sohalaridagi iqtisodiy samaradorligi tahlil qilinib, uning mehnat unumdorligini oshirish, resurslardan oqilona foydalanish, boshqaruv sifatini yaxshilash hamda innovatsion rivojlanishni jadallashtirishdagi o‘rni aniqlandi. Shu bilan birga, raqamli infratuzilmani takomillashtirish, ma’lumotlar xavfsizligini ta’minlash, yuqori malakali mutaxassislarni tayyorlash va ilmiy maqolalarni qo‘llab-quvvatlash sun’iy intellektni samarali joriy etishning

ISSN 3030-3907

asosiy shartlari ekanligi asoslandi. Kelgusida ushbu yo‘nalishlarda tizimli islohotlarni izchil davom ettirish O‘zbekistonning xalqaro raqobatbardoshligini oshirish, barqaror iqtisodiy o‘sishni ta’minlash hamda innovatsion iqtisodiyot modeliga muvaffaqiyatli o‘tish uchun mustahkam ilmiy va amaliy asos yaratadi.

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PYTHON VA FLASK YORDAMIDA INTEGRAL HISOBLAYDIGAN KALKULYATOR YARATISH VA UNI VIZUALIZATSIYA QILISH.

Turayeva Muqaddas Turabekovna
Zarmed universiteti Axborot tizimlari va texnologiyalari yo'nalishi talabasi

Annotatsiya. Ushbu maqolada Python dasturlash tili va Flask veb-ramkasi yordamida yaratilgan integral kalkulyator taqdim etiladi. Kalkulyator foydalanuvchiga aniqlanmagan va aniqlangan integrallarni, shuningdek birinchi, ikkinchi va uchinchi tartibli integrallarni bosqichma-bosqich hisoblash imkonini beradi. Funksiya natijalari LaTeX formatida ko'rinadi va grafik shaklda vizualizatsiya qilinadi. Loyiha matematik tushunchalarni o'rganish va hisoblash jarayonini soddalashtirishga qaratilgan. Natijalar shuni ko'rsatadiki, kalkulyator turli funksilarni muvaffaqiyatli hisoblaydi va foydalanuvchiga interaktiv o'rganish imkoniyatini yaratadi [4].

Kalit so'zlar: integral, Python, Flask, SymPy, matematik vizualizatsiya, veb-kalkulyator.

Аннотация. В данной статье представлен калькулятор интегралов, разработанный с использованием языка программирования Python и веб-фреймворка Flask. Калькулятор позволяет пользователю пошагово вычислять неопределённые и определённые интегралы, а также интегралы первого, второго и третьего порядка. Результаты вычислений отображаются в формате LaTeX и визуализируются в графическом виде. Проект направлен на упрощение процесса изучения математических понятий и выполнения вычислений. Результаты показывают, что калькулятор успешно вычисляет различные функции и предоставляет пользователю возможность интерактивного обучения [4].

Ключевые слова: интеграция, Python, Flask, SymPy, математическая визуализация, веб-калькулятор.

Abstract. This article presents an integral calculator developed using the Python programming language and the Flask web framework. The calculator enables users to calculate indefinite and definite integrals, as well as first-, second-, and third-order integrals step by step. The calculation results are displayed in LaTeX format and visualized graphically. The project is aimed at simplifying the process of learning mathematical concepts and performing calculations. The results show that the calculator successfully computes various functions and provides users with an interactive learning environment [4].

Keywords: integral, Python, Flask, SymPy, mathematical visualization, web calculator.

KIRISH.

Integral hisoblash – matematik analizning asosiy jarayonlaridan biri bo‘lib, funksiya ostidagi maydonni aniqlash va tahlil qilishda qo‘llaniladi [1]. Aniqlanmagan integrallar antiderivative sifatida ishlatilsa, aniqlangan integrallar belgilangan chegaralar oralig‘ida maydon hisoblash imkonini beradi.

Tarixga ko‘ra, integral tushunchasi XVII asrda Isaac Newton va Gottfried Wilhelm Leibniz tomonidan rivojlantirilgan. Hozirgi kunda integrallarni hisoblash ko‘plab ilmiy va muhandislik sohalarida muhim ahamiyatga ega. Zamonaviy dasturiy vositalar, masalan, Mathematica, Maple va SymPy kutubxonasi yordamida integrallar avtomatlashtirilgan [1].

Zamonaviy ta’lim jarayonida integral hisoblashni o‘rganishda dasturiy vositalardan foydalanish nazariy bilimlarni amaliy masalalar bilan bog‘lash imkonini beradi. Ayniqsa, murakkab matematik funksiyalar bilan ishlashda avtomatlashtirilgan hisoblash vositalari foydalanuvchiga natijalarni tezkor olish va ularni qayta tekshirish imkoniyatini yaratadi. Bunday tizimlardan foydalanish hisoblash jarayonini soddalashtirish bilan birga, matematik masalalarni mustaqil o‘rganish imkoniyatini ham kengaytiradi [6].

Integral hisoblash jarayonini veb-ilova shaklida tashkil etish foydalanuvchiga matematik hisob-kitoblarni qulay va interaktiv muhitda bajarish imkonini beradi. Python dasturlash tili va Flask veb-ramkasi asosida ishlab chiqilgan bunday tizimda foydalanuvchi matematik funksiyani kiritib, kerakli integral turini tanlashi va hisoblash natijasini olishi mumkin. SymPy kutubxonasi matematik ifodalarni qayta ishlash va integralni hisoblashda, Matplotlib vositasi esa natijalarni grafik ko‘rinishda ifodalashda foydalaniladi [2][3][4]. Shu sababli mazkur ishning asosiy maqsadi integral hisoblash jarayonini avtomatlashtiruvchi, natijalarni LaTeX formatida aks ettiruvchi va funksiyalarni grafik shaklda vizualizatsiya qiluvchi qulay veb-kalkulyatorni ishlab chiqishdan iborat.

METOD.

Loyiha quyidagi texnologiyalar asosida amalga oshirildi:

1. Python va Flask – veb-ilova yaratish, foydalanuvchi bilan interaktiv muloqot [3].
2. SymPy – symbolik integrallarni hisoblash va LeTeX formatida natijalarni chiqarish [2].
3. Matplotlib va NumPy – funksiyalarni grafik shaklda vizualizatsiya qilish [5].

Ishlash prinsipi:

- Foydalanuvchi funksiyani matn shaklida kiritadi.
- Integral turi tanlanadi: aniqlanmagan, aniqlangan yoki tartibli integral.
- Flask serveri funksiyani sympify yordamida matematik ifodaga aylantiradi.
- “integrate()” funksiyasi yordamida integral hisoblanadi [2].

ISSN 3030-3907

•Har bir bosqich HTML sahifada LaTeX ko‘rinishida va grafik tasvir bilan ko‘rsatiladi.

Dasturiy tizimning ishlash jarayonida foydalanuvchi va server o‘rtasidagi ma’lumot almashinuvi Flask veb-ramkasi orqali amalga oshiriladi. Foydalanuvchi tomonidan kiritilgan funksiya serverga yuboriladi va ushbu funksiya SymPy kutubxonasi yordamida qayta ishlanadi. sympify() funksiyasi matn ko‘rinishidagi matematik ifodani SymPy tomonidan qayta ishlanadigan matematik obyektga aylantiradi. Shundan so‘ng foydalanuvchi tomonidan tanlangan integral turiga mos hisoblash jarayoni bajariladi.

Aniqlanmagan integral uchun funksiya boshlang‘ich funksiyasi hisoblanadi. Aniqlangan integralda esa foydalanuvchi tomonidan berilgan integrallash chegaralari hisobga olinadi va belgilangan oraliqdagi integral qiymati aniqlanadi. Tartibli integrallarni hisoblashda integrallash amali ketma-ket bajarilib, tanlangan tartibga mos natija olinadi. Ushbu yondashuv turli murakkablikdagi integral masalalarni yagona dasturiy muhitda hisoblash imkonini beradi.

Hisoblash natijalarini foydalanuvchiga tushunarli ko‘rinishda taqdim etish uchun LaTeX formatidan foydalaniladi. LaTeX yordamida matematik formulalar standart matematik yozuvga yaqin shaklda aks ettiriladi. Bu usul ayniqsa murakkab integral ifodalarini ko‘rsatishda qulay bo‘lib, natijaning o‘qilishini yaxshilaydi. Hisoblash natijalarining grafik ko‘rinishda taqdim etilishi esa foydalanuvchiga berilgan funksiyaning xususiyatlarini vizual ravishda kuzatish imkonini beradi.

Grafik vizualizatsiya jarayonida Matplotlib kutubxonasi yordamida koordinatalar tizimi hosil qilinadi va funksiya qiymatlari grafik shaklda tasvirlanadi. NumPy esa hisoblash uchun zarur bo‘lgan sonli qiymatlar ketma-ketligini shakllantirishda foydalaniladi. Natijada foydalanuvchi matematik ifodaning hisoblangan natijasi bilan bir qatorda, unga mos grafik tasvirni ham ko‘rishi mumkin.

Dasturda hisoblash jarayonining alohida bosqichlarga ajratilishi tizimning ishlashini tushunarli va nazorat qilishga qulay holga keltiradi. Foydalanuvchi tomonidan kiritilgan ma’lumotlar qabul qilinadi, matematik ifodaga aylantiriladi, tanlangan integral turi aniqlanadi va tegishli hisoblash amalga oshiriladi. Yakuniy natija HTML sahifasiga uzatiladi hamda LaTeX va grafik ko‘rinishda foydalanuvchiga taqdim etiladi.

Mazkur metod yordamida integral hisoblash jarayonini avtomatlashtirish bilan birga, foydalanuvchiga hisoblash natijasini turli ko‘rinishlarda tahlil qilish imkoniyati yaratiladi. Dasturiy vositalarning o‘zaro integratsiyasi veb-interfeys, matematik hisoblash va grafik vizualizatsiyani yagona tizimda birlashtirishga xizmat qiladi.

Tahlil va natijalar

ISSN 3030-3907

•Aniqlanmagan integral: masalan, x**2 + 3*x funksiyasi uchun ∫x² + 3x) dx=x³/x + 3x²/2 + C [2]. (1-rasm)

Bosqich:

$$x^2 \to \frac{x^3}{3} + C$$

Bosqich:

$$3x \to \frac{3x^2}{2} + C$$

Natija:

$$\frac{x^3}{3} + \frac{3x^2}{2} + C$$

1- rasm. funkanalyzer.uz/integral dan olingan tasvir

•Aniqlangan integral [0,1] oralig‘ida hisoblangan qiymat: 11/6 [2](2-rasm).

Integral bosqichi:

$$x^2 \to \frac{x^3}{3}$$

Integral bosqichi:

$$3x \to \frac{3x^2}{2}$$

Natija hisoblangan:

1.83333333333333

2-rasm. funkanalyzer.uz/integral dan olingan tasvir

•2-tartibli integral: ∫∫(x² + 3x) dx² = x⁴/12 + x³/2 + C₁x + C₂. (3-rasm)

1-bosqich:

$$\int (x^2 + 3x)dx = \frac{x^3}{3} + \frac{3x^2}{2} + C_1$$

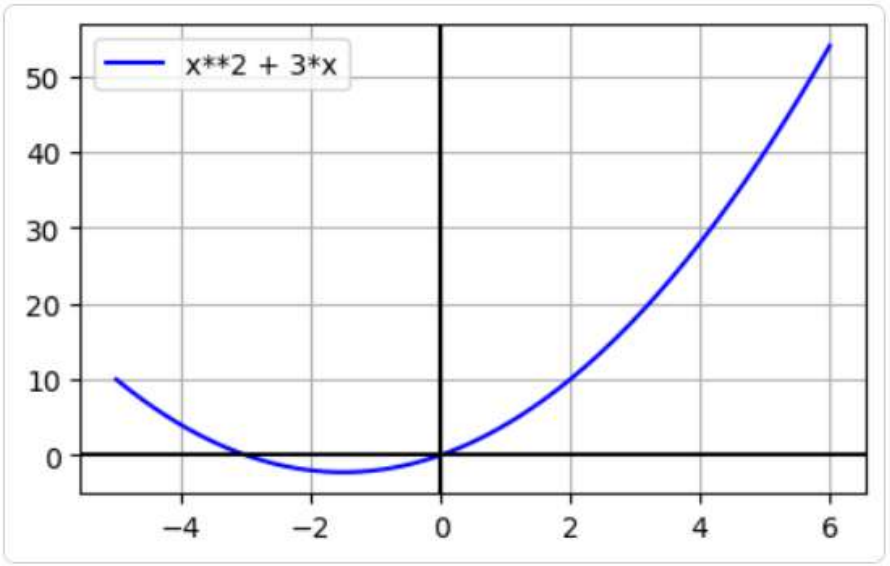
2-bosqich:

$$\int (\frac{x^3}{3} + \frac{3x^2}{2})dx = \frac{x^4}{12} + \frac{x^3}{2} + C_2$$

3-rasm. funkanalyzer.uz/integral dan olingan tasvir

•Funksiya grafigi foydalanuvchi uchun vuzal tasdiqlash shaklida taqdim etiladi. (4-rasm)

ISSN 3030-3907



4-rasm. funkanalyzer.uz/integral dan olingan tasvir

```
if integral_type == "aniqmas":
    steps_output.append({"text":"Funksiya:", "formula": latex(func), "plot": plot_img})
    for term in func.as_ordered_terms():
        term_int = integrate(term, x)
        steps_output.append({"text": "Bosqich:", "formula": f"{latex(term)} → {latex(term_int)} + C", "plot": None})
    res = integrate(func, x)
    steps_output.append({"text":"Natija:", "formula": f"{latex(res)} + C", "plot": None})

elif integral_type == "aniq":
    steps_output.append({"text": f"Aniq integral [{start},{end}] bosqichlari:", "formula": "", "plot": plot_img})
    for term in func.as_ordered_terms():
        term_int = integrate(term, x)
        steps_output.append({"text": "Integral bosqichi:", "formula": f"{latex(term)} → {latex(term_int)}", "plot": None})
    res = integrate(func, (x,start,end))
    steps_output.append({"text":"Natija hisoblangan:", "formula": f"{res}", "plot": None})

elif integral_type in ["1tartib","2tartib","3tartib"]:
    steps = int(integral_type[0])
    current = func
    steps_output.append({"text": f"{steps}-Tartibli integral bosqichlari:", "formula": "", "plot": plot_img})
    for i in range(1, steps+1):
        integ = integrate(current, x)
        steps_output.append({
            "text": f"{i}-bosqich:",
            "formula": f"∫({latex(current)}) dx = {latex(integ)} + C_{i}",
            "plot": None
        })
```

5-rasm. Integral turlarini hisoblashning dasturiy realizatsiyasi.

5-rasmda integral kalkulyatorida turli xil integral turlarini hisoblash uchun qo‘llanilgan dasturiy qism keltirilgan. Dastur aniqlanmagan va aniqlangan integrallarni hisoblash bilan bir qatorda birinchi, ikkinchi va uchinchi tartibli integrallarni ketma-ket hisoblash imkonini beradi. Aniqlangan integral uchun boshlang‘ich va yakuniy chegaralar hisobga olinadi, tartibli integrallarda esa integrallash amali tanlangan tartib bo‘yicha takrorlanadi. Ushbu dasturiy yechim kalkulyatorning asosiy hisoblash funksiyalarini amalga oshirishga xizmat qiladi.

MUHOKAMA.

Yaratilgan kalkulyator an’anaviy qo‘lda integral hisoblashdan tez va qulay [4]. Foydalanuvchi natijalarni bosqichma-bosqich ko‘rib, matematik tushunchalarni oson o‘rganadi.

ISSN 3030-3907

Boshqa dasturiy ta’minotlar bilan solishtirganda:
1. Mathematica va Maple professional va pullik, lekin kuchli.
2. SymPy bepul va Python bilan integratsiyalashgan [1].
Kelajakda loyiha quyidagilarni qo‘shish orqali rivojlantirilishi mumkin:
1. Murakkab trigonometric va maxsus dunksiyalarni qo‘llab- quvvatlash.
2. Interaktiv grafikla va real vaqt natijalar.
3. Mobil va responsive interfeys.

Ishlab chiqilgan kalkulyatorning qulay jihatlaridan biri hisoblash natijalarining foydalanuvchiga matematik formula va grafik ko‘rinishda taqdim etilishidir. Bu foydalanuvchiga faqat yakuniy natijani olish emas, balki kiritilgan funksiyaning grafik holatini ham kuzatish imkonini beradi. Natijalarni bosqichma-bosqich ko‘rsatish esa integral hisoblash jarayonini tushunishga yordam beradi.

Dasturda Python va Flask texnologiyalarining qo‘llanilishi veb-ilovaning matematik hisoblash imkoniyatlarini foydalanuvchi interfeysi bilan birlashtirish imkonini berdi. SymPy kutubxonasi orqali integral hisoblash jarayoni avtomatlashtirildi, Matplotlib va NumPy yordamida esa funksiyalarni grafik shaklda tasvirlash amalga oshirildi. Shu sababli yaratilgan tizim matematik hisoblash va vizual tahlil imkoniyatlarini bitta platformada birlashtiradi.

O‘tkazilgan sinovlar davomida tizimning aniqlanmagan, aniqlangan hamda turli tartibli integrallarni hisoblash imkoniyatlari tekshirildi. Hisoblash natijalari foydalanuvchiga tushunarli shaklda chiqarildi va grafik tasvirlar orqali funksiyalarni qo‘shimcha tahlil qilish imkoniyati yaratildi. Bu natijalar ishlab chiqilgan kalkulyatorning o‘quv jarayonida va mustaqil matematik hisoblashlarda foydalanish uchun qulay vosita ekanligini ko‘rsatadi.

XULOSA.

Mazkur ishda Python dasturlash tili va Flask veb-ramkasi yordamida integral hisoblaydigan kalkulyator yaratildi. Tizim foydalanuvchiga aniqlanmagan va aniqlangan integrallarni, shuningdek birinchi, ikkinchi va uchinchi tartibli integrallarni ketma-ket hisoblash imkonini beradi. SymPy kutubxonasi yordamida matematik ifodalar analitik tarzda yechiladi, Matplotlib esa funksiyalarni grafik ko‘rinishda vizualizatsiya qilishga yordam beradi, visual tasvirlar esa matematik tahlilni yanada soda va intuitive qiladi.

Yaratilgan tizim o‘quv jarayonida, mustaqil o‘rganishda va dastlabki ilmiy hisoblashlarda samarali vosita sifatida foydalanilishi mumkin. Kelajakda ushbu kalkulyatorni murakkab funksiyalarni qo‘llab-quvvatlash, interaktiv grafiklarni joriy etish va mobil qurilmalar uchun moslashtirish orqali yanada rivojlantirish mumkin.

Ushbu loyiha davomida integral hisoblash jarayonining asosiy bosqichlari dasturiy jihatdan amalga oshirildi. Foydalanuvchi tomonidan kiritilgan matematik

ISSN 3030-3907

funksiya qayta ishlanib, tanlangan integral turiga mos ravishda hisoblash bajariladi. Natijaning LaTeX formatida aks ettirilishi matematik ifodalarni tartibli ko‘rinishda taqdim etishga, grafik vizualizatsiya esa funksiyani qo‘shimcha ravishda tahlil qilishga imkon beradi. Shu jihatdan ishlab chiqilgan tizim matematik hisoblashlarni avtomatlashtirish bilan birga, natijalarni tushunarli shaklda taqdim etishga xizmat qiladi.

Umuman olganda, ishlab chiqilgan integral kalkulyator matematik hisoblashlarni soddalashtirish va foydalanuvchiga qulay interaktiv muhit yaratish vazifasini bajaradi. Tizimning Python, Flask, SymPy, Matplotlib va NumPy texnologiyalari asosida ishlab chiqilgani uning keyinchalik yangi matematik funksiyalar va hisoblash imkoniyatlari bilan kengaytirilishiga sharoit yaratadi. Kelgusidagi takomillashtirishlar orqali tizimning funksional imkoniyatlarini yanada oshirish va undan ta’lim hamda amaliy hisoblash jarayonlarida kengroq foydalanish mumkin.

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TELEGRAM BOT ORQALI UNIVERSAL MATN TARJIMA BOTINI YARATISH (PYTHON DASTURLASH TILI ASOSIDA)

Turayeva Muqaddas Turabekovna
Zarmed universiteti Axborot tizimlari va texnologiyalari yo'nalishi talabasi

Annotatsiya. Ushbu ish Python dasturlash tili va *aiogram* kutubxonasi yordamida Telegram messenjeri uchun universal matn va so'z tarjima qiluvchi bot yaratishga bag'ishlangan. Bot foydalanuvchidan olingan matn yoki so'zni foydalanuvchi tanlangan tilga (ENGLISH→UZBEK yoki UZBEK→ENGLISH) tarjima qiladi. Tarjima jarayoni *deep_translator* kutubxonasi orqali amalga oshiriladi. Foydalanuvchi interfeysi inline tugmalar yordamida til tanlash imkoniyatini beradi va xatolik yuz berganda matn yoki so'z asl holatida saqlanadi.

Kalit so'zlar: Python, aiogram, deep_translator, dispatcher, Google translator API

Аннотация. Данная работа посвящена разработке универсального Telegram-бота для перевода текста и отдельных слов с использованием языка программирования Python и библиотеки *aiogram*. Бот переводит введённый пользователем текст или слово на выбранный язык (ENGLISH→UZBEK или UZBEK→ENGLISH). Процесс перевода осуществляется с помощью библиотеки *deep_translator*. Пользовательский интерфейс реализован с использованием встроенных (inline) кнопок, позволяющих выбрать направление перевода. В случае возникновения ошибки исходный текст или слово сохраняется без изменений.

Ключевые слова: Python, aiogram, deep_translator, dispatcher, Google translator API

Abstract. This paper is devoted to the development of a universal Telegram bot for translating text and individual words using the Python programming language and the *aiogram* library. The bot translates user-entered text or words into the selected language (ENGLISH→UZBEK or UZBEK→ENGLISH). The translation process is performed using the *deep_translator* library. The user interface employs inline buttons to allow users to select the desired translation direction. In the event of an error, the original text or word is preserved without modification.

Keywords: Python, aiogram, deep_translator, dispatcher, Google translator API

KIRISH.

Tabiiy tilni qayta ishlash (NLP) va avtomatik tarjima tizimlari zamonaviy dasturiy xizmatlarda foydalanuvchi tajribasini sezilarli darajada oshirishga xizmat

ISSN 3030-3907

qiladi [1][5][6][7]. Telegram messenjeri interaktiv xizmatlar yaratish uchun keng imkoniyatlar beradi [2][3]. Shu kontekstda ishlab chiqilgan bot foydalanuvchidan olingan matn yoki so‘zni foydalanuvchi tanlagan tilga tezkor va aniq tarzda tarjima qiladi [2][4]. Botning universal xususiyati shundan iboratki, u ham oddiy so‘zlarni, ham butun matnlarni tarjima qila oladi, bu esa foydalanuvchi uchun bir nechta vositalarni birlashtirgan yagona tizimni ta’minlaydi.

Bugungi kunda mobil texnologiyalar va bulutli servislarning jadal rivojlanishi natijasida tezkor tarjima xizmatlariga bo‘lgan ehtiyoj tobora ortib bormoqda. Xususan, Telegram platformasi foydalanuvchilari sonining keskin ko‘payishi ushbu messenjer asosida turli avtomatlashtirilgan xizmatlarni yarastishga katta imkoniyat yaratmoqda. Tarjima botlar xorijiy tillarni o‘rganish, xalqaro muloqot, ilmiy axborot almashinuvi hamda kundalik yozishmalarni yengillashtirishda muhim vosita hisoblanadi.

Mavjud tarjima botlarning aksariyati foydalanuvchiga faqat oddiy matn tarjimasini taklif qiladi. Ayrim botlarda interfeys murakkab bo‘lib, foydalanuvchi tarjima yo‘nalishini har safar qayta tanlashi yoki qo‘shimcha buyruqlardan foydalanishi talab etiladi. Ushbu kamchiliklarni bartaraf etish maqsadida ishlab chiqilgan dastur foydalanuvchi uchun soda va tezkor ishlash mexanizmini taklif etadi.

Taklif etilgan dasturiy yechim Python dasturlash tili va aiogram freymvorkining asinxron imkoniyatlaridan foydalanishi sababli yuqori unumdorlikka ega. Shu bilan birga, *deep_translator* kutubxonasi orqali Google Translate xizmatidan foydalanish tarjimalarning aniqligi va tezkorligini ta'minlaydi. Mazkur yondashuv tizimni kelajakda yangi tillar, ovozli tarjima hamda sun'iy intellekt elementlari bilan kengaytirish imkonini ham beradi.

METOD.

Bot Python 3.11+ va aiogram kutubxonasi yordamida yaratilgan [3]. Tarjima jarayoni deep_translator (GoogleTranslator API) orqali amalga oshiriladi [2][4]. Foydalanuvchi interfeysi inline tugmalar orqali til tanlash imkoniyatini beradi [3]. Dasturiy arxitektura modul va asinxron ishlashga moslashtirilgan bo‘lib, foydalanuvchi tajribasi silliq va tezkor bo‘lishi ta’minlangan [3].

Taklif etilgan bot hodisalarga asoslangan (event-driven) dasturlash tamoyiliga asoslangan. Tizimda foydalanuvchidan kelayotgan barcha xabarlar Dispatcher tomonidan qabul qilindi va mos handler funksiyalariga yo‘naltiriladi. Ushbu yondashuv kodni modulli tashkil etish hamda yangi funksiyalarni qo‘shishni ancha soddalashtiradi.

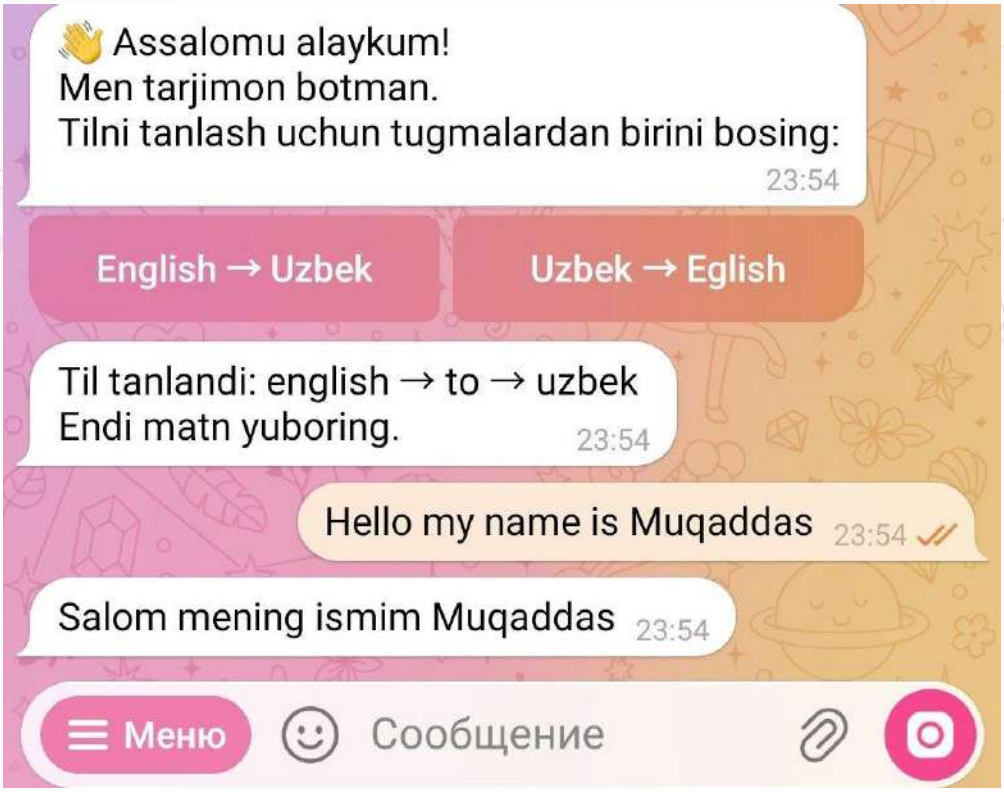
Botning funksiyalari quyidagicha:

• Dispatcher foydalanuvchi xabarlarini qabul qiladi va callback query orqali tilni belgilaydi [3].

ISSN 3030-3907

• Inline tugmalar foydalanuvchi uchun EN→UZ va UZ→EN tilini tez tanlash imkoniyatini beradi [3].

• /start komandasi botni ishga tushiradi va foydalanuvchini til tanlashga yo‘naltiradi [3].



1-rasm. @practise2_translateBot dan olingan tasvir

• /help komandasi foydalanuvchiga botning ishlash tartibi haqida ma’lumot beradi[3].

• Tarjima jarayoni GoogleTranslator yordamida amalga oshiriladi [2][4] va foydalanuvchiga natija tezkor tarzda yuboriladi. (2-rasm)



2-rasm. @practise2_translateBot dan olingan tasvir

ISSN 3030-3907

```python
@dp.message()
async def translate_message(message: types.Message):
    user_id = message.from_user.id
    if user_id not in user_language:
        await message.answer("Iltimos, avval tilni tanlang:", reply_markup=language_keyboard)
        return
    text = message.text.strip()
    if not text:
        await message.answer("Iltimos, matn kiriting.")
        return
    lang_choice = user_language[user_id]
    try:
        if lang_choice == "english_to_uzbek":
            translated = GoogleTranslator(source='en', target='uz').translate(text)
        elif lang_choice == "uzbek_to_english":
            translated = GoogleTranslator(source='uz', target='en').translate(text)
        else:
            translated = text
    except Exception:
        translated = text
    await message.answer(translated)
```

3-rasm. Telegram botni ishga tushirish funksiyasining dasturiy realizatsiyasi.

Bot arxitekturasi

Telegram bot uchta asosiy dasturiy qatlamdan tashkil topgan.

Birinchi qatlam foydalanuvchi interfeysi bo‘lib, Telegram messenjeri orqali foydalanuvchidan xabarlarni qabul qiladi hamda natijalarni ekranga chiqaradi. Ikkinchi qatlam aiogram freymvorki hisoblanadi. Ushbu qatlam Dispatcher, callback handler va message handler yordamida foydalanuvchi yuborgan barcha so‘rovlarni qayta ishlaydi. Asinxron ishlash mexanizmi sababli bot bir vaqtning o‘zida bir nechta foydalanuvchiga xizmat ko‘rsatishi mumkin.

Uchinchi qatlam tarjima moduli bo‘lib, unda deep_translator kutubxonasi yordamida Google Translate servisi bilan bog‘lanish amalga oshiriladi. Ushbu modul foydalanuvchi yuborgan matnni kerakli tilga tarjima qiladi va natijani Telegram interfeysiga uzatadi.

Bot universal bo‘lishi uchun u so‘zlarni alohida tekshirish va tarjima qilish imkoniyatiga ega, bu esa foydalanuvchiga lug‘at yoki tezkor tarjima sifatida qulaylik yaratadi.

TAHLIL VA NATIJALAR.

Dastur funksional testlash usuli asosida sinovdan o‘tkazildi. Sinov davomida ingliz va o‘zbek tillaridagi turli uzunlikdagi so‘zlar, oddiy gaplar hamda bir necha jumladan iborat matnlar yuborildi. Har bir sinovda tarjima sifati, javob qaytarish tezligi hamda foydalanuvchi interfeysining qulayligi baholandi.

Tajribalar natijasida bot tanlangan tarjima yo‘nalishini to‘g‘ri aniqlashi, matnlarni qisqa vaqt ichida tarjima qilishi va foydalanuvchiga uzluksiz xizmat ko‘rsatishi kuzatildi. Inline tugmalar yordamida tarjima yo‘nalishini almashtirish foydalanuvchining qo‘shimcha buyruqlar kiritish zaruratini bartaraf etdi. Asinxron

ISSN 3030-3907

ishlash mexanizmi esa ketma-ket yuborilgan bir nechta xabarlarni samarali qayta ishlash imkonini berdi.

Dasturda xatoliklarni boshqarish mexanizmi ham muvaffaqiyatli sinovdan o ‘tkazildi. Internet aloqasi yoki tarjima servisida vaqtinchalik uzilishlar yuz bergan hollarda tizim foydalanuvchiga asl matnni qaytarib berdi va ishlashni davom ettirdi. Bu esa ishlab chiqilgan dasturiy yechimning amaliy foydalanish uchun yetarli darajada barqaror ekanligini ko‘rsatdi.

1-jadval.

Telegram tarjima botining funksional sinov natijalari

№	Sinov turi	Natija	Izoh
1	Ingliz tilidan o‘zbek tiliga tarjima	Muvaffaqiyatli	Tarjima to‘g‘ri bajarildi
2	O‘zbek tilidan ingliz tiliga tarjima	Muvaffaqiyatli	Tarjima to‘g‘ri bajarildi
3	Qisqa matnlarni tarjima qilish	Muvaffaqiyatli	Javob tez qaytarildi
4	Bir necha jumladan iborat matn tarjimasi	Muvaffaqiyatli	Tarjima sifati qoniqarli
5	Inline tugmalar orqali tilni almashtirish	Muvaffaqiyatli	Xatoliksiz bajarildi
6	Xatolik yuz berganda asl matnni saqlash	Muvaffaqiyatli	Bot ishlashni davom ettirdi

2-jadval.

Taklif etilgan bot va mavjud tarjima botlarining taqqoslanishi

№	Taqqoslash mezoni	Taklif etilgan bot	Oddiy tarjima botlari
1	Ingliz → O‘zbek tarjimasi	Ha	Ha
2	O‘zbek → Ingliz tarjimasi	Ha	Ha
3	Inline tugmalar	Ha	Har doim mavjud emas
4	Asinxron ishlash	Ha	Cheklangan
5	Xatoliklarni boshqarish	Ha	Cheklangan
6	Kengaytirish imkoniyati	Yuqori	O‘rta

Bot foydalanuvchi tanlagan tilga avtomatik tarjima qiladigan tizim sifatida sinovdan o‘tkazildi [2]. Inline tugmalar yordamida til tezkor o‘zgartirildi va foydalanuvchi tajribasi silliq bo‘ldi. Kod xatoliksiz ishladi va foydalanuvchilar qulay interfeysdan foydalana oldi. Tarjima natijalari aniq va tezkor bo‘lib, matn yoki so‘z xatoligi yuz berganda bot asl holatni saqlaydi [4]. Bot universal

ISSN 3030-3907

arxitektura tufayli so‘zlar va matnlar uchun yagona interfeysni ta’minlaydi, bu esa foydalanuvchi uchun maksimal qulaylik yaratadi. (1-rasm)

Bozor va Telegramda mavjud tarjima botlarning ko‘pchiligi faqat matn kiritish va natija olish imkoniyatini beradi [2], so‘zlarni alohida tarjima qilish funksiyasi cheklangan yoki yo‘q. Ko‘pgina botlarda xatolik yuz berganda foydalanuvchi matnning asl holatini tiklash imkoniyatiga ega emas.

Yaratilgan botning afzalliklari:

- Universal ishlash: Matn va so‘zlarni alohida tarjima qilish imkoniyati mavjud.
- Intuitiv interfeys: Inline tugmalar yordamida til tanlash qulay va tezkor.
- Asinxron ishlash: Bir vaqtning o‘zida ko‘p foydalanuvchilar bilan samarali ishlash.
- Xatoliklarni boshqarish: Tarjima jarayonida xatolik yuz berganda foydalanuvchiga matnni asl holatda saqlash imkoniyati.
- Kengaytirilgan arxitektura: Python va modular kod tuzilishi yangi tillar va qo‘shimcha funksiyalarni oson integratsiya qilish imkonini beradi.

Shunday qilib, bu bot mavjud botlardan interaktivligi, universal ishlash xususiyati va foydalanuvchi tajribasini yaxshilash imkoniyati bilan ajralib turadi.

Taklif etilgan tizimning afzalliklari

Taklif etilgan Telegram tarjima boti mavjud yechimlar bilan taqqoslanganda bir qator afzalliklarga ega. Birinchidan, dastur foydalanuvchiga sodda va intuitiv interfeysni taqdim etadi. Tarjima yo‘nalishi inline tugmalar orqali tanlanishi sababli foydalanuvchi qo‘shimcha buyruqlarni eslab qolishi shart emas.

Ikkinchidan, tizim Python dasturlash tilining asinxron imkoniyatlariga asoslanganligi sababli foydalanuvchi so‘rovlariga qisqa vaqt ichida javob qaytaradi. Bu esa botning bir vaqtning o‘zida bir nechta foydalanuvchilar bilan samarali ishlashini ta'minlaydi.

Uchinchidan, dastur modulli arxitektura asosida ishlab chiqilgan. Shu sababli kelajakda yangi tarjima yo‘nalishlarini qo‘shish, boshqa tarjima servislarini ulash yoki qo‘shimcha funksiyalarni integratsiya qilish katta o‘zgarishlarni talab qilmaydi.

To‘rtinchidan, dasturda xatoliklarni qayta ishlash mexanizmi mavjud bo‘lib, tarjima bajarilmagan holatlarda foydalanuvchining asl matni saqlab qolinadi. Bu esa foydalanuvchi ma'lumotlarining yo‘qolishining oldini oladi va tizimning ishonchliligini oshiradi.

XULOSA.

Telegram bot orqali universal matn va so‘z tarjima tizimi yaratildi [2][3]. Bot foydalanuvchi interfeysi qulay, samarali va xatosiz ishlaydi. Loyihani yangi tillar va NLP integratsiyasi orqali kengaytirish mumkin [1][5]. Ushbu tizim

ISSN 3030-3907

dasturchilarga universal va samarali bot yaratish tajribasini oshiradi. Kelajakda bu botga audio funksiyasi va bir necha tillar ham qo‘shiladi (masalan fransuz, kareys, rus va xitoy tillari).

Tadqiqot natijalari shuni ko‘rsatadiki, ishlab chiqilgan dastur foydalanuvchi tomonidan yuborilgan matnlarni qisqa vaqt ichida qayta ishlab, tanlangan til yo‘nalishiga mos ravishda tarjima qilish imkoniyatiga ega. Botning asinxron ishlash tamoyili uning unumdorligini oshiradi hamda bir vaqtning o‘zida bir nechta foydalanuvchi murojaatlarini samarali qayta ishlashga xizmat qiladi. Dasturda qo‘llanilgan xatoliklarni qayta ishlash mexanizmi tizimning barqaror ishlashini ta’minlaydi va tarjima jarayonida yuzaga keladigan nosozliklarda foydalanuvchi ma’lumotlarining saqlab qolishiga imkon beradi.

Mazkur tadqiqot doirasida Python dasturlash tili, aiogram freymvorki va deep_translator kutubxonasi asosida Telegram messenjeri uchun universal matn va so‘z tarjima qiluvchi bot ishlab chiqildi. Yaratilgan bot foydalanuvchiga soda va qulay interfeysni taqdim qilib, ingliz va o‘zbek tillari o‘rtasida matnlarni tezkor hamda samarali tarzda tarjima qilish imkonini beradi. Trjima yo‘nalishini inline tugmalar yordamida tanlash foydalanuvchi bilan ishlash jarayonini soddalashtiradi va tizimning qulayligini oshiradi. Kelgusida foydalanuvchi tarixini saqlash, ovozni matnga aylantirish (Speech-to-text), rasmlardagi matnni aniqlash (OCR) va sun’iy intellekt asosidagi zamoaviy tarjima madellarini integratsiya qilish orqali tizimning funksional imkoniyatlarini yanada kengaytirish rejalashtirilmoqda.

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МАРКАЗДАН ҚОЧМА КУЧ ТАЪСИРИДА ЮҚОРИ ЭКСПЛУАТАЦИОН ХУСУСИЯТЛИ АНИЗОТРОП СТРУКТУРАЛИ ЦИЛИНДРСИМОН ФИЛЬТРЛАР ОЛИШ УСУЛИНИНГ НАЗАРИЙ ТАВСИФИ

Файзиев Мирғани Мирвалиевич
Техника фанлари номзоди, доцент, Ўзбекистон Республикаси ИИВ академияси, Тошкент ш., Ўзбекистон
E-mail: mirgani.fayziev@gmail.com.,
Каршиев Мамарайим
Техника фанлари доктори, И. Каримов номидаги ТДТУ «Фан ва тараққиёт" Давлат муассасаси Тошкент ш., Ўзбекистон
E-mail: vip.mrayim@mail.ru.

Аннотация. Ушбу мақолада марказдан қочма куч таъсирида юқори эксплуатацион хусусиятли анизотроп структурали цилиндрсимон фильтрларни олиш усулининг назарий асослари ишлаб чиқилган. Фильтр материалининг ғовак тузилиши шаклланиш жараёнини тавсифловчи математик модел таклиф этилган бўлиб, у экспериментал тадқиқотлар ҳажмини камайтириш имконини беради. Модел асосида ғоваклик, ғовак ўлчами, солиштирма сирт майдони ва ўтказувчанлик коэффициентининг ғовакларга киритилган майда заррачалар ҳажмига боғлиқ равишда ўзгариши аниқланган. Таклиф этилган ёндашув юқори самарадорликка эга анизотроп ғовак фильтрларни лойиҳалаш ва уларнинг эксплуатацион хусусиятларини олдиндан баҳолаш учун назарий асос бўлиб хизмат қилади.

Калит сўзлар: марказдан қочма куч, анизотроп структура, цилиндрсимон фильтр, металл кукуни, ғоваклик, ғовак ўлчами, солиштирма сирт майдони, ўтказувчанлик коэффициенти, математик модел.

Аннотация. В статье разработано теоретическое описание метода получения цилиндрических фильтров с анизотропной структурой и высокими эксплуатационными характеристиками под действием центробежной силы. Предложена математическая модель формирования пористой структуры фильтрующего материала, позволяющая сократить объём экспериментальных исследований. На основе модели определены зависимости пористости, размера пор, удельной поверхности и коэффициента проницаемости от объёма мелкодисперсных частиц, введённых в поровое пространство. Предложенный подход может служить теоретической основой для проектирования высокоэффективных

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анизотропных пористых фильтров и прогнозирования их эксплуатационных свойств.

Ключевые слова: центробежная сила, анизотропная структура, цилиндрический фильтр, металлический порошок, пористость, размер пор, удельная поверхность, коэффициент проницаемости, математическая модель.

Abstract. This paper presents a theoretical description of a method for manufacturing cylindrical filters with an anisotropic structure and enhanced performance under the action of centrifugal force. A mathematical model describing the formation of the porous filter structure is proposed to reduce the amount of experimental research required. The model makes it possible to determine the relationships between porosity, pore size, specific surface area, and permeability coefficient as functions of the volume of fine particles introduced into the pore space. The proposed approach provides a theoretical basis for the design of high-performance anisotropic porous filters and for predicting their operational properties.

Keywords: centrifugal force, anisotropic structure, cylindrical filter, metal powder, porosity, pore size, specific surface area, permeability coefficient, mathematical model.

КИРИШ.

Анизотроп ғовак тузилишга эга бўлган юқори эксплуатацион хусусиятли фильтрларни олишнинг самарали усули — марказдан қочма куч таъсирида турли ўлчамдаги металл кукунларини критик тезликда айланаётган контейнерга қаватма-қават жойлаштириш ва цилиндр шаклидаги фильтр ҳосил қилишдан иборат. Ишлаб чиқариш жараёни қуйидаги босқичлардан иборат: дастлаб катта ўлчамли металл кукунлари критик тезликда айланаётган контейнерга қалинлиги 5 мм дан кам бўлмаган хом ашё ҳосил қилиш учун жойлаштирилади. Сўнгра, турли ўлчамдаги кичик металл кукунлари олдинги қатлам устига кетма-кет жойлаштирилади ва унга ички диаметрни ҳосил қилувчи цилиндрсимон металл ўзак ўрнатилади. Айланиш тўхтатилиб, қурилмадан контейнер олинади ва ундаги цилиндрсимон ярим хом ашё куйдириб пиширилади, сўнгра тайёр маҳсулотнинг эксплуатацион хусусиятлари аниқланади.

Юқори эксплуатацион хусусиятларга эга фильтрларни яратишда янги технологияларни ишлаб чиқиш, унинг хоссаларини олдиндан башорат қилиш ва бошқариш муҳим босқич ҳисобланади. Кўпинча бундай баҳолаш асосий омилларни ва уларнинг маҳсулот хусусиятларига таъсир қилиш даражасини

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аниқлашга қаратилган катта ҳажмдаги экспериментал тадқиқотларни ўтказишни талаб қилади [1, 34-40-б., 2, 276 б., 102-110-б.].

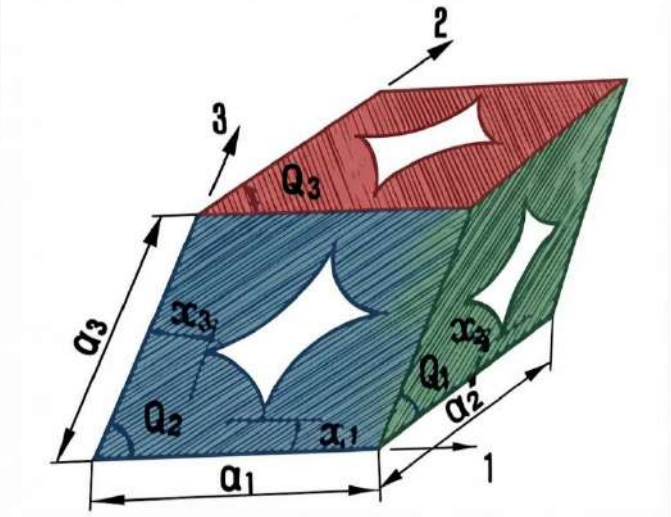
Экспериментал тажрибалар ҳажмини камайтириш мақсадида математик модел ишлаб чиқиш ва ундан таклиф этилаётган технология параметрлари ҳамда маҳсулот орасидаги боғлиқликни аниқлашда фойдаланиш юқори истиқболли усул ҳисобланади. Бундай модел янги технология ёрдамида олинган маҳсулотларнинг ишлаш хусусиятларини баҳолаш, шу билан бирга, кукунли металлургия материалларини ишлаб чиқаришда ушбу усулдан фойдаланишнинг мақсадга мувофиқлигини аниқлаш имконини беради. Шу нуқтаи назардан, анизотроп структура ҳосил бўлишини, уни ўзгартириш ва бошқаришни амалга ошириш учун назарий тадқиқотлар ўтказиш талаб этилади.

Металл кукунларидан олинган фильтрлар структурасини моделлаштириш таҳлили шуни кўрсатдики, уларнинг структуравий, физик-кимёвий ва механик хусусиятларини аниқлаш учун энг мос модел — кукунларнинг тартибли жойлашган элементар ғоваклигидир. Шу билан бирга, гидродинамик ва фильтрация хусусиятларини ҳисоблаш учун, хусусан, заррачаларнинг кетма-кет жойлашувида, намуна кўндаланг кесимида структура ўзгаришини капилляр найчалар шакли билан алмаштириш мақсадга мувофиқдир [4, 52-56-б.].

Ҳисоб-китобни амалга оширишда ғовак материал тузилишининг маълум бир моделидан фойдаланамиз: ушбу моделда материалнинг ҳар бир ҳажмий элементининг хоссалари мунтазам жойлашган саккизта кукун заррачасидан ҳосил бўлган параллелепипед шаклидаги элементар катакча параметрлари орқали аниқланади. 1-расмда тасвирланган элементар катакча ғовак металл каркас тузилишини моделлаштиради ва қуйидаги параметрлар билан тавсифланади: қирра ўлчамлари a_i, ўқлар ичидаги зарраларни жойлаштириш бурчаклари Q_i ҳамда зарраларараро контакт ўлчамлари X_i.

Ушбу параметрлар реал кукунсимон мухитларнинг таркибий хусусиятларига-зарралар орасидаги масофалар, уларнинг жойлашиш бурчаклари ва кукун зарралар орасидаги контакт майдонига мос келади.

ISSN 3030-3907



1-расм. Элементар ячайкани схемаси.

Натижада, фильтрнинг тузилиш хусусиятлари (ғоваклик, ғовак ўлчами, солиштирма сирт майдони) бевосита модел параметрлари орқали ифодаланиши мумкин. Ғовак муҳитидаги фильтрация жараёнини тавсифлаш учун элементар ячейка ғовагини ўзгарувчан кесимли цилиндрсимон капиллярларнинг кесишмаси сифатида ифодалаймиз. Бундай модел ғовак ичидаги фильтрация жараёнини тавсифлаш учун ишлатилади ва аниқ натижалар беради.

Шундай қилиб, ғоваклар орасига киритилган заррачалар билан фильтр материали тузилишининг таклиф қилинган такомиллаштирилган модели ғовакликни, ғовак ўлчамини, солиштирма сирт майдонини ва ўтказувчанлик коэффициенти қийматларини ғоваклар ичига киритилган заррачалар ҳажмига қараб ҳисоблаш имконини берди.

Ғовак тузилмали фильтрларнинг математик модели ва ўтказувчанлик коэффициентини аниқлаш

Шундай қилиб, ғоваклик қуйидагига тенг:

$$П = 1 - \frac{\alpha_v \pi D^3}{6a_1a_2a_3\left(1-\cos^2 Q_1 - \cos^2 Q_2 - \cos^2 Q_3 + 2\cos Q_1 \cos Q_2 \cos Q_3\right)^{1/2}}, \qquad (1)$$

Бу ерда, D – металл кукуни заррачаларининг ўртача диаметри, α_v – заррача шаклининг ўртача ҳажмий кўрсаткичи (шарсимон кукун учун $a_v = 1$ га тенг.

Солиштирма сирт майдони S_v қуйидаги муносабатдан аниқланади:

$$S_v = \frac{\alpha_s \pi D^2 \left(1 - 6\sum \frac{x_i^2}{D^2}\right)}{a_1a_2a_3\left(1-\cos^2 Q_1 - \cos^2 Q_2 - \cos^2 Q_3 + 2\cos Q_1 \cos Q_2 \cos Q_3\right)^{1/2}}. \qquad (2)$$

Металл кукунларининг ўртача ўлчами $d_{пі}$ куйидаги ифодага тенг

ISSN 3030-3907

$$d_{\Pi i} = \frac{\left(a_j^2 + a_k^2 - 2a_j a_k \cos Q_i\right)^{1/2}}{\sin Q_i} - 2R_i \qquad (3)$$

Бу ерда Ri – элементар катакчанинг і- ўқ текслигидаги заррачанинг самарали радиуси.

Фильтр материалининг ғовак бўшлиғига майда заррачаларнинг кириши жараёнида унинг тузилмавий хоссалари ўзгаради. Ғовакларга кирган зарралар ҳажмининг тавсифи сифатида нисбий кўрсаткич G ни қабул қиламиз:

$$G = \frac{V_{oc}}{V_0}, \qquad (4)$$

Бу ерда V_{oc} – говаклар орасига киритилган заррачалар ҳажми: V_0 – элементар ячайка ҳажми. Кичик заррачалар киритилгандан сўнгги говаклик куйидагича аникланади.

$$П^{oc} = П - G. \qquad (5)$$

Солиштирма сирт майдонидаги ўзгариш, ғоваклар орасига киритилган майда кукун заррачаларининг янги ҳосил бўлган сирт майдони асосида аниқланади:

$$S_v^{oc} = S_v - 12(1-П)\frac{G}{S_v D^2}. \qquad (6)$$

Шунга ўхшаш ёндашув асосида ғовак ўлчамининг ўзгариши аниқланади.

$$d_П^{oc} = d_П - \frac{2GП}{S_v(П-G)}. \qquad (7)$$

Таърифланган тенгламалар ғовак ўтказувчан муҳитнинг структуравий хусусиятларини ҳисобга олади. Бироқ заррачаларнинг ғовак бўшлиғидаги масса узатиш жараёнларини аниқ математик тавсифлаш жиддий мураккабликларни келтириб чиқаради.

Шу муносабат билан, ғовак муҳитидаги фильтрация жараёнини тавсифлаш учун мазкур тадқиқотда элементар ячейка ғовагини ўзгарувчан кесимли цилиндрсимон капиллярлар кесишмаси сифатида ифодалашни таклиф қиламиз. Ушбу капилляр ўтказувчанлик модели ғовак ичидаги фильтрация жараёнини тавсифлашда қўлланилади ва аниқ натижалар беради. Ҳар бир капилляр модели уч қисмдан иборат: улардан иккитаси элементар катак ғовагининг тор кириш қисмига, учинчиси эса ғовакнинг ички кенг қисмига мос келади (2-расм, а).

Заррачаларни жойлаштириш жараёнида капиллярларнинг ички юзасида кукунли ғовак структура ҳосил бўлиб, у юзани қоплайди (2-расм, б).

ISSN 3030-3907

Натижада, ғоваклар орасида янги анизотроп структура вужудга келади. Адабиёт [2] да таклиф қилинган ҳисоблаш усулидан фойдаланиб, ғоваклар ичида ҳосил бўлган янги анизотроп структуранинг ўтказувчанлик коэффициентини аниқлаш мумкин. Таклиф қилинган моделга мувофиқ, материал одатда анизотропияни намоён қилади ва бу Дарси қонуни асосида аниқланган ўтказувчанлик коэффициенти (K_a) нинг асосий компонентлари билан тавсифланади».

$$Q_\alpha = K_\alpha \frac{\Delta P_\alpha S_\alpha}{\mu L_\alpha}, \qquad (8)$$

Бу ерда Q_α ва ΔP_α – мос равишда тегишли ўққа перпендикуляр йўналган материал қатлами бўйлаб оқим сарфи ва босим пасайиши:

L_α и S – мос равишда қатламнинг қалинлиги ва сирт майдони; α – эса X, Y, Z қийматларни қабул қилади.

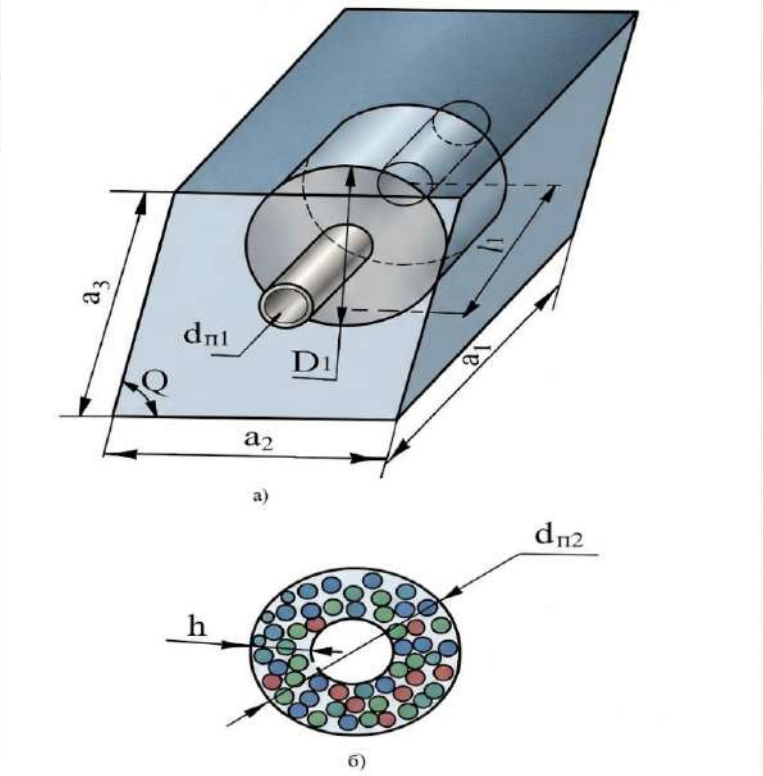
Z ўқи бўйлаб суюқлик оқимини кўриб чиқайлик ва Z ўқига перпендикуляр булган, L_z қалинликка ҳамда S_z юзага эга булган материал катламини ажратиб олайлик 3-расм. Қатламдаги умумий босим пасайиши қуйидагига тенг:

$$\Delta P_z = \left(\Delta P_{iz} + \Delta \overline{P}_{iz}\right)\frac{N_z}{n_{iz}}, \qquad (9)$$

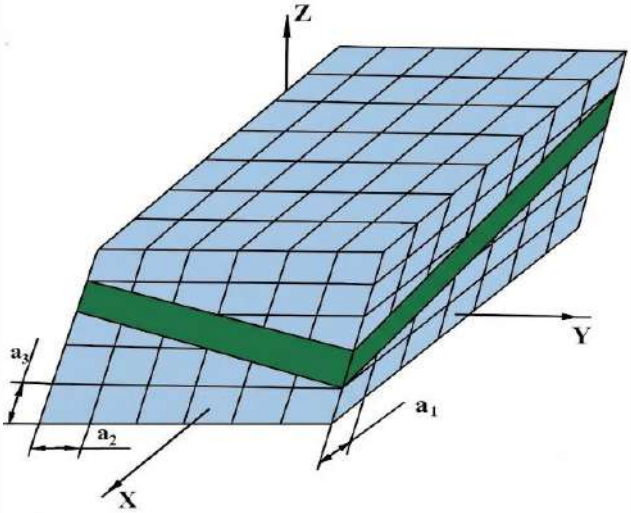
Бу ерда $n_{1z} = \frac{a_3 h_{3z}}{a_2 h_{2z}}$, $n_{2z} = \frac{a_3 h_{3z}}{a_1 h_{1z}}$, $n_{3z} = \frac{a_3^2 h_{3z}^2}{a_1 a_2 h_{1z} h_{2z}}$,

ΔP_{iz} и $\Delta \overline{P}_{iz}$ - мос равишда элементар капиллиарнинг торайган зоналари ва кенгайиш зонасидаги босимнинг пасайишлари

ISSN 3030-3907



Расм.2. Капиллиар модели (a) ва заррачаларни сакловчи капиллиар кесимининг (b) схемаси.



Расм.3. Z уки йуналишида фильтрацияни хисоблаш учун ажратиб олинган фильтр элементи катламининг диаграммаси.

$$\Delta P_{iz} = \Delta \overline{P}_{iz} \frac{\left[\frac{(D_i h)^4}{128} + \left(2D_i h - h^2\right)K_0\right](a_i - l_i)}{\left[\frac{(d_{\Pi i} - h)^4}{128} + (2d_{\Pi i} h - h^2)K_0\right] l_i}, \qquad (10)$$

Бу ерда $h = \int \frac{2d\sigma}{S_v}$ ғоваклар орасига киритилган заррачалар қатламининг умумий қалинлиги, K_0 – заррачалар ҳосил қилган ғовакли қатламнинг

ISSN 3030-3907

ўтказувчанлик коэффициенти. «і-чи капилляр орқали ўтадиган оқим тезлиги унинг исталган қисмида, хусусан, кенг қисмида бир хил (тенг) бўлади»

$$Q_{iz} = \frac{\Lambda P_{iz}\pi}{\mu l_i}\left[\frac{(D_i - h)^4}{128} + (2D_i h - h^2)K_0\right], \qquad (11)$$

Белгиланган қатлам орқали ўтадиган умумий сарф Q_z га тенг эканлигини ҳисобга олган ҳолда

$$Q_z = \sum_{i=1}^{3} Q_{iz} n_{iz}, \qquad (12)$$

(8–12) - тенгламалар асосида асосий Z – ўқи йўналишидаги ўтказувчанлик коэффициенти учун қуйидаги ифодани оламиз

$$K_z = \frac{\pi \sum_{i=1}^{3} n_{iz}^2 \frac{\left[\frac{D_i - h}{128} + (2D_i h - h^2)K_0\right]}{l_i}}{N_z a_3} \times \left\{1 + \frac{\left[\frac{(D_i - h)^4}{128} + (2D_i h - h^2)\right](a_i - l_i)}{\left[\frac{(D_{ni} - h)^4}{128} + (2D_{ni} h - h^2)\right] l_i}\right\} \times h_{1z} h_{2z} g$$

(13)

Бу ерда $g = (1 - \cos^2 Q_1 - \cos^2 Q_2 - \cos^2 Q_3 + 2\cos Q_1 \cos Q_2 \cos Q_3)^{1/2}$

Бошқа асосий ўқлар учун бажарилган шунга ўхшаш ҳисоб-китоблар, асосий ўқлардаги ўтказувчанлик коэффициенти тензори компонентлари учун умумлаштирилган ифодани олиш имкони яратилди.

$$K_\alpha = \frac{\pi \sum_{i=1}^{3} n_{m\alpha}^2 \frac{\left[\frac{D_m - h}{128} + (2D_m h - h^2)K_0\right]}{l_m}}{N_z a_3} \times \left\{1 + \frac{\left[\frac{(D_m - h)^4}{128} + (2D_m h - h^2)\right](a_i - l_i)}{\left[\frac{(D_{Пm} - h)^4}{128} + (2D_{Пm} h - h^2)K_0\right] l_i}\right\}^{-1} \times \frac{h_{j\alpha} h_{K\alpha} g}{N_\alpha a_i}$$

(14)

Шундай қилиб, ғоваклар орасига киритилган заррачалар билан фильтр материали тузилишининг таклиф қилинган такомиллаштирилган модели ғовакликни, ғовак ўлчамини, солиштирма сирт майдонини ва ўтказувчанлик коэффициенти қийматларини ғоваклар ичига киритилган заррачалар ҳажмига қараб ҳисоблаш имконини берди.

ХУЛОСА.

Тадқиқотда таклиф этилган ғовак муҳитнинг такомиллаштирилган модели фильтр материалининг структуравий хусусиятларини (ғоваклик, ғовак ўлчами, солиштирма сирт майдони) ҳамда ўтказувчанлик коэффициентини ғоваклар ичига киритилган заррачалар ҳажмига боғлиқ ҳолда ҳисоблаш имконини беради. Ишлаб чиқилган математик модел

ISSN 3030-3907

экспериментлар сонини камайтириш ва юқори сифатли анизотроп фильтрларни лойиҳалашда назарий асос бўлиб хизмат қилади.

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МАРКАЗДАН ҚОЧМА КУЧ ТАЪСИРИДА ОЛИНГАН АНИЗОТРОП СТРУКТУРАЛИ ФИЛЬТРЛАРНИНГ ҒОВАКЛИГИ, ҒОВАК ЎЛЧАМИ, ЎТКАЗУВЧАНЛИК КОЭФФИЦИЕНТИ ВА САМАРАДОРЛИК ПАРАМЕТРЛАРИНИ ЎЗГАРИШИНИ ҲИСОБЛАШ

Файзиев Мирғани Мирвалиевич
Техника фанлари номзоди, доцент, Ўзбекистон Республикаси ИИВ академияси, Тошкент ш., Ўзбекистон
E-mail: mirgani.fayziev@gmail.com.,
Каршиев Мамарайим
Техника фанлари доктори, И. Каримов номидаги ТДТУ "Фан ва тараққиёт" Давлат муассасаси Тошкент ш., Ўзбекистон
E-mail: vip.mrayim@mail.ru.

Аннотация. Мазкур мақолада марказдан қочма куч таъсирида олинган анизотроп структурали ғовакли фильтрларнинг ғоваклиги, ўртача ғовак ўлчами, ўтказувчанлик коэффициенти ва самарадорлик параметрларининг ўзгариш қонуниятлари назарий ҳисоб-китоблар асосида таҳлил қилинган. Тадқиқотда ғоваклар ичига майда кукун заррачаларини уч босқичда кетма-кет киритиш усулининг фильтрлаш самарадорлигига таъсири ўрганилган. Ҳисоблаш натижаларига кўра, ўлчамлари 220, 110 ва 55 мкм бўлган заррачаларни кетма-кет жойлаштириш бир босқичли усулга нисбатан фильтрнинг самарадорлик параметрини 55 фоизгача ошириши аниқланди. Таклиф этилган технология суюқлик ва газларни фильтрлаш сифатини яхшилаш ҳамда ғовакли материалларнинг оптимал структурасини шакллантириш имконини беради.

Калит сўзлар: анизотроп структура, ғовакли фильтр, ғоваклик, ўртача ғовак ўлчами, ўтказувчанлик коэффициенти, марказдан қочма куч, уч босқичли киритиш усули, самарадорлик параметри.

Аннотация. В данной статье на основе теоретических расчетов проанализированы закономерности изменения пористости, среднего размера пор, коэффициента проницаемости и параметра эффективности пористых фильтров с анизотропной структурой, полученных под действием центробежной силы. В ходе исследования изучено влияние трехступенчатого последовательного заполнения пор мелкодисперсными порошковыми частицами на эффективность процесса фильтрации. Результаты расчетов показали, что последовательное введение частиц размером 220, 110 и 55 мкм позволяет повысить параметр эффективности фильтра до 55 % по сравнению с одноступенчатым способом.

ISSN 3030-3907

Предложенная технология обеспечивает повышение качества фильтрации жидкостей и газов, а также позволяет формировать оптимальную структуру пористых материалов.

Ключевые слова: анизотропная структура, пористый фильтр, пористость, средний размер пор, коэффициент проницаемости, центробежная сила, трехступенчатый способ заполнения, параметр эффективности.

Abstract. This paper presents a theoretical analysis of the relationships between porosity, average pore size, permeability coefficient, and the performance parameter of porous filters with an anisotropic structure fabricated under the action of centrifugal force. The influence of a three-stage sequential filling of pores with fine powder particles on filtration efficiency was investigated. The calculation results showed that the sequential introduction of particles with sizes of 220, 110, and 55 μm increases the filter performance parameter by up to 55% compared with the conventional single-stage filling method. The proposed technology improves the filtration quality of liquids and gases and enables the formation of an optimized porous material structure.

Keywords: anisotropic structure, porous filter, porosity, average pore size, permeability coefficient, centrifugal force, three-stage filling method, performance parameter.

КИРИШ.

Замонавий техника ва технологияда юқори ўтказувчанлик хусусиятига эга бўлган ғовакли материаллардан фойдаланиш кенг аҳамият касб этади. Бундай материалларнинг эксплуатацион хоссалари, хусусан, уларнинг фильтрлаш самарадорлиги структуранинг бир жинсилиги ва ғоваклар тақсимотига бевосита боғлиқ. Мазкур тадқиқотнинг мақсади марказдан қочма куч таъсирида анизотроп структурали фильтрларни ҳосил қилишда майда заррачаларни босқичма-босқич киритиш усулининг самарадорлигини баҳолаш ва оптимал технологик параметрларни аниқлашдан иборат.

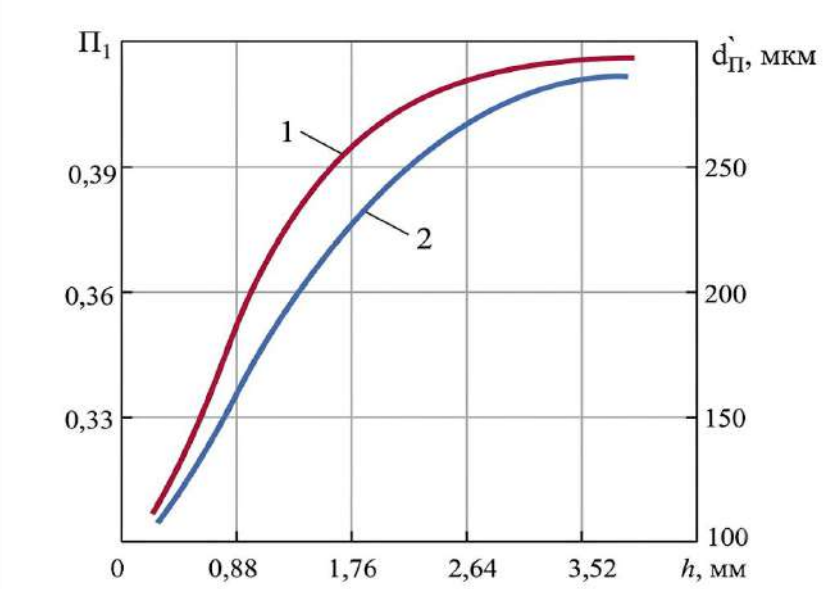
Ҳисоб-китоблар БрОФ-10-1 маркали сферик шаклдаги бронза кукунидан (ўртача диаметри D_0ўр = 1100 мкм бўлган) пресс-формага эркин солиб, қиздириб пиширш (спекание) орқали олинган ярим хом ашё намуналарида амалга оширилди. Ярим хом ашёнинг ғоваклиги П = 0,48 деб қабул қилинди.

Ғовакларнинг ўртача ўлчами $d_{П}$ўр} = 280 мкм, ярим хом ашёнинг етарлича механик мустаҳкамлигини таъминлаш ҳамда мунтазам структура ҳосил қилиш учун унинг қалинлиги 4,4 мм га тенг қилиб олинди. Марказдан

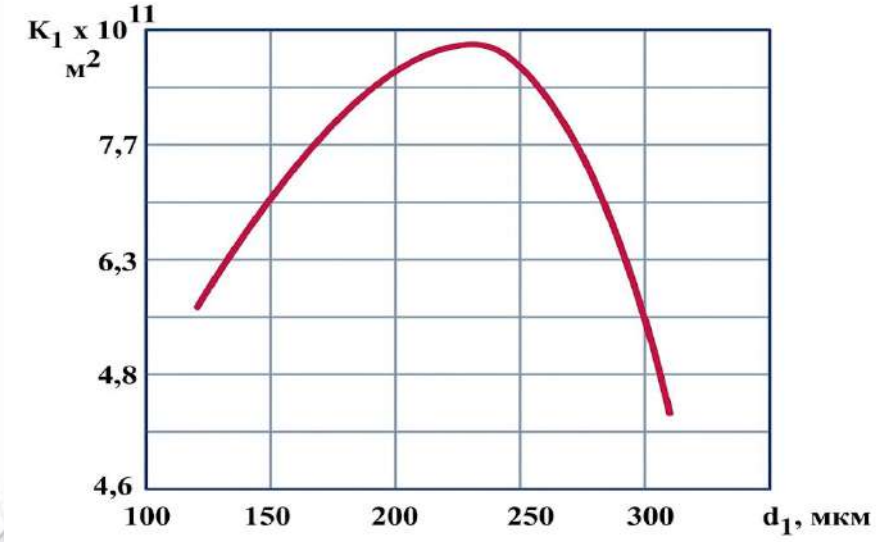
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қочма куч таъсирида ярим хом ашё ғоваклари орасига кетма-кет майда кукунлар киритила бошланди. Киритиш жараёни ярим хом ашё ғоваклари (капиллярлари) тўлиқ тўлгач ва майда кукунларнинг кириши тўхтагач, тугалланган деб ҳисобланди. Жараён давомида ўртача ўлчами мос равишда 160, 220 ва 300 мкм бўлган сферик майда заррачалар танлаб олинди.

1-расмда, мисол тариқасида, ўлчами 220 мкм бўлган майда заррачаларни ғоваклар орасига киритиш пайтида ярим хом ашё қалинлиги бўйича ғоваклик ва ўртача ғовак ўлчамининг тақсимоти кўрсатилган».



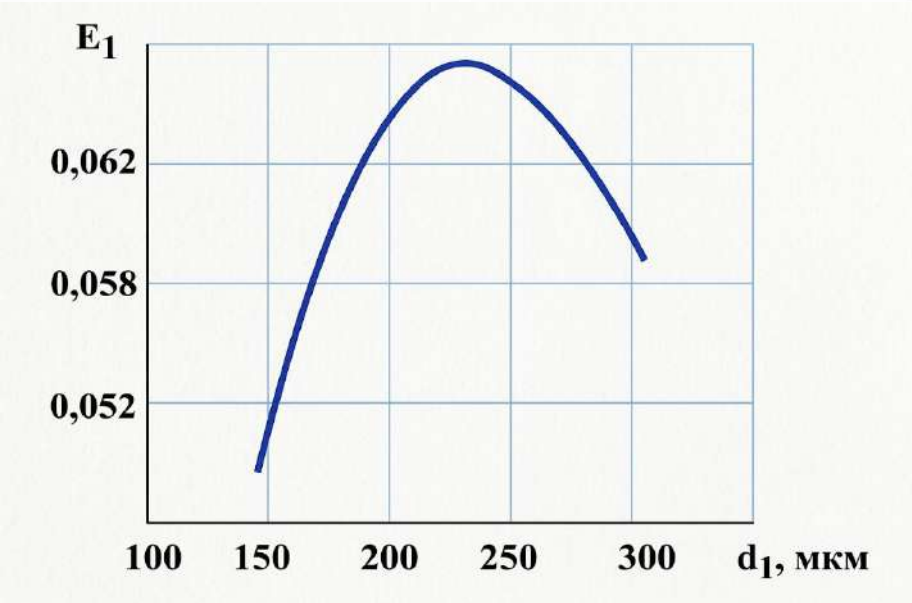
1-расм. Ғоваклик ва ўртача ғовак ўлчамининг хом ашё қалинлигига боғликлиги.



2-Расм. Ўтказувчанлик коэффициенти K_1 ни ғоваклар ичига i-нчи маротаба киритилаётган кичик кукунлар ўлчами d_1 га боғлиқлиги.

ISSN 3030-3907

3-расмда биринчи босқичдан сўнг ғоваклар орасига киритилган кичик заррачалар самарадорлик параметрининг кукун заррачалари ўлчамига боғлиқлиги тасвирланган. Ундан кўриниб турибдики, 220 мкм ўлчамдаги заррачалардан фойдаланиш, бошқа ўлчамдаги заррачалар қўлланилганда эришилган кўрсаткичдан 30–40% юқори самарадорлик параметрига эга фильтрлар олиш имконини беради.



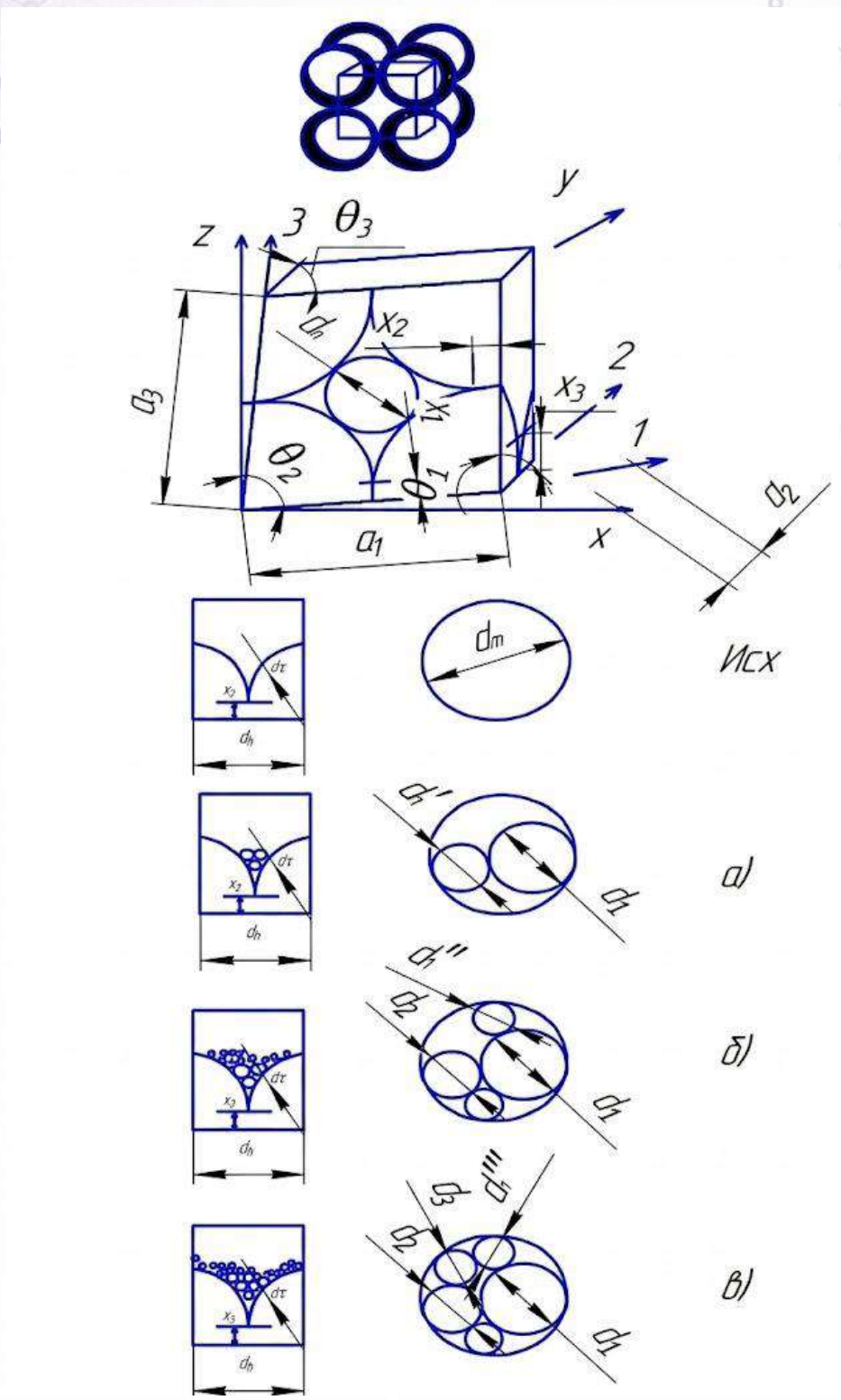
3-расм. Самарадорлик параметри E_1 ни ғоваклар ичига 1-инчи маротаба киритилаётган кичик кукунлар ўлчами d_1 га боғлиқлиги.

Турли ўтказувчан ғовакли материал-фильтрларни таққослаш имконини берувчи ўтказувчанлик характеристикаси сифатида кўпинча ўлчамсиз самарадорлик параметри (E_1) қабул қилинади [1, 68–72-б.; 2, 34–40-б.; 3, 102–110-б.].

$$E_1 = \frac{\sqrt{K}}{d_n^{cp}},$$

бу ерда: К- ўтказувчанлик коэффициенти ($м^2$); $d_{ғ}$.ўрт – ғовакнинг ўртача диаметри (мкм).

ISSN 3030-3907



4-расмда ярим хом ашё намунаси ўлчамларини ҳисоблаш диаграммаси келтирилган:

Ишчи (дастлабки) ҳолат: ўртача кукунлар ўлчами – 1100 мкм;

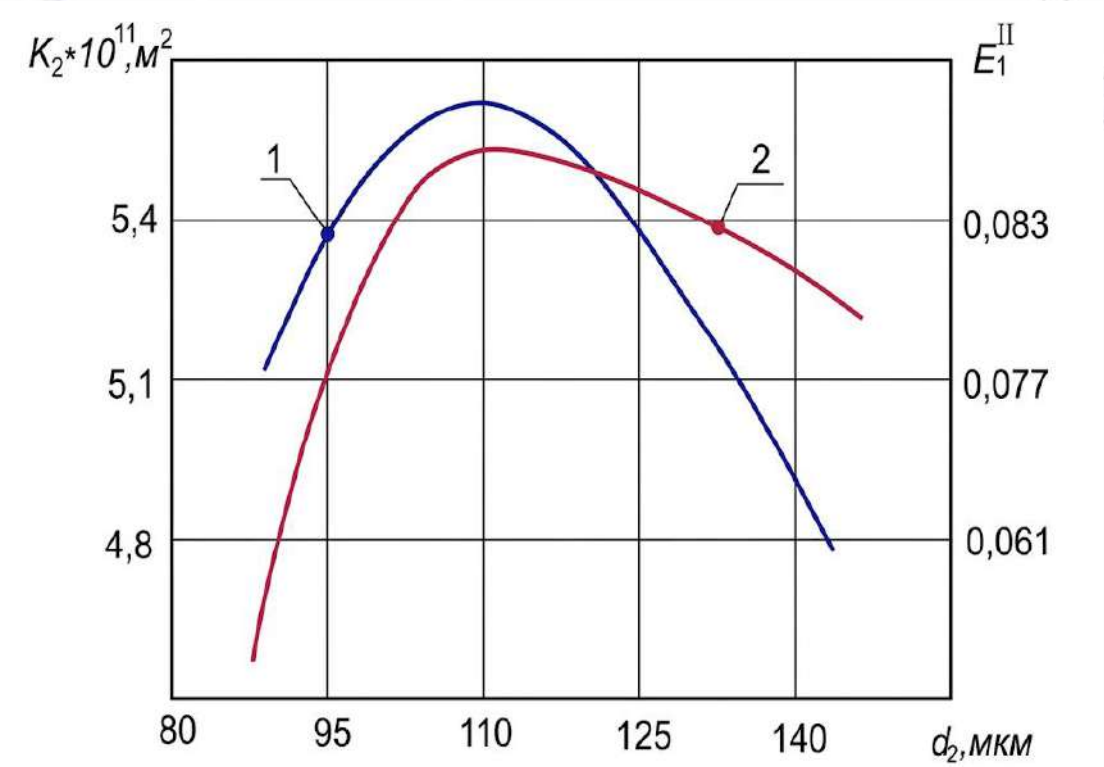
а) 1-босқич: ўртача кукунлар ўлчами – 220 мкм;

б) 2-босқич: ўртача кукунлар ўлчами – 110 мкм;

в) 3-босқич: ўртача кукунлар ўлчами – 55 мкм.

ISSN 3030-3907

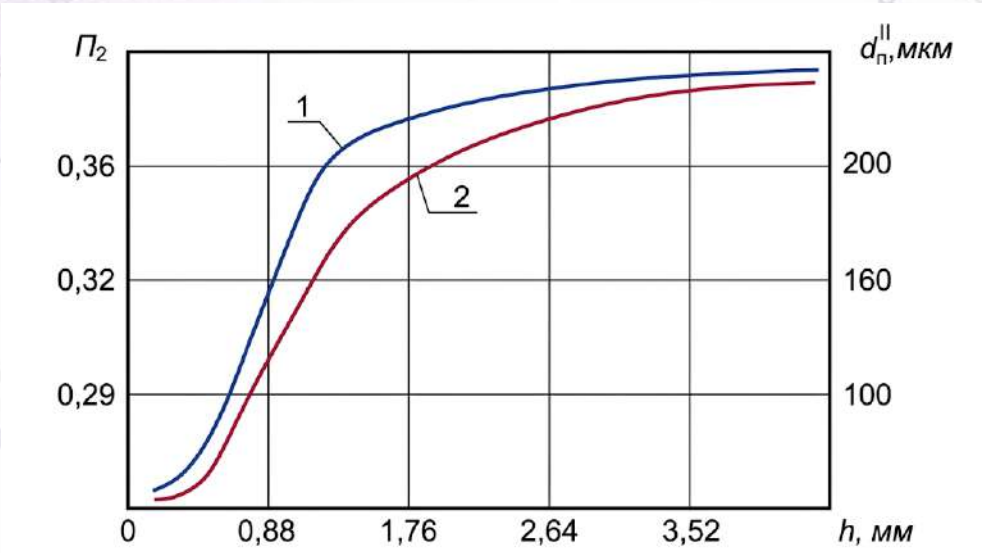
Кейинги киритиш босқичлари учун ҳам шунга ўхшаш ҳисоб-китоблар амалга оширилди. 220 мкм бўлган кичик заррачаларни ғовaклар орасига киритиш жараёнини ўрганиш учун турли ўлчамдаги заррачалар, хусусан, 110 ва 200 мкм ўлчамлилари учун ҳисоб-китоблар бажарилди. 5-расмда 2-босқич киритиш жараёнида ўтказувчанлик коэффициенти ва самарадорлик параметрларининг ғовакларга киритилган заррачалар ҳажмига боғлиқлиги кўрсатилган. Маълумотлар таҳлили шуни кўрсатдики, ўртача ўлчами 110 мкм бўлган заррачаларни қайта ғовакларга киритишдан олинган материал энг юқори самарадорликни намойиш этади.



5-расм. 2-нчи этап киритиш жараёнида ўтказувчанлик коэффициенти ва самарадорлик параметрларининг ғовакларга киритилган заррачалар ҳажмига боғликлиги.

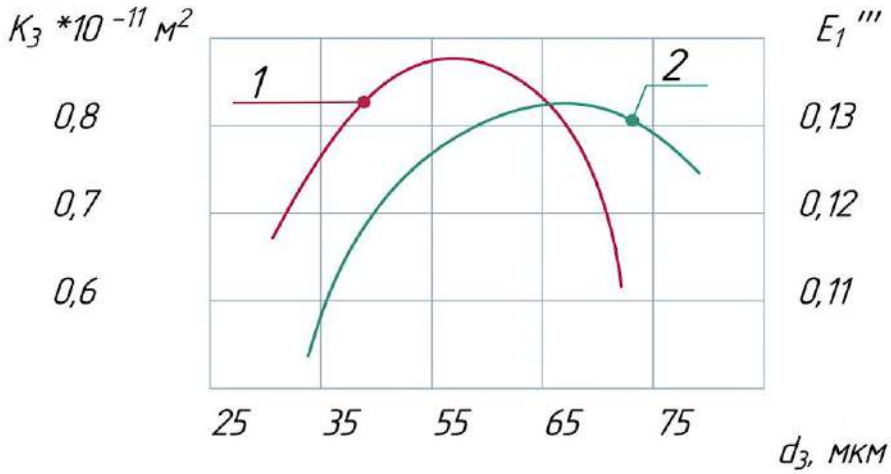
5-расмда 2-босқич киритиш жараёнида олинган намуналарнинг қалинлиги бўйича структуравий хусусиятларнинг тақсимланиши келтирилган. Унда 2-босқич киритиш жараёнида ғовакларга киритилган заррачаларнинг асосий қисми сирт қатламига тўпланганлиги кўрсатилган. Бу таъсир 1-босқичга нисбатан фильтр қатламидаги ғоваклик ҳажми ва ғовакликнинг янада пасайишига олиб келади, унинг қалинлиги тахминан дастлабки кукун диаметрининг 1,5 баробарига тенг бўлади.

ISSN 3030-3907



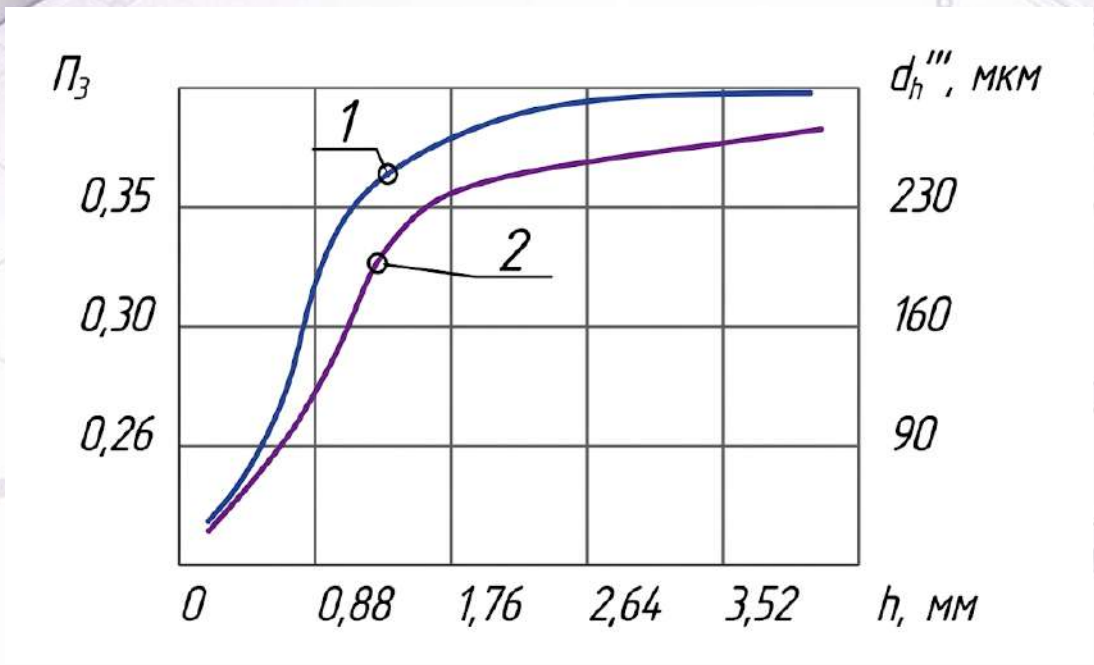
6-расм. Иккинчи киритиш босқичидан сўнг намуна қалинлиги бўйлаб ғоваклик $П_2$ (1) ва ғовакликнинг ўртача ўлчамларига $d''_П$ (2) боғликлиги.

Учинчи киритиш босқичида намунада ҳосил бўлган эксплуатацион хусусиятларнинг ўзгариш қонуниятларини ўрганиш мақсадида мос равишда ўлчамлари 40, 50 ва 80 мкм бўлган майда заррачали кукунлар танлаб олинди. 7-расмдаги таҳлил шуни кўрсатдики, ушбу катталиклар заррачалар ўлчами 55 мкм бўлганда ўзининг максимал қийматларига эришади. Бу ҳолда, самарадорлик параметри киритилган заррачаларнинг бошқа ўлчамлари учун мос келадиган қийматлардан ошмайди. Ғовакларнинг тақсимланиш табиати 2-босқичдагига ўхшаш бўлиб, сиртга яқин қатлам ичида ғоваклик ва ғовак ҳажмининг сезиларли даражада пасайиши кузатилади (8-расм).



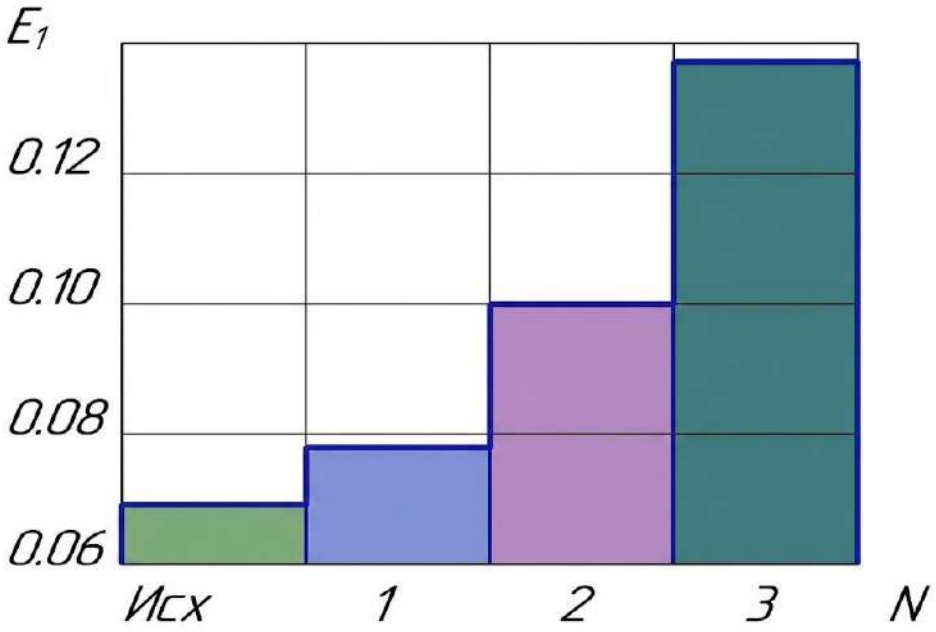
7-расм. Учинчи киритиш босқичида ўтказувчанлик коэффициенти K_3 (1) ва самарадорлик параметри E_1''' (2) нинг заррачалар ўлчами d_3 га боғликлиги

ISSN 3030-3907



8-расм. Учинчи киритиш босқичидан сўнг намуна қалинлиги бўйлаб ғоваклик $П_З$ (i) ғовак ўлчамининг ўртача қиймати $d_П'''$ (2) нинг тақсимоти.

Олинган маълумотларни умумлаштириш самарадорлик параметрининг киритиш босқичларига боғлиқлигини аниқлаш имконини берди (9-расм).



9 – расм. Самарадорлик параметрининг (E_1) майда заррачаларнинг киритиш боскичларига (N) боғликлиги.

Натижаларга кўра, 3 босқичли киритиш усулини қўллаш самарадорлик параметрини бир босқичли усулга нисбатан 55% гача ошириш имконини беради.

ISSN 3030-3907

Шундай қилиб, ғовакли ўтказувчан материаллар модели ва унга боғлиқ фильтрлаш жараёнлари асосидаги ҳисоб-китоблар шуни кўрсатдики, уч босқичли киритиш усулини қўллаш суюқлик ёки газларни фильтрлаш самарадорлигини 55% гача оширади. Бундан ташқари, ўртача кукун ўлчами 883 мкм бўлган ярим хом ашё ғовакларига мос равишда 220, 110 ва 55 мкм бўлган кичик заррачаларни кетма-кет қатламлаш орқали максимал самарадорликка эришиш мумкин.

ХУЛОСА.

Олиб борилган назарий ва амалий ҳисоб-китоблар асосида қуйидаги хулосаларга келинди:

1.Ғовакли материалларга майда заррачаларни киритишнинг уч босқичли усули, бир босқичли усулга нисбатан самарадорлик параметрини 55% гача ошириш имконини беради.

2.Максимал самарадорликка эришиш учун дастлабки 883 мкм бўлган ярим хом ашё ғовакларига заррачаларни 220, 110 ва 55 мкм кетма-кетлигида жойлаштириш энг мақбул натижа беради.

3.Ишлаб чиқилган уч босқичли қатламлаш технологияси фильтрлаш жараёнларида суюқлик ва газларни тозалаш сифатини сезиларли даражада яхшилайди.

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DEHYDRATION OF NATURAL GAS WITH VARIOUS ADSORBENTS AND DETERMINATION OF THE EFFICIENCY OF AN ADSORBER WITH A MULTILAYER ADSORBENT BED FOR GAS DEHYDRATION

Makhmudov Mukhtor Jamolovich
Bukhara State Technical University, Bukhara 200100, Uzbekistan
E-mail: makhmudov.mukhtor@inbox.ru
Nematov Khusan Ibodullayevich
Karshi State Technical University, Karshi 180000, Uzbekistan
Khujakulov Aziz Fayzullayevich
Bukhara State Technical University, Bukhara 200100, Uzbekistan
Ramazonov Bakhrom Gafurovich
Bukhara State Technical University, Bukhara 200100, Uzbekistan
Rasulov Ulugbek Askarovich
Bukhara State Technical University, Bukhara 200100, Uzbekistan
Anvarova Iroda Anvarovna
Karshi State Technical University, Karshi 180000, Uzbekistan
Mamadaminova Zulhumor Fakhriddinova
Bukhara State Technical University, Bukhara 200100, Uzbekistan
Shoymardonov Olmasbek Bolta ogli
Karshi State Technical University, Karshi 180000, Uzbekistan
Sunatov Shokhrukh Shamsi ogli
Bukhara State Technical University, Bukhara 200100, Uzbekistan
Rakhimov Zakhriddin Zafar ogli
Bukhara State Technical University, Bukhara 200100, Uzbekistan

Abstract. The selection of adsorbents for natural gas dehydration, the evaluation of their adsorption capacity and degree of dehydration under dynamic conditions, and the development of both the conditions for natural gas dehydration in a composite adsorbent bed and the design of the adsorber are all pressing challenges today. It is known that methane forms hydrate crystals with a linear structure, ethane forms spiral and atypical structures, and propane forms branched and disordered structures. Considering this, natural gases containing various hydrocarbons form mixed hydrate crystals with a complex, branched structure. This article presents the results of a study determining the dehydration efficiency of wet raw natural gas using composite adsorbent beds of silica gel, aluminum oxide, and zeolites. Based on the results obtained, a proposal is made to change the design of the single-bed adsorber used for gas dehydration to a multi-bed design.

Keywords: natural gas, gas hydrate, silica gel, aluminum oxide, zeolite, adsorption

ISSN 3030-3907

Annotatsiya. Tabiiy gazni suvsizlantirish uchun adsorbentlarni tanlash, ularning adsorbsion qobiliyatini va dinamik sharoitlarda suvsizlanish darajasini baholash, kompozitsion adsorbent qatlamida tabiiy gazni suvsizlantirish sharoitlarini ishlab chiqish va adsorberni loyihalash bugungi kunda dolzarb muammolardir. Ma'lumki, metan chiziqli tuzilishga ega gidrat kristallarini hosil qiladi, etan spiral va atipik tuzilmalarni hosil qiladi, propan esa shoxlangan va tartibsiz tuzilmalarni hosil qiladi. Buni hisobga olsak, turli uglevodorodlarni o‘z ichiga olgan tabiiy gazlar murakkab, tarvaqaylab ketgan tuzilishga ega aralash gidrat kristallarini hosil qiladi. Ushbu maqolada silikagel, alyuminiy oksidi va zeolitlardan tashkil topgan kompozit adsorbent qatlamlari yordamida nam xom tabiiy gazni suvsizlantirish samaradorligini aniqlash bo‘yicha tadqiqot natijalari keltirilgan. Olingan natijalarga asoslanib, gazni suvsizlantirish uchun ishlatiladigan bir o‘rinli adsorber konstruksiyasini ko‘p o‘rinli konstruksiyaga o‘zgartirish taklifi kiritildi.

Kalit so‘zlar: tabiiy gaz, gaz gidrati, silikagel, alyuminiy oksidi, zeolit, adsorbsiya.

Аннотация. Выбор адсорбентов для осушки природного газа, оценка их адсорбционной способности и степени осушки в динамических условиях, а также разработка как условий осушки природного газа в слое композитного адсорбента, так и конструкции адсорбера - все это насущные задачи на сегодняшний день. Известно, что метан образует гидратные кристаллы с линейной структурой, этан образует спиральные и нетипичные структуры, а пропан образует разветвленные и неупорядоченные структуры. Учитывая это, природные газы, содержащие различные углеводороды, образуют смешанные кристаллы гидратов со сложной разветвленной структурой. В данной статье представлены результаты исследования, в котором определялась эффективность обезвоживания влажного природного газа-сырца с использованием слоев композитного адсорбента из силикагеля, оксида алюминия и цеолитов. На основании полученных результатов предложено изменить конструкцию однослойного адсорбера, используемого для осушки газа, на многослойную конструкцию.

Ключевые слова: природный газ, газогидрат, силикагель, оксид алюминия, цеолит, адсорбция

1. INTRODUCTION.

Natural gas is one of the key components of the national economy and the fuel and energy sector worldwide. At the same time, it is a valuable raw material resource for the chemical industry [1]. The main advantages of gaseous fuels

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include their low-cost transportation through pipelines without the need for rail or water transport, the use of relatively simple processing technologies compared to other raw materials, and the significantly lower amount of toxic gases released during combustion [2]. These advantages have led to a growing demand for natural gas. Therefore, the development and improvement of processes aimed at enhancing the quality of natural gas are of great importance.

Around the world, extensive scientific research is being conducted to improve natural gas purification and dehydration processes and to develop modern combined methods for these purposes. In this regard, the dew point of commercial gas is one of the main regulated quality indicators [3, 4]. The presence of moisture in natural gas significantly affects pipeline corrosion during transportation and storage, the stable operation of automatic control equipment, compressor stations, and other technological systems. Therefore, particular attention is being paid to the development and implementation of technologies that improve natural gas dehydration processes, especially adsorption drying processes and the efficiency of the adsorbents used in them [5].

Gas humidity refers to the presence of water vapor in the gas. The moisture content of natural gas depends on pressure and temperature. The higher the gas temperature, the more moisture it can retain per unit volume. Pressure has an inverse effect: as gas pressure increases, its moisture content decreases [6-7].

Water vapor can saturate a gas up to the saturated vapor pressure corresponding to a given temperature. If this limit is exceeded, condensation occurs, and the vapor transforms into a liquid phase.

The temperature at which a gas becomes fully saturated with water vapor is called its dew point [8]. The presence of moisture in gas causes corrosion of pipeline systems during transportation and leads to the formation of hydrates and condensates in gas pipelines. In addition, moisture reduces the heating value of the gas. Therefore, gases are dried using solid or liquid absorbents [9]. However, the development of advanced technologies aimed at the complete removal of moisture from gas, particularly through adsorption processes, continues to this day [10, 11].

Gas humidity is classified into three types: relative, specific, and absolute humidity [12].

Absolute humidity is the mass or quantity of water vapor, expressed in grams, contained in a unit volume of gas. The unit of absolute humidity is g/m^3 [13].

Specific humidity is the mass of water vapor contained in a unit mass of wet gas. The unit of specific humidity is g/kg [14].

Relative humidity represents the percentage of the maximum amount of water vapor that can be absorbed by the gas at a given pressure and temperature.

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Relative humidity (φ) is measured as a percentage and is calculated as the ratio of the partial pressure of water vapor, ρ, to the saturated vapor pressure, P, at the same temperature [15]:

$$\varphi = \frac{p}{P}$$

For a saturated gas, the relative humidity is equal to 1 (or 100%) [16].

The dew point of hydrocarbon gases consisting of mixtures of simple gases depends on their composition and pressure.

The moisture content of a gas can be determined using the gravimetric method. This method is based on passing a measured volume of gas through a moisture-absorbing substance and determining the absorbed moisture by measuring the increase in the absorbent's weight. Calcium chloride or its mixture with phosphorus pentoxide is commonly used as the absorbent. Since the moisture-holding capacity of gas depends on temperature and pressure, moisture measurements should be carried out under the same conditions in which the gas is intended to be used [17].

Knowing the absolute humidity of the gas, it is possible to determine the dew point of the gas in the pipeline at the corresponding pressure.

1.1. Gas Hydrates and Conditions for Their Formation.

During the production and transportation of gas saturated with moisture, gas hydrates may form (Figure 1) [18, 19, 20]. Gas hydrates are chemical compounds of gases and water that resemble ice in appearance.

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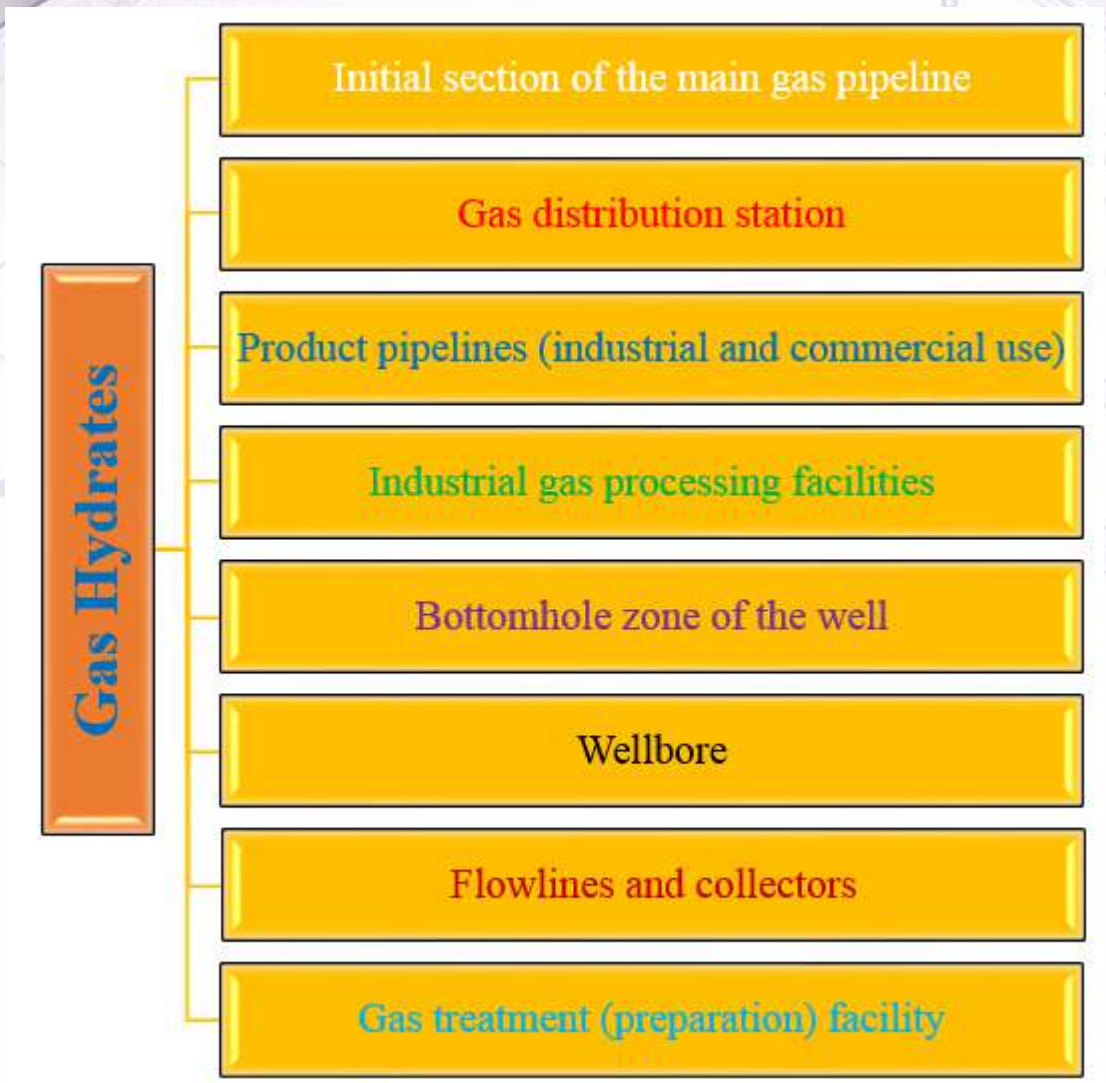


Figure 1. Gas Industry Systems in Which Hydrate Formation Occurs

Hydrocarbon hydrate crystals are formed when hydrocarbons interact with water at a relative humidity of $\varphi > 0.6$ [21]. These hydrates can cause blockages in gas pipelines, pressure control valves, and shut-off systems. The general composition of hydrate crystals is expressed as [22]:

$$M \cdot H_2O$$

where: M – hydrocarbon molecule.

Methane forms hydrates with water in the form of $CH_4 \cdot H_2O$ [23], ethane forms $C_2H_6 \cdot H_2O$ [24], and propane forms $C_3H_8 \cdot H_2O$ hydrates [25].

Gas hydrates can form at temperatures significantly higher than the freezing point of water [26].

The structure of gas hydrates consists of water molecules arranged in an ice-like open framework containing cavities of two different sizes (large and small), as shown in Figure 2 [27, 28-30].

These cavities are relatively large and may be partially or completely occupied by gas molecules. The degree of cavity occupancy depends on intermolecular interactions and thermobaric conditions.

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The stability of natural gas hydrates is generally maintained within a temperature range of –5 to 10°C [31, 32] and a pressure range of 6 to 20 kgf/cm² [33]. At higher temperatures and lower pressures, gas hydrates do not form [34].

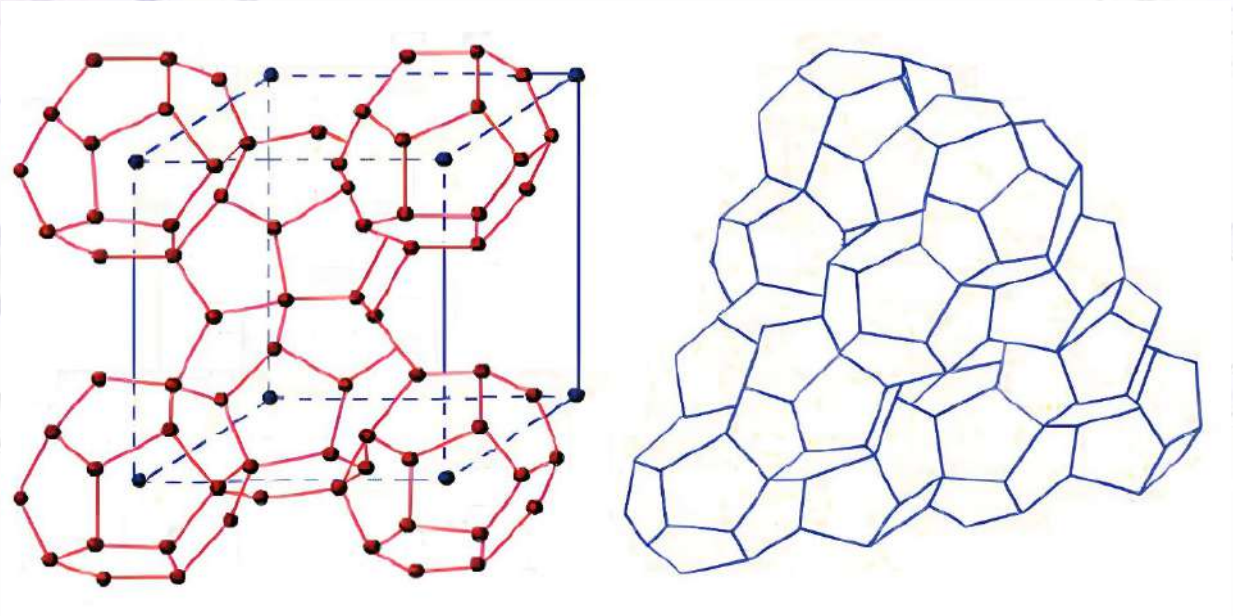


Figure 2. Structure of Gas Hydrates

For individual gases, there is an upper temperature limit above which hydrate formation cannot occur regardless of the pressure applied. This temperature is known as the critical hydrate formation temperature. It is 21.5°C for methane [35], 14.5°C for ethane [36], and 5.5°C for propane [37].

The dependence of hydrate formation by ethane and propane on pressure and temperature is presented in Table 1 [38, 39, 40].

Table 1

Hydrate Formation Conditions

Ethane		Propane	
Temperature, °C	**Pressure, MPa**	**Temperature, °C**	**Pressure, MPa**
-9,5	0,5	-11,9	0,10
-6,7	0,36	-9,0	0,12
-3,9	0,41	-6,3	0,13
-1,1	0,46	-5,6	0,13
0,6	0,51	-3,3	0,16
1,7	0,58	-1,0	0,17
10,8	1,70	1,7	0,24
13,0	2,70	2,3	0,27
14,5	3,40	3,3	0,34
-	-	4,4	0,41
-	-	5,5	0,48

ISSN 3030-3907

The heavier the hydrocarbon gas, the faster it forms hydrates in the presence of moisture.

The conditions for hydrate formation in wet gas can be explained graphically. Figure 3 [41] illustrates the conditions under which hydrate crystals form in wet gas for individual hydrocarbons. In the figure, line AD represents the vapor-pressure curve of an individual hydrocarbon. The region to the left of line BC corresponds to the hydrate formation zone, whereas the region to the right represents the hydrate-free zone [41].

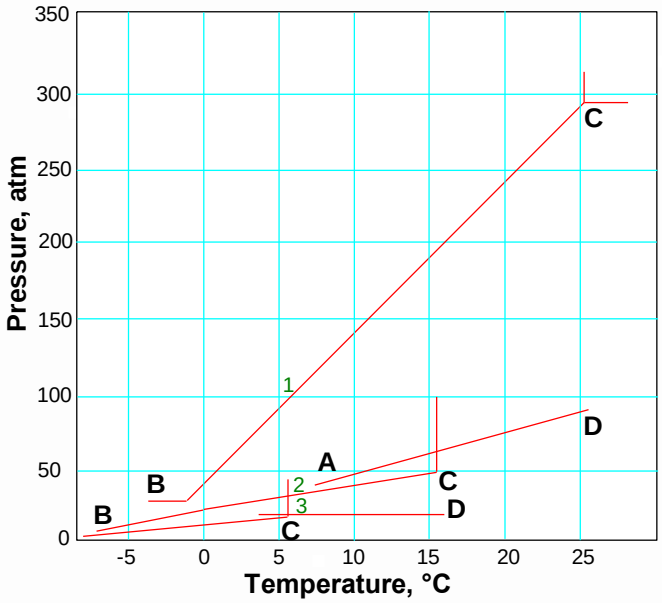


Figure 3. Conditions for the Formation of Hydrate Crystals in Wet Gas for Individual Hydrocarbons: *1 – Methane, 2 – Ethane, 3 – Propane*

Point C indicates the critical hydrate formation temperature. At temperatures above this value, hydrates cannot form regardless of the pressure applied [39]. The formation of gas hydrates can be prevented by several methods [40, 41, 42, 43, 44]:

- Preheating the gas to maintain its temperature above the hydrate formation temperature. This method is mainly used in gas distribution stations and gas processing facilities as part of their technological schemes [42].
- Reducing the pressure in gas pipelines below the hydrate equilibrium pressure. However, this method is economically costly, as it significantly reduces the pipeline's transportation capacity [43].
- Injecting hydrate inhibitors into gas pipelines. Common inhibitors include methanol, diethylene glycol (DEG) [44], triethylene glycol (TEG) solutions [45], and calcium chloride [46, 47]. The introduction of these inhibitors into the gas stream allows them to partially absorb water vapor and convert it into solutions that either do not form hydrates or form hydrates only at lower temperatures.

ISSN 3030-3907

In main gas pipelines, methanol is most commonly used to remove existing hydrate plugs or prevent their formation. In this case, methanol is typically injected at a rate of 0.26 kg per 1000 kg of gas [48].

The aim of the research is to improve natural gas adsorption drying processes through the application of combined adsorbent bed layers.

2. RESEARCH OBJECTS AND METHODS.

The research objects included wet natural gas used in adsorption drying at "Shurtanneftegaz" LLC (Republic of Uzbekistan, Kashkadarya Region), as well as various adsorbents employed for gas drying, including silica gels, aluminum oxide, and zeolites.

2.1. Laboratory Unit for Natural Gas Adsorption Drying.

The method for determining the adsorption capacity of adsorbents and the degree of drying under dynamic conditions includes the following steps. An adsorbent sample is calcined in a muffle furnace at a temperature of 350°C for 4 hours. It is then cooled in a desiccator over a layer of zeolite and weighed. After that, the adsorbent is loaded into the adsorption unit.



Figure 4. Laboratory Unit for Adsorption Drying of Gases Manufactured by EKSIS

A laboratory setup for determining the adsorption capacity of adsorbents and the drying efficiency under dynamic conditions is shown in Figure 4 (Laboratory unit for gas adsorption drying manufactured by the "EKSIS" company).

The laboratory unit consists of an adsorber, mixer**,** droplet separator, and gas flow meter. A stream of wet gas is passed through the unit. To determine the moisture content of the dried gas, a coulometric moisture analyzer is installed. The experimental tests are terminated after the highest value of the gas dew point is recorded.

2.2. Gravimetric Method for Determining Moisture Content in Gas COMPOSITION.

ISSN 3030-3907

The gravimetric (mass-based) method for determining moisture content in gas is based on the adsorption of water vapor by certain substances. Such substances include calcium chloride, silica gel, sulfuric acid, phosphorus pentoxide, and others. When selecting one of these moisture absorbents, it is necessary to consider that some of them may absorb not only water vapor but also gaseous impurities such as SO_2, Cl_2, CO_2, and other components. This can affect the accuracy of the final results obtained [49, 50].

In the gravimetric method, a known volume of gas is passed through a series of adsorbers connected in sequence and filled with a moisture-absorbing material (Figure 5).

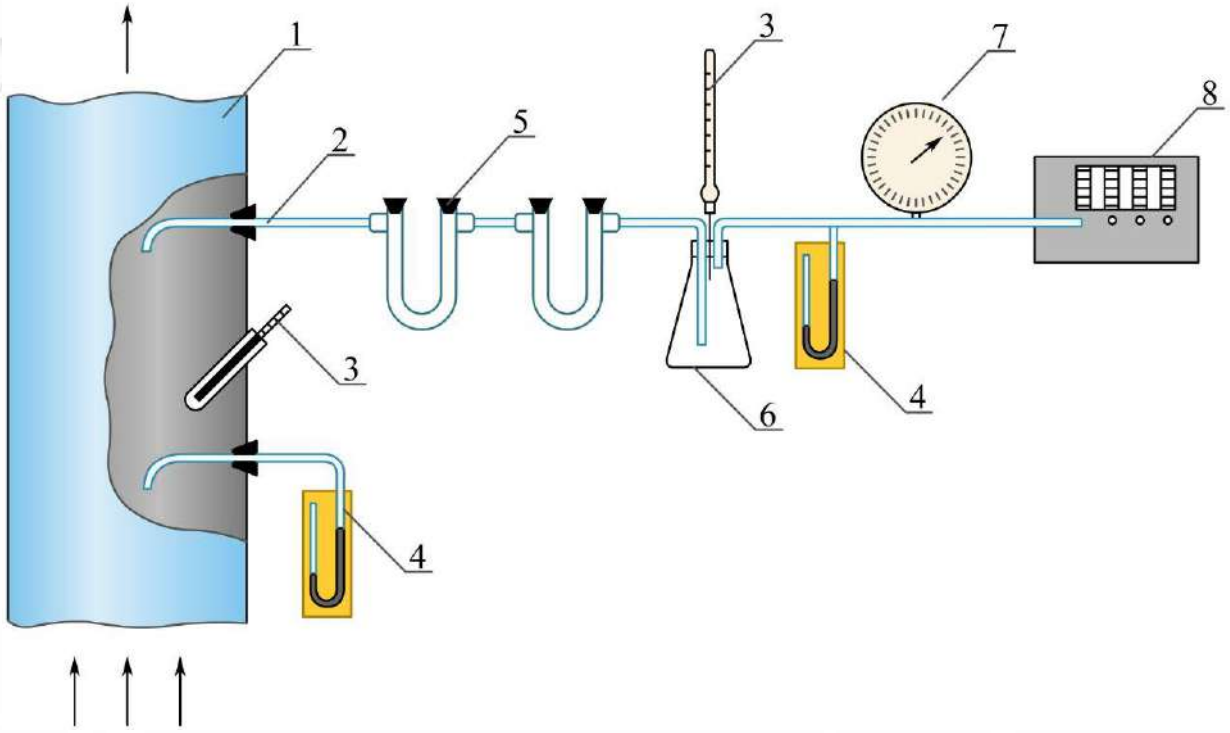


Figure 5. Schematic diagram for determining the moisture content of gas using the gravimetric method: *1 – gas line, 2 – sampling tube with filter, 3 – thermometer, 4 – manometer, 5 – U-shaped absorption tube, 6 – hydraulic barrier (installed only when using a liquid absorbent, such as sulfuric acid), 7 – gas meter, 8 – electric aspirator*

The tubes containing the absorbent are weighed on an analytical balance before the analysis (m_1) and after the analysis (m_2). Knowing the amount of absorbed moisture and the volume of gas passed through the system (V_G), the absolute moisture content of the gas is calculated using the following equation [51, 52, 53, 54]:

$$f'' = \frac{m_2 - m_1 * 1000}{\left(V_G\tau = \frac{273}{273 + t_G} \cdot \frac{B - R_P}{760}\right) + \left(\frac{m_2 - m_1}{0{,}804}\right)}$$

ISSN 3030-3907

where: *where: m_1 – is the mass of the adsorbent prior to water vapor adsorption, g; m_2 – is the mass of the adsorbent after water vapor adsorption, g; V_G – is the volume of gas passed through the adsorbent tube, L/min; τ – is the transit time of the gas sample under investigation through the adsorbent tube, min; t_G – is the temperature of the gas, measured after water vapor has been adsorbed, °C; R_P – is the pressure of the gas sample after water vapor has been adsorbed, mm Hg.*

During sampling, a decrease in the resistance of the solid absorbent filter must be avoided, as this indicates saturation with water vapor and will lead to erroneous results. Additionally, the gas sampling rate must be strictly controlled. The gas sample is taken at a rate of 0.5–1.0 L/min (sampling duration of 10–15 minutes). If the gas sample is taken at a rate lower than 0.5 L/min, the water vapor in the gas may condense in the sampling tube. If taken at a rate higher than specified, the hydraulic resistance in the system will increase, and the results will be inaccurate.

3. RESULTS AND ANALYSIS.

In the first stage of the research, the chemical composition and physicochemical properties of the natural gas processed at “Shurtanneftgaz” LLC, used as the object of study, are presented in Table 2.

Table 2

Chemical composition and physicochemical properties of natural gas processed at “Shurtanneftgaz” LLC

№	Physicochemical Properties of the Gas		Indicator
1	Chemical composition of natural gas, %	C_1	91,76
		C_2	5,79
		C_3	1,09
		n-C_4	0,16
		i-C_4	0,13
		n-C_5	0,05
		i-C_5	0,05
		$C_{6+\ high}$	0,07
		CO_2	0,05
		H_2S	0,01
		N_2	0,84
2	Density, kg/m^3		0,7301
3	Molecular Mass		17,880
4	Gross Calorific Value under normal conditions, kcal/m^3		9430,9

ISSN 3030-3907

5	Net Calorific Value under normal conditions, kcal/m^3	8505,3
6	Wobbe Index, kcal/m^3	10925,3
7	Moisture Content, ppm	745,5

3.1. Determining the dehydration level of natural gas using combination adsorbents.

It was determined that with the help of KSMG silica gel, it is possible to dehydrate gases corresponding to the summer period for cold and temperate climate regions. In turn, it is worth noting that, considering the lower water resistance and abrasion resistance of KA (3Å) zeolite compared to KSMG silica gel and K1 activated aluminum oxide, we studied the gas dehydration level by placing the aforementioned adsorbents in the adsorber in various combinations to increase the operational life of this zeolite and, furthermore, to improve the efficiency of the adsorption process.

In the next stage of our research, the natural gas dehydration processes in combined-layer adsorbent beds were investigated by sequentially placing the above-mentioned adsorbents in various ratios. The combination of adsorbents for natural gas dehydration is presented in Table 3.

Table 3

Combination of adsorbents for natural gas dehydration

№	Adsorbents	Names of Adsorbent Compositions	Ratio, %
1	K1 aluminum oxide: KA (3Å) zeolite	**(K1:KA)**	50:50
2	K1 aluminum oxide: KSMG silica gel	**(K1:KSMG)**	50:50
3	K1 aluminum oxide:NaA (3Å) zeolite	**(K1:NaA)**	50:50
4	K1 aluminum oxide:KSMG silica gel:KA (3Å) zeolite	**(K1:KSMG:KA-1)**	20:20:60
5	K1 aluminum oxide:KSMG silica gel: KA (3Å) zeolite	**(K1:KSMG:KA-2)**	30:30:40

The sequence for layering the adsorbents was selected based on their abrasion resistance and water stability indicators.

The adsorption process was conducted under experimental conditions to determine the adsorption capacity of the adsorbents. The results of using the K1:KA combined adsorbent layer for natural gas dehydration are shown in Figure 6.

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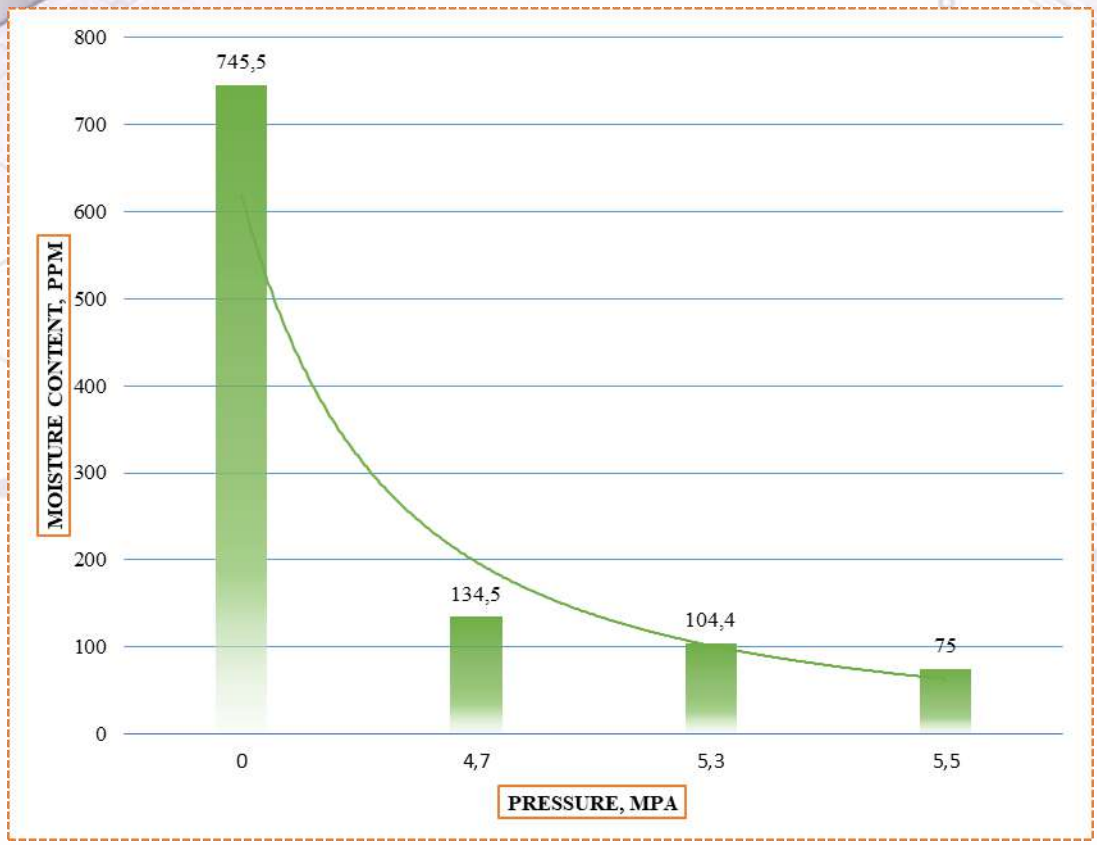


Figure 6. The degree of natural gas dehydration by the K1:KA combination adsorbent layer at a temperature of 28°C and various pressures

At a temperature of 28°C and a pressure of 5.5 MPa, the K1:KA combination adsorbent layer reduced the moisture content in natural gas to 75 ppm. This indicator is considered sufficient for temperate climate zones, particularly for the conditions in our country.

The results of natural gas dehydration using the K1:KSMG combination adsorbent layer are shown in Figure 7. The gas dehydration process in this combination adsorbent layer did not show particularly high results. However, it is possible to dehydrate natural gas with a dew point temperature near -10°C at a pressure of 3.92 MPa.

In our next study, the gas dehydration process was conducted in an adsorber with a K1:NaA combination adsorbent layer. The obtained results are presented in Figure 8.

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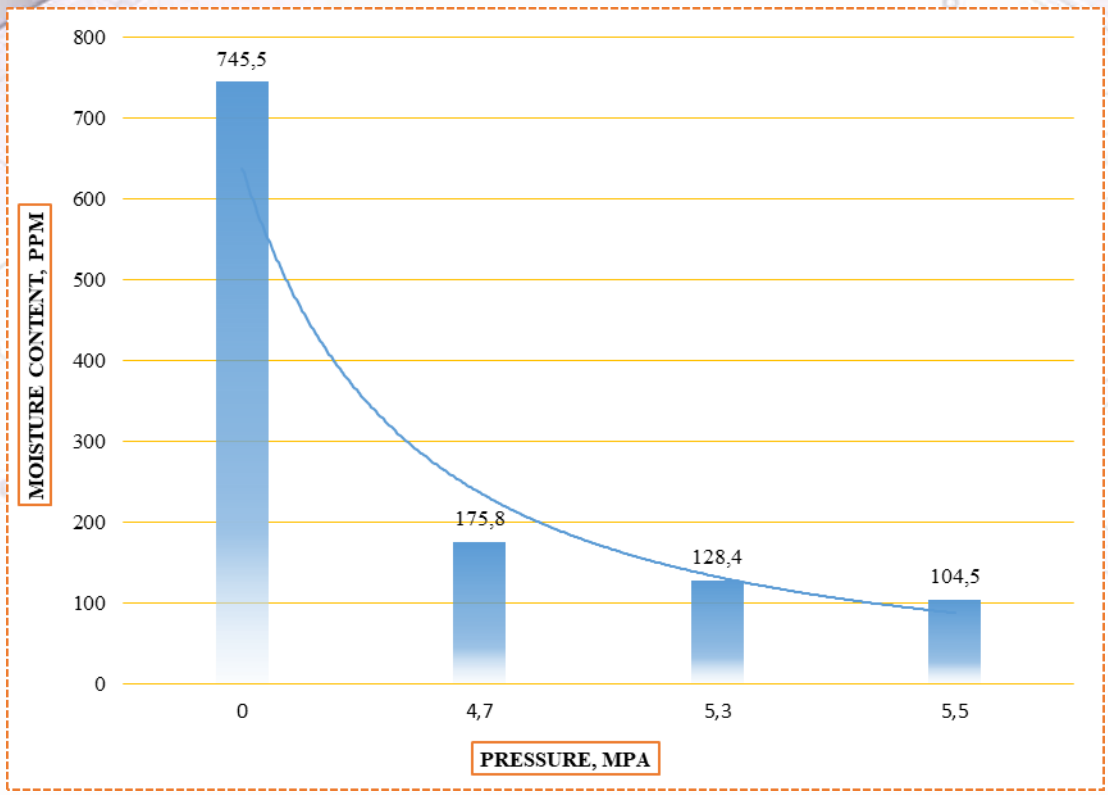


Figure 7. The degree of natural gas dehydration by the K1:KSMG combined adsorbent layer at 28°C and various pressures

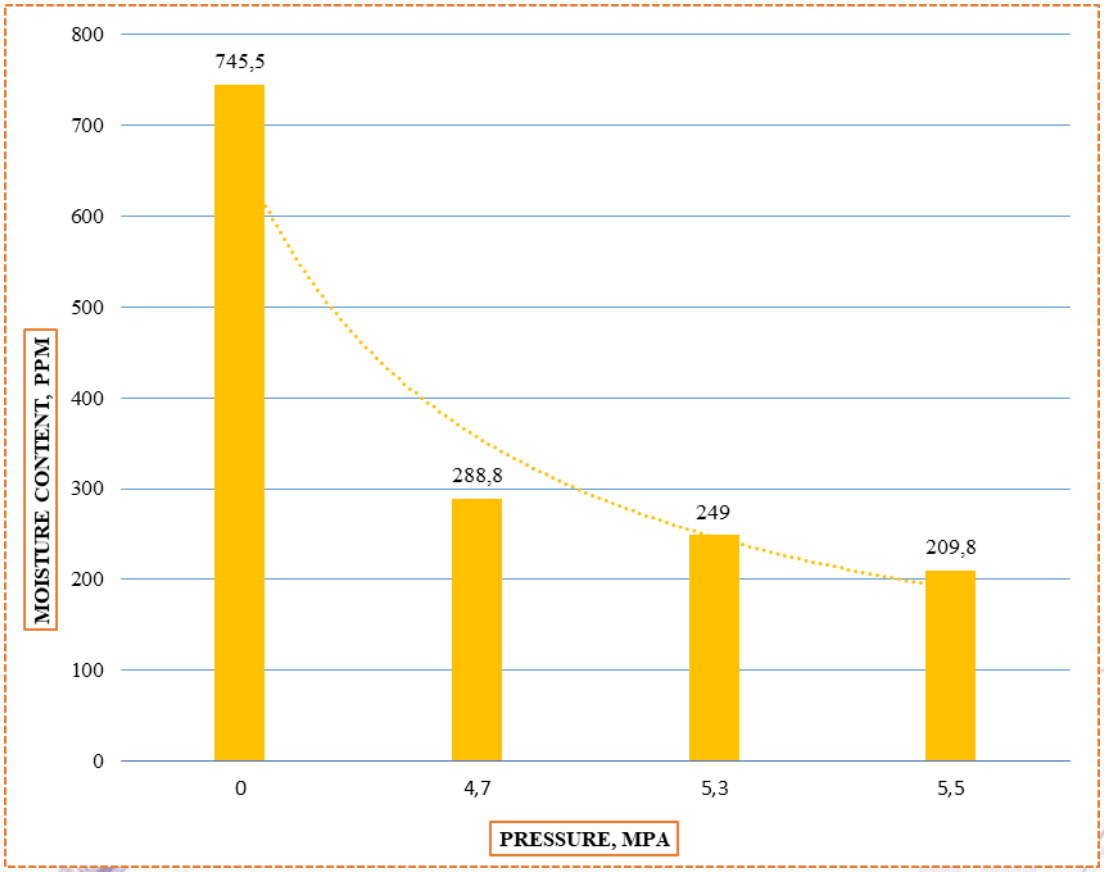


Figure 8. The degree of natural gas dehydration by the K1:NaA combination adsorbent layer at a temperature of 28°C and various pressures

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The degree of natural gas dehydration by the K1:NaA combination adsorbent layer at a temperature of 28°C and various pressures showed significantly lower results.

In the two types of combined-layer gas adsorption processes, the K1:KA adsorbent combination demonstrated a higher result. From the results of this study, we can see that the KA zeolite showed high results both individually and in combination. Therefore, an adsorption layer protected by K1 activated aluminum oxide, which showed the highest performance individually, was selected and tested in the gas dehydration process. This combination adsorbent layer was developed by varying the amount of KA zeolite.

The efficiency of the K1:KSMG:KA-1 combination adsorbent layer in natural gas dehydration is presented in Figure 9.

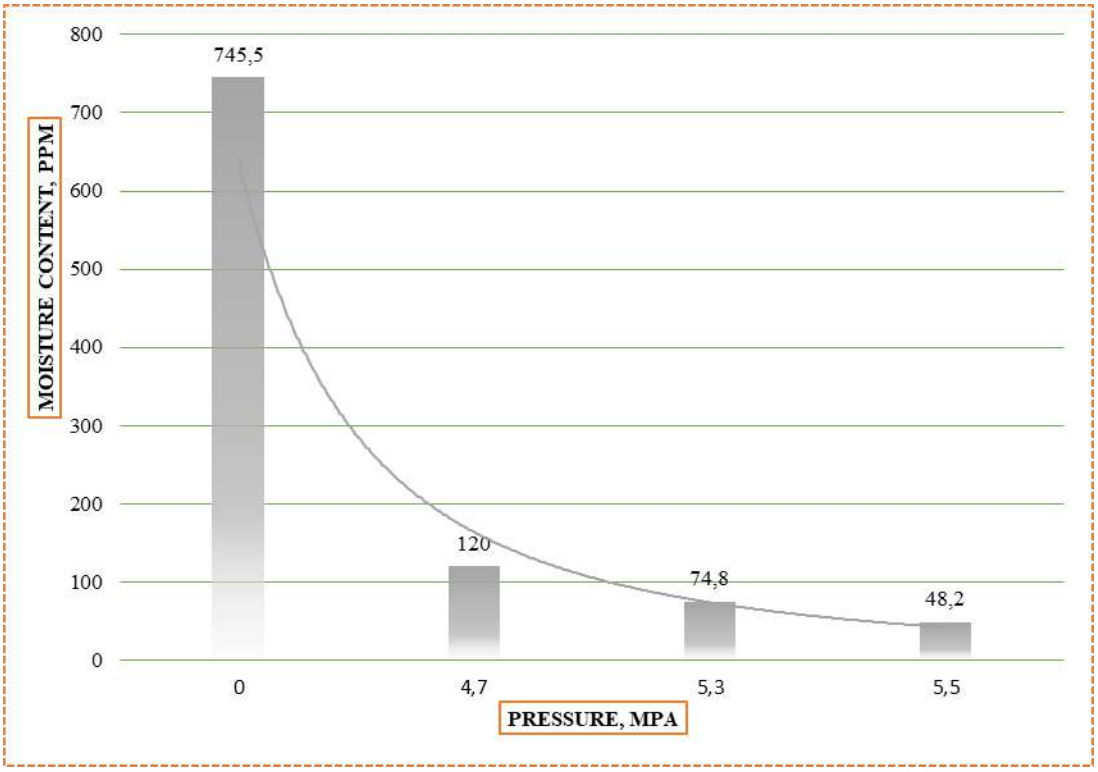


Figure 9. The degree of natural gas dehydration by the K1:KSMG:KA-1 combination adsorbent layer at 28°C and various pressures

The results showed that the K1:KSMG:KA-1 combination adsorbent layer reduces the moisture content in natural gas to 48.2 ppm at a temperature of 28°C and a pressure of 5.5 MPa. The efficiency of the K1:KSMG:KA-2 combination adsorbent layer in natural gas dehydration is shown in Figure 10.

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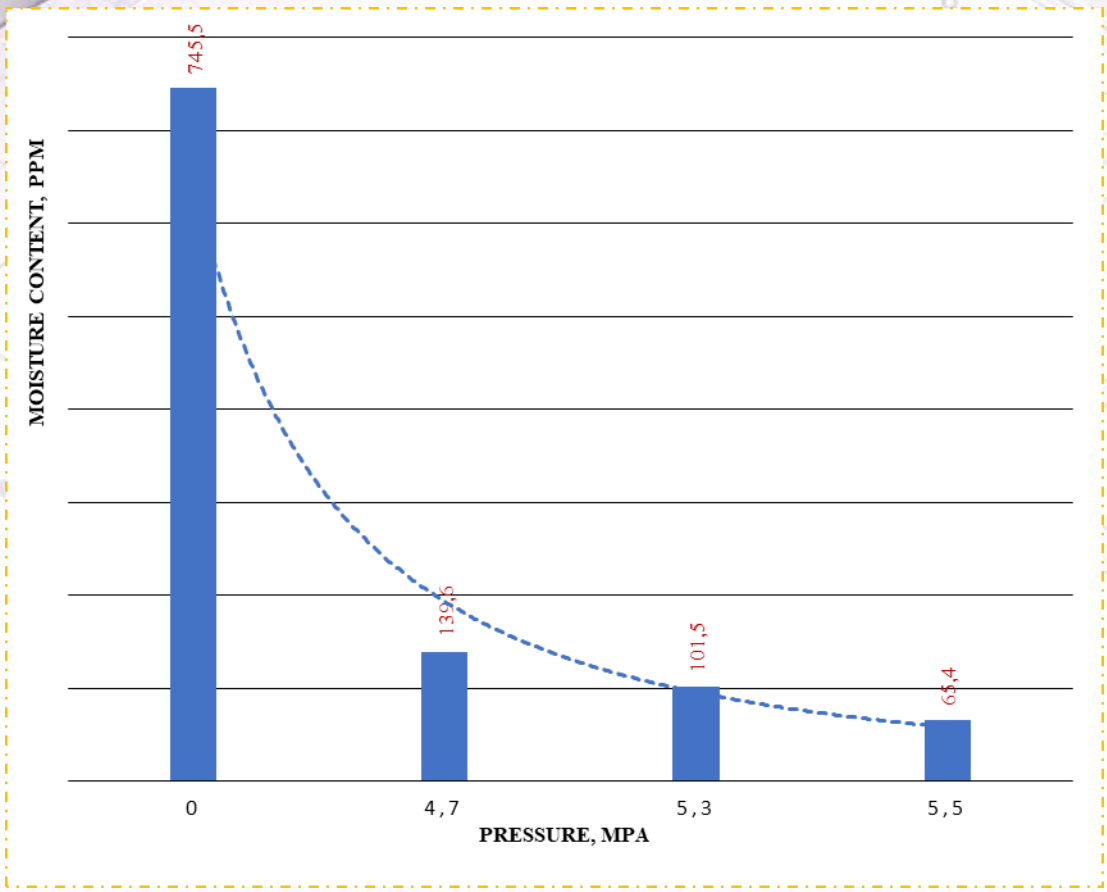


Figure 10. The degree of natural gas dehydration by the K1:KSMG:KA-2 combination adsorbent layer at a temperature of 28°C and various pressures

The results obtained showed that the K1:KSMG:KA-2 combination adsorbent layer reduces the moisture content in natural gas to 65.4 ppm at a temperature of 28°C and a pressure of 5.5 MPa.

In the gas dehydration combination consisting of three adsorbent layers, the superior result of K1:KSMG:KA-1 can be explained by its higher content of KA zeolite (60%).

Based on the conducted research, it is concluded that the K1:KSMG:KA-1 combination adsorbent layer and the individual KA (3Å) zeolite showed high results in dehydrating natural gas, and it is experimentally proven that they enable gas dehydration that meets both summer and winter requirements for all climatic conditions. In the next stage of our research, the adsorption cycle and regeneration conditions of this adsorbent and combination adsorbent layer were investigated.

Currently, at “Shurtanneftegaz” LLC, the adsorption cycle for the NaA zeolite used in gas dehydration is 6 hours, while the regeneration and cooling processes take 1.5 hours.

The adsorption process was conducted for 15 hours at a temperature of 28°C and a pressure of 3.923 MPa. The obtained results are presented in Figure 11.

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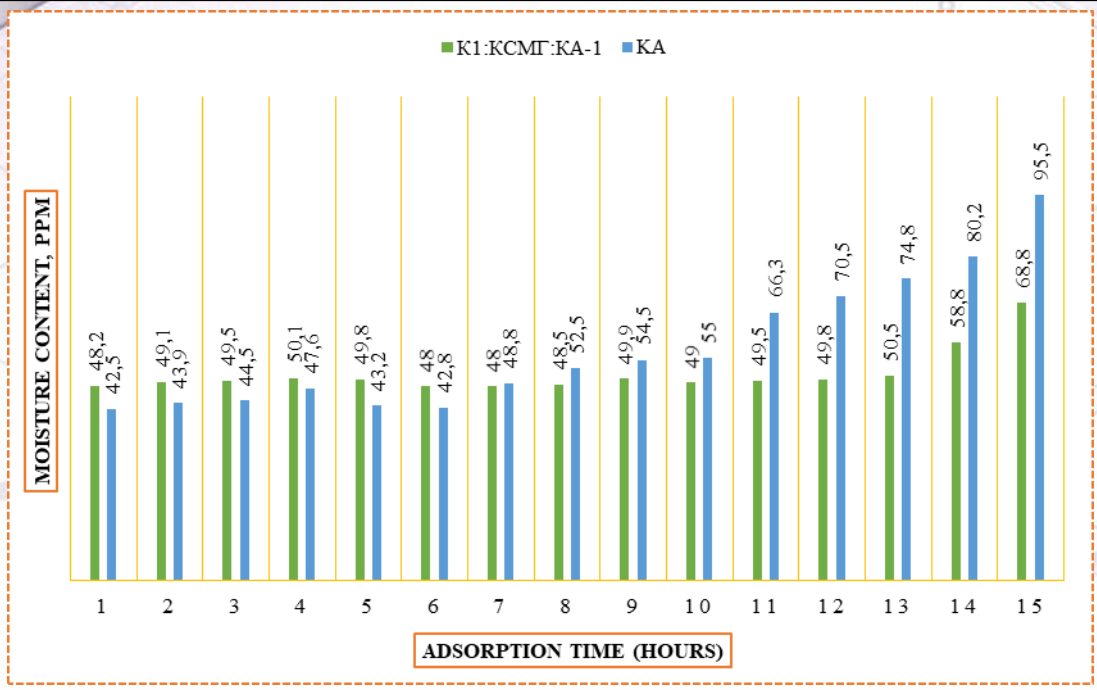


Figure 11. Adsorption duration of the K1:KSMG:KA-1 combination adsorbent layer and individual KA (3Å) zeolite during natural gas drying

The results of these experiments showed that the duration of adsorption activity for the K1:KSMG:KA-1 combination adsorbent layer was 12 hours, while that of the KA zeolite was 7 hours. This can be explained by the fact that in the K1:KSMG:KA-1 combination adsorbent layer, the K1 aluminum oxide partially absorbs various substances from the natural gas (mechanical particles, liquid hydrocarbons, etc.) and some moisture. This prevents the KSMG and KA components, which have a high capacity for water vapor absorption, from becoming saturated with these other substances. It can be inferred that the adsorption duration for the KA zeolite is significantly shorter because its pores become filled by absorbing several other substances along with water vapor.

3.2. Development of natural gas drying conditions and adsorber design for the K1:KSMG:KA-1 combination adsorbent layer.

The drying conditions for natural gas using the K1:KSMG:KA-1 combination adsorbent layer are presented in Table 4.

Table 4

Conditions for natural gas drying using the K1:KSMG:KA-1 combination adsorbent layer

№	Names of quantities	Unit of measure	Magnitude values		
			Min.	*Max.*	*Average*
1	**2**	**3**	**4**	**5**	**6**
Expenditure					

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1	Gas entering one block for purification	Thousand m^3/hour	100	500	400
2	Gas entering one adsorber for purification	Thousand m^3/hour	-	83	66
3	Purified gas used in zeolite regeneration and cooling	Thousand m^3/hour	30	60	45
4	Fuel gas supplied to the heating furnace	Thousand m^3/hour	100	630	580
5	Purified (commercial) gas	Thousand m^3/hour	90	450	360
Pressure					
6	Gas entering the purification process	MPa	5,5	5,7	5,5
7	Clean (commercial) gas	MPa	5,3	5,5	5,3
8	Regeneration and cooling gas	MPa	5,8	6,0	5,8
9	Pressure drop across one layer of the adsorber	MPa	0,65	0,65	0,65
Temperature					
10	Gas for purification	^oC	28	28	28
11	Cooling gas	^oC	25	25	25
Time					
12	Adsorption	Hour	12	12	12
13	Regeneration	Hour	1,5	2	1÷2
14	Cooling	Hour	1,5	2	1÷2

The parameters for these studies were determined based on the state standards presented in Chapter 2. The drying conditions for natural gas in the K1:KSMG:KA-1 combination adsorbent layer we are recommending are similar to those currently in use. However, the adsorption time for the K1:KSMG:KA-1 combination adsorbent layer is twice that of the NaA zeolite layer. This, in turn, allows for a twofold reduction in the frequency of adsorbent desorption, which consequently makes it possible to cut technological process costs by half.

At “Shurtanneftgaz” LLC, natural gas is dried using a single type of adsorbent, NaA. The structure of the adsorber used in this process is shown in Figure 12. To use the K1:KSMG:KA-1 combination adsorbent layer we have

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selected for natural gas applications, partial structural modifications to these adsorbers are required.

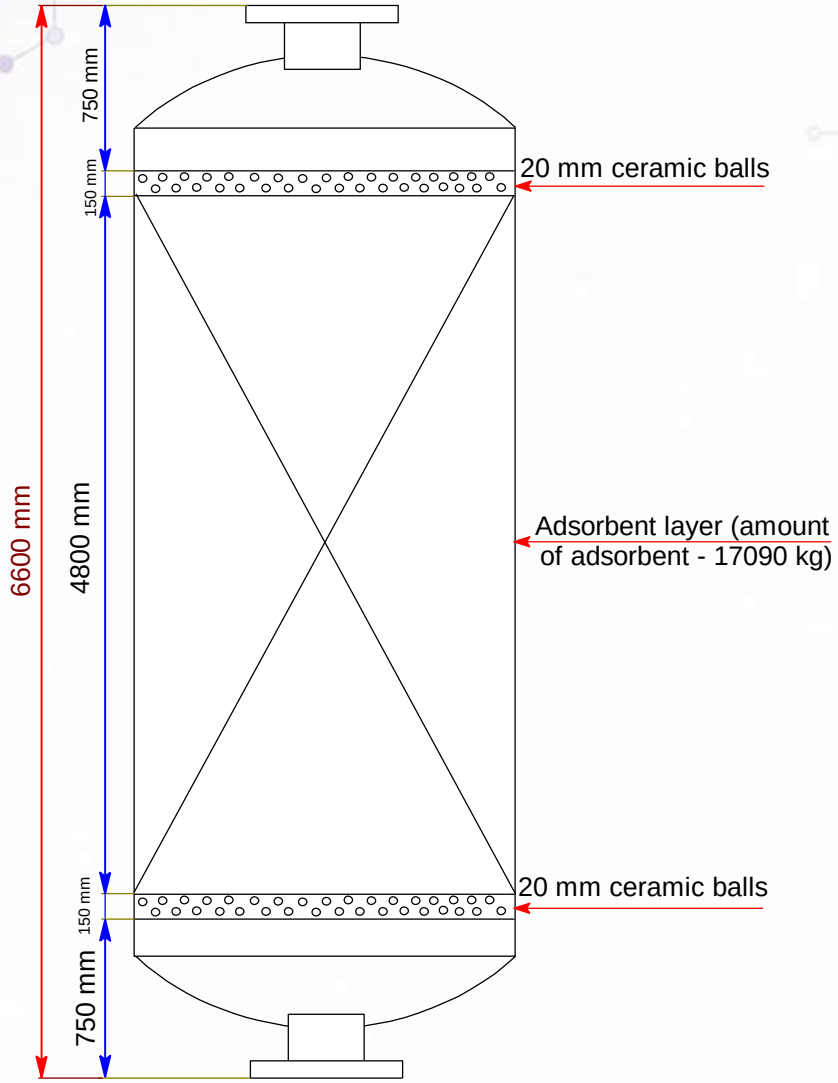


Figure 12. A general view of the adsorber used for natural gas dehydration at "Shurtanneftegaz" LLC

We, therefore, converted this single-layer adsorber into a three-layer design. Each layer was separated by a stainless steel mesh with 1x1 mm dimensions and 1 mm perforations. A general diagram of this adsorber is shown in Figure 13.

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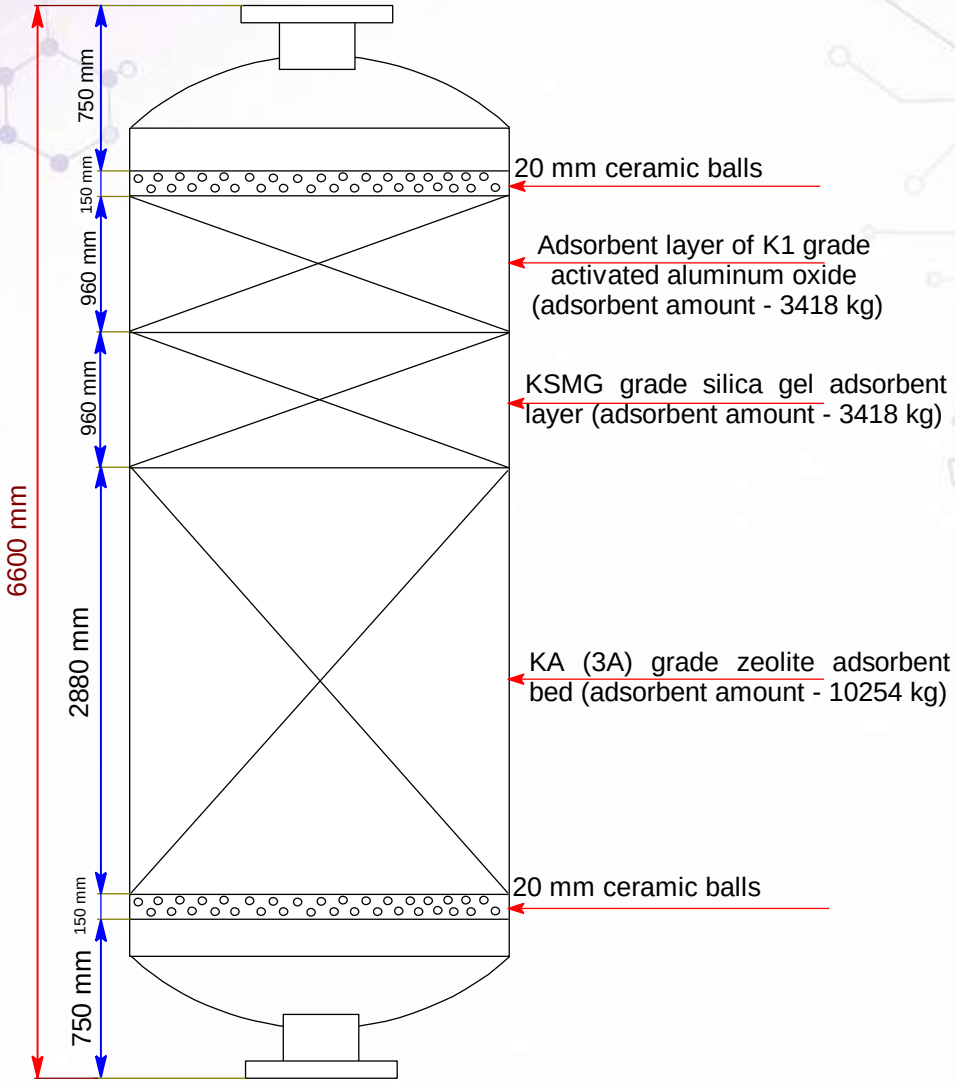


Figure 13. General view of the proposed adsorber

The physicochemical properties of the wet natural gas feedstock after adsorption dehydration at "Shurtanneftegaz" LLC using a K1:KSMG:KA-1 combination adsorbent layer are shown in Table 5.

Table 5

Physicochemical properties of the wet natural gas feedstock at "Shurtanneftegaz" LLC after adsorption dehydration

№	Physicochemical Properties of the Gas		Indicator
1	Chemical composition of natural gas, %	C_1	92,04
		C_2	6,00
		C_3	0,98
		n-C_4	0,12
		i-C_4	0,09
		n-C_5	0,04
		i-C_5	0,03

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		C_{6+} high	0,03
		CO_2	0,05
		H_2S	0,01
		N_2	0,61
2	Density, kg/m^3		0,7258
3	Molecular Mass		17,678
4	Gross Calorific Value under normal conditions, kcal/m^3		9435,4
5	Net Calorific Value under normal conditions, kcal/m^3		8512,1
6	Wobbe Index, kcal/m^3		10944,2
7	Moisture Content, ppm		48,2

As the results in the table above indicate, there is a partial decrease in the content of propane, butane, and liquid hydrocarbons in the dried natural gas. We can also observe that the reduction in the amount of C_{5+} hydrocarbons in the gas, along with the lowering of its dew point, has led to a slight increase in both its higher and lower heating values under normal conditions.

4. CONCLUSIONS.

1. Combination adsorbent layers K1:KA, K1:KSMG, K1:NaA, K1:KSMG:KA-1, and K1:KSMG:KA-2 were developed, and their natural gas dehydration levels were determined. It was demonstrated that the K1:KSMG:KA-1 combination adsorbent layer can reduce the water content in natural gas to 48.2 ppm at a temperature of 28°C and a pressure of 5.5 MPa.

2. The adsorption duration for the K1:KSMG:KA-1 combination adsorbent layer and the individual KA (3Å) zeolite in natural gas dehydration was determined. The research findings showed that the duration of adsorption activity was 12 hours for the K1:KSMG:KA-1 combination adsorbent layer, while it was 7 hours for the KA zeolite.

3. It was proven that by implementing the proposed combination adsorbent layer, the adsorption time can be extended from 6 to 12 hours, and the regeneration process can be reduced by up to two-fold.

4. Based on the results obtained, the operating conditions for applying the recommended K1:KSMG:KA-1 combination adsorbent layer for gas dehydration were developed, involving partial structural modifications to existing adsorbers.

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THERMOCHEMICAL ACTIVATION OF LOCAL NAVBAHOR BENTONITE FOR THE COMBINED COAGULATION–FLOCCULATION–ADSORPTION TREATMENT OF PETROLEUM REFINERY WASTEWATER

Nasiba Kambaralievna Sadikova
Department of Chemistry, Bukhara State University, Bukhara, Uzbekistan
Ruslan Rustamjonovich Khayitov
Department of Oil and Gas Processing Technology, Bukhara State Technical University, Bukhara, Uzbekistan
E-mail: ruslankhayitov7500@gmail.com

Abstract. Petroleum-refinery wastewater is a complex effluent containing oil products, heavy-metal ions, chloride and ammonium species that require multi-stage treatment prior to discharge or reuse. This study reports the development of a low-cost adsorbent from local Navbahor (Navoiy region, Uzbekistan) montmorillonite-rich bentonite through thermal, chemical (HNO_3) and combined thermochemical activation, and its application – together with coagulation and flocculation–to the treatment of real effluent from the Bukhara Oil Refinery. Systematic single-factor experiments (100-1000°C; HNO_3 3-30 wt.%) showed that thermal treatment alone raised the BET surface area from 95 to a maximum of 193 m^2/g at 500 °C, while acid treatment alone raised it to 214 m^2/g at 20% HNO3; beyond these levels dehydroxylation and partial framework collapse reduced performance. Combining 20% HNO_3 activation with subsequent calcination at 500°C produced the most effective adsorbent (MB), with a BET surface area of 284 m^2/g (+199%), total pore volume of 0.438 cm^3/g (+271%) and cation-exchange capacity of 118 mEq/100 g (+34%), confirmed by FTIR, EDXRF and DTA/TG analysis. Batch adsorption data fitted the Langmuir model well (R^2 = 0.980-0.995), giving maximum capacities for MB of 136.8, 107.2, 59.5 and 150.3 mg/g for oil products, Fe^{3+}, Cl^- and NH^{4+}, respectively – 2.8 to 3.9 times higher than for the unmodified clay. A three-stage combined treatment ($Al_2(SO_4)_3$ coagulation, sodium carboxymethylcellulose flocculation, MB adsorption) applied to actual refinery wastewater achieved removal efficiencies of 97.8% (oil products), 95.4% (Fe), 97.1% (suspended solids), 91.2% (NH^{4+}), 88.3% (COD), 78.6% (Cl^-) and 74.5% (total dissolved solids) under optimized conditions (100 mg/L coagulant, 2.5 mg/L flocculant, 5 g/L adsorbent, pH 6.0-7.0, 120 min contact time), bringing all parameters below the regulatory discharge limits. The results demonstrate that thermochemically modified local bentonite is a technically viable and economical substitute for imported adsorbents in petroleum-industry wastewater treatment.

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Keywords: bentonite; thermochemical activation; adsorption isotherm; petroleum refinery wastewater; coagulation-flocculation; Langmuir model.

Аннотация. Сточные воды нефтеперерабатывающих заводов представляют собой сложные сточные воды, содержащие нефтепродукты, ионы тяжелых металлов, хлориды и аммоний, которые требуют многоступенчатой очистки перед сбросом или повторным использованием. В этом исследовании сообщается о разработке недорогого адсорбента из местного бентонита, обогащенного монтмориллонитом, из Навбахора (Навоийская область, Узбекистан) путем термической, химической (HNO3) и комбинированной термохимической активации, и его применении - вместе с коагуляцией и флокуляцией - для очистки реальных сточных вод Бухарского нефтеперерабатывающего завода. Систематические однофакторные эксперименты (100-1000°C; HNO3 3-30 мас.%) показали, что только термическая обработка увеличивала площадь поверхности BET с 95 до максимальной 193 м2/г при 500°C, в то время как только кислотная обработка увеличивала ее до 214 м2/г при 20% HNO3; при превышении этих уровней дегидроксилирование и частичное разрушение каркаса снижали производительность. Сочетание 20%-ной активации HNO3 с последующим прокаливанием при 500°C позволило получить наиболее эффективный адсорбент (MB) с площадью поверхности BET 284 м2/г (+199%), общим объемом пор 0,438 см3/г (+271%) и катионообменной способностью 118 мэкв/100 g (+34%), что подтверждено результатами ИК-спектроскопии, EDXRF-анализа и DTA/TG-анализа. Данные по периодической адсорбции хорошо соответствовали модели Ленгмюра (R2 = 0,980-0,995), что дает максимальную производительность по MB в 136,8, 107,2, 59,5 и 150,3 мг/г для нефтепродуктов, Fe3+, Cl^- и NH4+ соответственно, что в 2,8–3,9 раза выше, чем для немодифицированной глины. Трехступенчатая комбинированная очистка (коагуляция Al2(SO4)3, флокуляция карбоксиметилцеллюлозы натрия, адсорбция MB) сточных вод нефтеперерабатывающего завода позволила достичь эффективности удаления 97,8% (нефтепродуктов), 95,4% (железа), 97,1% (взвешенных веществ), 91,2% (NH4+), 88,3% (ХПК), 78,6% (Cl^-) и 74,5% (общее количество растворенных твердых веществ) при оптимальных условиях (100 мг/л коагулянта, 2,5 мг/л флокулянта, 5 г/л адсорбента, pH 6,0-7,0, время контакта 120 мин), что позволяет снизить все параметры до нормативных пределов расхода. Результаты показывают, что термохимически модифицированный местный бентонит является

ISSN 3030-3907

технически целесообразной и экономичной заменой импортных адсорбентов для очистки сточных вод нефтяной промышленности.

Ключевые слова: бентонит; термохимическая активация; изотерма адсорбции; сточные воды нефтеперерабатывающих заводов; коагуляция-флокуляция; модель Ленгмюра.

Annotatsiya. Neftni qayta ishlash zavodining oqava suvlari neft mahsulotlari, og‘ir metallar ionlari, xlorid va ammoniy turlarini o‘z ichiga olgan murakkab oqava suv bo‘lib, ular oqizishdan oldin yoki qayta ishlatishdan oldin ko‘p bosqichli tozalashni talab qiladi. Ushbu tadqiqot mahalliy Navbahor (Navoiy viloyati, O‘zbekiston) montmorillonitga boy bentonitdan termal, kimyoviy (HNO3) va kombinatsiyalangan termokimyoviy aktivatsiya orqali arzon narxlardagi adsorbentni ishlab chiqish va uni koagulyatsiya va flokulyatsiya bilan birgalikda Buxoro neftni qayta ishlash zavodidan haqiqiy oqava suvlarni tozalash uchun qo‘llash haqida xabar beradi. Tizimli bir omilli tajribalar (100-1000°C; HNO3 3-30 Vt.%) kislota davolash yolg‘iz 95% HNO193 da 2 M500/g uni ko‘tardi esa issiqlik davolash yolg‘iz, 514 m2/g maksimal 3 dan BET yuzasi maydoni ko‘tardi ko‘rsatdi; bu darajadagi dehidroksillanish va qisman kesish buzish tushgan ishlash orqasida. 20% HNO3 aktivatsiyasini 500% da keyingi kalsinatsiya bilan birlashtirib, BET yuzasi 284 m2/g (+199%), umumiy teshik hajmi 0,438 sm3/g (+271%) va kation almashinuvi quvvati 118 mEq / 100 bo‘lgan eng samarali adsorbent (MB) ishlab chiqarildi. ftir, EDXRF va DTA/TG tahlillari tomonidan tasdiqlangan g (+34%). Ommaviy adsorbsion ma'lumotlar Langmuir modelini yaxshi jihozladi (R2 = 0.980-0.995), neft mahsulotlari uchun 136.8, 107.2, 59.5 va 150.3 mg/g MB uchun maksimal quvvat, Fe3 va Cl^- va NH4+ uchun mos ravishda – o‘zgartirilmagan loyga nisbatan 2.8 dan 3.9 baravar yuqori. A uch bosqichli Birlashgan davolash (Al2(SO4)3 ivish, natriy karboksimetilsellyuloza flokulation, MB yutish) 97,8% (neft mahsulotlari), 95,4% (Fe), 97,1% (to‘xtatib qattiq), 91,2% (NH4+), 88,3% (haqiqiy qayta ishlash zavodi chiqindi suv erishilgan ko‘chirish samaradorligi amaliy (Cod), 78,6% (Cl^-) va 74,5% (jami erigan qattiq moddalar) optimallashtirilgan sharoitlarda (100 mg/l koagulyant, 2,5 mg/L flokulyant, 5 g/L adsorbent, pH 6.0-7.0, 120 min aloqa vaqti), barcha parametrlarni tartibga solish razryad chegaralaridan pastga olib keladi. Natijalar shuni ko‘rsatadiki, termokimyoviy modifikatsiyalangan mahalliy bentonit neft sanoati chiqindi suvlarini tozalashda import qilinadigan adsorbentlarning texnik jihatdan foydali va iqtisodiy o‘rnini bosuvchi hisoblanadi.

ISSN 3030-3907

Kalit so‘zlar: bentonit; termokimyoviy faollashuv; adsorbsiya izotermi; neftni qayta ishlash zavodining oqava suvlari; koagulyatsiya-flokulyatsiya; Langmyur modeli.

1. INTRODUCTION.

Protection of water bodies from industrial effluents is among the most pressing environmental problems worldwide, and it is particularly acute for large process industries such as petroleum refining, petrochemistry, textile manufacturing and mining/metallurgy, whose wastewater has a complex and highly variable composition [1-3]. Refinery effluents typically contain free and emulsified oil products, suspended solids, heavy-metal ions (mainly Fe^{2+}/Fe^{3+}), chlorides, ammonium nitrogen and a high chemical oxygen demand (COD), so that a single treatment step is rarely sufficient to meet discharge standards [4,5]. Consequently, the development of complex, energy- and resource-saving treatment schemes that combine coagulation, flocculation and adsorption is of considerable scientific and practical interest.

Among the wide variety of adsorbents used for wastewater purification, natural clay minerals – and bentonite in particular – are attractive because of their wide availability, low cost, high specific surface area, well-developed layered structure and pronounced cation-exchange capacity [6-8]. The adsorption and structural properties of bentonites, as well as approaches to their activation and modification, have been studied extensively by Ozcan, Al-Khalaf, Marey, Zaki, Guo, Unuabonah, Pollard, Usman, Ekwueme, Alaje, Wang, Kormosh and other researchers abroad, and by Akhmedov, Narmetova, Aripov, Turabdjanov, Ikhtiyarova, Umarov, Narzullaeva, Abduraximov, Salikhanova, Eshmetov, Jumayeva and Adizov in Uzbekistan [6-19]. Acid activation (mainly with H2SO4, HCl or HNO_3), thermal (calcination) activation and combined thermochemical treatment are the most common ways of enhancing the specific surface area, pore volume and number of active adsorption sites of raw bentonite [9,10,20-24]. Acid leaching removes exchangeable Ca^{2+}, Mg^{2+} and Na^{+} cations and partially dealuminates the octahedral sheet, opening the interlayer space and developing mesoporosity, while subsequent calcination removes structural water and consolidates the newly formed pore network [20-23,25].

Despite this substantial body of work, two gaps remain. First, the colloid-chemical and textural properties of the alkaline-earth (Ca-Mg) bentonite of the Navbahor deposit (Navoiy region, Uzbekistan) – a large and, so far, only partially studied local raw-material base – have not been systematically compared with imported analogues, nor has a combined thermochemical activation protocol been

ISSN 3030-3907

optimized for this specific clay. Second, most published studies address the removal of a single contaminant class (oil, a given metal ion, or a dye) by a modified bentonite in synthetic solution, whereas real refinery wastewater simultaneously carries oil products, Fe, Cl^-, NH^{4+}, suspended solids and a high COD; a combined coagulation-flocculation-adsorption scheme using a single locally produced modified adsorbent has rarely been reported for such multicomponent effluents [26-31].

The aim of the present work was therefore to develop a technology for producing an efficient adsorbent from local Navbahor bentonite by thermal, chemical and thermochemical modification, and to use this adsorbent – in combination with a coagulant and a flocculant – for the complex treatment of real petroleum-refinery wastewater. The specific objectives were: (i) to characterize the colloid-chemical and textural properties of natural Navbahor bentonite in comparison with other local and foreign clays; (ii) to establish, through single-factor experiments, the optimum conditions of thermal (100-1000°C), chemical (HNO_3, 3-30%) and combined thermochemical modification; (iii) to characterize the resulting adsorbent by FTIR, DTA/TG and EDXRF; (iv) to quantify, through batch experiments and Langmuir/Freundlich isotherm modelling, the adsorption capacity of the modified bentonite towards oil products, Fe^{3+}, Cl^- and NH^{4+}; and (v) to determine the optimum parameters of a combined coagulation-flocculation-adsorption process for real wastewater from the Bukhara Oil Refinery and to compare the resulting effluent quality with regulatory discharge limits.

2. MATERIALS AND METHODS.

2.1. Materials

Natural bentonite clay from the Navbahor deposit (Navoiy region, Republic of Uzbekistan) was used as the raw material. For comparison, samples of Gumbria (Georgia), Kattakurgan, Shorsu, Tamdi-Tau and Cherkassy (Ukraine) bentonites/palygorskite, as well as Tulsakh alkaline-earth bentonite (Fergana region), were used as reference materials. Analytical-grade nitric acid (HNO3, 65%), aluminium sulphate $Al_2(SO_4)_3 \cdot 18H_2O$ (coagulant), sodium salt of carboxymethyl cellulose (Na-CMC, flocculant) and polyacrylamide (PAA) were used as received. The wastewater under study was sampled from the water-and-sewage (VIK) unit of the ‘Bukhara Oil Refinery’ LLC.

2.2. Preparation of thermally, chemically and thermochemically modified bentonite

Raw bentonite was crushed to a particle size below 0.08 mm, dried at 120°C for 5 h, dispersed in distilled water (1:10, w/v) and left to sediment for 24 h at room temperature; the finest (colloidal) fraction was separated by centrifugation (3000 rpm, 5 min), air-dried for 12 h and oven-dried at 75°C for 4 h. For thermal

ISSN 3030-3907

modification, this fraction was calcined in a muffle furnace at temperatures from 100 to 1000°C (step 100°C) for 1-2 h. For chemical modification, the clay was treated with HNO_3 solutions of 3, 5, 10, 15, 20, 25 and 30 wt.% (solid:liquid = 1:3.5) at 80-90°C for 3 h under stirring, then washed repeatedly with distilled water until pH 6.0-6.5 and dried at 65°C for 12 h. For thermochemical (combined) modification, the sample was first activated with 15-20% HNO_3 as above and then calcined at 300, 500 or 700°C for 1-2 h. On the basis of these experiments, the sample obtained with 20% HNO_3 followed by calcination at 500°C was selected as the optimum modified bentonite (denoted MB below); the untreated clay is denoted TB (natural bentonite).

2.3. Characterization methods

The textural properties (specific surface area SBET, total pore volume, pore-size distribution) were determined by low-temperature N_2 adsorption-desorption at 77 K over the relative pressure range 0.05-0.99 on an ASAP-2400 analyser, with the specific surface calculated by the Brunauer-Emmett-Teller (BET) method and the mesopore-size distribution by the Barrett-Joyner-Halenda (BJH) method [32,33]. The granulometric composition was determined by sedimentation analysis (Sabanin-Robinson method) [34]; the swelling of the clays in water at 45°C, the wetting heat and the cation-exchange capacity (CEC, ammonium acetate method) were determined by standard colloid-chemical procedures [34,35]. Functional groups were analysed by Fourier-transform infrared spectroscopy (FTIR) over the range 4000-400 cm^{-1}. Thermal behaviour was studied by derivatography (simultaneous TG/DTG/DTA) on a Shimadzu DTG/DTA instrument under a controlled heating rate in air. Elemental and oxide composition were determined by energy-dispersive X-ray fluorescence spectroscopy (EDXRF) on a Rigaku NEX DE spectrometer operated in air in two measurement modes for a total counting time of 200 s.

2.4. Wastewater sampling and analytical methods

The quality of the raw and treated wastewater was assessed by standard methods used at the analytical laboratory of the refinery and in the present study: pH was measured potentiometrically with a glass electrode (interstate standard GOST ISO 10523-2017, equivalent to ISO 10523:2008); oil-product content was determined by the gravimetric method (Uz DSt 0697:2015, Uz DSt 0791:2019); suspended solids were determined gravimetrically after filtration through a 0.45 μm membrane and drying at 105 °C; total iron was determined photometrically with sulfosalicylic acid (GOST 4011-72, Uz DSt 0706:2016) at 400-430 nm; chloride ion was determined by argentometric titration with $AgNO_3$ (RD 52.24.407-2006); total dissolved solids (dry residue) were determined gravimetrically after evaporation and drying at 105-110°C (GOST 18164-72); and

ISSN 3030-3907

ammonium ion/ammonium nitrogen were determined photometrically after colour development with Nessler's reagent (GOST 23268.10-78). Chemical oxygen demand (COD) was determined by the standard dichromate method.

2.5. Batch adsorption experiments and isotherm modelling

Batch adsorption isotherms were obtained for four target contaminants using both the natural (TB) and the optimum thermochemically modified (MB) bentonite. Oil-product adsorption was studied using a model diesel-fuel/water emulsion (C_0 = 2-100 mg/L) at T = 25 ± 1°C, pH 6.8 ± 0.2, adsorbent dose m = 5 g/L, stirring at 180 rpm, contact time 120 min; the residual oil-product concentration was measured by IR spectroscopy (λ = 3420 nm) after CCl_4 extraction. Fe^{3+} adsorption was studied with a $FeCl_3$ solution (C_0 = 1-100 mg/L) at pH 4.5 (to avoid hydroxide precipitation), m = 3 g/L, contact time 90 min; residual Fe^{3+} was measured by atomic absorption spectroscopy (AAS). Cl^- adsorption was studied with a NaCl solution (C_0 = 10-500 mg/L) at pH 7.0, m = 5 g/L, contact time 60 min; residual Cl^- was measured by argentometric titration. NH^{4+} adsorption was studied with an NH_4Cl solution (C_0 = 5-350 mg/L) at pH 7.0, m = 3 g/L, contact time 120 min; residual NH^{4+} was measured photometrically with Nessler's reagent. Equilibrium data were fitted to the Langmuir ($q_e = q_m K L C_e / (1+KLC_e)$) and Freundlich ($q_e = KFC_e 1/n$) isotherm models by linear regression; the corresponding linear forms $C_e/q_e = f(C_e)$ and $\log q_e = \log KF + (1/n)\cdot \log C_e$ were used to obtain qm, KL, KF, 1/n and the coefficient of determination R^2 for each system.

2.6. Combined coagulation-flocculation-adsorption treatment

The combined treatment of real refinery wastewater was carried out in three consecutive stages: (i) coagulation with $Al_2(SO_4)_3 \cdot 18H_2O$ at 20-140 mg/L; (ii) flocculation with Na-CMC at 0.5-3.5 mg/L (with PAA and $Ca(OH)_2$ (3-5 mL of a 10% solution) used to intensify floc settling); and (iii) adsorption with the thermochemically modified bentonite (MB, particle size 0.2-0.4 μm) at adsorbent doses and contact times optimized in preliminary experiments. Jar-test experiments were performed at T = 25°C over the pH range 5.0-9.0, with settling for 10-15 min prior to sampling of the supernatant for analysis. Colour and turbidity were monitored with a FEK-LF-72M photoelectric colorimeter using a 10 mm standard cuvette and distilled water as the reference.

2.7. Pilot-scale trial and technical-economic evaluation

In addition to the laboratory-scale jar tests, a two-stage pilot trial was carried out directly at the physico-chemical treatment unit of the Bukhara Oil Refinery, in cooperation with the plant's ecology laboratory, to compare the developed MB-based technology with the aluminium-sulphate/polyacrylamide technology currently used on site under identical raw-wastewater conditions. Reagent doses (including an auxiliary $Ca(OH)_2$ addition to promote floc settling) were first tested

ISSN 3030-3907

at an initial level and then adjusted in a second trial to avoid excessive alkalization of the treated water. A preliminary technical-economic evaluation of an industrial-scale production line for the modified bentonite was subsequently performed using standard capital-budgeting indicators (total investment, annual production cost, unit production cost, selling price at a fixed profit margin, annual revenue, net economic effect relative to import substitution, and simple payback period), based on the material and energy balances of the designed process.

3. RESULTS AND DISCUSSION.

3.1. Colloid-chemical characterization of natural Navbahor bentonite

Sedimentation analysis (Sabanin-Robinson method, Table 1) showed that all investigated clays belong to a finely dispersed raw-material class dominated by particles of 1.0-10 μm; the alkaline-earth bentonites contain a larger proportion of the finest (<0.01 mm) fraction than the Cherkassy palygorskite reference, confirming their comparatively lower mechanical strength.

Table 1.

Particle-size distribution of local and foreign natural bentonites

Deposit / clay type	<0.01 mm, %	<0.1 mm, %	<1.0 mm, %
Cherkassy palygorskite (Ukraine, reference)	65.1	31.3	3.6
Tulsakh alkaline-earth bentonite (Fergana region)	71.3	26.0	2.7
Navbahor carbonate alkaline-earth bentonite (Navoiy region)	76.5	21.4	2.1

The specific surface area of the natural Navbahor carbonate alkaline-earth bentonite (286 m^2/g, Table 2) is comparable with, and in some cases exceeds, that of well-known foreign analogues such as the Cherkassy (295 m^2/g) and Gumbria (270 m^2/g) bentonites, indicating that the local raw material is a promising substitute for imported adsorbents even prior to modification.

Table 2.

Specific surface area of local and foreign natural bentonites

Deposit / clay type	Specific surface area, m^2/g
Gumbria bentonite (Georgia), reference	270
KattaqUrg‘on bentonite	155
Shorsu bentonite	170

ISSN 3030-3907

Deposit / clay type	Specific surface area, m^2/g
Tamdi-Tau bentonite	195
Navbahor alkaline bentonite	105
Navbahor alkaline-earth bentonite	110
Cherkassy alkaline-earth bentonite, reference	295
Tulsakh alkaline-earth bentonite	273
Navbahor carbonate alkaline-earth bentonite	286

Chemical analysis (Table 3) confirmed that both the alkaline (AB) and alkaline-earth (AEB) Navbahor bentonite fractions are dominated by SiO_2 and Al_2O_3, consistent with a montmorillonite-based aluminosilicate structure with a general formula $(Na,Ca)_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$; the AEB fraction contains more SiO_2 (61.2%) but less Fe_2O_3 than the AB fraction, while both are relatively rich in exchangeable Ca, Mg and Na oxides, which strongly influence subsequent sorption and processing behaviour.

Table 3.

Chemical (oxide) composition of natural Navbahor bentonite fractions, wt.%

Deposit / clay type	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Other, %
Alkaline bentonite (AB)	57.91	13.69	5.10	1.84	0.48	1.53	1.75	17.7
Alkaline-earth bentonite (AEB)	61.2	15.9	2.3	3.1	3.2	1.1	0.6	12.6

Swelling and wetting-heat measurements (t = 45°C) showed a maximum water uptake of 1.22-1.40 cm^3/g and a wetting heat of 17.3-25.8 kcal/g across the samples studied, with the bound-water content ranging from 8 to 21% depending on clay type; these values, together with textural data obtained by low-temperature N_2 adsorption (SBET = 94.6-96.8 m^2/g, total adsorption volume 0.34-0.38 × 10^{-3} m^3/kg for the natural alkaline and alkaline-earth bentonite, respectively), were noticeably lower than those of standard industrial adsorbents ($S \geq 150$ m^2/g), which justified the subsequent modification study.

3.2. Effect of thermal activation on textural properties

Calcination of Navbahor bentonite over the range 100-1000°C (Table 4, Fig. 1) produced a characteristic bell-shaped dependence of SBET and pore volume on temperature. Below 500°C, progressive loss of physisorbed and interlayer water opens new mesopores and increases the specific surface area from 95 to a

ISSN 3030-3907

maximum of 193 m²/g (pore volume 0.264 cm³/g) at 500°C. Above 600°C, dehydroxylation of the montmorillonite lattice and the onset of structural collapse reduce the surface area; above 900°C, sintering causes pore closure and a sharp decline to 31 m²/g at 1000 °C. The optimum calcination temperature for Navbahor bentonite is therefore 400-500°C, consistent with the general behaviour reported for other smectite clays [20,21].

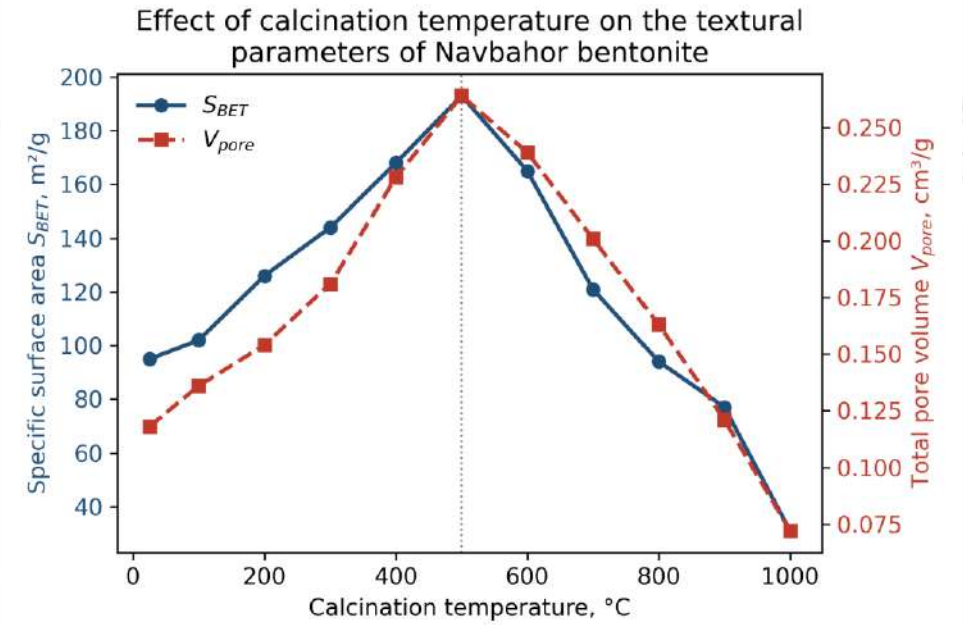


Fig. 1. Effect of calcination temperature on the specific surface area (SBET) and total pore volume of Navbahor bentonite.

Table 4.

Effect of calcination temperature on the textural properties of Navbahor bentonite

Calcination temperature, °C	S_{BET}, m²/g	Total pore volume, cm³/g	Structural state
Raw bentonite	95	0.118	Natural layered structure preserved
100	102	0.136	Onset of physisorbed water release
200	126	0.154	Partial interlayer water release
300	144	0.181	Mesopore development
400	168	0.228	Maximum surface activity

ISSN 3030-3907

Calcination temperature, °C	S_{BET}, m^2/g	Total pore volume, cm^3/g	Structural state
500	193	0.264	Optimal textural parameters
600	165	0.239	Onset of dehydroxylation
700	121	0.201	Partial collapse of crystal structure
800	94	0.163	Increasing amorphous-phase fraction
900	77	0.121	Partial pore closure (sintering onset)
1000	31	0.072	Sintering and structural degradation

3.3. Effect of chemical activation with HNO_3

Acid activation with HNO_3 (3-30%, Table 5, Fig. 2) removes exchangeable Ca^{2+}, Mg^{2+} and Na^+ cations and partially dealuminates the octahedral sheet (Bentonite-Ca + $2HNO_3$ → Bentonite-2H + $Ca(NO_3)_2$), progressively opening the interlayer space. S_{BET} increased monotonically from 95 m^2/g (raw) to a maximum of 214 m^2/g at 20% HNO_3 (pore volume 0.347 cm^3/g, mesopore fraction 85%). At 25-30% HNO_3, however, excessive acid attack caused partial collapse of the montmorillonite framework, closing some pores and reducing the surface area to 149-186 m^2/g. The optimum HNO_3 concentration for chemical activation of Navbahor bentonite was therefore taken as 15-20%.

ISSN 3030-3907

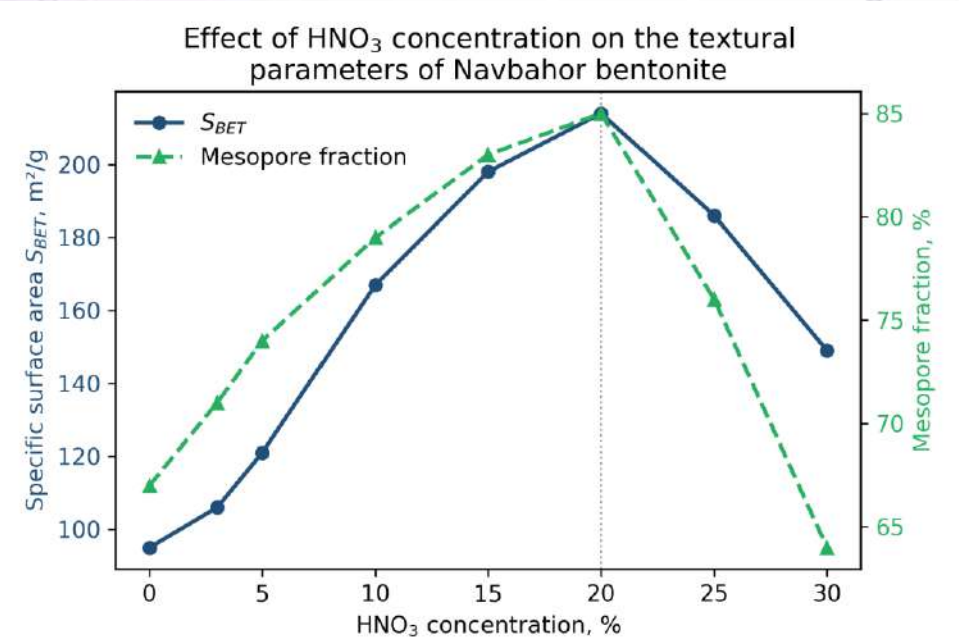


Fig. 2. Effect of HNO_3 concentration on the specific surface area and mesopore fraction of Navbahor bentonite

Table 5.

Effect of HNO_3 concentration on the textural properties of Navbahor bentonite

HNO_3 concentration, %	S_{BET}, m^2/g	Total pore volume, cm^3/g	Average pore diameter, nm	Mesopore fraction, %
0 (raw)	95	0.118	6.8	67
3	106	0.158	7.3	71
5	121	0.204	8.0	74
10	167	0.276	9.1	79
15	198	0.318	10.0	83
20	214	0.347	10.8	85
25	186	0.291	11.9	76
30	149	0.228	13.5	64

3.4. Thermochemical (combined) modification: optimum conditions

Combining chemical and thermal activation gave a markedly greater improvement in textural properties than either treatment alone (Table 6, Fig. 3). The sample activated with 20% HNO_3 and subsequently calcined at 500°C (denoted MB) exhibited the best overall performance: SBET = 284 m^2/g (a 2.99-fold increase relative to raw bentonite), total pore volume = 0.438 cm^3/g (3.71-fold increase) and a mesopore fraction of 91%. Complementary titration confirmed an

ISSN 3030-3907

increase in cation-exchange capacity from 88 to 118 mEq/100 g. These improvements are attributed to the synergistic combination of (i) an acid stage that removes octahedral Al^{3+}/Mg^{2+} and generates coordinatively unsaturated sites, and (ii) a thermal stage that removes structural water, opens new micro- and mesopores and strengthens the Si-O-Si framework, together widening the interlayer space available for ion exchange and molecular adsorption.

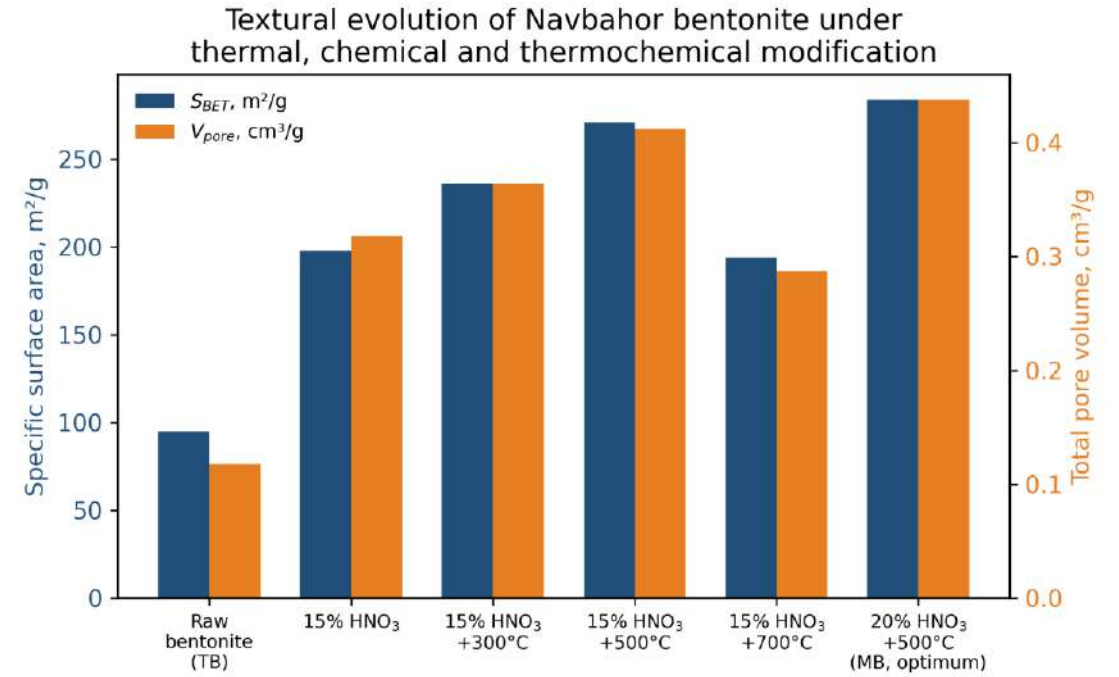


Fig. 3. Textural evolution of Navbahor bentonite under thermal, chemical and combined thermochemical modification.

Table 6.

Textural parameters of Navbahor bentonite modified by different thermochemical protocols

Modification condition	S_{BET}, m^2/g	Total pore volume, cm^3/g	Mesopore fraction, %	Average pore diameter, nm
Raw bentonite (TB)	95	0.118	67	6.8
15% HNO_3	198	0.318	83	10.0
15% HNO_3 + 300°C	236	0.364	86	11.2
15% HNO_3 + 500°C	271	0.412	89	12.4
15% HNO_3 + 700°C	194	0.287	73	14.8
20% HNO_3 + 500°C (MB, optimum)	284	0.438	91	13.1

ISSN 3030-3907

The pore-size distribution obtained from the same N_2 adsorption-desorption data (BJH method) clarifies the mechanism behind this optimum (Table 6a). As the calcination temperature rises from ambient to 500°C, the micropore fraction (<2 nm) increases steadily from 18% to 31% and the mesopore fraction (2-50 nm) remains dominant (64-70%), while the macropore fraction (>50 nm) falls to a minimum of about 5%, reflecting progressive opening of fine porosity without loss of the mesoporous framework. Above 600°C, this trend reverses sharply: the micropore fraction collapses to 16% at 800°C while the macropore fraction rises to 33%, consistent with pore coalescence and the onset of sintering identified in Table 4, and confirming that 400-500°C is the thermodynamically and texturally optimal calcination window for this clay.

Table 6a.

Temperature dependence of the micro-, meso- and macropore fractions of Navbahor bentonite (BJH analysis)

Temperature, °C	Micropores <2 nm, %	Mesopores 2-50 nm, %	Macropores >50 nm, %
Raw bentonite	18	67	15
100	20	68	12
200	23	70	7
300	26	69	5
400	29	66	5
500	31	64	5
600	27	61	12
700	22	57	21
800	16	51	33

3.5. Structural characterization of the modified bentonite (FTIR, DTA/TG, EDXRF)

FTIR spectra of the natural bentonite showed characteristic bands at 507-455 cm^{-1} (Si-O-Al / Al-O-Si framework vibrations), 536 and 526 cm^{-1} (Si-O-Al and Al-O-Si bonds typical of montmorillonite), 476 and 445 cm^{-1} (Fe-O and Al-O bonds) and 795-780 cm^{-1} (quartz impurity), confirming a montmorillonite-dominated aluminosilicate structure. After thermochemical modification, the Si-O-Si silicate framework was preserved (1000-1050 cm^{-1}), while the intensity of the Al-Al-OH deformation band at 914 cm^{-1} decreased, indicating partial

ISSN 3030-3907

dealumination and dehydroxylation; the persistence of the 794.7 cm^{-1} quartz band confirmed the stability of the silica phase throughout the treatment.

Derivatographic (TG/DTG/DTA) analysis of the natural bentonite showed a small mass loss at 50-150°C (loss of physisorbed water), minor effects at 200-400°C (loss of cation-bound water and decomposition of organic impurities) and a pronounced mass loss at 500-700°C corresponding to dehydroxylation of structural OH groups. In the thermochemically modified sample, the low-temperature mass loss (100-200°C) was larger, consistent with the higher hydrophilicity and porosity generated by acid activation, while the dehydroxylation step (500-650°C) was more intense, reflecting the larger number of reactive functional groups introduced by the combined treatment.

EDXRF analysis (Table 7) confirmed a progressive increase in the relative SiO_2 content, from 57.9% in the raw clay to 70.4% after treatment with 20% HNO_3, accompanied by a decrease in Al_2O_3 (16.4 → 12.5%), Fe_2O_3 (5.8 → 3.7%), MgO (3.1 → 1.1%), CaO (2.8 → 0.4%) and Na_2O (2.6 → 0.3%). Magnesium fell below the detection limit after modification, confirming near-complete removal of Mg^{2+} from the octahedral sheet – a hallmark of effective acid activation. These compositional changes are fully consistent with the FTIR and textural results and confirm that the thermochemically modified Navbahor bentonite is a high-silica, mesoporous aluminosilicate adsorbent with a substantially enlarged number of surface-active sites.

Table 7.

Change in the chemical composition of Navbahor bentonite during chemical (HNO_3) modification, wt.%

Component, %	Raw bentonite	5% HNO_3	15% HNO_3	20% HNO_3
SiO_2	57.9	60.4	66.8	70.4
Al_2O_3	16.4	15.1	13.2	12.5
Fe_2O_3	5.8	5.1	4.2	3.7
MgO	3.1	2.4	1.6	1.1
CaO	2.8	1.9	0.9	0.4
Na_2O	2.6	1.7	0.8	0.3
K_2O	1.5	1.3	1.0	0.8

3.6. Adsorption isotherms and mechanism for oil products, Fe^{3+}, Cl^- and NH^{4+}

Batch equilibrium data for all four contaminants were well described by the Langmuir model (R^2 = 0.980-0.995), indicating predominantly monolayer

ISSN 3030-3907

adsorption on energetically near-uniform sites, while the Freundlich model also gave a satisfactory fit (R^2 = 0.958-0.988) with 1/n < 1 in every case, confirming favourable adsorption on a moderately heterogeneous surface (Table 8, Fig. 4). Thermochemical modification increased the maximum Langmuir capacity (qm) by factors of 3.9 (oil products, 35.2 → 136.8 mg/g), 2.8 (Fe3+, 38.5 → 107.2 mg/g), 3.9 (Cl^-, 15.4 → 59.5 mg/g) and 3.2 (NH^{4+}, 47.6 → 150.3 mg/g); the corresponding Freundlich KF values increased 3.9-5.9-fold, providing independent confirmation of the enhanced adsorption capacity.

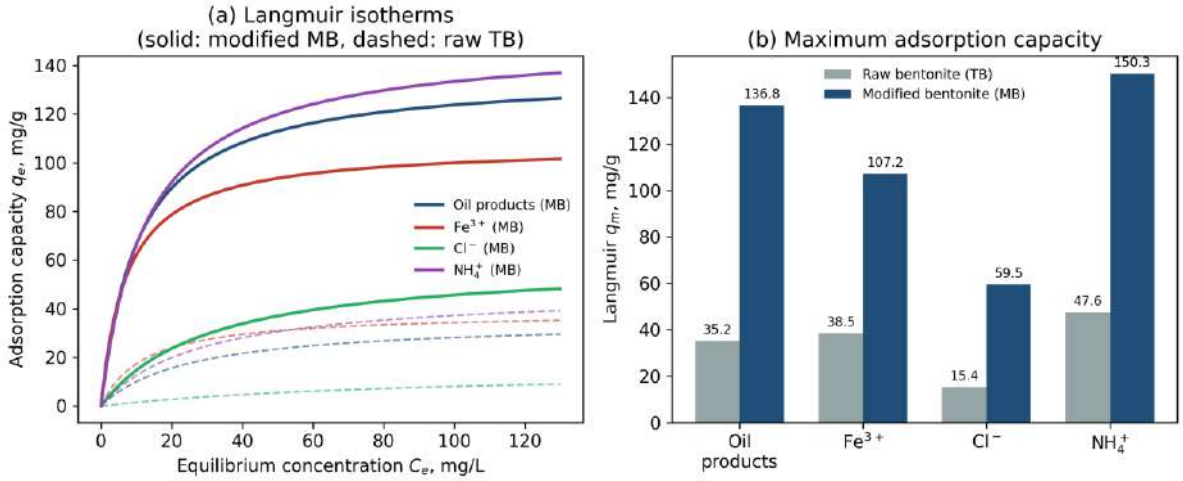


Fig. 4. (a) Langmuir isotherms of oil products, Fe^{3+}, Cl^- and NH^{4+} on raw (TB, dashed) and thermochemically modified (MB, solid) Navbahor bentonite; (b) comparison of the Langmuir maximum adsorption capacities.

Table 8.

Langmuir and Freundlich isotherm parameters for oil products, Fe^{3+}, Cl^- and NH^{4+} on raw (TB) and modified (MB) Navbahor bentonite

Adsorbate	Sample	q_m, mg/g	KL, L/mg	R^2 (Langmuir)	KF, mg/g	R^2 (Freundlich)
Oil products	TB	35.2	0.040	0.985	4.85	0.962
Oil products	MB	136.8	0.095	0.994	27.50	0.981
Fe^{3+}	TB	38.5	0.082	0.989	7.65	0.974
Fe^{3+}	MB	107.2	0.138	0.995	29.80	0.986
Cl^-	TB	15.4	0.011	0.980	1.38	0.958
Cl^-	MB	59.5	0.033	0.992	8.15	0.981
NH^{4+}	TB	47.6	0.036	0.987	8.12	0.969

ISSN 3030-3907

Adsorbate	Sample	q_m, mg/g	KL, L/mg	R^2 (Langmuir)	KF, mg/g	R^2 (Freundlich)
NH^{4+}	MB	150.3	0.079	0.995	33.40	0.988

The mechanistic origin of these improvements differs somewhat between adsorbates. Oil-product uptake is governed largely by hydrophobic interactions with the Si-OH groups generated during acid activation and by physical entrapment within the newly developed micro- and mesopores, which provide additional access channels for hydrocarbon molecules [26,27]. Fe^{3+} removal proceeds mainly by cation exchange and coordination at the unsaturated sites left by Al^{3+} removal from the octahedral sheet, which is consistent with the measured qm for raw bentonite (38.5 mg/g) closely matching a literature value of 37.7 mg/g for a comparable untreated clay [28]. Cl^- adsorption on the naturally cation-selective bentonite surface is intrinsically limited, but protonation of newly formed Al-OH and Si-OH groups on MB to $Al\text{-}OH^{2+}$ and $Si\text{-}OH^{2+}$ generates positively charged sites capable of electrostatically binding Cl^- [29,30]. Finally, NH^{4+}, with an ionic radius (1.48 Å) close to that of Na^+ (1.02 Å) and a matching valence, is readily exchanged into the expanded montmorillonite interlayer space, and its 3.2-fold capacity increase closely tracks the 34% increase in cation-exchange capacity (88 → 118 mEq/100 g) measured for MB [31].

3.7. Combined coagulation-flocculation-adsorption treatment of real refinery wastewater

The raw wastewater sampled from the Bukhara Oil Refinery (Table 9, influent column) exceeded regulatory limits for nearly every parameter measured (oil products, suspended solids, total iron, chloride, TDS and ammonium), confirming the need for a multi-stage treatment scheme. In the coagulation stage, increasing the $Al_2(SO_4)_3$ dose from 20 to 100 mg/L raised the removal of suspended solids from 48.5% to 92.3% (Fig. 5); above 100 mg/L, efficiency decreased slightly owing to charge reversal (restabilization) of the colloidal particles, so 100 mg/L was selected as the optimum coagulant dose.

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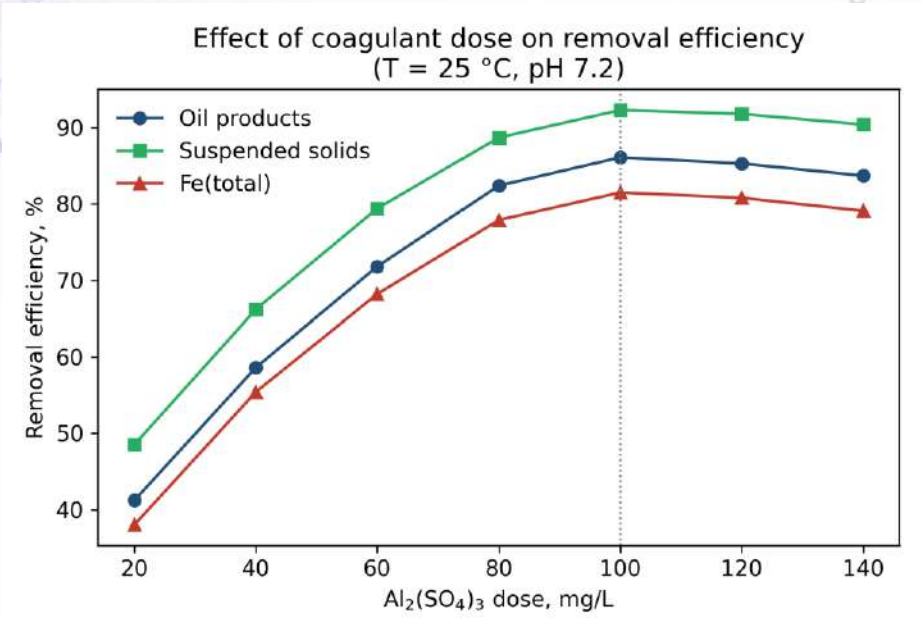


Fig. 5. Effect of coagulant ($Al_2(SO_4)_3$) dose on the removal efficiency of oil products, suspended solids and total iron (T = 25°C, pH 7.2).

In the flocculation stage, the optimum Na-CMC dose was found to be 2.5 mg/L, beyond which floc size and settling rate no longer improved; the settling rate of the flocs increased with temperature over 293-323 K and was strongly pH-dependent, reaching a maximum increase of 67-73% under alkaline conditions. In the adsorption stage, an MB dose of 5 g/L and a contact time of 120 min were found sufficient to bring the residual concentrations of dissolved contaminants close to their equilibrium (isotherm-predicted) values, and the optimum pH range for the overall process was 6.0-7.0.

Under these optimized conditions (100 mg/L coagulant, 2.5 mg/L flocculant, 5 g/L MB adsorbent, pH 6.0-7.0, 120 min contact), the combined three-stage treatment reduced all measured parameters below the regulatory discharge limits (Table 9, Fig. 6): oil products from 86.4 to 1.9 mg/L (97.8% removal), total iron from 12.8 to 0.59 mg/L (95.4%), suspended solids from 420 to 12 mg/L (97.1%), ammonium from 48.5 to 4.3 mg/L (91.2%), COD from 1180 to 138 mg/L (88.3%), chloride from 640 to 137 mg/L (78.6%) and TDS from 3850 to 980 mg/L (74.5%).

Table 9.

Composition of raw and treated wastewater after the combined coagulation-flocculation-adsorption process

Parameter	Influent, mg/L	Effluent, mg/L	Discharge limit, mg/L	Removal, %
Oil products	86.4	1.9	≤ 5.0	97.8
Total iron	12.8	0.59	≤ 0.3-1.0	95.4

ISSN 3030-3907

Parameter	Influent, mg/L	Effluent, mg/L	Discharge limit, mg/L	Removal, %
Chloride (Cl^-)	640	137	≤ 250	78.6
Ammonium (NH^{4+})	48.5	4.3	≤ 5.0	91.2
Suspended solids	420	12	≤ 15	97.1
Total dissolved solids	3850	980	≤ 1000	74.5
COD	1180	138	≤ 150	88.3
pH	7.8	7.2	6.5-8.5	–

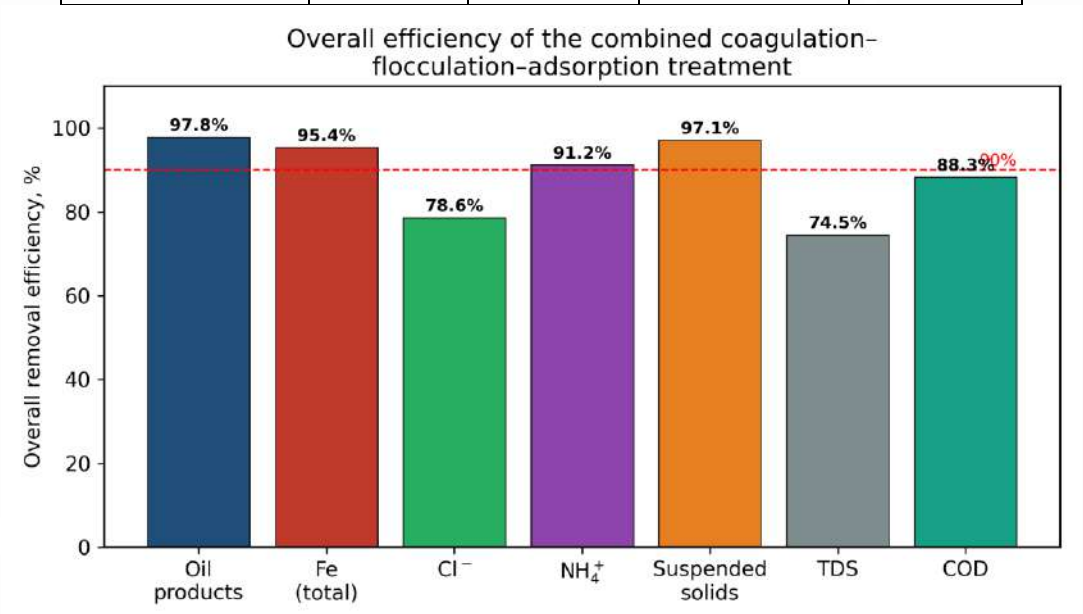


Fig. 6. Overall removal efficiency of the combined coagulation-flocculation-adsorption treatment for each monitored parameter.

The comparatively lower removal of chloride (78.6%) and TDS (74.5%) reflects the intrinsically limited capacity of an aluminosilicate adsorbent for highly soluble, non-specifically adsorbed ions, which are removed mainly through electrostatic interaction with protonated surface groups rather than through the stronger cation-exchange and coordination mechanisms available to Fe^{3+} and NH^{4+}; nonetheless, both parameters were brought within their respective regulatory limits. The synergy between the three stages is noteworthy: coagulation and flocculation remove the bulk of the colloidal load and free/emulsified oil before the water reaches the adsorption stage, which prevents premature pore blockage of the

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bentonite and preserves its adsorption capacity for the dissolved ionic contaminants (Fe^{3+}, Cl^{-}, NH^{4+}), so that the efficiency of the combined process exceeds what would be expected from the individual stages applied separately.

3.8. Comparison with the literature and practical significance

The maximum adsorption capacities obtained for thermochemically modified Navbahor bentonite (136.8 mg/g for oil products, 107.2 mg/g for Fe^{3+}) are comparable with, or exceed, values reported for magnetically modified and carbon-combined bentonite adsorbents used for diesel-oil and heavy-metal removal in other studies [26-30], while requiring only a simple, two-stage acid-thermal protocol and no imported reagents other than technical-grade nitric acid, which is manufactured domestically. Given that the specific surface area of raw Navbahor bentonite already approaches that of imported reference clays (Table 2), and that thermochemical modification nearly triples this value while more than tripling the pore volume, the developed technology offers a resource-efficient route to replacing imported sorbents in the petroleum-refining industry with a Uzbekistan-sourced alternative, consistent with recent industrial-development priorities in the country [36,37].

3.9. Pilot-scale validation at the Bukhara Oil Refinery

To verify that the laboratory-scale results translate into a real industrial setting, the modified bentonite (MB) was tested directly at the physico-chemical treatment unit of the Bukhara Oil Refinery, in cooperation with the plant's ecology laboratory. Mechanically pre-treated wastewater was split into parallel streams: (i) a control (no reagent), (ii) the technology currently used at the plant (aluminium sulphate coagulant with polyacrylamide flocculant) and (iii) the newly developed technology (MB adsorbent with Na-CMC flocculant and a small dose of $Ca(OH)_2$ to promote settling). In a first trial, an excessive $Ca(OH)_2$ dose raised the pH of the treated water to 9.5-10, which is unfavourable for the downstream biological treatment stage; the lime dose was therefore reduced from 40 to 10 mL of a 10% solution in a second trial, stabilizing the pH at about 7.5 without loss of treatment performance.

Under the optimized second-trial conditions, the MB-based technology consistently outperformed the plant's existing aluminium-sulphate technology on identical raw wastewater (Table 10): the residual oil-product concentration was reduced to 6.4 mg/L versus 8.4 mg/L for the existing technology (a 23.8% relative improvement), suspended solids to 33.3 mg/L versus 58.0 mg/L (42.6% improvement), and total iron to 2.0 mg/L versus 2.5 mg/L (20% improvement); chloride and total dissolved solids were also reduced further, although by smaller margins (12.8% and 0.2%, respectively), consistent with the comparatively limited affinity of an aluminosilicate adsorbent for these highly soluble species discussed

ISSN 3030-3907

in Section 3.6. Flocs formed with the MB-based reagent system settled faster and produced a denser, more compact sludge than those formed with the conventional coagulant, and the clarified water showed noticeably improved transparency.

Table 10.

Comparison of the existing ($Al_2(SO_4)_3$-based) and newly developed (MB-based) treatment technologies on real Bukhara Oil Refinery wastewater (second-stage pilot trial)

Parameter	Raw wastewater	Existing technology	MB-based technology	Additional improvement
Oil products, mg/L	22.8	8.4	6.4	23.8%
Suspended solids, mg/L	61.7	58.0	33.3	42.6%
Total iron, mg/L	3.2	2.5	2.0	20.0%
Chloride, mg/L	607	601	524	12.8%
Total dissolved solids, mg/L	1828	1788	1784	0.2%

These pilot-scale results confirm that the advantages of thermochemically modified Navbahor bentonite observed in controlled batch experiments (Sections 3.6-3.7) are reproducible under real operating conditions with actual, highly variable refinery wastewater, and that the reagent dosing (including the auxiliary lime dose used to promote settling) can be tuned to avoid an excessively alkaline effluent that would otherwise compromise subsequent biological treatment. Before full industrial implementation, continuous pilot-plant trials and complete monitoring of biochemical oxygen demand (BOD), COD, heavy metals and other regulated parameters are recommended.

4. INDUSTRIAL-SCALE PRODUCTION TECHNOLOGY AND ECONOMIC EVALUATION

4.1. Process design and optimized production parameters

On the basis of the single-factor optimization described in Sections 3.2-3.4, a two-stage production technology for thermochemically modified bentonite was designed for direct integration into the wastewater-treatment system of the Bukhara Oil Refinery. In the first (chemical) stage, natural Navbahor bentonite reacts with

ISSN 3030-3907

a 20% HNO_3 solution (solid:liquid = 1:3.5) at 80-90°C for 4 h, during which part of the structural Al, Fe and Mg oxides pass into solution, exchangeable cations are released, and new silanol (≡Si-OH) and aluminol (≡Al-OH) surface groups are formed – the same functional groups identified by FTIR (Section 3.5) as primary adsorption sites for heavy-metal ions, ammonium and oil-product molecules. The acid-treated slurry is filtered and washed with process water in several steps until the filtrate reaches pH 6.0-6.5, ensuring complete removal of residual HNO_3 and dissolved metal nitrates and providing a stable feed for the subsequent thermal stage. In the second (thermal) stage, the washed cake is pre-dried at 15°C to reduce moisture from 40-42% to 8-10%, and then calcined in a rotary kiln at 500°C for 45-60 min, which removes adsorbed and structural water, widens the interlayer spacing and substantially develops the mesopore network, consistent with the textural evolution reported in Table 6. The finished product is cooled, milled and classified to a working particle size of 0.1-2 mm before packaging.

Table 11.

Optimized parameters of the industrial-scale thermochemical modification process

Parameter	Selected value
HNO_3 concentration	20%
Chemical activation temperature	80-90°C
Chemical activation time	4 h
Solid:liquid ratio	1:3.5
Final wash-water pH	6.0-6.5
Pre-drying temperature	150°C
Calcination (thermal activation) temperature	500°C
Calcination time	45-60 min
Finished-product moisture content	≤ 2%

The plant-integrated process flow comprises eleven principal unit operations: a receiving and storage hopper for raw bentonite (B-1); an acid-preparation reactor for the 20% HNO_3 working solution (R-1); a process-water storage tank (H-1); the acid-activation reactor (R-2), in which Al_2O_3, Fe_2O_3 and MgO are partially dissolved; a first filter press (F-1) separating the acid filtrate (recycled or neutralized) from the wet cake; a washing tank (J-1) that removes residual acid and dissolved metal nitrates; a second filter press (F-2); a rotary drum

ISSN 3030-3907

dryer (Q-1) reducing moisture from about 40% to 8-10%; a rotary calcination kiln (P-1, together with a hot-air generator) operating at 400-500°C, where thermal activation develops the adsorption centres and mesoporous structure; a cooler (S-1) that lowers the product temperature from 400-500°C to 40-50°C prior to size reduction; a final crusher (D-2) and classifier (K-1) that produce a uniform 0.1-2 mm working fraction (oversize particles being recycled to the crusher); and a dosing/packaging unit (U-1, 25 kg polypropylene bags or big-bags) feeding the finished-product warehouse (O-1). This modular scheme allows the technology to be readily scaled beyond the pilot capacity described below, using the same unit operations at larger throughput.

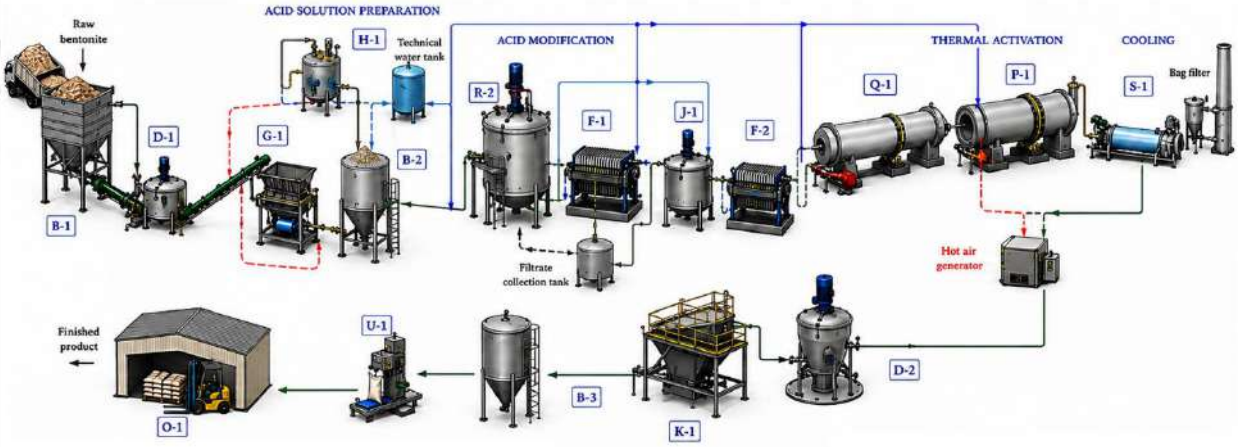


Fig. 7. Process flow diagram of the proposed industrial-scale production line for thermochemically modified Navbahor bentonite. Equipment codes: *B-1 – raw-bentonite receiving/storage hopper; D-1 – primary crusher; G-1 – vibrating screen; E-1 – belt conveyor; B-2 – intermediate (buffer) hopper; R-1 – 20% HNO_3 solution-preparation reactor; H-1 – process-water tank; R-2 – acid-activation reactor; F-1, F-2 – first/second-stage filter presses; T-1 – filtrate collection tank; J-1 – washing tank; N-1 – neutralization tank; Q-1 – rotary drum dryer; HG-1 – hot-air generator; P-1 – rotary calcination kiln; S-1 – cooler; CY-1 – cyclone; MF-1 – fabric filter; EX-1 – aspiration fan; CH-1 – stack; D-2 – final crusher; K-1 – vibrating classifier (0.1-2 mm); K-3 – elevator/conveyor; B-3 – finished-product hopper; U-1 – dosing/packaging unit; O-1 – finished-product warehouse.*

4.2. Production capacity and material balance

The required adsorbent dose was set at 5 g/m^3 (5 mg/L) of treated wastewater, in line with the optimum adsorption-stage parameters established in Section 3.7. Given an average wastewater flow of 1300 m^3/day at the Bukhara Oil Refinery, the daily and annual adsorbent demand were calculated as Qads = 1300 × 1000 × 5 = 6,500,000 mg/day = 6.5 kg/day, i.e. 6.5 × 365 = 2372.5 kg/year ≈ 2.37 t/year. This modest but continuous demand defines the design capacity of the

ISSN 3030-3907

proposed production line and confirms that a compact, low-capital installation is sufficient to fully cover the plant's own adsorbent requirement from local raw material.

The corresponding annual material balance (Table 12) shows that production of 2.37 t/year of finished modified bentonite requires 6.07 t of raw bentonite (12% moisture), 5.58 t of concentrated (65%) HNO_3, 12.55 t of dilution water and 18.13 t of wash water as principal inputs, with acid filtrate (14.50 t, containing HNO_3 and dissolved metal salts), wash filtrate (18.60 t), evaporated moisture (1.45 t), thermal off-gases (H_2O, CO_2, NO_x; 0.27 t) and dust/mechanical losses (5.14 t) as the principal outputs, closing at 42.33 t of total annual throughput on both sides of the balance.

Table 12.

Annual material balance of the thermochemically modified bentonite production line (design capacity 2.37 t/year)

Stream	Input, t/year	Output, t/year
Raw bentonite (12% moisture)	6.07	–
Concentrated HNO_3 (65%)	5.58	–
Dilution water	12.55	–
Wash water	18.13	–
Finished modified bentonite	–	2.37
Acid filtrate (HNO_3 + metal salts)	–	14.50
Wash filtrate	–	18.60
Evaporated moisture (drying)	–	1.45
Thermal off-gases (H_2O, CO_2, NO_x)	–	0.27
Dust and mechanical losses	–	5.14
Total	42.33	42.33

4.3. Economic evaluation

A preliminary technical-economic assessment was carried out for the designed production line (Table 13). At the design capacity of 2.37 t/year, operating 365 days/year with a workforce of four, and consuming 111,000 kWh/year of electricity, 16,000 m^3/year of natural gas and 30 m3/year of process water, the total investment (equipment, buildings/infrastructure and installation) was estimated at 3570.5 million UZS, and the annual production cost – comprising raw materials, utilities, wages, social contributions, depreciation (6%), maintenance and

ISSN 3030-3907

packaging – at 897.32 million UZS, giving a unit production cost of about 378.62 million UZS per tonne. At an assumed 20% profit margin, the corresponding selling price is 454.34 million UZS/t, yielding an annual revenue of 1076.79 million UZS for the full 2.37 t/year output.

Table 13.

Technical-economic indicators of the proposed thermochemically modified bentonite production line

Indicator	Value
Production capacity	2.37 t/year
Total investment	3570.5 million UZS
Annual production cost	897.32 million UZS
Unit production cost	378.62 million UZS/t
Selling price (20% margin)	454.34 million UZS/t
Annual revenue	1076.79 million UZS
Cost of equivalent imported adsorbent (~850 million UZS/t)	2014.50 million UZS
Net annual economic benefit vs. import substitution	937.71 million UZS
Profitability	20%
Payback period	≈ 3.8 years

The economic benefit of the proposed technology becomes particularly clear when compared with the cost of importing an equivalent quantity of organo-modified bentonite adsorbent, conservatively priced at about 850 million UZS/t on the current market, which would cost the enterprise approximately 2014.50 million UZS/year for the same 2.37 t. Substituting this import with locally produced, thermochemically modified Navbahor bentonite is therefore estimated to generate a net annual economic effect of about 937.71 million UZS, with the initial investment recovered within approximately 3.8 years at the stated 20% profitability. Beyond the direct cost saving, import substitution also reduces the enterprise's exposure to currency and supply-chain risk and makes productive use of an abundant domestic mineral resource, in line with the national strategy of expanding domestic innovation-driven industrial capacity referenced in Section 1.

5. CONCLUSIONS.

Systematic thermal, chemical and thermochemical activation of natural Navbahor bentonite established that: (i) calcination alone develops an optimum

ISSN 3030-3907

textural structure at 500°C (SBET = 193 m^2/g, pore volume 0.264 cm^3/g); (ii) acid activation alone reaches an optimum at 20% HNO3 (SBET = 214 m^2/g, pore volume 0.347 cm^3/g); and (iii) combining 20% HNO3 activation with subsequent calcination at 500°C produces a substantially more effective adsorbent (MB), with SBET = 284 m^2/g (2.99-fold increase), total pore volume = 0.438 cm^3/g (3.71-fold increase), mesopore fraction of 91% and cation-exchange capacity increased from 88 to 118 mEq/100 g, confirmed by FTIR, DTA/TG and EDXRF analysis showing progressive dealumination, dehydroxylation and enrichment of the silica framework.

Batch adsorption experiments fitted the Langmuir model well (R^2 = 0.980-0.995) and showed that thermochemical modification increased the maximum adsorption capacity by 2.8-3.9-fold for oil products (136.8 mg/g), Fe^{3+} (107.2 mg/g), Cl^- (59.5 mg/g) and NH^{4+} (150.3 mg/g) relative to the untreated clay, with the improvements explained by a combination of hydrophobic interaction, cation exchange, coordination at dealuminated sites and electrostatic interaction with protonated surface groups, depending on the adsorbate.

A three-stage combined coagulation ($Al_2(SO_4)_3$, 100 mg/L) - flocculation (Na-CMC, 2.5 mg/L) - adsorption (modified bentonite, 5 g/L, 120 min, pH 6.0-7.0) process applied to real Bukhara Oil Refinery wastewater achieved removal efficiencies of 97.8% (oil products), 97.1% (suspended solids), 95.4% (iron), 91.2% (ammonium), 88.3% (COD), 78.6% (chloride) and 74.5% (total dissolved solids), bringing every monitored parameter below the applicable regulatory discharge limits. Independent pilot-scale trials conducted directly at the refinery's treatment unit confirmed that the modified-bentonite technology outperformed the plant's existing aluminium-sulphate-based process by 23.8% (oil products), 42.6% (suspended solids) and 20% (iron), while allowing the process pH to be stabilized at about 7.5, a favourable condition for the downstream biological treatment stage.

A complete production technology was designed around these optimized parameters, comprising acid activation, filtration/washing, drying, rotary-kiln calcination, cooling, milling, classification and packaging. For the Bukhara Oil Refinery (wastewater flow 1300 m^3/day, adsorbent dose 5 g/m^3), the required production capacity is 2.37 t/year, achievable with a total investment of about 3570.5 million UZS and an annual production cost of about 897.32 million UZS. Replacing an equivalent quantity of imported organo-modified bentonite (estimated cost 2014.50 million UZS/year) with the locally produced adsorbent yields an estimated net annual economic benefit of 937.71 million UZS at 20% profitability, with a payback period of approximately 3.8 years.

Taken together, these results demonstrate that thermochemically activated local Navbahor bentonite is a technically effective, low-cost, and environmentally

ISSN 3030-3907

and economically sound substitute for imported adsorbents in the treatment of complex petroleum-refinery wastewater, and provide both the scientific and the engineering-economic basis needed to scale up the developed technology to full industrial application.

Author contributions

Conceptualization and methodology: N.K. Sadikova, R.R. Khayitov; investigation and formal analysis: N.K. Sadikova; supervision: R.R. Khayitov; writing – original draft: N.K. Sadikova; writing – review and editing: N.K. Sadikova, R.R. Khayitov. All authors have read and agreed to the published version of the manuscript.

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Data availability

The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare no conflict of interest.

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VALORIZATION OF WASTE HEAVY HEXANE FRACTION FROM POLYETHYLENE PRODUCTION INTO OCTANE-BOOSTING ADDITIVES FOR AUTOMOTIVE GASOLINE: SYNTHESIS, PHYSICOCHEMICAL CHARACTERIZATION, AND TECHNO-ECONOMIC EVALUATION

Hasan Rahmatovich Abdulloyev
Bukhara State Technical University, Q. Murtazayev str. 15, 200100 Bukhara, Uzbekistan
E-mail: abdulloyev.hr@buxdti.uz
Nodir Shavkatovich Panoyev
Bukhara State Technical University, Q. Murtazayev str. 15, 200100 Bukhara, Uzbekistan
Jasur Alijonovich Safarov
Bukhara State Technical University, Q. Murtazayev str. 15, 200100 Bukhara, Uzbekistan
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Abstract. The polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture generates, as a technological residue, a waste heavy hexane fraction that is currently disposed of without added value and poses an environmental hazard. This work reports the conversion of this waste stream into octane-boosting additives for automotive gasoline through fractional distillation followed by catalytic oxidation, isomerization, alkylation, and esterification. Waste heavy hexane was separated into three temperature cuts (84–180, 180–220 and 220–247 °C) using an ARNS-1E fractionating unit, and each cut was characterized by gas chromatography–mass spectrometry (GC-MS, Agilent 5975C/7890A), which revealed a hydrocarbon group composition of 95.63 % paraffins, 0.96 % olefins, 0.35 % naphthenes and 3.07 % arenes, with individual components ranging from C_6 to C_{30}. Density, refractive index, kinematic viscosity, molecular weight and pour point increased monotonically with the boiling range of the fraction (density 708.3–740.9 kg/m³; kinematic viscosity 0.8423–1.6001 mm²/s; molecular weight 109.3–139.8 g/mol). Catalytic treatment of the three fractions with a $K_2Cr_2O_7$–H_2SO_4 oxidizing system over a Pt/Al_2O_3 catalyst (150–200 °C, 0.5–3 MPa, 90–180 min) produced three oxygenated additives, denoted E1, E2 and E3, with research octane numbers (RON) of 95, 97 and 99, respectively; Fourier-transform infrared (FT-IR) spectroscopy confirmed the appearance of carbonyl (1647–1750 cm^{-1}) and hydroxyl (3566–3736 cm^{-1}) absorption bands consistent with the formation of alcohols, ketones and ethers. Blending E1–E3 into AI-85 automotive gasoline at 5, 10 and 15 wt % raised the octane number from 85 up to 96.8 (motor method), the largest gain (11.8 units) being obtained with 15 wt % of E1. A process flow diagram and material balance were developed for a feedstock capacity of 730 t/y, and a techno-economic assessment showed

ISSN 3030-3907

an annual economic benefit of 2.744 billion UZS, a product profitability of 7.05 %, and a capital payback period of 23 months. The results demonstrate that waste heavy hexane, previously regarded as an unusable by-product, is a viable and economically attractive feedstock for import-substituting octane-boosting additives.

Keywords: waste heavy hexane; octane-boosting additive; catalytic oxidation; isomerization; gas chromatography–mass spectrometry; FT-IR spectroscopy; gasoline blending; techno-economic assessment.

Annotatsiya. “Uz-Kor Gas Chemical” qo‘shma korxonasining polietilen ishlab chiqarish sexi texnologik qoldiq sifatida og‘ir geksan fraksiyasi chiqindisini ishlab chiqaradi, u hozirda qo‘shimcha qiymat qo‘shmasdan utilizatsiya qilinadi va ekologik xavf tug‘diradi. Ushbu ishda ushbu chiqindi oqimini fraksiyonel distillash, so‘ngra katalitik oksidlanish, izomerizatsiya, alkillash va esterifikatsiya qilish orqali avtomobil benzini uchun oktanni kuchaytiruvchi qo‘shimchalarga aylantirish haqida xabar berilgan. Chiqindilarni og‘ir geksan uch harorat kesilgan (84-180, 180-220 va 220-247 va 1e-1E fraksiyonlama birligidan foydalanib, va har bir kesilgan gaz xromatografiya bilan xarakterlanadi (GC-MS, Agilent 5975c/7890a), qaysi 95.63% parafinlar bir uglevodorod guruh tarkibini nozil, 0.96 % olefinlar, 0,35% naftenlar va 3,07% arenlar, alohida komponentlar bilan Cix dan Cividualgacha. Zichlik, sinishi indeksi, kinematik yopishqoqlik, molekulyar og‘irlik va quyish nuqtasi fraktsiyaning qaynash oralig‘i bilan monoton ravishda ortib bordi (zichlik 708,3–740,9 kg/m³; kinematik yopishqoqligi 0,8423–1,6001 mm²/s; molekulyar og‘irligi 109,3–139,8 g/mol). (150-200, 0.5–3 MPa, 90-180 min) o‘z navbatida 1, 95 va 97, tadqiqot hisoblanishadi raqamlar (RON) bilan, E1, E3 va E9, belgilangan uch kislorod hissa ishlab chiqarilgan bir Pt/Al₂oendo katalizator (99-97; Fourier-Transform infraqizil (FT-IR) spektroskopiya karbonil (1647-1750 sm⁻1) va gidroksil (3566-3736 sm⁻1) spirtlar, ketonlar va efirlarning shakllanishiga mos keladigan yutilish bantlarining ko‘rinishini tasdiqladi. E1–e3ni 85, 5 va 10 Vt % da AI-15 avtomobil benziniga aralashtirish oktan sonini 85 dan 96.8 gacha (motor usuli), eng katta daromad (11.8 dona) E15 Vt % bilan olingan 1. Xom ashyo quvvati 730 t/y bo‘lgan texnologik oqim sxemasi va moddiy balans ishlab chiqildi va texno-iqtisodiy baholash yillik iqtisodiy foyda 2,744 milliard so‘m, mahsulot rentabelligi 7,05% va kapitalni qoplash muddati 23 oyni ko‘rsatdi. Natijalar shuni ko‘rsatadiki, ilgari yaroqsiz qo‘shimcha mahsulot sifatida qaralgan og‘ir geksan chiqindilari import o‘rnini bosuvchi oktanni kuchaytiruvchi qo‘shimchalar uchun hayotiy va iqtisodiy jihatdan jozibador xom ashyo hisoblanadi.

ISSN 3030-3907

Kalit so‘zlar: og‘ir geksan chiqindilari; oktanni kuchaytiruvchi qo‘shimcha; katalitik oksidlanish; izomerizatsiya; gaz xromatografiyasi-mass-spektrometriya; FT-IR spektroskopiyasi; benzin aralashtirish; texnik-iqtisodiy baholash.

Аннотация. В цехе по производству полиэтилена совместного предприятия “Uz-Kor Gas Chemical” в качестве технологического остатка образуется отработанная тяжелая гексановая фракция, которая в настоящее время утилизируется без дополнительной ценности и представляет опасность для окружающей среды. В этой работе сообщается о преобразовании этого потока отходов в добавки, повышающие октановое число для автомобильного бензина, путем фракционной перегонки с последующим каталитическим окислением, изомеризацией, алкилированием и этерификацией. Отработанный тяжелый гексан был разделен на три температурные группы (84-180, 180-220 и 220-247 °C) с использованием установки фракционирования ARNS-1E, и каждая группа была охарактеризована методом газовой хромато–масс-спектрометрии (GC-MS, Agilent 5975C/7890A), который выявил состав углеводородных групп, состоящий из 95,63 % парафинов, 0,96 % олефинов, 0,35 % нафтенов и 3,07 % аренов, причем содержание отдельных компонентов варьируется от C_6 до C_{3030}. Плотность, показатель преломления, кинематическая вязкость, молекулярная масса и температура застывания монотонно увеличивались с увеличением диапазона кипения фракции (плотность 708,3–740,9 кг/м3; кинематическая вязкость 0,8423–1,6001 мм2/с; молекулярная масса 109,3–139,8 г/моль). Каталитическая очистка трех фракций с $K_2Cr_2O_7$–H_2SO_4 окислительной системе за ст/Al_2O_3 катализаторы (150-200 °c, 0.5–3 МПа, 90-180 мин) производят три кислородсодержащие добавки, которая обозначается как E1, E2 и E3, с исследовательское октановое число (оч) 95, 97 и 99, соответственно; Фурье-ИК - (Фурье-ИК) спектроскопии подтвердили появление карбонильных (1647-1750 $см^{-1}$) и гидроксильных (3566-3736 $см^{-1}$) полосы поглощения в соответствии с образованием спиртов, кетоны и эфиры. При добавлении E1–E3 в автомобильный бензин марки АИ-85 в количестве 5, 10 и 15 мас. % октановое число повышается с 85 до 96,8 (автомобильный метод), при этом наибольший прирост (11,8 единиц) достигается при 15 мас. % E1. Для производства сырья производительностью 730 тонн в год были разработаны технологическая схема и материальный баланс, а технико-экономическая оценка показала, что годовой экономический эффект составляет 2,744 млрд. сум, рентабельность продукции - 7,05 %, а срок

ISSN 3030-3907

окупаемости капитала - 23 месяца. Результаты показывают, что отработанный тяжелый гексан, ранее считавшийся непригодным для использования побочным продуктом, является жизнеспособным и экономически привлекательным сырьем для производства импортозамещающих добавок, повышающих октановое число.

Ключевые слова: отработанный тяжелый гексан; добавка, повышающая октановое число; каталитическое окисление; изомеризация; газовая хромато-масс–спектрометрия; инфракрасная спектроскопия; смешивание бензинов; технико-экономическая оценка.

INTRODUCTION.

The accelerating growth of gas-chemical complexes and oil- and gas-processing capacity worldwide is accompanied by a parallel increase in the volume of hydrocarbon-containing residues and by-products that are generated at almost every stage of primary and secondary processing [1–3]. Deep conversion of these residues into competitive, standard-compliant motor and aviation fuels is recognized as one of the most important directions for improving the resource efficiency of the petrochemical sector, while systematic collection and reprocessing of waste streams simultaneously reduces the environmental burden associated with their uncontrolled disposal [4,5]. Among such residues, waste heavy hexane generated in polyethylene- and polypropylene-producing suspension units is of particular interest: it is formed continuously as a mixture of unreacted or thermally degraded hexane carrier and dissolved higher-molecular-weight hydrocarbons, and its accumulation is already estimated at close to two million tonnes annually within the region under study [6].

The chemistry of hydrocarbons and their classification, structure and physicochemical behavior are well established [7,8]; however, the practical value of a waste hydrocarbon stream depends less on generic classification than on a rigorous, feedstock-specific determination of its fractional and group composition, because this composition dictates which conversion route — cracking, isomerization, alkylation, oxidation, or esterification — will be technically and economically justified [9,10]. Octane number is the principal quality parameter governing the resistance of automotive gasoline to knock, and a substantial body of literature has examined routes to raise it, including nuclear-magnetic-resonance-based octane prediction models [11], catalytic isomerization process modification [12], isobutane–olefin alkylation chemistry for high-quality fuel production [13], and reviews of state-of-the-art high-octane gasoline production technologies [14].

ISSN 3030-3907

In parallel, growing attention has been paid to oxygen-containing (oxygenate) additives — alcohols, ethers, esters and ketones — as octane boosters that also improve combustion completeness and reduce carbon monoxide emissions [15,16], although the toxicological profile of some aromatic and oxygenated gasoline components requires that new additive chemistries be evaluated carefully [17]. Renewable and waste-derived feedstocks for such additives are increasingly preferred over petroleum-derived aromatics, both for cost and sustainability reasons [16,18].

Despite this progress, the specific problem of converting the heavy hexane residue of olefin-polymer suspension processes into octane-boosting gasoline additives has not been systematically investigated. Existing octane-improver formulations described in the technical literature are based either on aromatic amines (e.g., N-methylaniline blended with a benzine fraction), on multicomponent mixtures of anilines, methylbutenes and toluene derivatives, or on iron-complex/amide/aromatic-amine packages and dioxolane-methanol derivatives [19,20]; all of these rely on purpose-synthesized or imported reagents rather than on an in-country hydrocarbon waste stream. This creates both an economic burden, because octane-improving imports must be paid for in hard currency, and an environmental liability, because the waste heavy hexane itself accumulates without a defined utilization route.

The present study was carried out on the heavy hexane residue of the primary polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture. The purpose of the work was to develop and scientifically justify a technology for obtaining octane-boosting additives for automotive gasoline from this waste stream and to evaluate the resulting additives’ effect on the octane number of AI-85 automotive gasoline, together with the associated material balance and economic effect of process implementation.

Beyond the immediate technical problem, the present work is aligned with the broader national strategy of the Republic of Uzbekistan for deepening the processing of hydrocarbon raw materials, reducing dependence on imported fuel-quality-improving reagents, and expanding the country’s export potential in high-value petrochemical products [4,5]; it also responds to policy directions on energy conservation and the wider use of alternative and secondary energy resources, as well as to the strategic priority of developing cooperation between industrial enterprises and scientific institutions in the chemical-technology and nanotechnology fields. The specific technological context of the present feedstock deserves emphasis: in the primary polyethylene production shop of “Uz-Kor Gas Chemical,” hexane serves as the suspension (diluent) medium in which ethylene is polymerized; during continuous operation, a portion of the hexane undergoes

ISSN 3030-3907

thermal degradation and becomes progressively enriched with dissolved and entrained low-molecular-weight polymer, yielding, over time, a heavy, viscous residue that can no longer be economically recycled back into the suspension loop and must instead be periodically withdrawn from the process as waste. Because this residue combines an already elevated paraffin content with a wide molecular-weight distribution (C_6–C_{30}, as shown below), it is compositionally distinct from ordinary petroleum-refinery slops or used lubricating/motor oils that have previously been investigated for octane-improver or fuel-blending applications [6,10], and its systematic characterization and upgrading therefore constitutes a genuinely new research problem rather than an incremental extension of prior waste-oil valorization studies.

The scientific novelty of the study can be summarized as follows:

- The composition and physicochemical properties of the waste heavy hexane residue of a suspension-process polyethylene shop were determined for the first time using combined GC-MS and standard petroleum-analysis methods (GOST/ASTM).

- The waste heavy hexane was separated into three defined boiling-range fractions (84–180, 180–220, 220–247 °C), and the qualitative and quantitative hydrocarbon composition of each fraction, together with the associated physicochemical properties (density, refractive index, kinematic viscosity, molecular weight, pour point), was established.

- Oxygen-containing isomerized organic compounds were synthesized from the fractionated heavy hexane by oxidation with a $K_2Cr_2O_7$–H_2SO_4 oxidizing mixture in the presence of a Pt/Al_2O_3 catalyst, and the reaction mechanism (radical oxidation, carbocation-mediated isomerization, alkylation and esterification) was established.

- Three octane-boosting additives, E1, E2 and E3, with RON values of 95, 97 and 99, respectively, were obtained, and their physicochemical properties were characterized by FT-IR spectroscopy.

-The influence of E1–E3 on the octane number of AI-85 automotive gasoline was quantified at 5, 10 and 15 wt % blending ratios, and a technological principal flow scheme, material balance, and techno-economic assessment (annual economic effect of 2.744 billion UZS) were developed for practical implementation.0

MATERIALS AND METHODS. 2.1. Feedstock. The object of the study was the waste heavy hexane residue generated in the main polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture, where hexane is continuously used as a suspension medium; the fraction of hexane that undergoes thermal degradation and becomes mixed with residual polymer during the process is periodically removed as a technological waste stream. Samples were collected in

ISSN 3030-3907

accordance with ISO 3170 and ASTM D4057 requirements for representative sampling and storage of petroleum products [21].

All chemicals used in the fractionation and catalytic-conversion steps (potassium dichromate, sulfuric acid, platinum-on-alumina catalyst) were of analytical or catalytic grade and were used as received, without further purification. Prior to each experimental campaign, the ARNS-1E fractionating apparatus, the stirred-tank reactor, and the analytical instrumentation (gas chromatograph–mass spectrometer, FT-IR spectrometer, viscometer, pycnometers) were calibrated against certified reference materials, and blank runs were performed to verify the absence of cross-contamination between successive samples.

2.2. Fractional distillation. Preliminary clarification of the waste heavy hexane from mechanical and colloidal impurities was carried out by a sedimentation (settling) technique, after which the clarified product was separated into fractions in an ARNS-1E laboratory petroleum-fractionating unit in accordance with GOST 2177-99. Distillation was carried out stepwise up to 247 °C, yielding three principal cuts: fraction I (84–180 °C), fraction II (180–220 °C) and fraction III (220–247 °C); the combined distillate accounted for up to 99 % of the clarified feed.

2.3. Standard physicochemical analysis.The following standard methods were used to characterize the waste heavy hexane and its fractions: mechanical (insoluble) impurities — GOST 6370-2018; water content — the Dean–Stark method in accordance with GOST 2477-2014; density — the areometric and pycnometric methods in accordance with GOST 3900-85 (ASTM D1298); kinematic viscosity — the Ostwald–Pinkevich capillary viscometer method in accordance with GOST 31391-2009 (ASTM D445); pour point — GOST 20287-2023 (ASTM D97); refractive index was determined by standard refractometry. All measurements were performed in triplicate, with the maximum admissible deviation between replicates not exceeding 0.0004 g for gravimetric determinations.

2.4. Gas chromatography–mass spectrometry (GC-MS). The qualitative and quantitative hydrocarbon composition of the waste heavy hexane and of its individual fractions was determined using an Agilent 5975C inert MSD/7890A GC gas chromatograph–mass spectrometer (Agilent Technologies) equipped with an Agilent HP-INNOWax capillary column (30 m × 250 μm × 0.25 μm). The oven temperature program was 60 °C (10 min hold), heated at 4 °C/min to 220 °C (10 min hold), then at 1 °C/min to 240 °C (20 min hold). The injected sample volume was 0.2 μL (solution in hexane); hydrogen was used as carrier gas at a flow rate of 1 mL/min, and the injector temperature was 250 °C. Electron-impact mass spectra were recorded over the m/z range 10–550, and components were identified using

ISSN 3030-3907

the NIST17 spectral library, retaining only assignments with a match quality of 90 % or higher.

2.5. Reactor configuration. The stirred-tank reactor used for catalytic conversion was equipped, in addition to the components listed above, with a gas-inlet valve, an inline filter, a check (non-return) valve, a needle valve, a pressure safety valve (PSV), a product-discharge valve, a K-type thermocouple, a vent valve, and a magnetically coupled stirrer drive; this configuration allowed the reaction atmosphere, pressure and temperature to be controlled independently for each of the three fractions processed, while permitting safe venting of any light gaseous by-products generated during oxidation. The oxidizing reagents (1 M $K_2Cr_2O_7$ and concentrated H_2SO_4) were metered from dedicated feed vessels into the reactor in a 1:4 volume ratio immediately prior to each run, minimizing premature reaction of the oxidant prior to contact with the hydrocarbon substrate.

2.6. Catalytic conversion (oxidation, isomerization, alkylation and esterification). Catalytic conversion of the fractionated heavy hexane was carried out in a 2 L stainless-steel (SS 316L) stirred batch reactor rated to 22 MPa and 300–350 °C, equipped with a magnetically driven stirrer (0–800 rpm), an electric heating jacket (2–3 kW) with PID temperature control, a pressure gauge, a safety relief valve and a K-type thermocouple. The oxidizing mixture consisted of 1 M $K_2Cr_2O_7$ and concentrated H_2SO_4 combined in a 1:4 volume ratio; Pt/Al_2O_3 served as the catalyst for the isomerization and alkylation steps. Reaction conditions were: temperature 150–200 °C (fraction-dependent), pressure 0.5–3 MPa, reaction time 90–180 min, in an acidic medium (pH ≈ 2–3). Fraction I (84–180 °C) was processed under these conditions to yield product E1; fraction II (180–220 °C) was processed at 180–200 °C to yield product E2; and fraction III (220–247 °C) was processed at 200–220 °C to yield product E3.

2.7. FT-IR spectroscopy. The oxygenated reaction products were identified by Fourier-transform infrared spectroscopy on a Shimadzu IRTracer-100 spectrometer over the range 400–4000 cm^{-1} (resolution 4 cm^{-1}; signal-to-noise ratio 60,000:1; scan rate 20 spectra/s), using the KBr pellet technique.

2.8. Octane number determination and gasoline blending. The octane-boosting effect of the fractions and of the synthesized additives E1–E3 was evaluated by blending them into commercial AI-85 automotive gasoline at mass ratios of gasoline:additive equal to 95:5, 90:10 and 85:15. The octane number of the blends was determined by the motor method, consistent with the principles of ASTM D2699 (research method) and ASTM D2700 (motor method).

2.9. Material balance and economic evaluation. A material balance for the proposed process was constructed on the basis of an annual effective operating time of 8000 h and a feedstock (waste heavy hexane) throughput of 730 t/y, using mass-

ISSN 3030-3907

conservation relationships for the settling, fractionation, and catalytic-conversion blocks. The techno-economic assessment followed standard capital-cost, operating-cost, profitability and payback-period methodology, with market reference prices for octane-boosting additives, capital equipment and reagents taken at the time of the study.

RESULTS AND DISCUSSION

3.1. Group and fractional composition of the waste heavy hexane. GC-MS analysis of the waste heavy hexane sampled from the polyethylene production shop showed that the residue is a complex hydrocarbon mixture spanning the C_6–C_{30} range, with the principal individual components being hexane, isooctane, decane, dodecane and pentadecane. On a hydrocarbon-class basis (Table 1), the residue consists overwhelmingly of paraffins.

Table 1.

Hydrocarbon group composition of the waste heavy hexane residue (GC-MS)

Hydrocarbon class	Paraffins	Olefins	Naphthenes	Arenes
Content, %	95.625	0.955	0.35	3.07

This overwhelmingly paraffinic composition is consistent with the origin of the waste stream as a hexane carrier solvent contaminated with dissolved oligomeric/polymeric residues rather than with cracked or aromatized material, and it scientifically justifies the choice of oxidative isomerization and alkylation — rather than, for example, aromatization — as the most suitable conversion route for raising the octane number of this feedstock [12,13].

Table 2 summarizes the physicochemical properties of the raw waste heavy hexane and of the three fractions obtained by distillation up to 180, 220 and 247 °C, respectively.

Table 2.

Physicochemical properties of the waste heavy hexane and its fractions

Sample	Density at 20 °C, kg/m³ (GOST 3900-2002)	Refractive index	Kinematic viscosity at 20 °C, mm²/s (GOST 31391-2020)	Molecular weight, g/mol	Pour point, °C (GOST 20287-2023)
Raw waste	708.3	1.402	0.8423	109.3	−53

ISSN 3030-3907

Sample	Density at 20 °C, kg/m³ (GOST 3900-2002)	Refractive index	Kinematic viscosity at 20 °C, mm²/s (GOST 31391-2020)	Molecular weight, g/mol	Pour point, °C (GOST 20287-2023)
heavy hexane					
Fraction I (84–180 °C)	726.2	1.412	1.3259	139.9	−44
Fraction II (180–220 °C)	737.9	1.418	1.6008	139.8	−32
Fraction III (220–247 °C)	740.9	1.419	1.6001	139.8	−30

The systematic increase in density, refractive index, kinematic viscosity and molecular weight, together with the increase in pour point, from the raw residue to the heaviest fraction confirms the progressive concentration of longer-chain hydrocarbons during fractionation and demonstrates that the distillation step successfully separated the feedstock into fractions with distinguishable and reproducible physicochemical profiles, a prerequisite for a controlled downstream catalytic conversion [9].

3.2. GC-MS compositional profile of the individual fractions. The light fraction (up to 180 °C) was dominated by C_6–C_{12} paraffins (Table 3): hexane (14.51 %), isooctane (19.00 %), 3-methylheptane (9.12 %), n-decane (21.90 %) and dodecane (14.66 %) together accounted for close to 80 % of this cut.

Table 3.

Hydrocarbon composition of the fraction distilled up to 180 °C

Component	Retention time, min	Content, %
Hexane	0.930	14.51
Methylcyclopentane	0.952	4.97
Hexahydrobenzene	0.962	2.31
3-Methylheptane	0.997	9.12
Isooctane	1.014	19.00
1-Cyclopentylpropane	1.098	0.69
5-Methylnonane	1.255	5.00

ISSN 3030-3907

Component	Retention time, min	Content, %
3-Methylnonane	1.289	2.11
n-Decane	1.401	21.90
1-Hexyl-2-methylcyclopropane	1.525	0.51
Methylundecane	2.367	0.71
3-Methylundecane	2.553	0.33
Dodecane	3.002	14.66
n-Tetradecane	8.859	0.62

The intermediate fraction (180–220 °C) was dominated by dodecane (43.70 %) and pentadecane (17.05 %), together with decane (18.59 %) (Table 4), while the heaviest fraction (220–247 °C) was dominated by pentadecane (36.41 %), dodecane (35.22 %) and eicosane (12.25 %), with smaller contributions from nonacosane and higher homologues up to dotriacontane (Table 5).

Table 4.

Hydrocarbon composition of the fraction distilled between 180 and 220 °C

Component	Retention time, min	Content, %
Octane	1.025	3.73
Nonane	1.205	0.11
3-Methylnonane	1.300	1.99
Decane	1.401	18.59
5-Methylundecane	2.390	2.99
Undecane	2.575	1.46
Dodecane	3.215	43.70
Tridecane	7.354	0.32
Pentadecane	9.094	17.05
Eicosane	21.987	2.56

Table 5.

Hydrocarbon composition of the fraction distilled between 220 and 247 °C

Component	Retention time, min	Content, %
Decane	1.96	4.83
Undecane	2.379–2.581	3.03
Dodecane	2.232	35.22
Tridecane	6.714–7.376	2.60
Pentadecane	9.510	36.41
Eicosane	22.588	12.25
Nonacosane	39.698	2.10
10-Methylnonadecane	43.269	0.50
Dotriacontane	44.314	0.08

ISSN 3030-3907

The progressive shift of the dominant carbon number from C_6–C_{10} in the light cut to C_{15}–C_{20} in the heavy cut confirms an effective and controllable fractionation and provides the compositional basis required to select the oxidative conversion conditions applied to each cut individually.

3.3. Catalytic oxidation, isomerization, alkylation and esterification chemistry. Long, straight-chain saturated hydrocarbons such as those dominating the waste heavy hexane fractions are characterized by a low research octane number (RON 20–30) because of their propensity to auto-ignite (detonate) under compression [12]. Two complementary strategies were used to raise the octane rating of these paraffins: (i) partial oxidation to oxygen-containing organic compounds (alcohols, ketones, ethers, esters), and (ii) skeletal isomerization to branched isoalkanes, optionally combined with alkylation and esterification.

In the oxidative pathway, the $K_2Cr_2O_7$–H_2SO_4 system generates atomic oxygen and, indirectly, hydroxyl and alkoxy radicals:

$$2K_2Cr_2O_7 + 8H_2SO_4 \rightarrow 2K_2SO_4 + 2Cr_2(SO_4)_3 + 8H_2O + [O]$$

$$R–H + [O] \rightarrow R\bullet + \bullet OH$$

$$R\bullet + \bullet OH \rightarrow RO\bullet + ROH \rightleftharpoons RO\bullet + \bullet OH \rightarrow ROH + O\bullet$$

which, for example, converts n-decane into decanol and decanone isomers; in the presence of the Pt/Al_2O_3 catalyst, chain restructuring proceeds further toward hydroxylated and carbonylated branched species:

$$R–CH_2–CH_3 \rightarrow R–CH=CH_2 + \bullet OH \rightarrow R–CH(OH)–CH_2OH + R–CO–CH_3$$

Table 6 lists the classes of oxygen-containing products obtained and their approximate contribution to octane rating.

Table 6.

Principal products formed during catalytic oxidation of the paraffinic fractions

Product class	General formula	RON (indicative)	Characteristic
Monohydric alcohol	$CH_3(CH_2)_nCHOHCH_3$	95	Good oxygen donor, clean combustion
Monohydric alcohol (isomer)	$CH_3(CH_2)_nCHOHCH_3$	96	Improves combustion stability
Ketone	$CH_3(CH_2)_nCOCH_3$	100	Stable, high octane
Ether	$CH_3(CH_2)_nO(CH_2)_nCH_3$	105	Introduces oxygen, lowers CO_2

In parallel, acid-catalyzed skeletal isomerization of the n-alkanes proceeds through protonation, carbocation formation, hydride/methyl shift, and

ISSN 3030-3907

deprotonation:

$CH_3–(CH_2)_n–CH_3 + H^+ \rightarrow CH_3–(CH_2)_n–CH^+–CH_3 \rightarrow$ (1,2-hydride/methyl shift) → branched carbocation → isoalkane + H^+

Table 9 (Section 3.9, in the original process design) lists Pt/Al_2O_3, $Pt–SO_4^{2-}$, Pt/H-Y zeolite and $WO_3–ZrO_2$ as candidate isomerization catalysts, of which Pt/Al_2O_3 was selected for the present work owing to its high activity and selectivity under the mild oxidative-acidic conditions used. Isomerization of n-decane under these conditions (150–200 °C, 1–3 MPa, 90–120 min, $K_2Cr_2O_7/H_2SO_4$ as a mild acid-oxidant medium) achieved a conversion of 70–90 %, yielding branched C_8–C_9 isomers such as 2,2,5-trimethylhexane and 2,2,4-trimethylpentane with RON values of 97–100 (Table 7).

Table 7.

Isomerization products of n-decane and their octane numbers

Product	Formula	RON	Remark
2,2,5-Trimethylhexane	C_9H_{20}	97–100	Isooctane analogue, high octane
2,5-Dimethylheptane	C_9H_{20}	94	Stable combustion, low smoke
3,4-Dimethylhexane	C_8H_{18}	92	High thermal stability
2,2,4-Trimethylpentane	C_8H_{18}	100	Reference isooctane

Alkylation of the paraffinic fractions with light olefins over Pt/Al_2O_3 (and, in supplementary trials, $MnO_2–SO_4^{2-}$) produced isoparaffins with RON 95–100, while acid-catalyzed esterification of the intermediate alcohols (e.g., decanol, dodecanol) with organic acids yielded oxygenated esters (decyl acetate, dodecyl formate) with RON 95–105, and transesterification over Pt/Al_2O_3 produced methyl/ethyl decanoates and dodecanoates with RON 90–100 (Table 8).

Table 8.

Comparison of catalytic conversion routes

Reaction type	Catalyst	Main product	Effect on octane number	Practical significance
Alkylation	Pt/Al_2O_3	Isodecane, isododecane	Strong increase (95–100)	Gasoline blend components
Esterification	H_2SO_4, Pt/Al_2O_3	Esters (decyl acetate)	Strong increase (95–105)	Octane-boosting ethers/esters

ISSN 3030-3907

Reaction type	Catalyst	Main product	Effect on octane number	Practical significance
Transesterification	Pt/Al_2O_3	Methyl/ethyl decanoates	Strong increase (90–100)	Biofuel-type components

Taken together, these reaction pathways raise the octane number of the paraffinic feedstock from an initial RON of 20–35 to 95–105 in the model reaction products, while improving combustion completeness and reducing exhaust-gas volume — findings that are consistent with, and extend to a waste-derived feedstock, the broader literature on oxygenate- and isoparaffin-based octane improvers [11,13,15].

3.4. GC-MS analysis of the oxidized reaction products. GC-MS analysis of the catalytically treated 180 °C fraction (Table 9) confirmed the appearance of diethyl ether (1.37 %), isopropanol (0.72 %), and butanol (0.74 %) alongside retained isooctane (14.36 %), decane (10.39 %), and dodecane (13.24 %); the calculated weighted-average RON of this blend was approximately 92, reflecting the combined contribution of branched hydrocarbons and oxygenates.

Table 9.

Compositional changes after catalytic treatment of the fraction distilled up to 180 °C

Component	Retention time, min	Content, %	Match quality, %
Diethyl ether	2.776	1.37	88
Isopropanol	4.483	0.72	2
Octane	4.879	8.16	87
Isooctane	4.958	14.36	74
Heptyl-hexyl ether	7.476	4.91	78
Decane	8.146	10.39	93
Undecane	10.548	7.61	74
Dodecane	11.200	13.24	87
Butanol	13.321	0.74	86
Heptadecane	14.083	20.02	80

Analysis of the fraction treated above 180 °C (Table 10) revealed a markedly higher proportion of branched hydrocarbons and cyclic ethers, including 2-ethyl-2-methyloxirane (18.25 %), 3-methylheptane (21.51 %), and isodecane (11.37 %), together with methanol (3.69 %), consistent with more extensive isomerization and oxygenation at the harsher processing conditions applied to the heavier cut.

ISSN 3030-3907

Table 10.

Compositional changes after catalytic treatment of the fraction distilled above 180 °C

Component	Retention time, min	Content, %	Match quality, %
Methanol	2.569	3.69	37
2-Methylbutane	2.636	6.66	47
2-Ethyl-2-methyloxirane	2.758	18.25	47
3-Methylpentane	2.928	6.16	60
3-Methylheptane	4.452	21.51	80
2,3-Dimethylheptane	4.848	12.05	59
3-Ethyl-2-methylhexane	7.451	3.14	86
Isodecane	8.134	11.37	90
Dodecane	11.194	17.17	87

For the fraction treated above 220 °C, isooctane (11.35 %), 2,3-dimethyldecane (25.32 %), propyl-dodecyl ether (20.09 %), isotetradecane (23.36 %) and isononadecane (8.90 %) were identified, indicating that both branching and etherification proceed extensively at the higher processing temperature, in agreement with the RON = 99 obtained for the corresponding additive E3.

3.5. FT-IR characterization of the octane-boosting additives. FT-IR spectra of the three chemically treated fractions confirmed the formation of oxygen-containing functional groups predicted by the proposed reaction mechanism. In the additive obtained from the 180 °C fraction, strong absorptions at 2957.60, 2923.20 and 2855.81 cm^{-1} were assigned to C–H stretching of $–CH_2–$ and $–CH_3$ groups, confirming the long-chain aliphatic backbone; bands at 1458.01 and 1377.73 cm^{-1} corresponded to $–CH_2–$ deformation and symmetric $–CH_3$ deformation, respectively, while bands at 722.56 and 668.08 cm^{-1} were assigned to long-chain $–(CH_2)_n–$ rocking vibrations. Critically, bands at 1750.48 and 1647.25 cm^{-1} were attributed to carbonyl (C=O) stretching, consistent with the formation of esters, aldehydes and conjugated carbonyl species.

In the additive obtained from the fraction treated above 180 °C, broad absorptions at 3736.07, 3650.05 and 3566.90 cm^{-1} were assigned to free O–H stretching of alcohols and carboxylic acids, while the band at 1744.74 cm^{-1} confirmed strong carbonyl character (esters, higher fatty-acid oxides) and the band at 1684.53 cm^{-1} was attributed to ketone and conjugated C=C/N–H absorption. A weaker band at 1508.19 cm^{-1} indicated the presence of aromatic C=C bonds, and the 721.12 cm^{-1} band confirmed long-chain branched hydrocarbons. The spectrum of the additive obtained from the fraction treated above 220 °C reproduced the same O–H (3566–3736 cm^{-1}) and C=O (1647.25, 1750 cm^{-1}) features, together with an

ISSN 3030-3907

additional band at 2348.3 cm^{-1} attributable to atmospheric O=C=O and bands at 1541.17 and 1508.19 cm^{-1} confirming N–H and aromatic C=C absorptions, respectively.

Collectively, the systematic appearance of O–H and C=O absorption bands across all three treated fractions provides direct spectroscopic confirmation that the $K_2Cr_2O_7$–H_2SO_4/Pt–Al_2O_3 system converts the paraffinic waste hexane fractions into the oxygenated, isomerized products (alcohols, ketones, ethers, esters) responsible for the observed octane improvement, corroborating the GC-MS results in Section 3.4.

3.6. Effect of the additives on the octane number of AI-85 gasoline. Blending trials were first performed with the untreated (raw) fractions to establish a baseline. As shown in Table 11, the octane number of the resulting blends increased with both the boiling range of the fraction used and the blending ratio, rising from 30 (raw feed alone) to 74 for fraction III at an 85:15 (gasoline:fraction) ratio; this baseline confirms that even without catalytic modification, the heavier, more paraffin-concentrated fractions provide some octane benefit, consistent with their higher content of branched and cyclic species (Section 3.2).

Table 11.

Effect of the raw fractions on the octane number of AI-85 gasoline blends

Fraction	Boiling range, °C	Baseline RON	Blend ratio (gasoline:additive)	Blend RON
Raw waste heavy hexane	—	30	95:5	34
			90:10	39
			85:15	41
Fraction I	84.1–180	61	95:5	64
			90:10	69
			85:15	72
Fraction II	180–220	64	95:5	64
			90:10	69
			85:15	72
Fraction III	220–247	76	95:5	72
			90:10	73
			85:15	74

After catalytic treatment, the resulting additives E1 (from fraction I, RON 95), E2 (from fraction II, RON 97) and E3 (from fraction III, RON 99) produced substantially larger octane gains (Table 12). E1 raised the octane number of AI-85 gasoline from 85 to 88.9, 93.2 and 96.8 at blending ratios of 5, 10 and 15 wt %, respectively — a maximum gain of 11.8 units. E2 produced gains of 1.8–7.6 units

ISSN 3030-3907

(final RON 86.8–92.6), and E3 produced gains of 2.4–9.1 units (final RON 87.4–94.1). A combined blend of E1, E2 and E3 in equal proportion produced intermediate gains of 2.7–9.5 units.

Table 12.

Effect of the catalytically treated additives (E1–E3) on the octane number of AI-85 gasoline

Additive	Treatment temperature, °C	Blend ratio (gasoline:additive)	Blend RON
E1	150–180	95:5	88.9
		90:10	93.2
		85:15	96.8
E2	180–200	95:5	86.8
		90:10	89.1
		85:15	92.6
E3	200–220	95:5	87.4
		90:10	91.7
		85:15	94.1
E1+E2+E3 (combined)	150–180	95:5	87.7
		90:10	91.5
		85:15	94.5

The superior performance of E1 relative to E2 and E3 is attributed to the milder oxidation temperature applied to the lightest fraction, which favored the formation of low-molecular-weight, highly branched and oxygenated species (Section 3.4, Table 9) with the strongest inherent octane-boosting effect, whereas the heavier fractions, despite a higher content of branched paraffins, retained a larger proportion of straight-chain, higher-boiling material that partially offset the benefit of oxygenation. Overall, the results confirm that a 15 wt % addition of E1 to AI-85 gasoline meets and exceeds the octane requirement of AI-92/AI-95-grade gasoline, demonstrating the technical feasibility of the proposed valorization route.

3.7. Proposed technological scheme and material balance. A principal technological flow scheme was developed for continuous conversion of the waste heavy hexane into octane-boosting additives. Waste heavy hexane is first pumped into a settling vessel, where mechanical particles and heavy impurities are separated by gravity; the clarified hexane is then pumped through a heat exchanger and a fired heater (up to 300 °C) into a fractionating column. Light volatile fractions leave the top of the column, are condensed in air and water coolers, and are separated in a knock-out drum, with a portion returned to the column as reflux. Within the column, three principal fractions are withdrawn according to their

ISSN 3030-3907

boiling range and, after cooling, are each pumped to a dedicated stirred-tank reactor, where they are treated with the 1 M $K_2Cr_2O_7$/concentrated H_2SO_4 oxidizing mixture (prepared in dedicated reagent vessels) at 150–220 °C and approximately 0.3 MPa, using steam heating, to yield additives E1, E2 and E3, respectively. The column bottoms (heavy residue) are withdrawn separately.

The material balance was calculated for a feedstock throughput of G_1 = 730 t/y (G_1' = 91.25 kg/h) at an annual effective operating time of 8000 h, together with $K_2Cr_2O_7$ consumption of G_2 = 0.2521 t/y and H_2SO_4 consumption of G_3 = 5.0575 t/y. Low-molecular-weight polymer impurities separated during clarification amounted to G_4 = 131.4 t/y (18 % of feed); the clarified hexane (598.6 t/y) was distributed among fraction I (299.90 t/y, x_3 = 0.501), fraction II (155.64 t/y, x_4 = 0.26), fraction III (75.42 t/y, x_5 = 0.126) and a residual bottoms stream (65.85 t/y, x_6 = 0.11), with a light-gas fraction of 1.80 t/y (x_7 = 0.003). Accounting for a 1 wt % addition of the oxidizing mixture to each distillate stream (x_8 = 0.01), the resulting annual yields of the additives were G_6 (E1) = 302.90 t/y, G_7 (E2) = 157.19 t/y and G_8 (E3) = 76.18 t/y — a combined annual additive output of 536.27 t/y from 730 t/y of feedstock, i.e., a 73.5 % overall mass yield (Table 13). An auxiliary catalyst consumption of 5 t/y of Al_2O_3–Pt was also established.

Table 13.

Material balance of the waste heavy hexane conversion process (feed capacity 730 t/y)

Stream	t/y	kg/h	mass %
Input			
Waste heavy hexane	730.000	91.250	99.278
$K_2Cr_2O_7$	0.252	0.0315	0.034
H_2SO_4	5.057	0.632	0.688
Total input	**735.310**	**91.914**	**100**
Output			
Low-molecular polymer impurities	131.400	16.425	17.870
Off-gas	1.796	0.0224	0.244
Additive E1	302.898	37.862	41.193
Additive E2	157.192	19.645	21.377
Additive E3	76.178	9.522	10.360
Residual bottoms	65.846	8.231	8.956
Total output	**735.310**	**91.707**	**100**

3.8. Techno-economic assessment. The techno-economic assessment was performed for the Bukhara oil refinery (“Buxoro neftni qayta ishlash zavodi” LLC, part of the “Uzbekneftegaz” joint-stock company) as the illustrative

ISSN 3030-3907

implementation site. At a prevailing market price of 11.64, 11.76 and 11.52 million UZS per tonne for E1, E2 and E3, respectively, the annual revenue from additive sales was calculated as A_1 = 3.526 billion UZS (E1), A_2 = 1.849 billion UZS (E2) and A_3 = 0.878 billion UZS (E3), giving a total annual revenue of A_{total} = 6.252 billion UZS.

Capital expenditure for implementing the new technology comprised design, commissioning and pilot-sample costs of 0.8 billion UZS and equipment/installation costs of 4.447 billion UZS (four reactors, a settling vessel, a fractionating column, storage vessels, seven pumps, heat exchangers, air and water coolers, a fired heater, a separator, piping and instrumentation, transportation and installation), giving a total capital investment of T_{impl} = 5.247 billion UZS (Table 14).

Table 14.

Capital expenditure for implementation of the proposed technology

Cost item	Amount, million UZS
Process design	600
Commissioning	100
Pilot-sample production	100
Sub-total (implementation)	**800**
Reactors (4 units)	1600
Settling vessel	100
Fractionating column	1200
Storage/reagent vessels (3)	60
Pumps (7)	280
Heat exchanger	80
Air coolers (4)	80
Water coolers (4)	100
Fired heater	300
Separator	100
Instrumentation and piping accessories	17
Auxiliary materials	300
Transportation	80
Installation and commissioning of equipment	90
Miscellaneous	60
Sub-total (equipment)	**4447**
Total capital investment (T_{impl})	**5247**

Annual production and operating costs, dominated by raw-material (waste heavy hexane, 1825.0 million UZS) and catalyst (Al_2O_3–Pt, 991.7 million UZS)

ISSN 3030-3907

costs, net of the value of recoverable by-products (low-molecular polymer and residual heavy fraction), totaled 3457.8 million UZS in direct production costs; including administrative and sales overheads of 50.0 million UZS, the full cost of production reached 3507.8 million UZS/y (Table 15).

Table 15.

Annual production and operating costs

Cost item	Annual consumption	Unit price, UZS	Annual cost, thousand UZS
Waste heavy hexane feedstock	730,000 kg	2,500	1,825,000.0
Recovered polymer (by-product credit)	131,400 kg	3,000	394,200.0
Recovered heavy fraction (by-product credit)	65,846 kg	2,000	131,692.0
Process steam	16,000 kg	1,000	16,000.0
Al_2O_3–Pt catalyst	1,666.7 kg	595,000	991,662.7
$K_2Cr_2O_7$	252.1 kg	1,000	252.1
H_2SO_4	5,057.5 kg	1,500	7,586.2
Electric power	40,000 kWh	2,000	80,000.0
Total material costs (net of by-product credit)			**2,931,911.0**
Labor costs (2 employees)			8,000.0
Social-security contributions			2,550.0
Depreciation of fixed assets			250.0
Other costs			30.0
Total production cost			**3,457,803.0**
Administrative and sales overheads			50,000.0
Full cost of production			**3,507,803.0**

The resulting annual profit was F = A − (production and operating costs) = 6.252 − 3.508 = 2.744 billion UZS. Product profitability, defined as F divided by production and operating costs, was 2.744/35.078 × 100 % = 7.05 %, and the capital payback period, $\tau = T_{impl}/F = 5.247/2.744 = 1.92$ years (approximately 23 months). These figures indicate that, at the prevailing octane-additive market price, conversion of waste heavy hexane into E1–E3 additives is both technically feasible and economically self-sustaining within a two-year investment horizon, in addition to eliminating an environmentally problematic waste stream.

3.9. Consolidated FT-IR band assignment. For clarity, Table 16 consolidates

ISSN 3030-3907

the diagnostic FT-IR absorption bands observed across the three catalytically treated fractions and their structural assignments, providing a single reference point for the spectroscopic evidence discussed in Section 3.5.

Table 16.

Consolidated FT-IR band assignments for additives E1–E3

Wavenumber range, cm^{-1}	Assignment	Structural implication
3736–3566	O–H stretching (free)	Alcohols, carboxylic acids
2957–2854	C–H stretching (–CH_2–, –CH_3)	Long-chain aliphatic backbone
2348	O=C=O stretching	Atmospheric CO_2 (background)
1750–1647	C=O stretching	Esters, aldehydes, ketones, conjugated carbonyls
1684	C=O / C=C / N–H	Ketones, conjugated unsaturation
1559–1541	N–H bending (amide II region)	Trace nitrogen-containing species
1508	Aromatic C=C	Residual aromatic/arene content
1458–1375	CH_2/CH_3 deformation	Branched aliphatic structure
722–668	–$(CH_2)_n$– rocking	Long, unbranched alkyl segments

The internal consistency of these assignments across all three additives — persistent long-chain C–H stretching combined with a systematic and reproducible appearance of O–H and C=O bands only after catalytic treatment — provides strong, independent structural confirmation of the oxidation/isomerization mechanism proposed in Section 3.3 and of the GC-MS identification of alcohols, ethers, and esters reported in Section 3.4.

3.10. Comparison with the literature and industrial relevance. The octane-boosting performance achieved in this work (RON up to 99 for the neat additive E3 and a blended AI-85 octane number of up to 96.8) is comparable to, and in several respects exceeds, values reported for oxygenate- and isoparaffin-based octane improvers derived from conventional or renewable feedstocks [11,13,15,16], while relying on a feedstock that is presently a net environmental liability rather than a purchased raw material. Unlike aromatic-amine-based commercial octane improvers, whose long-term combustion toxicology has been questioned [17], the additives obtained in this study are structurally dominated by aliphatic alcohols, ketones and ethers, which are generally associated with a more favorable emissions and toxicological profile, consistent with the broader shift toward oxygenate-based, non-aromatic octane enhancement strategies documented

ISSN 3030-3907

in the recent literature [14,15]. From an industrial-implementation perspective, the fact that the proposed process uses commercially available, low-cost oxidant and catalyst systems ($K_2Cr_2O_7/H_2SO_4$, Pt/Al_2O_3) rather than specialized proprietary reagents, and that it can be integrated directly at the site where the waste stream is generated, materially reduces both the capital intensity and the logistical complexity of implementation relative to import-substitution strategies based on synthetic octane-improver packages.

At the same time, several limitations of the present study should be acknowledged. First, the reported octane numbers were obtained on a laboratory scale using batch reactors and motor-method octane determination; validation on a continuous pilot unit, and confirmation by the standard research-method (RON) and motor-method (MON) engine tests specified in ASTM D2699/D2700, will be required before large-scale deployment. Second, the long-term storage stability of the oxygenated additives, their compatibility with existing fuel-distribution and engine-sealing materials, and their behavior in phase-separation and water-tolerance tests were outside the scope of the present investigation and merit dedicated follow-up studies, in line with established practice for the qualification of new fuel oxygenates [14,16]. Third, the economic analysis presented in Section 3.8 is based on prevailing reagent, equipment and product-market prices at the time of the study and on a single implementation site; sensitivity of the payback period to feedstock availability, reagent-price volatility and octane-additive market price would benefit from further scenario analysis before investment decisions are finalized.

CONCLUSION. Waste heavy hexane generated in the polyethylene production shop of the “Uz-Kor Gas Chemical” joint venture, previously accumulated without a defined utilization pathway, was shown to be a technically and economically viable feedstock for octane-boosting automotive gasoline additives. Fractional distillation separated the waste stream into three cuts (84–180, 180–220, 220–247 °C) with progressively increasing density, viscosity, molecular weight and pour point, and GC-MS analysis established an overwhelmingly paraffinic bulk composition (95.6 %) spanning the C_6–C_{30} range. Catalytic oxidation of these fractions with a $K_2Cr_2O_7$–H_2SO_4 oxidizing mixture over a Pt/Al_2O_3 catalyst, proceeding through radical oxidation, carbocation-mediated isomerization, alkylation and esterification, produced three octane-boosting additives, E1, E2 and E3, with RON values of 95, 97 and 99, whose oxygenated (alcohol, ketone, ether) character was independently confirmed by FT-IR spectroscopy. Blending these additives into AI-85 automotive gasoline at 5–15 wt % raised the octane number by 2.4–11.8 units, with the best performance (RON 96.8) obtained using 15 wt % of additive E1. A process flow scheme and material

ISSN 3030-3907

balance were developed for a feedstock capacity of 730 t/y, converting it into 536.3 t/y of combined additive output (73.5 % mass yield), and a techno-economic assessment demonstrated an annual economic benefit of 2.744 billion UZS, a product profitability of 7.05 %, and a capital payback period of approximately 23 months. These results support the practical implementation of the proposed technology at petroleum-refining and petrochemical enterprises within the Republic of Uzbekistan, both as a means of import substitution for octane-boosting additives and as an environmentally beneficial route for the utilization of an otherwise unmanaged industrial waste stream. Future work should extend the present laboratory-scale findings to pilot-scale continuous operation, evaluate the storage stability and corrosion/compatibility behavior of the additives in commercial fuel-distribution infrastructure, and quantify the emissions benefit of the additives in engine-bench tests.

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ISSN 3030-3907

TECHNOLOGY FOR THE PRODUCTION OF HIGHER FATTY ACIDS FROM SECONDARY PARAFFIN FEEDSTOCKS FOR ENHANCING THE LUBRICITY OF DIESEL FUELS

Fozilov Hasan Sadriddinovich
PhD, Associate Professor, Department of Oil and Gas Processing Technology, Bukhara State Technical University, Bukhara, Uzbekistan
Turobjonov Sadriddin Makhamatdinovich
Doctor of Technical Sciences, Academician, Tashkent State Technical University, Tashkent, Uzbekistan
Fozilov Sadriddin Fayzulloevich
Doctor of Technical Sciences, Professor, Department of Oil and Gas Processing Technology, Bukhara State Technical University, Bukhara, Uzbekistan

Abstract. The objective of this study is to develop an efficient technology for the synthesis of higher fatty acids from secondary paraffinic feedstock and to evaluate their effect on the lubricating properties of diesel fuels. The scientific novelty lies in a comprehensive approach to the processing of paraffinic waste, involving oxidation, saponification, thermal treatment, and fractional distillation stages. The regularities in the formation of the composition of the obtained fatty acids and their influence on the operational characteristics of diesel fuel have been established. It has been shown that the use of the synthesized acids as additives significantly improves the lubricity of the fuel and reduces wear. The developed technology enables the effective utilization of secondary raw materials and the production of competitive additives for modern diesel fuels.

Keywords: higher fatty acids, oxidation of paraffins, saponification process, distillation, diesel fuel, additive, lubricity, anti-wear properties, secondary raw materials, EURO-6.

Аннотация. Целью данной работы является разработка эффективной технологии синтеза высших жирных кислот из вторичного парафинового сырья и оценка их влияния на смазывающие свойства дизельных топлив. Научная новизна заключается в комплексном подходе к переработке парафиновых отходов с использованием стадий окисления, омыления, термической обработки и фракционной дистилляции. Установлены закономерности формирования состава получаемых кислот и их влияние на эксплуатационные характеристики топлива. Показано, что применение синтезированных кислот в качестве присадок обеспечивает значительное улучшение смазывающей способности и снижение износа. Разработанная технология позволяет эффективно использовать вторичное сырьё и

ISSN 3030-3907

создавать конкурентоспособные добавки для современных дизельных топлив.

Ключевые слова: высшие жирные кислоты, окисление парафинов, процесс омыления, дистилляция, дизельное топливо, присадка, смазывающая способность, противоизносные свойства, вторичное сырье, EURO-6.

Annotatsiya. Ushbu tadqiqotning maqsadi ikkilamchi parafin xomashyosidan yuqori yog‘li kislotalarni sintez qilishning samarali texnologiyasini ishlab chiqish va ularning dizel yoqilg‘isining moylash xususiyatlariga ta'sirini baholashdan iborat. Ilmiy yangilik oksidlanish, sovunlash, termik ishlov berish va fraksiyonel distillash bosqichlarini o‘z ichiga olgan parafin chiqindilarini qayta ishlashga kompleks yondashishdan iborat. Olingan yog 'kislotalarining tarkibini shakllantirish qonuniyatlari va ularning dizel yoqilg‘isining ekspluatatsion xususiyatlariga ta'siri aniqlandi. Sintezlangan kislotalardan qo‘shimchalar sifatida foydalanish yoqilg‘ining moylash qobiliyatini sezilarli darajada yaxshilashi va eskirishni kamaytirishi isbotlangan. Ishlab chiqilgan texnologiya ikkilamchi xom ashyolardan samarali foydalanish va zamonaviy dizel yoqilg‘ilari uchun raqobatbardosh qo‘shimchalar ishlab chiqarish imkonini beradi.

Kalit so‘zlar: yuqori yog‘li kislotalar, parafinlarning oksidlanishi, sovunlanish jarayoni, distillash, dizel yoqilg‘isi, qo‘shimchalar, moylash, aşınmaya qarshi xususiyatlar, ikkilamchi xom ashyo, EURO-6.

INTRODUCTION.

At present, the global oil and gas processing and petrochemical industries are developing rapidly, with ongoing reforms aimed at introducing new technologies for the processing of hydrocarbon raw materials. In our country, significant progress has been achieved in developing various products based on local raw materials and secondary resources, improving the preparation and processing of hydrocarbon feedstocks, and implementing innovative technologies to enhance both the quality and volume of production. In this regard, scientific research focused on increasing the efficiency of utilizing paraffinic hydrocarbon mixtures of various compositions formed during the development of oil fields is of great importance.

The technology of hydrogenation of higher fatty acid esters has made it possible to produce fatty alcohols on an industrial scale, and this process has been implemented in many countries with sufficient raw material bases. Currently, the

ISSN 3030-3907

majority of such fatty acids are synthesized from petroleum paraffins, which significantly reduces the demand for natural oil and fat raw materials.

MATERIALS AND METHODS.

The development of technologies for breaking oil emulsions began in the 1920s in the United States with the industrial use of soap solutions. Numerous studies were conducted in which chemical compounds were synthesized and their efficiency was evaluated. As a result, reagents based on unsaturated fatty acids were found to be the most effective demulsifiers [1]. The first industrial demulsifiers were obtained based on mixtures of fatty acids and inorganic salts. Later, they were replaced by petroleum sulfonic acids and their ammonium salts. At subsequent stages, additives such as castor oil, glycerin, and high-molecular-weight fatty acids were introduced into the composition of demulsifiers. These modifications significantly improved demulsification efficiency and demonstrated higher performance compared to previously used anionic surfactants, namely sulfonates and oils.

New nonionic demulsifiers exhibited high stability and efficiency due to their عدم reaction with water-soluble metal salts present in emulsions. Moreover, they were capable of effectively breaking complex emulsions even when used in amounts two times lower than anionic surfactants.

Scientific and technological advances in oil refining and petrochemical industries have enabled the comprehensive utilization of hydrocarbon raw materials and significantly reduced the use of food-based feedstocks for technical purposes. As a result, the use of grain and potatoes for the production of ethanol for technical applications has been completely eliminated. The development of technologies for producing higher fatty acids, alcohols, and surfactants based on petroleum feedstocks has contributed to substantial savings in animal and vegetable fats [2]. In the paint and coatings industry, the use of petroleum-polymer resins and low-molecular-weight rubbers represents an effective example of replacing food raw materials with chemical materials. The implementation of these technologies has led to annual savings of approximately 50 thousand tons of vegetable oils.

However, in current practice, only a portion of unsaponifiable substances is separated from the obtained fatty acids; the acids are not purified, not fractionated, and are used as mixtures of oxidation products. Such products do not fully replace natural fats, and this approach to paraffin utilization cannot be considered efficient. Further development of the higher fatty acid industry should be based on the максимально эффективное использование исходного сырья (paraffin) and the production of high-quality, well-fractionated distilled fatty acids. Although several plants producing distilled higher fatty acids exist in our country, their capacity is insufficient. Therefore, solving this problem is currently of great importance,

ISSN 3030-3907

especially considering that higher fatty acids and alcohols are still imported from foreign countries using foreign currency resources [3].

At present, in industry, higher fatty acids are divided into the following fractions: low-molecular-weight water-soluble C_1–C_4 acids, which are removed вместе with water. The main raw material for their production is paraffin, from which C_{10}–C_{16} and C_{17}–C_{20} fractions are obtained [4].

A large body of industrial research data exists, demonstrating with sufficient accuracy how specific technological parameters affect the efficiency and quality of higher fatty acids obtained during the processing of solid petroleum paraffins. A detailed study of higher fatty acids shows that they have a complex composition. In addition to simple monocarboxylic acids, they contain branched-chain radicals, radicals with naphthenic rings, dicarboxylic acids of various structures, unsaturated, hydroxy-, and keto acids, as well as certain amounts of hydrocarbons and neutral oxygen-containing compounds. The content of individual components depends on the composition of the raw materials and the technological processes used for obtaining and separating fatty acids, which ultimately determines their fields of application [5].

Higher fatty alcohols (HFA) are among the main types of organic raw materials used to produce a wide range of products. Conventionally, HFA include monohydric alcohols containing more than five carbon atoms in their molecules. This group includes primary and secondary alcohols with both even and odd numbers of carbon atoms, as well as saturated and unsaturated compounds.

Such alcohols are produced by various synthesis methods based on petrochemical feedstocks, as well as by the reduction of acids obtained from natural fats and oils.

According to their consumer properties, higher fatty alcohols can be conditionally classified into the following groups: individual alcohols such as C_8, C_{10}, and C_{13}, as well as fractions consisting of homologues ranging from C_6 to C_{13}; and fractions composed of homologues with carbon numbers of C_{10} and higher (mainly C_{10}–C_{18}). Alcohols in the C_{10}–C_{18} range are widely used in the production of surfactants and related products, especially high-performance detergents. Surfactants based on higher fatty alcohols exhibit good biodegradability, low toxicity, and effective washing performance in hard water [6].

RESULTS AND DISCUSSIONS.

In industry, the oxidation of higher paraffins can be carried out in both batch and continuous modes.

The oxidation process is typically performed in vertical columns made of aluminum with a capacity of 8–12 m^3, since low-molecular-weight acids cause severe corrosion. Oxidation occurs with the release of a significant amount of heat.

ISSN 3030-3907

For example, when oxidizing paraffin until the acid number of the oxidate reaches 70 mg KOH/g, approximately 2095 kJ of heat is released per 1 kg of oxidized paraffin. Heat is removed from the column through internal coils cooled by water. The process is conducted at atmospheric pressure, and the oxidation duration ranges from 20 to 24 hours. Industrial installations are equipped with multiple reactors to ensure the required production capacity. The oxidate formed during the oxidation process is treated with soda and alkali (this process is known as saponification). Fatty acids are rapidly neutralized and transferred into a soap solution [7].

The unsaponifiable fraction I, consisting of unoxidized paraffins containing oxygenated compounds, is recycled back to the oxidation stage. In addition to fatty acids, the oxidate also contains small amounts of hydroxy acids, esters, lactones, ketones, and alcohols, which are saponified only under severe conditions. These compounds dissolve in the soap solution along with small amounts of paraffin and exhibit surface-active properties.

However, their removal is necessary, as they ухудшают detergent and foaming properties of the soap and impart an unpleasant odor (especially hydroxy acids). For this purpose, the soap solution is subjected to heat treatment at 320 °C, resulting in a “refining” process: lactones and ketones undergo saponification, while hydroxy acids are dehydrated.

$$RCH_2 - CO - CH_2R + NaOH \rightarrow RCH_2 - COONa + CH_2R$$

$$RCH_2 - \underset{\underset{OH}{|}}{CH} - CH_2 - COOH + H_2O \rightarrow RCH = CH - CH_2 - COOH$$

During heat treatment, the unsaponifiable fraction II is stripped from the soap solution by superheated steam, which is either generated by the evaporation of water present in the soap or supplied externally. The separated unsaponifiable fraction II is recycled back to the oxidation stage [8]. The technological scheme for obtaining higher fatty acids is shown in Figure 1. The catalyst solution prepared in vessel 1 is mixed with paraffin in apparatus 2. A 15% solution of potassium permanganate (at a loading of 0.1–0.3%) is introduced into paraffin heated to 120 °C. Water evaporates, while $KMnO_4$ becomes dispersed in the paraffin. The paraffin–catalyst mixture is then fed into the oxidation column 3, where purified air is supplied.

The temperature in the column is maintained at 105–115 °C using heating and cooling coils. During the induction period (2–3 hours), heat is supplied to the column by feeding steam into the lower coil. The outgoing air carries water vapor, low-molecular-weight acids, and other volatile products, which are condensed in

ISSN 3030-3907

cooler 4. The condensate is separated in separator 5 and sent to collector 7. The cooled air is washed in column 6 and then directed to the furnace. The washing water from column 6 is also sent to collector 7, where the mixture separates into two layers: an upper (organic) layer and a lower (aqueous) layer. The aqueous phase is either collected or sent to washing column 9 for oxidate purification. This phase may contain C_1–C_4 acids [9]. The oxidate from the reactor is directed to sludge settler 8 and then to washing column 9 to remove water-soluble low-molecular-weight acids.

Clean water and aqueous condensate from collector 7 may be supplied to the column. The washed oxidate is fed into saponifier 10, where acids are neutralized with a 25% soda solution at 90–100 °C (first stage of saponification), and then transferred to apparatus 11, where sodium hydroxide solution is used (second stage). The saponified product is separated in settler 12 at 70 °C into unoxidized paraffin (unsaponifiable I) and soap solution. The paraffin is recycled to the oxidation stage, while the soap is fed under a pressure of 2 MPa into furnace 13, heated by flue gases. In the furnace, the temperature is gradually increased: first to 180 °C, then to 220 °C, and finally to 320 °C. After heating, the soap enters an evaporator, where at atmospheric pressure the unsaponifiable fraction II is stripped by superheated steam and transferred to absorption column 17 irrigated with cold water from settler 18. The condensate and water are collected in settler 18, from which the unsaponifiable fraction II is recycled to the oxidation stage. The dry soap is diluted in vessel 14 with an aqueous solution of sodium sulfate, after which the soap solution is decomposed in vessel 15 with 92% sulfuric acid at 100 °C under intensive mixing. The resulting mixture of higher fatty acids and sodium sulfate is washed with water in column 16. The washed acids are then sent for distillation (not shown in the scheme). Equipment used for treating soap solutions with sulfuric acid is coated to protect against corrosion [10]. The obtained acids are distilled in stills equipped with packed columns. The stills are made of acid-resistant cast iron, while the coils and columns are made of stainless steel [10]. As the molecular weight of the acids increases, the temperature in the stills is increased and the residual pressure is reduced.

Table 1

Distillation conditions and yield of higher fatty acids

Still №	Temperature, °C	Residual pressure, Pa	Acid fractions	Acid yield, % (wt. of feed)
1	160-180	266-400	C_5 - C_6	4-5
2	170-180	26,6	C_7 – C_9	12-13
3	185	20	C_{10} – C_{13}	-

ISSN 3030-3907

4	200	20	$C_{14} – C_{16}$	65
5	280	20	$C_{17} – C_{20}$	-
6	310	20	C_{20}	4-5

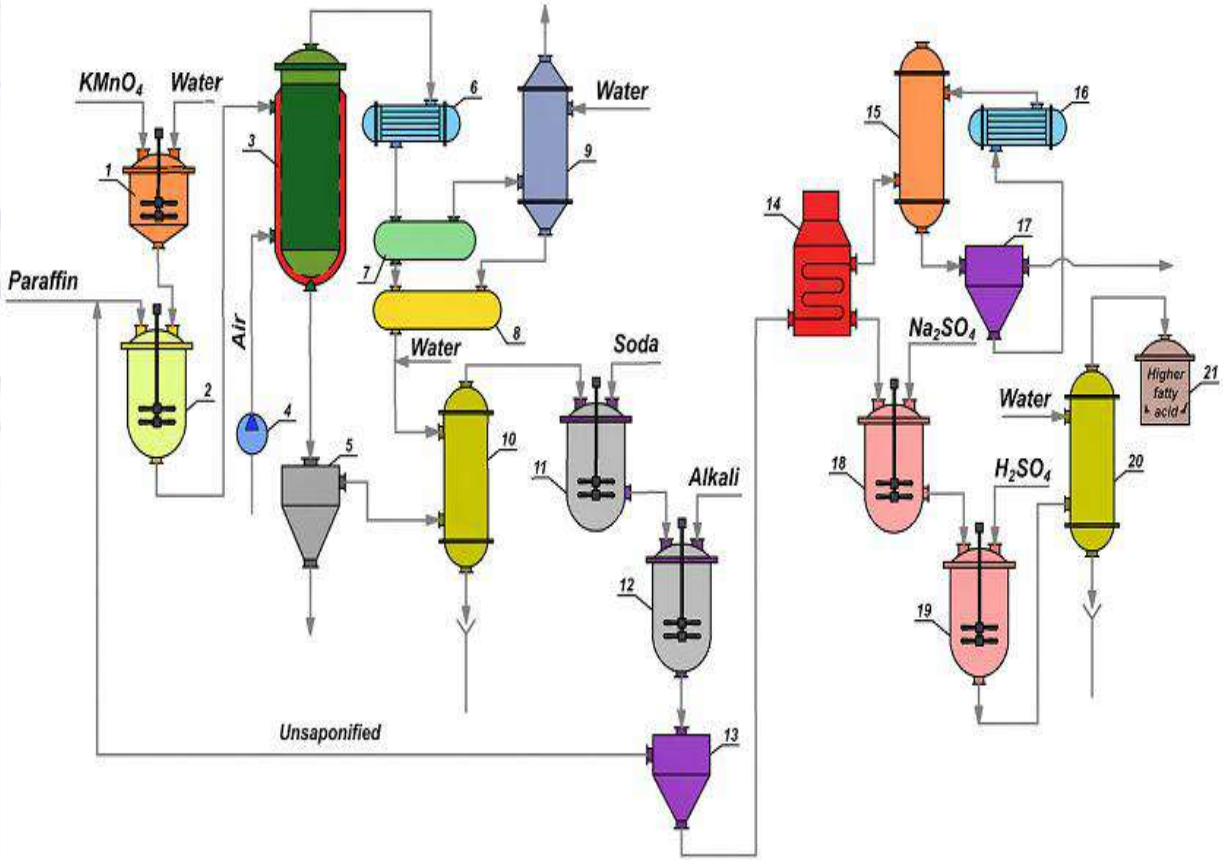


Figure 1. Technological scheme for obtaining higher fatty acids by oxidation of paraffin: *1, 18, 19 – mixing tanks; 2 – mixer; 3 – oxidation column; 4 – air compressor; 5 – sludge settling tank; 6, 16 – heat exchangers; 7 – separator; 8 – collection tank; 9 – washing scrubber; 10, 20 – washing columns; 11, 12 – saponification units; 13, 17 – settlers (clarifiers); 14 – heating furnace; 15 – absorption column; 21 – higher fatty acid tank.*

The use of unsaponifiable-II fractions for obtaining alcohols, as well as the separation of low-molecular acids from water condensate (scrubber) and from washing waters after oxidate washing, can improve the economic indicators of the process.

During the analysis, it was found that higher fatty acids synthesized from local secondary raw materials positively affect the operational properties of diesel fuels, improving their viscosity, lubricity, and anti-wear characteristics [12].

CONCLUSION

Thus, higher fatty acids obtained based on the proposed technology can compete with imported branded additives purchased from abroad. The synthesized higher fatty acids enable the production of environmentally clean diesel fuels at domestic oil refining plants with improved operational properties, enhanced

ISSN 3030-3907

lubricity and anti-wear characteristics, and a sulfur content that fully meets EURO-6 requirements.

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PHYSICOCHEMICAL, ENVIRONMENTAL, AND OPERATIONAL PROPERTIES OF SYNTHETIC GTL AND CONVENTIONAL DIESEL FUEL BLENDS

Ozoda Bakhranovna. Akhmedova
Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan
E-mail: zodamedova@gmail.com
Aliakbar To‘raqulyevich Ro‘ziyev
Bukhara State Technical University, Bukhara, Uzbekistan
Ruslan Rustamjonovich Hayitov
Bukhara State Technical University, Bukhara, Uzbekistan
Shokhruh Boboxon ogli Mavlonov
Bukhara State Technical University, Bukhara, Uzbekistan

Abstract. This study investigates the development of environmentally improved diesel fuels through blending synthetic Gas-to-Liquids (GTL) fuel with conventional diesel fuel and gas oil fractions. The objective was to determine how blend composition influences key physicochemical, operational, and environmental properties and to identify formulations suitable for practical use under EURO K4 requirements. Experimental blends were prepared by mechanical mixing at different volume ratios under laboratory conditions. Their cetane number and index, density, distillation behavior, kinematic viscosity, flash point, cold filter plugging point, sulfur content, polycyclic aromatic hydrocarbon content, oxidation stability, total contamination, copper-strip corrosion, and lubricity were determined using ASTM, EN, GOST, and O‘zDSt standard methods. The results showed that increasing the proportion of GTL significantly improved ignition quality and environmental performance. Blends containing 50–60% GTL achieved cetane numbers of 62–63, densities of 791.2–796.1 kg/m³, and kinematic viscosities of 3.27–3.33 mm²/s. Their sulfur content decreased to 9.4–17.2 mg/kg, while polycyclic aromatic hydrocarbons were reduced to 2.9–3.8%. The cold filter plugging point reached −10 to −11 °C, indicating satisfactory low-temperature operability. Distillation characteristics also confirmed a favorable balance between volatility and complete combustion. Overall, the study demonstrates that GTL-based blending is an effective approach for producing cleaner and more efficient diesel fuels. The optimized blends provide improved combustion stability, lower pollutant-forming components, acceptable lubricity, and reliable operation under low-temperature conditions, supporting their potential application in modern diesel engines

Keywords: GTL fuel, synthetic diesel, fuel blending, cetane number, density, viscosity, sulfur content, low-temperature properties, environmentally friendly fuel.

Annotatsiya. Ushbu tadqiqot sintetik gazdan suyuqlikka (GTL) yoqilg‘ini an'anaviy dizel yoqilg‘isi va gaz moylari fraktsiyalari bilan aralashtirish orqali ekologik jihatdan yaxshilangan dizel yoqilg‘isini ishlab chiqishni o‘rganadi. Maqsad - aralashmaning tarkibi asosiy fizik-kimyoviy, ekspluatatsion va ekologik xususiyatlarga qanday ta'sir qilishini aniqlash va EURO K4 talablari bo‘yicha amaliy foydalanish uchun mos formulalarni aniqlash edi. Laboratoriya sharoitida turli hajm nisbatida mexanik aralashtirish orqali eksperimental aralashmalar tayyorlandi. Ularning setan soni va indeksi, zichligi, distillash harakati, kinematik yopishqoqlik, chaqnash nuqtasi, sovuq filtrni ulash nuqtasi, oltingugurt miqdori, politsiklik aromatik uglevodorod miqdori, oksidlanish barqarorligi, umumiy ifloslanish, mis-chiziqli korroziya va moylash ASTM, EN, GOST va O‘zDSt standart usullari. Natijalar shuni ko‘rsatdiki, GTL ulushini oshirish ateşleme sifati va atrof-muhit ko‘rsatkichlarini sezilarli darajada yaxshiladi. 50-60% GTL bo‘lgan aralashmalar 62-63 setan soniga, 791,2–796,1 kg/m3 zichlikka va 3,27–3,33 mm2/s kinematik yopishqoqlikka erishdi. Ularning oltingugurt miqdori 9,4–17,2 mg/kg gacha kamaydi, polisiklik aromatik uglevodorodlar esa 2,9–3,8% gacha kamaydi. Sovuq filtrni ulash nuqtasi -10 dan -11 °C gacha yetdi, bu past haroratda ishlashning qoniqarli ekanligini ko‘rsatadi. Distillash xususiyatlari ham uchuvchanlik va to‘liq yonish o‘rtasidagi qulay muvozanatni tasdiqladi. Umuman olganda, tadqiqot shuni ko‘rsatadiki, GTL asosidagi aralashtirish toza va samaraliroq dizel yoqilg‘isini ishlab chiqarish uchun samarali yondashuvdir. Optimallashtirilgan aralashmalar yonishning yaxshilangan barqarorligini, ifloslantiruvchi moddalarni hosil qiluvchi komponentlarning kamayishini, maqbul moylash qobiliyatini va past harorat sharoitida ishonchli ishlashini ta'minlaydi, bu ularning zamonaviy dizel dvigatellarida qo‘llanilishini qo‘llab-quvvatlaydi.

Kalit so‘zlar: GTL yoqilg‘isi, sintetik dizel, yoqilg‘ini aralashtirish, setan soni, zichlik, yopishqoqlik, oltingugurt miqdori, past haroratli xususiyatlar, ekologik toza yoqilg‘i.

Аннотация. Это исследование посвящено разработке экологически более совершенного дизельного топлива путем смешивания синтетического газожидкостного топлива (GTL) с обычным дизельным топливом и газойлевыми фракциями. Цель состояла в том, чтобы определить, как состав смеси влияет на ключевые физико-химические, эксплуатационные и экологические свойства, а также определить составы, подходящие для практического применения в соответствии с требованиями стандарта EURO K4. Экспериментальные смеси были приготовлены путем механического смешивания при различных объемных соотношениях в

ISSN 3030-3907

лабораторных условиях. Их цетановое число и индекс, плотность, характеристики при дистилляции, кинематическая вязкость, температура вспышки, температура закупорки холодного фильтра, содержание серы, содержание полициклических ароматических углеводородов, устойчивость к окислению, общее загрязнение, коррозия медной ленты и смазывающая способность были определены с использованием стандартных методов ASTM, EN, ГОСТ и O‘ZDST. Результаты показали, что увеличение доли GTL значительно улучшило качество зажигания и экологические показатели. Смеси, содержащие 50-60% GTL, достигали цетановых чисел 62-63, плотности 791,2–796,1 кг/м3 и кинематической вязкости 3,27–3,33 мм2/с. Содержание серы в них снизилось до 9,4–17,2 мг/кг, а содержание полициклических ароматических углеводородов – до 2,9-3,8%. Температура закупорки холодного фильтра достигла -10- -11°C, что свидетельствует об удовлетворительной работе при низких температурах. Характеристики дистилляции также подтвердили благоприятный баланс между летучестью и полным сгоранием. В целом, исследование показывает, что смешивание на основе GTL является эффективным способом получения более чистого и экономичного дизельного топлива. Оптимизированные смеси обеспечивают повышенную стабильность горения, меньшее количество загрязняющих веществ, приемлемую смазывающую способность и надежную работу в условиях низких температур, что подтверждает их потенциальное применение в современных дизельных двигателях.

Ключевые слова: топливо GTL, синтетическое дизельное топливо, топливная смесь, цетановое число, плотность, вязкость, содержание серы, низкотемпературные свойства, экологически чистое топливо.

INTRODUCTION.

The production of environmentally safe and highly efficient motor fuels that meet modern operational requirements is one of the major global scientific and technological challenges in the fuel and energy sector [1]. The increasing number of vehicles, the expansion of industrial production, and the growing amount of harmful emissions released into the atmosphere have created a need to improve fuel quality and energy efficiency while reducing the environmental impact [2]. At the same time, increasingly stringent international environmental standards require the development of a new generation of fuels that provide more complete combustion in engines, produce lower levels of harmful gaseous emissions, and ensure stable operation under low-temperature conditions [3]. Synthetic liquid fuels, particularly

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Gas-to-Liquids (GTL) products obtained through the conversion of natural gas, are of considerable scientific and practical importance in addressing these challenges [4].

Recent scientific studies have demonstrated that synthetic diesel fuels are characterized by a high cetane number, low sulfur and aromatic hydrocarbon contents, a stable chemical composition, and high combustion efficiency [5]. A number of studies have also shown that the physicochemical, operational, and environmental properties of fuels can be purposefully controlled by blending synthetic components with conventional petroleum fractions [6]. Some researchers have demonstrated that the selective blending of narrow-boiling hydrocarbon fractions can improve low-temperature properties, optimize density and viscosity, and regulate the kinetic parameters of the combustion process [7].

However, the comprehensive technological principles governing the blending of synthetic and conventional fuels have not yet been studied systematically. In particular, the influence of the component ratio on the physicochemical and environmental properties of the resulting fuel remains insufficiently investigated. Some previous studies have been limited to the analysis of individual fuel properties, while the relationships among the operational efficiency, low-temperature performance, oxidation stability, and engine performance of blended fuels have not been adequately clarified. Furthermore, significant research gaps remain in the development of new motor fuels that meet environmental requirements through the scientifically justified blending of synthetic fuels produced from regional raw materials with locally available petroleum fractions.

Accordingly, the main objective of this study is to produce fuels with improved environmental and operational properties by blending synthetic and conventional fuels and to conduct a comprehensive investigation of their physicochemical characteristics. To achieve this objective, the following tasks were defined: to determine the main physicochemical properties of synthetic and conventional fuel components; to prepare blended fuel compositions by mixing these components in different proportions; to evaluate the low-temperature properties, combustion efficiency, environmental performance, and oxidation stability of the blended fuels; to determine the optimal composition; and to develop the scientific and technological principles for producing environmentally friendly and highly efficient motor fuels [8-12].

MATERIALS AND METHODS.

Diesel fuel produced by the Bukhara Oil Refinery (BNQIZ), EURO K4 grade, and synthetic diesel fuel produced by Uzbekistan GTL (a product obtained using GTL technology) were selected as the study objects. The study aimed to

ISSN 3030-3907

determine the physicochemical and performance characteristics of these fuels (Table 1) and to evaluate the properties of blended fuel compositions obtained by mixing them. Synthetic diesel fuel is characterized by a high proportion of paraffinic hydrocarbons and very low contents of aromatic hydrocarbons and sulfur compounds. Conventional diesel fuel is a product obtained through primary petroleum refining and hydrotreating processes (Table 2).

Table 1

Physicochemical Characteristics of Conventional and Synthetic Diesel Fuels

No.	Parameter	Test method	O‘zDSt requirement	EURO K4 diesel fuel	Synthetic diesel fuel (GTL)
1	Cetane number, min.	ASTM D613	51	58	84.0
2	Cetane index, min.	ASTM D4737	46.0	54.9	74.5
3	Density at 20°C, kg/m³, max.	GOST 3900	860	828	769.9
4	**Distillation characteristics:**				
	Volume recovered at 250°C, %, min.	GOST 2177	65	24	54
	Volume recovered at 350°C, %, min.		85	96	98
	Temperature at 95% recovery, °C, max.		360	345	323
5	Water content, mg/kg, max.	GOST 2477	0.02	104.2	0
6	Cold filter plugging point, °C, max.	EN 116	−5	−1	below −35
7	Carbon residue of the 10% distillation residue, %, max.	ASTM D4530	0.3	0.01	0.016
8	Ash content, %, max.	GOST 1461	0.01	0.003	0.0028
9	Sulfur content, mg/kg, max.	EN ISO 20884	50	23.7	4.2

ISSN 3030-3907

10	Copper strip corrosion (3 h at 50°C)	ASTM D130	Class 1	1a	1a
11	Kinematic viscosity at 40°C, mm²/s	GOST 33	2.0–4.5	3.5	3.3
12	Flash point (closed cup), °C, min.	GOST 6356	55	83	70
13	Polycyclic aromatic hydrocarbons, %, max.	GOST EN 12916	8.0	4.0	1.0
14	Total contamination, mg/kg, max.	EN 12662	24	7.0	4.9
15	**Oxidation stability:**				
	Sediment content, g/m³, max.	ASTM D2274	25	3.8	2.8
	Stability time, h, min.		20	20	20
16	Fatty acid methyl esters, %, max.	GOST EN 14078	7.0	0.12	0
17	Lubricity (WSD 1.4 at 60°C), µm, max.	ASTM D6079	460	387	625

Table 2

Laboratory Analysis Results for Gas Oils from Unit 10 of BNQIZ

No.	Parameter	Specification (ANSA)	Light gas oil (Unit 10)	Heavy gas oil (Unit 10)	Gas oil (Unit 10)
1	Density at 15°C, kg/m³	815–840	817.9	836.6	–
2	Distillation characteristics:				
	50% distillation temperature, °C	≤280	238	280	179
	95% distillation temperature, °C	≤340	251	334	355
	Final boiling point, °C	≤360	278	388	365
	Residue in the flask, vol. %	≤2	1.0	1.6	2.8
3	Kinematic viscosity at 20°C, mm²/s	2.5–5.0	3.8	7.4	7.3

ISSN 3030-3907

4	Cloud point, °C	≤ −10	–	−1	+2

Fuel compositions were prepared under laboratory conditions by mechanical mixing. During the blending process, synthetic and conventional diesel fuels were mixed at different volume ratios to obtain homogeneous mixtures. Mixing was performed at room temperature, and the prepared blends were stored in airtight containers for subsequent physicochemical analyses.

Physicochemical Analysis Methods

The cetane number of the fuels was determined according to ASTM D613 to assess the ignition rate and smoothness of engine operation. The cetane index was calculated in accordance with ASTM D4737. Fuel density at 20°C was determined according to GOST 3900, and the effect of blend composition on energy efficiency was evaluated. Distillation characteristics were determined according to GOST 2177 to investigate fuel volatility and its effect on combustion kinetics. Water content was determined according to GOST 2477, and its effect on blend stability was assessed. Low-temperature properties, particularly the cold filter plugging point, were determined according to EN 116 to evaluate the applicability of the blended fuels under cold-climate conditions. Carbon residue was determined according to ASTM D4530 to assess the likelihood of deposit formation in the combustion chamber. Ash content was determined according to GOST 1461 to evaluate fuel contamination by mineral impurities. Sulfur content was determined according to EN ISO 20884 to assess the environmental characteristics of the blended fuels. Copper strip corrosion was determined according to ASTM D130 to evaluate the interaction of the fuel with metallic components. Kinematic viscosity at 40°C was determined according to GOST 33 to analyze fuel pumpability and atomization characteristics. The closed-cup flash point was determined according to GOST 6356 to assess fuel safety. The content of polycyclic aromatic hydrocarbons was determined according to GOST EN 12916 to evaluate environmental safety. Total contamination was determined according to EN 12662 to assess fuel cleanliness. Oxidation stability was determined according to ASTM D2274 to evaluate the long-term storage stability of the fuel. Lubricity was determined according to ASTM D6079 to assess the effect of the fuel on engine fuel-system components [13-16].

Results and Discussion: The laboratory results showed that the physicochemical and performance properties of the fuel can be significantly controlled by blending GTL and conventional diesel fuels at different ratios.

ISSN 3030-3907

Table 3

"Physicochemical and Performance Characteristics of Blends of Synthetic GTL Fuel with Conventional Gas Oil and Diesel Fuel at Different Ratios"

No.	**Parameter**	**10% GTL + 90% gas oil**	**22% GTL + 78% gas oil**	**25% GTL + 75% diesel fuel**	**30% GTL + 70% diesel fuel**
1	Density at 15°C, kg/m³	813.7	813.7	816.0	816.4
2	Cetane number		62	59	58
3	Cetane index		66	61.2	61.4
4	Distillation characteristics				
	50% distillation temperature, °C	239	239	272	278
	90% distillation temperature, °C	259	259	348	346
	Final boiling point, °C	320	311	385	373
	Residue volume, %	1.0	1.0	1.6	1.7
5	Flash point, °C	78	78	57	60
6	Kinematic viscosity at 40°C, mm²/s	4.0	4.0	4.0	4.2
7	Sulfur content, %	0.068	0.068	0.07	0.062
8	Cloud point, °C	−28	−32	−3	−3
9	Copper strip corrosion	Class 1	Class 1	Class 1	Class 1

As the proportion of GTL in the prepared fuel compositions increased, the fuel density decreased to a certain extent, amounting to 813.7 kg/m³ for the blend containing 10% GTL + 90% gas oil and 816.0 kg/m³ for the blend containing 25% GTL + 75% diesel fuel. The cetane number increased with the GTL content and reached 62 in the 22% GTL + 78% gas oil blend, which improved combustion stability. Distillation characteristics were also important indicators of the blending process. The 50% distillation temperature varied from 239 to 278°C, while the final boiling point ranged from 311 to 385°C. These changes indicate that the amount of heavy fractions decreases as the proportion of synthetic GTL fuel increases. Kinematic viscosity was within the range of 4.0–4.2 mm²/s for all blends, supporting stable operation of the engine fuel system. Sulfur content ranged from 0.062 to 0.07% and decreased as the GTL proportion increased. The variation in

ISSN 3030-3907

cloud point from −28 to −3°C, together with the blending of narrow-cut hydrocarbon components, demonstrates the possibility of controlling the low-temperature properties of the fuel.

Table 4

"Environmental and Performance Characteristics of GTL and Diesel Fuel Blends at Different Ratios Meeting EURO K4 Requirements"

No.	Parameter	GTL 50% + EURO K4 diesel 50%	GTL 55% + EURO K4 diesel 45%	GTL 60% + EURO K4 diesel 40%
1	Cetane number, min.	62	63	62
2	Cetane index, min.	59.5	60.0	60.0
3	Density at 20°C, kg/m³	796.1	793.1	791.2
4	Distillation characteristics: Volume recovered at 250°C, vol. %, min. Volume recovered at 350°C, vol. %, min. Temperature at 95% recovery, °C, max.	 44 96 340	 43 96 342	 44 97 335
5	Water content, mg/kg, max.	43.7	44.5	42.8
6	Cold filter plugging point, °C, max.	–11	–10	–10
7	Carbon residue of the 10% distillation residue, %, max.	0.018	0.016	0.018
8	Ash content, %, max.	0.0032	0.0030	0.0033
9	Sulfur content, mg/kg, max.	17.2	11.3	9.4
10	Copper strip corrosion (3 h at 50°C)	1a	1a	1a
11	Kinematic viscosity at 40°C, mm²/s	3.33	3.31	3.27
12	Flash point, °C, min.	75	73	71
13	Polycyclic aromatic hydrocarbons, %, max.	3.8	3.4	2.9
14	Total contamination, mg/kg, max.	5.8	5.4	5.6

ISSN 3030-3907

15	Oxidation stability: sediment content, g/m³, max.	3.7	3.4	3.3
	Stability time, h, min.	20	20	20
16	Fatty acid methyl esters (FAME), %, max.	0.05	0.04	0.05
17	Lubricity (WSD 1.4) at 60°C, μm, max.	450	455	460

Blends obtained by combining EURO K4 diesel fuel and GTL products at different ratios were found to have high performance characteristics. The cetane number was in the range of 62–63, indicating improved combustion efficiency. Density values ranged from 791.2 to 796.1 kg/m³ and decreased as the GTL content increased. Distillation analysis showed that the proportion of light fractions distilled at temperatures up to 250°C was 43–44%. The proportion distilled at temperatures up to 350°C was 96–97%, which had a positive effect on complete fuel combustion. The cold filter plugging point was −10 to −11°C, demonstrating that the blends can also operate under low-temperature conditions. Sulfur content was within the range of 9.4–17.2 mg/kg, while the polycyclic aromatic hydrocarbon content was 2.9–3.8%, indicating improved environmental characteristics. Kinematic viscosity was 3.27–3.33 mm²/s, which positively affects fuel atomization and combustion characteristics.

DISCUSSION OF THE RESULTS.

The obtained results demonstrated that synthetic GTL fuel, owing to its high paraffinic hydrocarbon content, improves the combustion characteristics of conventional diesel fuels. The increase in the cetane number enhances the self-ignition capability of the fuel and, consequently, ensures stable engine operation. At the same time, the decrease in fuel density with an increasing proportion of GTL improves the atomization of the fuel supplied to the engine and promotes more complete combustion in the combustion chamber.

The optimization of the fractional composition regulates the fuel evaporation rate and improves engine start-up characteristics under cold conditions. A significant reduction in sulfur content is of considerable environmental importance, as it contributes to a decrease in SOx emissions. Furthermore, the reduction in the cloud point and cold filter plugging point improves the operational performance of the fuel in low-temperature regions [17-20].

Blends of GTL and EURO K4 diesel fuel are characterized by compliance with the requirements of international standards in terms of their physicochemical properties, as well as by improved operational characteristics. The results indicate

ISSN 3030-3907

that GTL-based blends make it possible to develop environmentally friendly, highly efficient, and promising types of diesel fuel and contribute to reducing dependence on petroleum resources.

CONCLUSION.

The conducted studies established that the environmental and operational characteristics of fuel can be significantly improved by blending synthetic GTL fuel with conventional diesel fuel and gas oil fractions in various proportions. The experimental results showed that an increase in the proportion of the GTL component leads to an increase in the cetane number and cetane index, while the sulfur content, proportion of aromatic hydrocarbons, and level of total contamination decrease. These changes promote more complete combustion, reduce the amount of harmful emissions, and improve engine operating efficiency [21].

According to the results of the fractional composition analysis, GTL-based blends were characterized by optimized distillation temperatures and boiling ranges. This improves the evaporation characteristics of the fuel and enhances engine start-up performance under cold conditions. The results obtained in accordance with EURO K4 requirements confirmed the environmental safety of diesel blends containing GTL. In particular, the reduction in sulfur content and the proportion of polycyclic aromatic hydrocarbons decreases the adverse environmental impact of the fuel. At the same time, maintaining the lubricity characteristics at an acceptable level reduces the wear of engine components and ensures the reliable operation of the fuel system [22,23].

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ISSN 3030-3907

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BLACK POWDER IN NATURAL GAS TRANSMISSION SYSTEMS: EDXRF CHARACTERIZATION AND METROLOGICAL IMPLICATIONS

Ozoda Bakhranovna Akhmedova
Tashkent State Technical University named after Islam Karimov University Street 2, Tashkent 100095, Uzbekistan
Email: zodamedova@gmail.com
Sh.M.Isamadinov
Chief Engineer, Fergana Main Gas Pipeline Administration, JSC Uztransgaz, Fergana, Uzbekistan
Abdurasul Qayumov Shonazarovich
Tashkent State Technical University named after Islam Karimov University Street 2, Tashkent 100095, Uzbekistan
M.B.Akhmedova
Bukhara State Technical University K. Murtazayev Street 15, Bukhara 200117, Uzbekistan

Abstract. Mixed deposits comprising corrosion products, mineral particles, condensate, and heavy hydrocarbons can accumulate in filters and orifice-based metering units at gas distribution stations, thereby reducing the accuracy of natural gas flow measurement. This study aimed to determine the elemental composition of pipeline deposits locally referred to as perafor or black powder and to assess their potential influence on differential-pressure gas metering. A deposit sample collected from a gas transmission system was analysed using energy-dispersive X-ray fluorescence spectrometry. The elemental mass fractions were calculated using the fundamental parameters method, and the analysis was repeated three times to verify the reproducibility of the results. The estimated carbon content was 71.60 mass%, while the principal directly detected elements were Fe at 16.30 mass%, S at 6.58 mass%, Si at 1.30 mass%, Cl at 1.22 mass%, and Ca at 1.18 mass%. The results indicate that the deposit is a complex heterogeneous mixture of carbonaceous binders, iron-containing corrosion products, sulfur-containing compounds, and mineral particulates rather than solely soot or rust. Accumulation of this material on the orifice bore and upstream edge reduces the effective flow area, artificially increases the differential pressure, and may consequently result in overestimation of the measured gas flow rate. The findings demonstrate the importance of deposit monitoring and support the targeted application of dispersants upstream of filters and metering units, particularly in pipeline sections prone to moisture and condensate formation. The results can contribute to improving the operational reliability and measurement accuracy of natural gas transmission systems.

ISSN 3030-3907

Keywords: natural gas transmission pipeline; black powder; pipeline deposits; EDXRF; orifice flow measurement; differential pressure; corrosion products; gas metering; dispersant.

Annotatsiya. Korroziya mahsulotlari, mineral zarrachalar, kondensat va og‘ir uglevodorodlarni o‘z ichiga olgan aralash konlar gaz taqsimlash stansiyalaridagi filtrlar va teshikli o‘lchash qurilmalarida to‘planishi mumkin, bu esa tabiiy gaz oqimi o‘lchovining aniqligini pasaytiradi. Ushbu tadqiqot mahalliy darajada perafor yoki qora kukun deb ataladigan quvur liniyasi konlarining elementar tarkibini aniqlash va ularning differentsial bosimli gazni o‘lchashga potentsial ta'sirini baholashga qaratilgan. Gaz uzatish tizimidan olingan kon namunasi energiya-dispersiv rentgen floresans spektrometriyasi yordamida tahlil qilindi. Elementar massa fraksiyalari asosiy parametrlar usuli yordamida hisoblab chiqilgan va natijalarning takrorlanishi tekshirilishi uchun tahlil uch marta takrorlangan. Taxminiy uglerod tarkibi 71,60 massa % ni tashkil etdi, asosiy aniqlangan elementlar esa Fe 16,30 massa% da, S 6,58 massa% da, Si 1,30 massa% da, Cl 1,22 massa% da va Ca 1,18 massa%da. Natijalar shuni ko‘rsatadiki, depozit faqat kuyikish yoki zang emas, balki uglerodli bog‘lovchilar, temir o‘z ichiga olgan korroziya mahsulotlari, oltingugurt o‘z ichiga olgan birikmalar va mineral zarrachalarning murakkab heterojen aralashmasidir. Ushbu materialning teshik teshigi va yuqori oqim chetida to‘planishi samarali oqim maydonini kamaytiradi, differentsial bosimni sun'iy ravishda oshiradi va natijada o‘lchangan gaz oqim tezligini ortiqcha baholashga olib kelishi mumkin. Topilmalar depozit monitoringining muhimligini namoyish etadi va dispersantlarni filtrlar va o‘lchash moslamalarining yuqori qismida, ayniqsa namlik va kondensat hosil bo‘lishiga moyil bo‘lgan quvur liniyalarida maqsadli qo‘llanilishini qo‘llab-quvvatlaydi. Natijalar tabiiy gaz uzatish tizimlarining ekspluatatsion ishonchliligi va o‘lchov aniqligini oshirishga yordam beradi.

Kalit so‘zlar: tabiiy gazni uzatish quvuri; qora kukun; quvur liniyasidagi konlar; EDXRF; teshik orqali oqimni o‘lchash; differentsial bosim; korroziya mahsulotlari; gazni o‘lchash; dispersant.

Аннотация. Смешанные отложения, содержащие продукты коррозии, минеральные частицы, конденсат и тяжелые углеводороды, могут накапливаться в фильтрах и дозирующих устройствах на газораспределительных станциях, тем самым снижая точность измерения расхода природного газа. Целью данного исследования было определить элементный состав отложений на трубопроводах, которые в местных условиях называют перафором или черным порошком, и оценить их

ISSN 3030-3907

потенциальное влияние на измерение перепада давления газа. Образец отложений, взятый из газотранспортной системы, был проанализирован с помощью энергодисперсионной рентгенофлуоресцентной спектрометрии. Массовые доли элементов были рассчитаны с использованием метода фундаментальных параметров, и анализ был повторен три раза для проверки воспроизводимости результатов. Предполагаемое содержание углерода составило 71,60 мас.%, в то время как основными непосредственно обнаруженными элементами были Fe - 16,30 мас.%, S - 6,58 мас.%, Si - 1,30 мас.%, Cl - 1,22 мас.% и Ca - 1,18 мас.%. Результаты показывают, что отложения представляют собой сложную гетерогенную смесь углеродистых связующих, железосодержащих продуктов коррозии, серосодержащих соединений и минеральных частиц, а не только сажу или ржавчину. Скопление этого материала на отверстии и входной кромке уменьшает эффективную площадь потока, искусственно увеличивает перепад давления и, следовательно, может привести к завышению измеренного расхода газа. Полученные результаты демонстрируют важность мониторинга отложений и способствуют целенаправленному применению диспергаторов перед фильтрами и дозирующими узлами, особенно на участках трубопроводов, подверженных образованию влаги и конденсата. Результаты могут способствовать повышению эксплуатационной надежности и точности измерений в системах транспортировки природного газа.

Ключевые слова: газопровод для транспортировки природного газа; сажа; отложения на трубопроводе; EDXRF; измерение расхода через диафрагму; перепад давления; продукты коррозии; дозирование газа; диспергатор.

INTRODUCTION.

Main natural-gas transmission pipelines are used in the Republic of Uzbekistan to transport natural gas and deliver it to socially important consumers, including households and public-sector institutions, as well as wholesale consumers, compressed-natural-gas filling stations, and strategically important facilities such as thermal power plants and mineral-fertilizer production enterprises. Main gas pipelines receive natural gas from compressor stations and deliver it to consumers through gas distribution stations (GDSs). A gas distribution station is a technological facility designed to receive natural gas from a main pipeline, reduce its pressure, meter and purify the gas, and distribute it to consumers [1].

ISSN 3030-3907

Depending on their service coverage, gas distribution stations are divided into two types:

1. Main GDSs, which primarily serve cities with large numbers of consumers or major industrial facilities.

2. Local GDSs, which serve districts, villages, or small production enterprises with comparatively fewer consumers.

The main functional units of a gas distribution station are as follows:

1. Inlet unit, which receives natural gas from the main gas pipeline.
2. Filters, which retain, as far as practicable, “perafor” and other foreign materials contained in the natural gas.
3. Pressure regulators, which stabilize the natural-gas pressure at the specified level.
4. Metering unit, which determines the natural-gas flow rate.
5. Safety valves, which monitor excessive pressure and protect the system against overpressure.
6. Odorant storage vessel, which stores ethyl mercaptan used for natural-gas odorization.
7. Outlet headers, which distribute the natural gas to consumer networks.

At present, the year-by-year decline in available natural-gas resources and the need to deliver gas safely to residential, wholesale, and compressed-natural-gas filling-station consumers make accurate accounting of every cubic metre of supplied gas an increasingly important task. Under these conditions, it is appropriate to install an electronic gas flow computer that complies with the applicable GOST requirements within the GDS metering complex [2–3].

The electronic gas flow computers currently installed at GDSs in Uzbekistan include AutoPilot, AutoPilot PRO, and Floobus units. These devices determine the flow rate of high-pressure natural gas passing through the metering assembly from the measured differential pressure. They are measurement-and-information systems that determine the natural-gas flow rate in real time, convert the measured values to standard conditions, and transmit the results to dispatching systems by telemetry; the stated accuracy class is ±1.5 %. The flow computer calculates the natural-gas flow rate from the pressure differential ΔP generated by a restriction device, namely an orifice plate, installed in the pipeline. A restriction device is a hydraulic element that reduces the flow cross-section inside the pipe, thereby changing the velocity and pressure of the stream and enabling the flow rate to be calculated from ΔP.

The operating principle of the restriction device is as follows: high-pressure natural gas passes through the orifice plate, the flow velocity increases, the static pressure decreases, and a differential pressure ΔP is generated between the

ISSN 3030-3907

upstream and downstream pressure-tapping points. The gas flow rate is then calculated from this differential pressure.

The pressure signal generated in the sealed section containing the orifice plate is transmitted to the electronic flow computer through impulse lines.

Impulse lines are elements that establish a hydraulic connection between the natural-gas pipeline and the measuring instrument, such as a pressure or differential-pressure transmitter, and transmit the process-medium parameters without distortion. Two impulse lines are used: one for the positive-pressure side and one for the negative-pressure side.

During natural-gas transmission, contaminants and deposits accumulate on the orifice bore and on its upstream and downstream edges. In operating practice, this material is locally referred to as “perafor”. Perafor mainly consists of sand, dust, corrosion products, metal particles, and heavy hydrocarbons mixed with condensate.



Figure 1. Perafor contamination and deposits accumulated on the orifice plate and inside the adjacent pipeline section.

Several practical assumptions may be proposed regarding the formation of perafor:

1. Insufficient purification of the natural gas.
2. The presence of corrosion in the natural-gas pipeline.
3. The presence of moisture in the natural gas.
4. Inefficient operation of the natural-gas filters or failure to clean them at the required intervals.

This condition may adversely affect natural-gas accounting because the effective diameter of the orifice bore decreases, the differential pressure ΔP may be artificially increased, and the electronic flow computer may overestimate the gas flow rate. The deposits may also contribute to malfunction of process equipment, including ball valves, various control and safety valves, and pressure

ISSN 3030-3907

regulators operating within the GDS, and may reduce the thermal or operational efficiency of gas-consuming equipment installed at consumer facilities.

Such operational problems not only threaten the reliable performance of the measuring instruments, but also interrupt gas delivery because the flow inside the pipeline must be stopped while the orifice plate is cleaned, and pressure control in the isolated line becomes more difficult. According to field observations, approximately 30–60 min is required to clean a contaminated orifice plate and return the metering line to service. During this period, gas-delivery interruption and a reduction in pressure in the isolated line may occur.

Factors contributing to perafor formation include localized pitting corrosion and under-deposit corrosion in pipelines. Moisture, internal corrosion, and ineffective filtration may be emphasized as the principal causes. Under these conditions, the key conclusion is that the problem is not pure “gas corrosion”, but a combination of moisture, condensate, solid particles, low-point deposits, and low-point corrosion. In gas-transmission pipelines, properly dried gas alone generally does not cause severe internal corrosion. Corrosion develops mainly when water condenses and forms an electrolyte with CO_2 or other aggressive components. Materials prepared for the Gas Research Institute/Internal Corrosion Direct Assessment (GRI/ICDA) approach for gas-transmission systems likewise indicate that internal corrosion commonly develops following an upstream gas-treatment upset that permits free water or another corrosive liquid to enter the pipeline. Guidance from the Pipeline and Hazardous Materials Safety Administration (PHMSA) also indicates that sales-quality dry gas does not normally corrode the internal surface and that the problem begins when water condenses. Thermodynamic hydrate inhibitors such as methanol or monoethylene glycol can help prevent hydrate formation by reducing moisture; however, they do not eliminate sand, rust, metal particles, or heavy-hydrocarbon deposits and, in some cases, may become an additional factor affecting formation of an aqueous phase at pipeline low points.

The concentration of hydrogen sulfide in the transported gas is very low, at the ppm level. However, because carbon dioxide is present, corrosion of the metal may occur through the action of CO_2 in the presence of moisture. The principal simplified reactions are:

$$CO_2 + H_2O \rightarrow H_2CO_3 \text{ (carbonic acid)}$$

$$H_2CO_3 + Fe \rightarrow FeCO_3 + H_2$$

When the carbon-dioxide content of the transported gas exceeds approximately 0.5 %, the tendency toward corrosion may increase. Carbon-dioxide solubility increases particularly at elevated pressure, while corrosion can become

ISSN 3030-3907

active at moderate and low temperatures. Localized pitting corrosion may develop in the pipeline, accompanied by an increase in iron-carbonate ($FeCO_3$) deposits [4].

MATERIALS AND METHODS.

To identify possible solutions to the operational problems described above, the component composition and physicochemical properties of the gas transported through the main gas pipeline were first examined (Tables 1 and 2).

Table 1.

Component composition of the natural gas sampled at the Khojaabad gas distribution station

No.	Component	mol %
1	CO_2	1.35
2	N_2	0.68
3	O_2	0.00
4	Methane (CH_4)	94.01
5	Ethane (C_2H_6)	3.28
6	Propane (C_3H_8)	0.52
7	i-Butane	0.06
8	n-Butane	0.06
9	i-Pentane	0.02
10	n-Pentane	0.02
11	Hexane	0.00

Table 2.

Properties of the natural gas sampled at the Khojaabad gas distribution station

No.	Facility	Gas density (kg/m^3)	Calorific value ($kcal/m^3$)	CO_2 (%)	N_2 (%)
1	Khojaabad GDS	0.716	8123	1.35	0.68
2	Gazli Main Gas Pipeline Administration	0.717	8009	0.977	1.866

Analysis of the natural gas sampled at the Khojaabad gas distribution station showed that the gas consisted predominantly of methane (94.01 mol %), while the CO_2 content was 1.35 mol %. Under high-pressure conditions (3–8 MPa) and in the possible presence of moisture, this level is considered sufficient to activate corrosion processes [5].

The practical problem is not pipeline corrosion alone, but accumulation in filters and at the orifice bore of perafor consisting of sand, dust, rust, corrosion

ISSN 3030-3907

products such as $FeCO_3$, metal particles, condensate, and heavy hydrocarbons. This deposit reduces the effective orifice diameter, may artificially increase ΔP, and can create a risk of overestimation of the gas flow rate. This represents one of the most significant adverse effects in the system.

Many GDS metering systems use electronic flow computers connected to differential-pressure transmitters and an orifice plate. For a geometrically compliant and hydraulically developed installation, the mass-flow rate is related to the pressure drop according to the standard orifice-meter relation:

$$q_m = (C\,\varepsilon / \sqrt{(1-\beta^4)})\,(\pi d^2/4)\,\sqrt{(2\Delta p\,\rho_1)} \quad (1)$$

where q_m is the mass-flow rate, C is the discharge coefficient, ε is the expansibility factor, $\beta = d/D$ is the diameter ratio, d is the orifice bore, D is the pipe internal diameter, Δp is the differential pressure, and ρ_1 is the upstream density. Deposits that modify the bore, upstream edge, surface roughness, pressure-tap condition, or local flow profile can therefore change the measurement response

To identify an appropriate solution for protecting the electronic gas flow computer against the principal adverse influence in the system, the composition of the contaminants and deposits accumulated on the orifice bore and on the upstream and downstream edges during natural-gas transmission was determined.

The black powder (perafor) sample was collected from the orifice-metering assembly of a gas distribution station and transported to the laboratory in a hermetically sealed container. A representative laboratory portion was separated, dried at 40 ± 5 °C to constant mass, and cooled in a desiccator. The dried sample was deagglomerated, reduced to a particle-size fraction of <75 μm, and homogenized. For EDXRF analysis, 4.0 ± 0.1 g of the sample was placed in a 32/40 mm XRF sample cup fitted with a 4 μm Prolene film. Three independent test portions were prepared. The instrument was operated in the NEX CG II configuration over the Na–U elemental range, using selected secondary-target channels and validated counting times. Quantitative analysis was performed using the fundamental-parameters method and matrix-matched reference materials. For calibration verification, an independent certified reference material, a blank, and a laboratory duplicate were measured in each analytical batch. The results were expressed as mean ± standard deviation (n = 3), together with the relative standard deviation, lower limit of detection, and lower limit of quantification. The C* value generated by the fundamental-parameters calculation was treated as a model-dependent balance estimate, while the oxide-equivalent values were regarded as software-normalized representations rather than direct identification of crystalline phases.

The perafor sample was analysed by energy-dispersive X-ray fluorescence spectrometry (EDXRF). The instrument employed 90° Cartesian geometry,

ISSN 3030-3907

indirect excitation through secondary targets, a 50 kV/50 W X-ray tube with a palladium anode, and a large-area silicon-drift detector (SDD); it was capable of direct detection of elements from Na to U [15]. The laboratory spectrum contained the Si, RX9, Cu, Mo, and Al secondary-target/polarizer channels. When the sample is excited by X-rays, characteristic fluorescence lines specific to each element are generated. The energy of each line is used to identify the element, while its intensity is used to calculate the mass fraction.

Quantification was performed by the instrument software using the fundamental-parameters (FP) method. The FP algorithm deconvolutes spectral lines, accounts for matrix absorption and enhancement effects, and normalizes the result in mass %. In the NEX CG II system, low-atomic-number constituents from hydrogen to fluorine, including carbon, may be estimated from scattering parameters and mass balance rather than from a directly measured XRF line [6].

RESULTS.

In the elemental report, the principal components were C* at 71.60 mass %, Fe at 16.30 mass %, S at 6.58 mass %, Si at 1.30 mass %, Cl at 1.22 mass %, and Ca at 1.18 mass %. The high iron content indicates the presence of iron-containing corrosion products originating from the pipe, orifice plate, or other metallic equipment. Silicon, calcium, aluminium, and magnesium may indicate mineral dust, sand, or process-derived solid particles.

The appreciable sulfur and chlorine contents indicate the presence of sulfur-containing and chlorine-containing constituents in the deposit. However, EDXRF does not determine the valence state of an element or identify a specific chemical compound. Consequently, sulfur cannot be assigned exclusively to SO_3, iron exclusively to Fe_2O_3, or chlorine to a specific chloride on the basis of the EDXRF result alone.

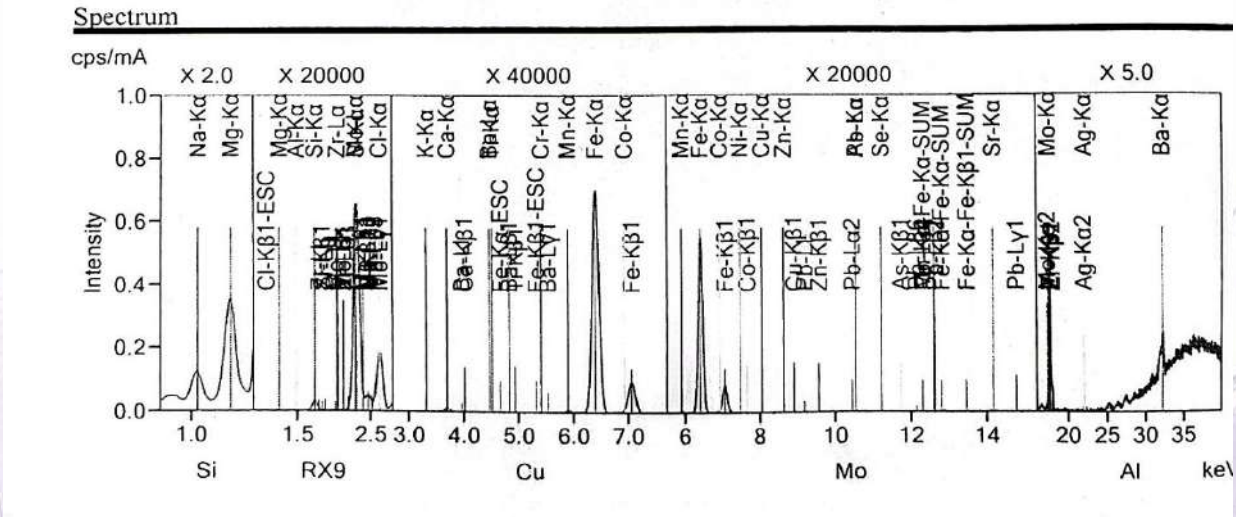


Figure 2. EDXRF spectrum of the perafor powder sample obtained with the NEX CG II instrument using the fundamental-parameters method.

ISSN 3030-3907

Table 3.

Elemental composition of the perafor sample (general FP calculation)

No.	Component	Result (mass %)	Stat. error	LLD	LLQ
1	C	71.60	—	—	—
2	Fe	16.30	0.0087	0.0003	0.0009
3	S	6.58	0.0032	0.0004	0.0012
4	Si	1.30	0.0030	0.0025	0.0074
5	Cl	1.22	0.0010	0.0003	0.0008
6	Ca	1.18	0.0040	0.0022	0.0067
7	Na	0.793	0.0527	0.0686	0.206
8	Zr	0.218	0.0009	0.0002	0.0005
9	Mg	0.205	0.0075	0.0078	0.0233
10	Al	0.196	0.0025	0.0054	0.0162
11	Mn	0.186	0.0009	0.0009	0.0026
12	K	0.0775	0.0019	0.0039	0.0116
13	Co	0.0274	0.0010	0.0029	0.0088
14	Sr	0.0206	<0.0001	<0.0001	0.0001
15	Cu	0.0198	0.0002	0.0002	0.0007
16	Ba	0.0180	0.0005	0.0011	0.0033
17	Ti	0.0097	0.0006	0.0015	0.0045
18	Eu	(0.0080)	0.0019	0.0058	0.0174
19	Hf	0.0079	0.0004	0.0011	0.0033
20	Ni	0.0065	0.0002	0.0003	0.0010
21	Cr	0.0062	0.0003	0.0007	0.0021
22	Zn	0.0052	0.0001	0.0001	0.0004
23	Br	0.0048	<0.0001	<0.0001	0.0002
24	As	0.0035	<0.0001	<0.0001	0.0002
25	Rb	0.0020	<0.0001	0.0002	0.0005
26	Te	0.0017	0.0001	0.0003	0.0009
27	Sn	0.0012	<0.0001	0.0002	0.0005

ISSN 3030-3907

No.	Component	Result (mass %)	Stat. error	LLD	LLQ
28	Nb	0.0009	<0.0001	0.0001	0.0004
29	Ag	0.0008	<0.0001	<0.0001	0.0002
30	Pb	(0.0007)	0.0001	0.0003	0.0010
31	Ga	(0.0003)	<0.0001	0.0001	0.0004

Note: LLD is the lower limit of detection and LLQ is the lower limit of reliable quantification. Values in parentheses are below the LLQ or were not confirmed by the algorithm as reliable quantitative results and should be interpreted only as indications of trace presence. The C value was estimated using the FP scattering/balance algorithm.

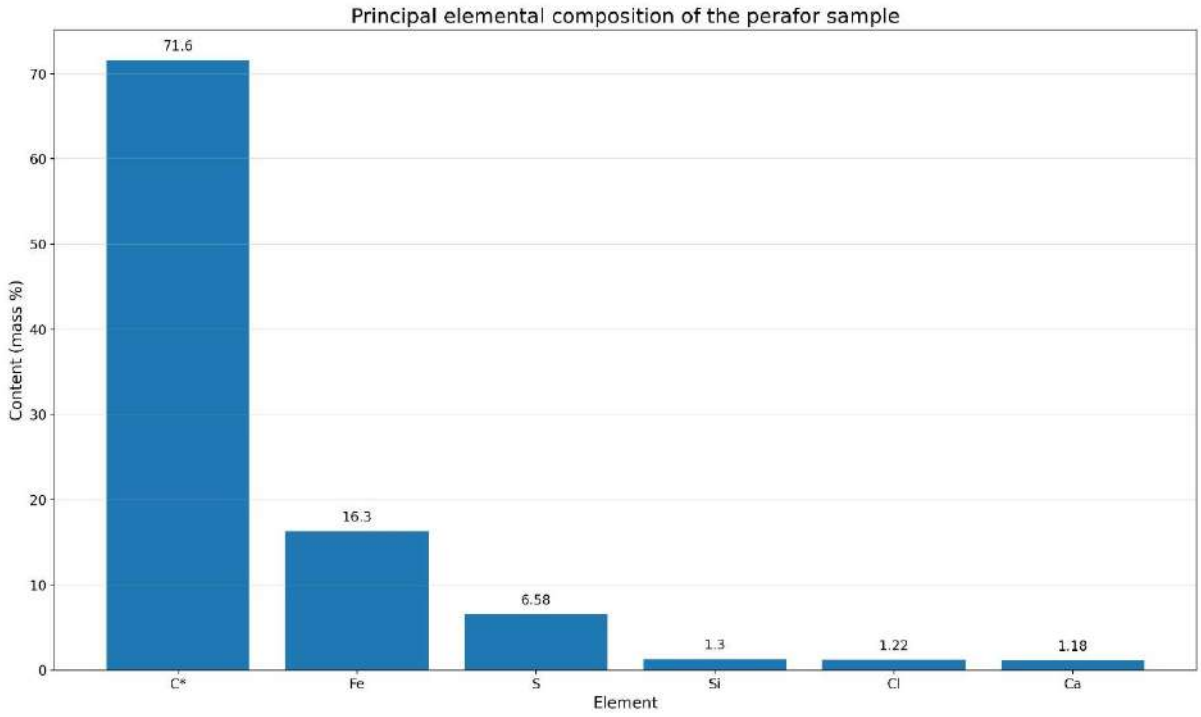


Figure 3. Distribution of the principal elements in the perafor sample (C* is the FP balance/matrix estimate).

Accordingly, the reported C = 71.60 mass % and C = 37.50 mass % values are not directly measured concentrations, but FP estimates obtained under two different normalization modes. Fe_2O_3, SO_3, SiO_2, and the other reported oxides are likewise not identified crystalline phases, but conditional oxide-equivalent representations of the corresponding elements [7].

ISSN 3030-3907

Table 4.

Oxide-equivalent composition of the perafor sample (FP calculation)

No.	Component	Result (mass %)	Stat. error	LLD	LLQ
1	C	37.50	—	—	—
2	Fe_2O_3	30.50	0.0143	0.0004	0.0013
3	SO_3	21.60	0.0070	0.0009	0.0028
4	SiO_2	3.63	0.0059	0.0049	0.0146
5	CaO	2.15	0.0073	0.0041	0.0124
6	Cl	1.61	0.0009	0.0003	0.0008
7	Na_2O	1.13	0.0645	0.110	0.329
8	Al_2O_3	0.489	0.0044	0.0093	0.0280
9	MgO	0.410	0.0113	0.0141	0.0422
10	ZrO_2	0.375	0.0022	0.0008	0.0023
11	MnO	0.324	0.0015	0.0014	0.0041
12	K_2O	0.119	0.0030	0.0062	0.0185
13	Co_2O_3	0.0460	0.0018	0.0055	0.0164
14	CuO	0.0345	0.0004	0.0003	0.0009
15	SrO	0.0319	0.0001	<0.0001	0.0002
16	BaO	0.0234	0.0009	0.0021	0.0064
17	TiO_2	0.0219	0.0012	0.0032	0.0097
18	NiO	0.0125	0.0003	0.0005	0.0014
19	Cr_2O_3	0.0117	0.0005	0.0013	0.0040
20	ZnO	0.0092	0.0002	0.0002	0.0006
21	As_2O_3	0.0071	0.0001	0.0001	0.0004
22	MoO_3	0.0024	0.0006	0.0007	0.0022
23	PbO	(0.0010)	0.0002	0.0005	0.0015
24	Ag_2O	0.0008	0.0001	0.0001	0.0004
25	SeO_2	(0.0002)	<0.0001	<0.0001	0.0003

The oxide-equivalent results represent software-calculated and normalized fractions obtained by converting the elements to conventional oxide formulae. The oxide-equivalent calculation reported C* at 37.50 mass %, Fe_2O_3 at 30.50 mass %,

ISSN 3030-3907

SO_3 at 21.60 mass %, SiO_2 at 3.63 mass %, CaO at 2.15 mass %, Cl at 1.61 mass %, and Na_2O at 1.13 mass %. The difference between the C* values in the elemental and oxide reports may be associated with the use of two different software matrix models and normalization schemes.

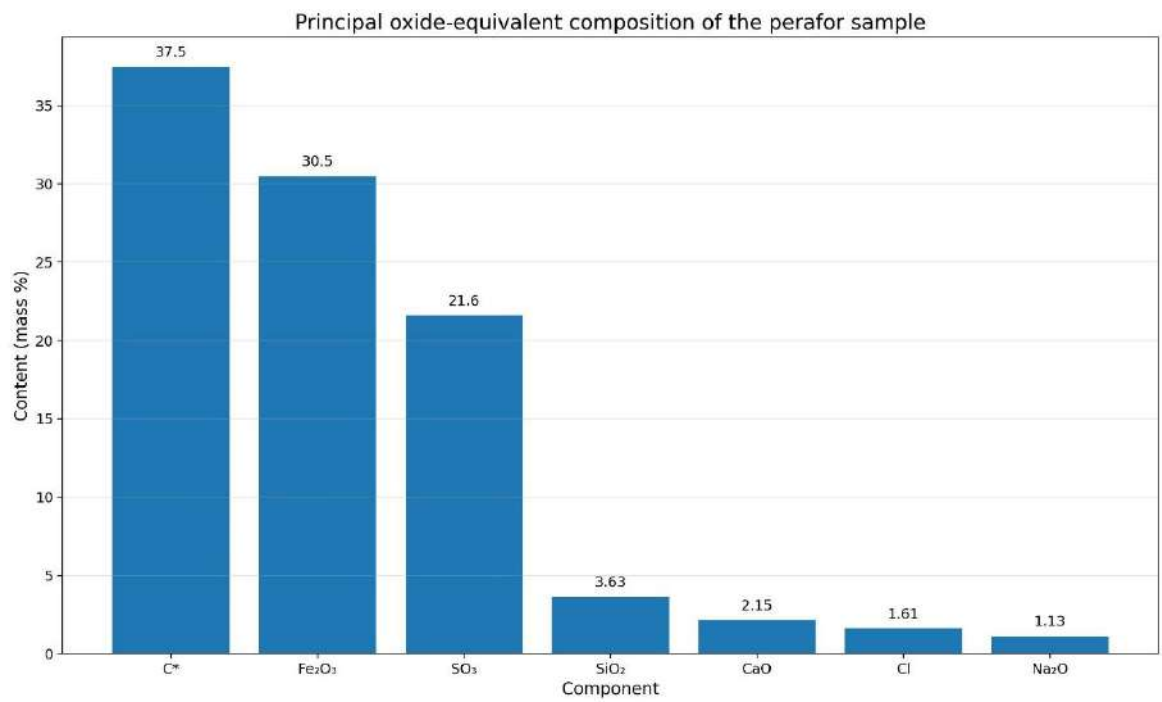


Figure 4. Distribution of the principal oxide-equivalent components in the perafor sample

Among the principal directly detected elements, Fe, S, Si, Cl, and Ca were present at 16.30, 6.58, 1.30, 1.22, and 1.18 mass %, respectively. The high iron content indicates that corrosion products detached from the orifice plate, pipeline, and other metallic components constitute a substantial fraction of the perafor. Si, Ca, Al, and Mg indicate the participation of sand, dust, and mineral particles. Chlorine indicates chlorine-containing constituents that, in an environment containing moisture or condensate, may increase the risk of localized and under-deposit corrosion. Sulfur at 6.58 mass % indicates the participation of sulfur-containing deposits or process contaminants, although their precise chemical form cannot be determined from XRF results alone [8-9].

In the oxide-equivalent mode, Fe_2O_3, SO_3, SiO_2, CaO, Cl, and Na_2O were reported at 30.50, 21.60, 3.63, 2.15, 1.61, and 1.13 mass %, respectively. Perafor should therefore not be considered solely as “soot” or “rust”, but as a mixed deposit comprising a carbonaceous binder, iron-containing corrosion products, sulfur-containing constituents, and mineral particles. Such a deposit can accumulate on the orifice bore and upstream edge, reduce the effective cross-sectional area, increase ΔP, and create a risk of overestimation of the gas flow rate.

DISCUSSION.

ISSN 3030-3907

To determine the forms of corrosion that may occur and identify potential solutions, a number of published investigations were analysed in relation to the composition of the gas transported through main gas pipelines.

Imidazoline is currently regarded as one of the most widely used and effective corrosion-inhibitor chemistries in industrial oil and gas applications. The efficiency of a volatile corrosion inhibitor synthesized on an imidazoline basis was evaluated for reducing top-of-the-line and bottom-of-the-line corrosion of carbon-steel pipelines in a CO_2-saturated environment. The authors tested an imidazoline produced from higher fatty acids and diethylenetriamine (DETA) under model conditions approximating those of a gas pipeline. Corrosion protection was analysed by weight-loss measurements, electrochemical impedance spectroscopy (EIS), potentiodynamic polarization (PDP), linear polarization resistance (LPR), scanning electron microscopy (SEM), energy-dispersive X-ray analysis (EDAX), and contact-angle measurements. At a concentration of 300 ppm, the inhibitor exhibited protection efficiencies of up to 91.6 % under bottom-of-the-line (BOL) conditions and 89.9 % under top-of-the-line (TOL) conditions. A decrease in the oxide layer and surface roughness, an increase in surface hydrophobicity, and adsorption consistent with the Langmuir isotherm were also reported. These observations indicate that imidazoline may be used as an effective volatile inhibitor in gas pipelines, particularly in regions containing condensate and a vapour phase. A major advantage of the study is that the inhibitor was shown to act not only in the liquid phase but also in the vapour–condensate TOL region, which represents a model close to actual operating conditions in main gas pipelines. A second advantage is the combined application of electrochemical, mass-loss, and surface-morphology methods, which provided mutually supporting results. Third, imidazoline was shown to function as a mixed-type inhibitor, simultaneously suppressing anodic and cathodic processes. The principal limitation is that only imidazoline itself was tested; a complex formulation containing a quaternary ammonium compound (QAC) and a dispersant was not evaluated. Furthermore, real pipeline contaminants such as under-deposit corrosion products, sand, rust, metal particles, or perafor were not modelled separately. Another limitation is that the results were obtained under laboratory conditions, and no long-term field-trial data were presented. Consequently, the study clearly demonstrates the baseline effectiveness of imidazoline, but further investigation is required before it can be regarded as a fully developed industrial solution for a complex mixed environment in a main gas pipeline [10].

The hydrolysis of an imidazoline corrosion inhibitor prepared from tall-oil fatty acid and diethylenetriamine (TOFA/DETA), and its effect on protection of X65 steel in a CO_2-saturated 3 wt.% NaCl medium, were investigated. The authors

ISSN 3030-3907

analysed the chemical evolution of the inhibitor with time, including hydrolysis of the imidazoline ring, protonation, and micelle formation. The results showed that, as hydrolysis proceeds, the composition and adsorption behaviour of the inhibitor change, directly affecting the efficiency of the protective film formed on the X65 steel surface. The hydrolysis process was accelerated in an acidic medium, imidazoline consumption followed pseudo-first-order kinetics, and the reported activation energy was 72.0 ± 2.9 kJ/mol. In addition, the "aged" inhibitor was found to affect general and localized corrosion differently. The work demonstrates that, when imidazoline-based inhibitors are applied to pipeline-grade X65 steel, not only their initial performance but also their time-dependent stability is of decisive importance. Rather than evaluating the inhibitor merely in terms of whether it works, the study provides an in-depth analysis of hydrolysis, protonation, micelle formation, and the adsorption mechanism, showing how compositional changes with time influence inhibition performance. A second important feature is the use of X65 steel as the test material, which makes the study highly relevant to main pipelines. The findings are practically significant for sweet-corrosion conditions, that is, a wet environment containing CO_2, and provide useful engineering information for selecting pipeline inhibitors. Nevertheless, the study was conducted in a laboratory CO_2-saturated brine and did not fully reproduce sand, rust, heavy-hydrocarbon deposits, turbulent flow, or a condensate-containing multiphase environment representative of an operating main gas pipeline. Only an imidazoline-based inhibitor was examined; complex formulations containing quaternary ammonium salts or a dispersant were not assessed. The article therefore mainly describes a laboratory mechanism rather than field-trial or long-term industrial operating results. Although the work explains the fundamental mechanism of imidazoline very well, additional practical testing is required before the formulation can be adopted directly as a ready industrial treatment [11].

In the study presented by Wong and Park, the effects of active corrosion-inhibitor components, particularly a quaternized amine monomer, on the growth of an iron-carbonate ($FeCO_3$) scale and on the development of protective properties at the metal surface under CO_2 conditions were investigated. The work showed that the $FeCO_3$ scale formed under sweet-corrosion conditions is not merely a corrosion product, but an important factor affecting inhibitor adsorption and film stability. The authors analysed how a quaternized-amine active component can enhance the protective mechanism at the metal surface in association with $FeCO_3$-scale formation. The study suggests that QAC or quaternized-amine components play an important role in increasing the density and stability of the protective film under sweet-corrosion conditions. It therefore provides a scientific basis for adding a quaternized amine to imidazoline-based inhibitor packages, particularly for main-

ISSN 3030-3907

pipeline corrosion in the presence of CO_2. The active component is analysed not only in terms of overall inhibition efficiency, but also through the mechanism associated with $FeCO_3$-scale formation, explaining the interaction of a QAC-type substance with the natural carbonate layer on the metal surface. This provides an important theoretical basis for the rational design of inhibitor packages for main gas pipelines. However, the study did not evaluate a complete complex formulation such as imidazoline + QAC + dispersant, but only the role of an individual active inhibitor component. A ready-to-use industrial formulation cannot therefore be derived directly from the work. In addition, factors characteristic of actual main-pipeline operation, including sand, rust, organic deposits, and under-deposit corrosion, were not specifically addressed. Although the article is a strong source for understanding the role of QACs, it should not be regarded as the sole evidence for the complete performance of a complex inhibitor package [12].

The study reported by Tsui and co-authors examined the effects of active corrosion-inhibitor components on the formation of an iron-carbonate ($FeCO_3$) layer on carbon steel in a CO_2 environment. The principal emphasis was placed on the interaction of quaternized-amine active substances with the $FeCO_3$ scale and the mechanism by which this interaction improves the effectiveness of the protective film. The authors showed that, under sweet-corrosion conditions, the iron-carbonate layer may act as a natural protective film on the internal pipeline surface, while quaternized-amine components influence the kinetics and compactness of layer formation and thereby enhance its corrosion-protection properties. According to the findings, some active inhibitor components may retard $FeCO_3$-scale formation, whereas quaternized-amine components can support its formation and promote a denser and more stable protective layer on the metal surface. The work therefore provides a scientific explanation for the use of QAC components in complex inhibitor packages for sweet-corrosion environments. Although the article is highly informative for understanding the role of QACs, it does not by itself demonstrate the complete performance of a complex formulation [13].

A subsequent investigation evaluated the performance of quaternary-amine corrosion inhibitors as a function of hydrocarbon-chain length and temperature. The authors synthesized C10-, C12-, and C16-chain quaternary-amine inhibitors and examined their protective properties for coiled-tubing steel in concentrated HCl by gravimetric and electrochemical methods. At low temperature, inhibitors with longer hydrocarbon chains showed higher efficiency: at 30 °C and 50 ppm, the protection efficiencies of the C16, C12, and C10 inhibitors were 80.4 %, 78.3 %, and 67.2 %, respectively. However, when the temperature was increased to 90 °C, this order changed and the overall efficiency decreased. The study demonstrates

ISSN 3030-3907

that the anticorrosion action of quaternary-amine inhibitors depends not only on the functional groups, but also directly on hydrocarbon-chain length, solubility, and temperature. It is therefore an important source for understanding structure–performance relationships when selecting a QAC type. However, the investigation was not performed under sweet-corrosion conditions in a main gas pipeline, but in concentrated HCl, which is closer to an acidizing environment. Direct transfer of the conclusions to a gas-pipeline environment containing CO_2, moisture, and condensate therefore requires caution. Another limitation is that only QAC-type inhibitors were considered, without evaluation of a complex formulation containing imidazoline or a dispersant [14].

In their review, Wang, Pang, and Zheng comprehensively analysed under-deposit corrosion (UDC) in oil and gas pipelines. They identified UDC as a serious threat to safe pipeline operation and systematically summarized test methods, corrosion mechanisms, and mitigation strategies. Two deposit-modelling methods and three UDC test systems were reviewed, and two principal UDC mechanisms were discussed in relation to the degree of deposit coverage and its protective characteristics. Uneven deposit distribution, which creates a galvanic couple, was identified as a principal cause of localized corrosion. Scale control and corrosion inhibition were considered important approaches for reducing UDC, and the need to develop more representative deposit models, effective UDC inhibitors, and in-situ monitoring technologies was emphasized. This article is an important theoretical and practical source for understanding deposits, perafor, and localized-corrosion phenomena. It provides strong support for explaining under-deposit corrosion mechanisms and the potential need for dispersant-assisted control, although additional specialized experimental studies are required to develop a specific formulation [15].

Fayyad and co-authors published a study in 2024 that used a laboratory approach close to practical conditions to evaluate under-deposit corrosion of carbon steel. The study was performed in a CO_2/sulfide environment using a sulfate-containing CO_2-saturated brine at 60 °C and a reported test concentration of 1000 ppm. The effects of different mineral deposits, namely FeS_2, FeS, and SiO_2 (sand), on inhibitor efficiency were examined. The authors separately evaluated deposit type, particle characteristics, and complete or partial coverage of the steel surface. According to EIS, morphology, and elemental-analysis results, a commercial UDC inhibitor showed its highest performance at 400 ppm. After 6 h, reported inhibition efficiencies were 77.5 % for FeS, 94.5 % for FeS_2, and 94.6 % for SiO_2. At the same time, the authors showed that the inhibitor did not reach the steel surface beneath all deposits to the same extent: it performed effectively in the presence of FeS and SiO_2, whereas access to the steel surface beneath the FeS_2

ISSN 3030-3907

deposit was limited. EDX and XPS analyses confirmed that the inhibitor could penetrate some deposits and adsorb on the metal surface. Although this study is close to the problem considered here, it did not fully reproduce multiphase flow, pressure variation, heavy-hydrocarbon condensate, or long-term operation in an actual main gas pipeline. Nevertheless, its demonstration that deposits, rust, sand, and corrosion products can accumulate in metering assemblies and main pipelines provides scientific support for investigating the addition of a dispersant [16].

Yang and co-authors reported in 2024 on the synergistic effect of thioureido imidazoline (TU-IM) and cationic surfactants with different carbon-chain lengths in reducing corrosion of X80 steel in a CO_2-saturated NaCl solution. TU-IM was evaluated both separately and together with cationic additives, including dodecyltrimethylammonium bromide (DTAB) and tetradecyltrimethylammonium bromide (TTAB). When TU-IM and the cationic surfactants were used together, the inhibition efficiency increased sharply. The best result was obtained with a combination of 10 mg/L TU-IM and 10 mg/L DTAB/TTAB, for which the corrosion-inhibition efficiency reached 97.68 %. The authors attributed this behaviour to cooperative adsorption of the two components on the metal surface, formation of a denser and more stable protective film, and intermolecular interactions. The article shows that the corrosion-protection effect of an imidazoline derivative can be enhanced by introducing an additional cationic component, thereby providing scientific support for the use of QAC or QAC-like cationic additives in complex inhibitor packages. The work investigated synergy with QAC-like cationic surfactants rather than a conventional oilfield QAC package, and no dispersant was added. It therefore demonstrates primarily adsorption-protection synergy rather than dispersion of deposits or reduction of perafor. The principal concept that can be derived from the study is that addition of a cationic component to an imidazoline-based formulation can increase film stability. The protection efficiency increased substantially when the imidazoline derivative was used together with the cationic additive. This source can therefore provide an important scientific basis for including QAC or QAC-like additives in a complex inhibitor formulation [17].

Patent CN104233310B describes a complex corrosion inhibitor based on an imidazoline quaternary ammonium salt and a method for its preparation. The disclosed composition contains functional components such as an alkyl-acid imidazoline quaternary ammonium salt, a dispersant, a co-solvent, a surfactant, and a phosphonate. The technology first forms an imidazoline from a fatty acid and a polyamine, after which the product is quaternized with benzyl chloride and then combined with the dispersant and other auxiliary components. According to the patent, the imidazoline-formation stage is conducted at approximately 140–180 °C,

ISSN 3030-3907

followed by formation of the quaternary ammonium salt. This source provides a technological basis for the structure, function, and preparation sequence of a complex formulation. However, additional laboratory and pilot testing would be required before the patented composition could be regarded as a proven, ready industrial solution directly suitable for a purified-gas environment in a main gas pipeline [18].

CONCLUSIONS.

In this study, a black powder (perafor) sample collected from the orifice-metering assembly of a gas distribution station was characterized by energy-dispersive X-ray fluorescence spectrometry (EDXRF). The principal directly detected elements were Fe at 16.30 mass %, S at 6.58 mass %, Si at 1.30 mass %, Cl at 1.22 mass %, and Ca at 1.18 mass %. The results demonstrated that perafor should be regarded not merely as soot or rust, but as a complex heterogeneous deposit consisting of iron-containing corrosion products, sulfur-containing components, and mineral particles.

Determination of the perafor composition indicates that it is advisable to reduce processes such as agglomeration of perafor particles, adhesion caused by condensate and heavy hydrocarbons, attachment to the orifice-plate and pipeline surfaces, and formation of a dense layer in filters by means of a dispersant [19–22].

When purified natural gas is transmitted into a main gas pipeline, adding a dispersant formulation not as a general additive to the entire gas stream, but at sections where moisture and condensate occur, at low points, in post-compressor cooling zones, upstream of GDS filters and metering assemblies, and in lines where perafor regularly accumulates may provide a solution to the problems described above.

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MODELING OF TERPOLYMERIZATION KINETICS AND DETERMINATION OF REACTIVITY RATIOS IN THE TDMA–STYRENE–MALEIC ANHYDRIDE SYSTEM

Mavlonov Shohrux Boboxon ogli

Doctor of Philosophy (PhD) in Technical Sciences, Associate Professor, Department of Chemical Technology, Bukhara State Technical University, Bukhara, Republic of Uzbekistan; E-mail: shoxrux-mavlonov@mail.ru

https://orcid.org/0009-0009-1652-6369, Science ID: FBX-0325-0012

Fozilov Sadriddin Fayzullayevich

Doctor of Science, Professor, Academician of the Academy of Sciences of the Republic of Uzbekistan, Professor of the Department of Chemical Technology, Bukhara State Technical University, Bukhara, Republic of Uzbekistan: https://orcid.org/0009-0009-0313-6134, Science ID: DBX-0326-0003

Abstract. In this study, the kinetics of terpolymerization, compositional evolution, and monomer reactivity ratios in the TDMA–styrene–maleic anhydride system were comprehensively investigated. Increasing the initiator concentration from 16.8×10^{-6} to 51.3×10^{-6} mol•L^{-1} led to an increase in conversion from 6.4% to 15.2% and reaction rate from 4.075×10^{-6} to 8.965×10^{-6} mol•L^{-1}•s^{-1}. At low conversion (Xw≈0.02–0.09), the terpolymer composition remained close to the initial feed, although deviations due to differences in monomer reactivity were observed. With increasing conversion, some systems exhibited stable composition (±0.02), while others showed compositional drift (increase of MA fraction from 0.50 to 0.70). The determined reactivity ratios (rTDMA/St≈0.99; rSt/TDMA≈1.62; rTDMA/MA≈2.02; rMA/TDMA≈0.34; rSt/MA≈1.50; rMA/St≈0.32) indicate the dominant incorporation of TDMA and styrene and selective incorporation of MA. The ternary kinetic model demonstrated high agreement with experimental data (±0.03).

Keywords: TDMA, styrene, maleic anhydride, terpolymerization, radical polymerization, kinetics, compositional drift, reactivity ratios, kinetic modeling, ternary system, donor–acceptor mechanism, molecular weight, polydispersity, functional polymers.

Anatatsiya. Ushbu tadqiqotda TDMA–stirol–malein angidrid uch monomerli sistemasida terpolimerlanish kinetikasi, tarkibiy o`zgarishlari va monomerlarning reaktivlik nisbatlari kompleks o‘rganildi. Inisiator konsentratsiyasi $16,8\times10^{-6}$ dan $51,3\times10^{-6}$ mol·L^{-1} gacha oshirilganda konversiya 6,4 % dan 15,2 % gacha, reaksion tezlik $4,075\times10^{-6}$ dan $8,965\times10^{-6}$ mol·L^{-1}·s^{-1} gacha ortdi. Past konversiyada (Xw≈0,02–0,09) tarkib boshlang‘ich qiymatlarga yaqin bo‘ldi, ammo reaktivlik farqlari sabab og‘ishlar kuzatildi. Konversiya ortishi bilan ayrim uch monomerli sistemalarda tarkib barqaror (±0,02),

boshqalarida esa kompozitsion drift (MA 0,50–0,70 gacha ortishi) aniqlandi. Reaktivlik nisbatlari ($r_{TDMA/St}$≈0,99; $r_{St/TDMA}$≈1,62; $r_{TDMA/MA}$≈2,02; $r_{MA/TDMA}$≈0,34; $r_{St/MA}$≈1,50; rMA/St≈0,32) TDMA va stirolning ustun, MA ning selektiv inkorporatsiyasini ko‘rsatdi. Uch komponentli model eksperimental natijalar bilan yuqori moslik (±0,03) namoyon etdi.

Kalit so`zlar: TDMA, stirol, malein angidrid, terpolimerlanish, radikal polimerlanish, kinetika, kompozitsion drift, reaktivlik nisbatlari, kinetik modellashtirish, uch monomerli sistema, donor–akseptor mexanizmi, molekulyar massa, polidisperslik, funksional polimerlar.

Аннотация: В данной работе комплексно исследованы кинетика терполимеризации, составные изменения и реакционные способности мономеров в системе TDMA–стирол–малеиновый ангидрид. При увеличении концентрации инициатора от $16{,}8\times10^{-6}$ до $51{,}3\times10^{-6}$ моль•л$^{-1}$ конверсия возрастает с 6,4 % до 15,2 %, а скорость реакции — с $4{,}075\times10^{-6}$ до $8{,}965\times10^{-6}$ моль•л$^{-1}$•с$^{-1}$. В области низких конверсий (X_w≈0,02–0,09) состав терполимера близок к исходному, однако наблюдаются отклонения, обусловленные различиями реакционной способности мономеров. С ростом конверсии в одних системах состав остается стабильным (±0,02), в других наблюдается композиционный дрейф (увеличение доли MA с 0,50 до 0,70). Определённые реакционные коэффициенты ($r_{TDMA/St}$≈0,99; $r_{St/TDMA}$≈1,62; rTDMA/MA≈2,02; rMA/TDMA≈0,34; rSt/MA≈1,50; $r_{MA/St}$≈0,32) свидетельствуют о преобладающем включении TDMA и стирола и селективной инкорпорации MA. Трёхкомпонентная модель показала высокое соответствие экспериментальным данным (±0,03).

Ключевые слова: TDMA, стирол, малеиновый ангидрид, терполимеризация, радикальная полимеризация, кинетика, композиционный дрейф, реакционные коэффициенты, кинетическое моделирование, трёхкомпонентная система, донорно-акцепторный механизм, молекулярная масса, полидисперсность, функциональные полимеры.

INTRODUCTION

Currently, the demand for highly efficient functional additives in the petrochemical industry, as well as in fuel and lubricant production, is rapidly increasing [1,2]. In particular, polymer-based modifiers that enhance rheological, thermal, and low-temperature properties are of great importance for fuels operating under severe conditions. In this context, terpolymers based on long-chain alkyl methacrylates, aromatic vinyl monomers, and functional anhydrides are considered

ISSN 3030-3907

promising additives [3,4]. Ternary systems based on TDMA (tetradecyl methacrylate), styrene, and maleic anhydride are distinguished by their structural diversity, the presence of functional groups, and the ability to control chain formation [5,6]. The terpolymers obtained in such systems can exhibit a high viscosity index, good dispersing properties, and improved low-temperature performance. Therefore, a detailed study and theoretical modeling of the kinetics of TDMA–St–MA terpolymerization are of significant scientific and practical importance [7].

Radical copolymerization and terpolymerization processes have been extensively studied in the literature and are primarily based on monomer reactivity ratios, as well as chain growth and termination mechanisms. Classical methods such as the Mayo–Lewis and Fineman–Ross equations have been developed to determine reactivity ratios for binary systems [8,9]. The styrene–maleic anhydride system is well known as a donor–acceptor pair and typically forms alternating copolymers [10,11]. However, systems involving long-chain alkyl methacrylates (including TDMA) have not been sufficiently investigated with respect to diffusion limitations, gel effect, and enhanced chain transfer reactions. In recent years, kinetic modeling of multicomponent systems has increasingly employed advanced approaches such as PREDICI simulations, Monte Carlo methods, and deterministic kinetic models[12]. These approaches enable the prediction of monomer conversion, molecular weight distribution, and structural composition [13,14].

Nevertheless, in existing studies, several aspects of ternary systems such as TDMA–St–MA remain insufficiently investigated. In particular, the accurate determination of reactivity ratios and their dependence on conversion, as well as the complex influence of diffusion-controlled (DC) effects on propagation and termination rate constants, have not been systematically studied. Furthermore, the kinetic parameters in the high-conversion region (50–95%) and the level of agreement between experimental data and mathematical models have not been adequately analyzed. In particular, the integration of diffusion limitations arising from the significant increase in medium viscosity due to the presence of long-chain TDMA into kinetic models, as well as their influence on terpolymer composition, has not been fully elucidated. In addition, the distribution of structural units formed as a result of monomer interactions in ternary systems and their relationship with reactivity ratios have not been sufficiently investigated.

The main objective of this study is to model the kinetics of terpolymerization in the TDMA–styrene–maleic anhydride ternary system, determine reactivity ratios, and provide a scientific basis for the influence of monomer composition and diffusion limitations on process kinetics. Accordingly, the study aims to identify the initial kinetic regularities of radical terpolymerization in the TDMA–St–MA

ISSN 3030-3907

system, analyze the time dependence of monomer conversion using both experimental data and modeling approaches, and evaluate the variation of propagation and termination rate constants as a function of conversion. Furthermore, a kinetic model incorporating diffusion limitations is developed, reactivity ratios for the ternary system are determined and their effect on terpolymer composition is assessed, the agreement between experimental results and model predictions is evaluated, and optimal synthesis conditions are established.

Research Methods and the Received Results

General experimental procedure: To investigate the kinetics of terpolymerization in the TDMA–styrene–maleic anhydride (TDMA–St–MA) ternary system and to determine the initial kinetic regularities, experiments were carried out in the low conversion range (0–15%) [15]. This region corresponds to the kinetic control regime, where diffusion limitations are minimal. The overall kinetic process can be described by the following scheme [16,17]:

Table 1

Kinetic scheme and rate constants adopted for modeling the terpolymerization of TDMA, styrene, and maleic anhydride using the PREDICI® software *(M1 – TDMA, M2 – St, M3 – MA)*

Process description	Reaction expression	Symbol	Value $L \cdot mol^{-1} \cdot s^{-1}$
Formation of active centers (initiation)			
Initiator decomposition	I → 2I•	ki, f	7,4609E-6, 0.58 (s^{-1})
First addition of TDMA monomer	I• + M1 → P1(1)•	kp1	1333.8
First addition of styrene monomer	I• + M2 → P2(1)•	kp2	33,395
First addition of MA monomer	I• + M3 → P3(1)•	kp3	683.24
Chain propagation			
Growth of TDMA radical with TDMA	P1(s)• + M1 → P1(s+1)•	kp1	1333.8
Growth of styrene radical with styrene	P2(s)• + M2 → P2(s+1)•)	kp2	33.395
Growth of MA radical with MA	P3(s)• + M3 → P3(s+1)•	kp3	683.24
Cross-propagation			

ISSN 3030-3907

TDMA radical reacting with styrene	P1(s)• + M2 → P2(s+1)•	kp12	1333.8/r12
TDMA radical reacting with MA	P1(s)• + M3 → P3(s+1)•	kp13	1333.8/r13
Styrene radical reacting with TDMA	P2(s)• + M1 → P1(s+1)•	kp21	33,395/r21
Styrene radical reacting with MA	P2(s)• + M3 → P3(s+1)•	kp23	33,395/r23
MA radical reacting with TDMA	P3(s)• + M1 → P1(s+1)•	kp31	683.24/r31
MA radical reacting with styrene	P3(s)• + M2 → P2(s+1)•	kp32	683.24/r32
Chain transfer			
Transfer to TDMA monomer			
Transfer of TDMA radical to TDMA	P1(s)• + M1 → P(s) +P1(1)•	kf1	0.1492
Transfer of TDMA radical to TDMA	P2(s)• + M1 → P(s) +P1(1)•	kf21	3.5/r21
Transfer of styrene radical to TDMA	P3(s)• + M1 → P(s) +P1(1)•	kf31	1.9321E-2/r31
Chain transfer to styrene monomer			
Chain transfer to styrene monomer	P1(s)• + M2 → P(s) +P2(1)•	kf12	0.1492/r12
Transfer of TDMA radical to styrene	P2(s)• + M2 → P(s) +P2(1)•	kf2	4.5
Transfer of MA radical to styrene	P3(s)• + M2 → P(s) +P3(1)•	kf32	1.9321E-2/r32
Chain transfer to MA monomer			
Chain transfer to MA monomer	P1(s)• + M3 → P(s) +P3(1)•	kf13	0.1492/r13
Transfer of TDMA radical to MA	P2(s)• + M3 → P(s) +P3(1)•	kf23	3.5/r23
Transfer of MA radical to MA	P3(s)• + M3 → P(s) +P3(1)•	kf3	1.9321E-2
Intramolecular chain transfer of BA			
Formation of secondary radical	P1(s)• → Q1(s)•	kbb	553
Short-chain branching			

ISSN 3030-3907

Formation of secondary radical	Q1(s)• + M1 → P1(s+1)•	kp1tert	49.401
Reaction with styrene	Q1(s)• + M2 → P2(s+1)•	kp12tert	49.401/r12
Reaction with MA	Q1(s)• + M3 → P3(s+1)•	kp13tert	49.401/r13
Degradative chain transfer			
With TDMA	Q1(s)• + M1 → P(s)+P1(1)•	kf1tert	6
With styrene	Q1(s)• + M2 → P(s)+P2(1)•	kf12tert	6/r12
With MA	Q1(s)• + M3 → P(s)+P3(1)•	kf13tert	6/r13

Materials and reagents: In the present study, tetradecyl methacrylate (TDMA) was synthesized via esterification of methacrylic acid with higher molecular weight alcohols, specifically tetradecyl alcohol. The reaction was carried out in the presence of an acid catalyst (sulfuric acid) and proceeded with the elimination of water.

$$CH_2=C(CH_3)COOH+C_{14}H_{29}OH \rightarrow CH_2=C(CH_3)COOC_{14}H_{29}+H_2O$$

Methacrylate monomers and their quality parameters in the CIS region are regulated by GOST 20370–74 (for methacrylic acid esters) or corresponding technical specifications (TU). Styrene (St) (GOST 10003–90) and maleic anhydride (MA) (GOST 11138–78) were used as monomers. An azo-type compound (IMDN) was employed as the initiator. The monomer-to-initiator ratios were selected within the range of 125:1, 200:1, and 800:1. Toluene was used as a solvent to ensure homogeneity of the reaction medium and efficient heat transfer. The monomers were studied at molar ratios of 80TDMA/10St/10MA, 10TDMA/80St/10MA, and 10TDMA/10St/80MA. All reagents used in the study were of high purity and were applied without additional purification. However, considering that monomer purity and the absence of inhibitors significantly affect polymerization kinetics, the monomers were pretreated when necessary by vacuum distillation or inhibitor removal prior to use.

The concentrations of the reactants in the overall kinetic equation are expressed as follows:

$$R_p=kp[M][R\ ]\ (1)$$

Terpolymerization process: The terpolymerization reactions were carried out under an inert atmosphere (N_2) at a temperature of 95 ± 5 °C. The reaction time was varied within the range of 0–360 minutes. Samples were withdrawn at specific

ISSN 3030-3907

time intervals, and the monomer conversion was determined. The reaction rate is described by the following general kinetic expression:

$$R_p = -\frac{d[M]}{dt} \quad (2)$$

Under steady-state conditions in radical terpolymerization:

$$[R^{\cdot}] = \sqrt{\frac{2fk_d[I]}{k_t}} \quad (3)$$

As a result, the overall rate equation is expressed as follows:

$$R_p = k_p[M] = \sqrt{\frac{2fk_d[I]}{k_t}} \quad (4)$$

Monomer conversion was calculated using the following equation:

$$ln(\frac{[M]()}{[M]}) = k_{app} \quad (5)$$

Here, $k_{app}t$ is the apparent rate constant. The linear dependence of $\ln([M]_0/[M])$ on time indicates that the process follows a pseudo-first-order kinetic model.

$$k\frac{eff}{p} = p_t.exp(-\alpha X) \quad (6)$$

$$k\frac{eff}{t} = k_t.exp(-\beta X) \quad (7)$$

Here, X denotes conversion, while α, β represent the diffusion limitation coefficients.

$$\frac{d[TDMA_1]}{d[St_2]} = \frac{[TDMA_1]\cdot\left\{\frac{[TDMA_1]}{r_{21}\cdot r_{31}} + \frac{[St_2]}{r_{21}\cdot r_{32}} + \frac{[MA_3]}{r_{23}\cdot r_{31}}\right\}}{[St_2]\cdot\left\{\frac{[TDMA_1]}{r_{21}\cdot r_{31}} + \frac{[St_2]}{r_{21}\cdot r_{32}} + \frac{[MA_3]}{r_{23}\cdot r_{31}}\right\}} \cdot \frac{\left\{[TDMA_1] + \frac{[St_2]}{r_{12}} + \frac{[MA_3]}{r_{13}}\right\}}{\left\{\frac{[TDMA_1]}{r_{21}} + [St_2] + \frac{[MA_3]}{r_{13}}\right\}} \quad (8)$$

$$\frac{d[TDMA_1]}{d[St]} = \frac{[TDMA_1]\cdot\left\{\frac{[TDMA_1]}{r_{21}\cdot r_{31}} + \frac{[St_2]}{r_{21}\cdot r_{32}} + \frac{[MA_3]}{r_{23}\cdot r_{31}}\right\}}{[MA_3]\cdot\left\{\frac{[TDMA_1]}{r_{13}\cdot r_{31}} + \frac{[St_2]}{r_{12}\cdot r_{23}} + \frac{[MA_3]}{r_{13}\cdot r_{32}}\right\}} \cdot \frac{\left\{[TDMA_1] + \frac{[St_2]}{r_{12}} + \frac{[MA_3]}{r_{13}}\right\}}{\left\{\frac{[TDMA_1]}{r_{31}} + \frac{[St_2]}{r_{32}} + [MA_3]\right\}} \quad (9)$$

ISSN 3030-3907

$$\frac{d[St_2]}{d[MA_3]} = \frac{[St_2]\cdot\left\{\frac{[TDMA_1]}{r_{21}\cdot r_{31}} + \frac{[St_2]}{r_{21}\cdot r_{32}} + \frac{[MA_3]}{r_{23}\cdot r_{32}}\right\}}{[MA_3]\cdot\left\{\frac{[TDMA_1]}{r_{13}\cdot r_{31}} + \frac{[St_2]}{r_{12}\cdot r_{23}} + \frac{[MA_3]}{r_{13}\cdot r_{23}}\right\}} \cdot \frac{\left\{\frac{[TDMA_1]}{r_{21}} + [St_2] + \frac{[MA_3]}{r_{23}}\right\}}{\left\{\frac{[TDMA_1]}{r_{31}} + \frac{[St_2]}{r_{32}} + [MA_3]\right\}} \quad (10)$$

Here, r_{ij} / r_{ji} are the reactivity ratios (terpolymerization reaction parameters) for the *i/j* monomer pair, and $[M_i]$ denotes the monomer concentration.

Determination of reactivity ratios: For a ternary system, the reactivity ratios are determined based on the extended form of copolymerization equations. The general form of the Alfred Goldfinger equation for evaluating reactivity coefficients is expressed as follows:

$$\frac{d[TDMA_1]}{d[St_2]} = \frac{[TDMA_1]\cdot\left\{\rho\cdot\frac{[TDMA_1]}{r_{21}} + \frac{[St_2]}{r_{21}} + \rho\cdot\frac{[MA_3]}{r_{23}}\right\}}{[St_2]\cdot\left\{\rho\cdot\frac{[TDMA_1]}{r_{12}} + \frac{[St_2]}{r_{12}} + \frac{[MA_3]}{r_{13}}\right\}} \cdot \frac{\left\{[TDMA_1] + \frac{[St_2]}{r_{12}} + \frac{[MA_3]}{r_{13}}\right\}}{\left\{\frac{[TDMA_1]}{r_{21}} + [St_2] + \frac{[MA_3]}{r_{13}}\right\}} \quad (11)$$

$$\frac{d[TDMA_1]}{d[MA_3]} = \frac{[TDMA_1]\cdot\left\{\rho\cdot\frac{[TDMA_1]}{r_{21}} + \frac{[St_2]}{r_{21}} + \rho\cdot\frac{[MA_3]}{r_{23}}\right\}}{[MA_3]\cdot\left\{\rho\cdot\frac{[TDMA_1]}{r_{13}\cdot r_{21}} + \frac{[St_2]}{r_{12}\cdot r_{23}} + \frac{[MA_3]}{r_{13}\cdot r_{23}}\right\}} \cdot \frac{\left\{[TDMA_1] + \frac{[St_2]}{r_{12}} + \frac{[MA_3]}{r_{13}}\right\}}{\{\rho\cdot[TDMA_1] + [St_2]\}} \quad (12)$$

$$\frac{d[St_2]}{d[MA_3]} = \frac{[St_2]\cdot\left\{\rho\cdot\frac{[TDMA_1]}{r_{12}} + \frac{[St_2]}{r_{12}} + \frac{[MA_3]}{r_{13}}\right\}}{[MA_3]\cdot\left\{\frac{[TDMA_1]}{r_{13}\cdot r_{21}} + \frac{[St_2]}{r_{12}\cdot r_{23}} + \frac{[MA_3]}{r_{13}\cdot r_{23}}\right\}} \cdot \frac{\left\{\frac{[TDMA_1]}{r_{21}} + [St_2] + \frac{[MA_3]}{r_{23}}\right\}}{\{\rho\cdot[TDMA_1] + [St_2]\}} \quad (13)$$

$$\rho = \frac{k_{31}}{k_{32}} \quad (14)$$

Here, [Mi] denotes the monomer concentration, r_{ij}/r_{ji} represent the terpolymerization parameters (reactivity ratios) of the monomers, where M1 - TDMA, M2 - ST, M3 - MA.

ISSN 3030-3907

Mathematical modeling: The terpolymerization process was described using a mathematical model. The model is based on the following system of differential equations:

$$\frac{d[M_i]}{dt} = -k_p[M_i][R^{\cdot}] \quad (14)$$

$$\frac{d[R^{\cdot}]}{dt} = 2fk_d[I] - k_t[R^{\cdot}]^2 \quad (15)$$

The model parameters were adjusted as a function of conversion while accounting for diffusion limitations. The optimal kinetic conditions were determined based on the Fisher diagram, and maximum efficiency was observed under the following condition:

$$k_t/k_p \rightarrow max \quad (17)$$

Under these conditions, terpolymers with high molecular weight and narrow polydispersity are formed.

Effect of initiator (IMDN) concentration on terpolymerization kinetics: In the terpolymerization process involving TDMA, styrene, and maleic anhydride, the effects of reaction time, initiator type and concentration, solvent nature, and temperature variation on monomer conversion, as well as on the molecular weight and structural formation of the resulting terpolymer, were investigated.

Table 2

Effect of IMDN concentration on the terpolymerization rate at 95 ± 5 °C for 150 minutes

Sample №	IMDN × 10^{-6} mol·L^{-1}	Conversion, %	R_p × 10^{-6} mol·L^{-1}·s^{-1}
1	16.8	6.4	4.075
2	25.2	8.2	4.89
3	33.6	10.6	5.705
4	42.0	12.4	7.335
5	51.3	15.2	8.965

[TMDA]=2.01 mol. L^{-1}, [St] = 1.44 mol. L^{-1}, [MA] 0.72 mol. L^{-1}

ISSN 3030-3907

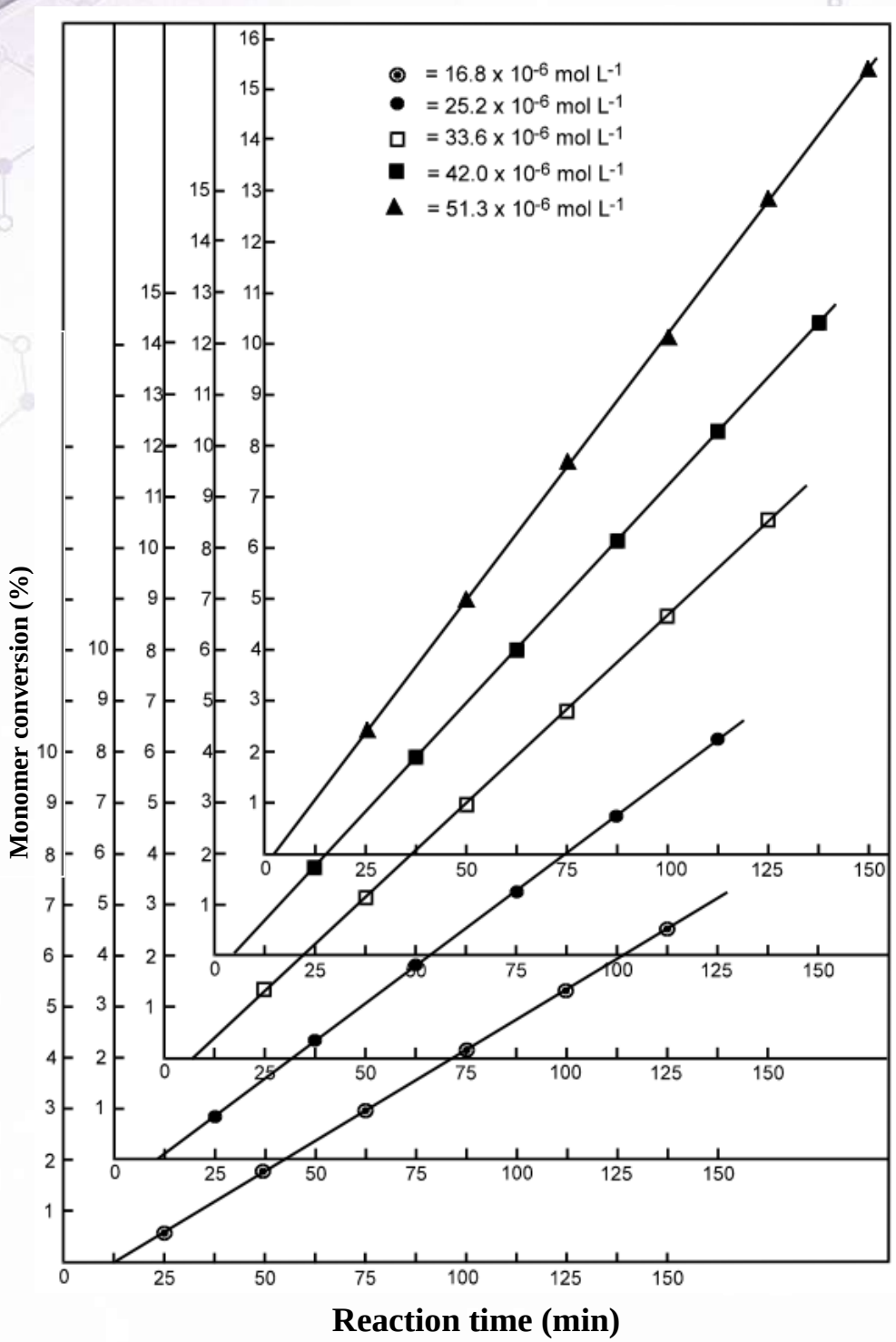


Figure 1. Effect of time on the conversion of TDMA, styrene (St), and maleic anhydride (MA) in terpolymerization at 95–105 °C in the presence of the initiator (IMDN)

These results indicate that with increasing concentration of the IMDN initiator, the number of active radicals increases, leading to an acceleration of chain propagation reactions. This behavior is consistent with the fundamental equation of radical polymerization kinetics (Eq. 3), according to which the polymerization rate is proportional to the square root of the initiator concentration. At low initiator concentrations (16.8×10^{-6} mol·L^{-1}), the limited number of active centers results in

ISSN 3030-3907

a slower incorporation of monomers into the polymer chain. As the concentration increases, the number of active centers rises, enhancing the incorporation rate of TDMA, styrene, and maleic anhydride into the growing chain. The results also demonstrate that within the temperature range of 95–105 °C, the initial stages of the process proceed under kinetic control, and diffusion limitations are not yet significant.

Furthermore, the nearly linear increase in conversion and reaction rate confirms that the system follows pseudo-first-order kinetics (Eq. 5). The results indicate that the terpolymerization process in the TDMA–St–MA system can be effectively controlled by adjusting the initiator concentration. This provides a practical opportunity to tailor the structure and properties of functional terpolymers. In addition, the obtained results serve as a basis for determining reactivity ratios and optimizing the parameters of the kinetic model in subsequent stages.

Initial incorporation behavior of monomers at low conversion: The experimental results obtained for TDMA–St–MA terpolymers synthesized at different monomer ratios in the low conversion region ($X_v \approx 0.02–0.09$) were used to evaluate the initial incorporation behavior of the monomers. The results for three optimal initial composition combinations are presented in Table 3.

Table 3

Experimental data for TDMA–St–MA terpolymerization at low conversion (temperature 95 ± 5 °C, IMDN, reaction time 150 ± 5 min)

Optimal initial composition (mol ratio)	X_w (conversion)	f TDMA,0	f St,0	f MA,0	F TDMA	F St	F MA,0
1	0.066	0.8	0.1	0.1	0.761	0.135	0.104
	0.071	0.8	0.1	0.1	0.778	0.137	0.085
	0.083	0.8	0.1	0.1	0.783	0.136	0.081
	0.091	0.8	0.1	0.1	0.750	0.146	0.104
2	0.036	0.1	0.8	0.1	0.123	0.826	0.052
	0.043	0.1	0.8	0.1	0.122	0.824	0.054
	0.071	0.1	0.8	0.1	0.107	0.836	0.057
	0.079	0.1	0.8	0.1	0.115	0.817	0.069
	0.088	0.1	0.8	0.1	0.110	0.823	0.067
3	0.021	0.1	0.2	0.7	0.123	0.374	0.503
	0.025	0.1	0.2	0.7	0.121	0.382	0.496

ISSN 3030-3907

	0.030	0.1	0.2	0.7	0.122	0.384	0.494
	0.034	0.1	0.2	0.7	0.118	0.368	0.514
	0.040	0.1	0.2	0.7	0.117	0.372	0.511
	0.056	0.1	0.2	0.7	0.125	0.377	0.498
	0.059	0.1	0.2	0.7	0.124	0.374	0.502
	0.064	0.1	0.2	0.7	0.121	0.368	0.511
	0.087	0.1	0.2	0.7	0.114	0.344	0.542

X_w – *conversion,*

$f_i,0$ – *initial monomer composition (i-th monomer),*

F_i – *cumulative terpolymer composition.*

According to the results presented in Table 3, for the system with the initial composition (TDMA = 0.8; St = 0.1; MA = 0.1), the conversion varies within the range of 0.066–0.091. The terpolymer composition shows that the TDMA fraction is F_{TDMA}=0,750–0,783, the styrene fraction is F_{St}=0,135–0,146, while the maleic anhydride fraction remains comparatively low. The high content of TDMA in this system indicates its stable incorporation into the growing polymer chain and its kinetic predominance, which can be attributed to the active participation of long-chain alkyl methacrylates in radical propagation.

For the system with the initial composition (TDMA = 0.1; St = 0.8; MA = 0.1), the conversion varies within the range of 0.036–0.088. The terpolymer composition is dominated by styrene, with F_{St}=0,817–0,836, while the TDMA fraction is lower and the maleic anhydride fraction is F_{MA}=0,052–0,069. The high incorporation of styrene is attributed to its high reactivity in radical processes and its donor characteristics. Furthermore, the donor–acceptor interaction between styrene and maleic anhydride enhances its active participation in copolymerization.

For the system with the initial composition (TDMA = 0.1; St = 0.2; MA = 0.7), the conversion ranges from 0.021 to 0.087. The terpolymer composition reveals that the maleic anhydride fraction is F_{MA}=0,494–0,542,, the styrene fraction is F_{St}=0,344–0,384, and the TDMA fraction is F_{TDMA}=0,114–0,125. Despite its low tendency toward homopolymerization, the relatively high incorporation of maleic anhydride indicates that, within the ternary system, it forms a complex with styrene and is actively incorporated into the growing polymer chain.

These results indicate that, in the low conversion region, the terpolymer composition remains close to the initial monomer composition; however, certain deviations are observed due to differences in monomer reactivity. In general, the composition changes in accordance with the overall terpolymerization kinetic equations for ternary systems (Eqs. 8–10). The results also demonstrate that under low conversion conditions, the relationship $F_i \approx f_i$ is maintained, although slight

ISSN 3030-3907

deviations confirm the presence of reactivity ratios in ternary terpolymerization systems. This highlights the necessity of considering ternary reactivity coefficients when developing a kinetic model for the TDMA–St–MA system. Furthermore, the systematic deviation of Fi from f_i indicates that each monomer plays an individual kinetic role in the formation of the terpolymer microstructure. Therefore, these findings provide an important experimental basis for determining reactivity ratios and for the mathematical modeling of the terpolymerization process.

Dependence of terpolymer composition on conversion and comparison with the kinetic model: The degree of monomer incorporation into the polymer chain during the terpolymerization of the synthesized monomer mixtures was evaluated using the cumulative composition function *Fi*. The experimental results were compared with the values predicted by the kinetic model (Figure 2).

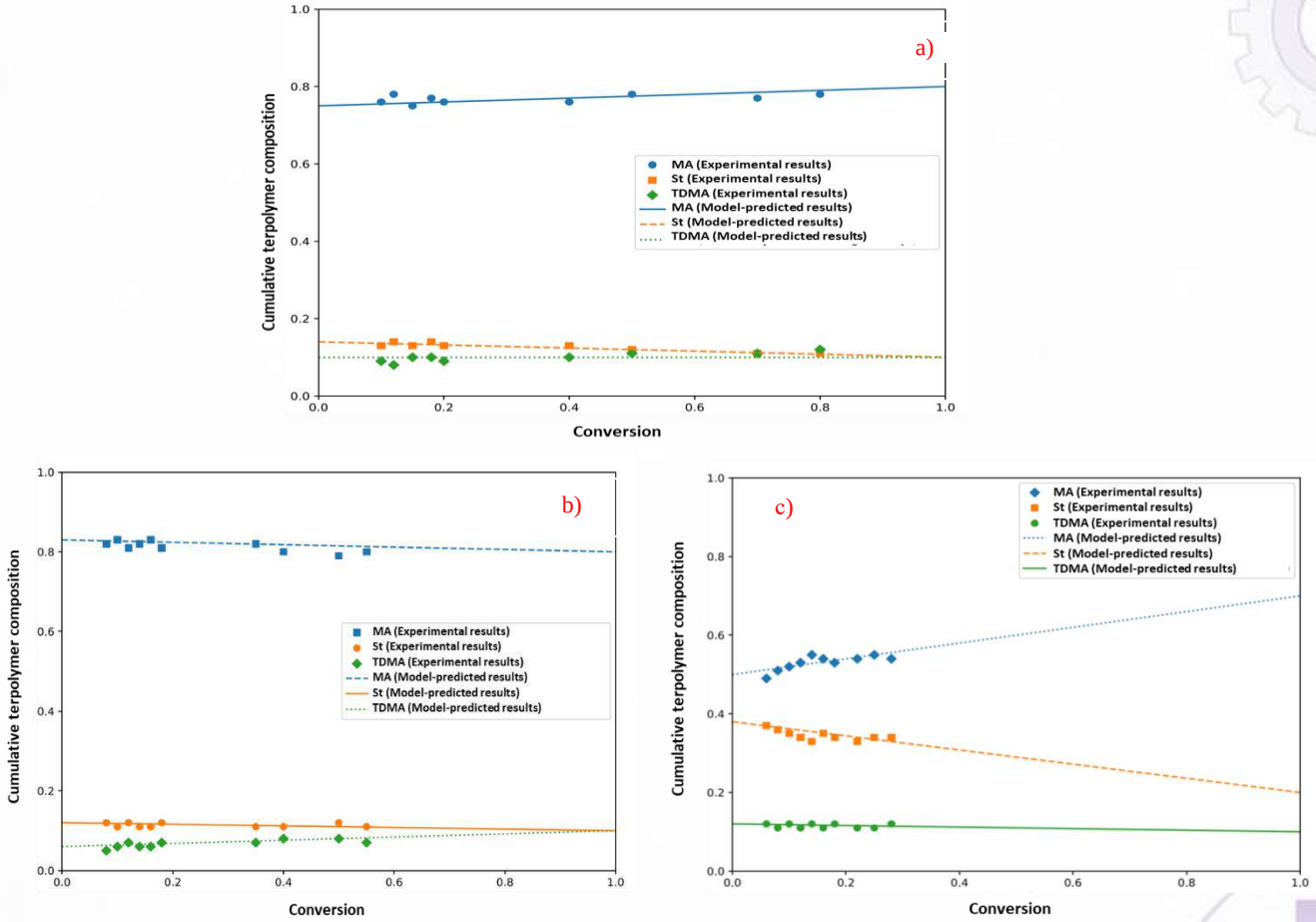


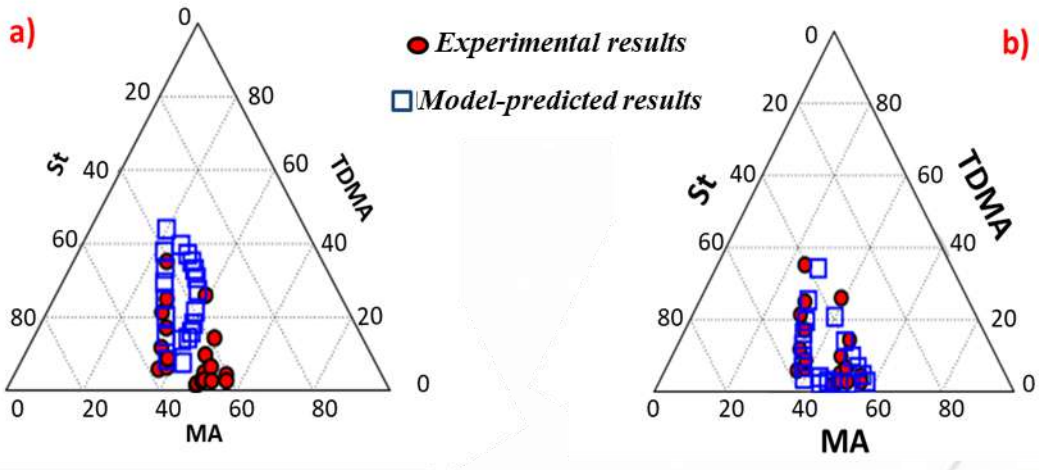
Figure 2. Cumulative terpolymer composition *Fi* for TDMA–St–MA monomer ratios: (a) 0.8/0.1/0.1, (b) 0.1/0.8/0.1, and (c) 0.1/0.2/0.7 (experimental data and model predictions)

For the initial composition (0.8/0.1/0.1), when the conversion varies within the range of 0.05–0.90, the TDMA fraction as the main component in the terpolymer remains nearly constant at F≈0,75–0,80, while the fractions of the second and third monomers are approximately F≈0,12–0,15, with only minor variations (±0.02) as conversion increases. Similarly, for the (0.1/0.8/0.1) system,

ISSN 3030-3907

styrene remains the dominant component throughout the entire conversion range, with a fraction F≈0,80–0,83, while TDMA and MA fractions are ≈0,10–0,13 and F≈0,06–0,10, respectively. In contrast, for the (0.1/0.2/0.7) system, a noticeable compositional redistribution is observed with increasing conversion. At low conversion, the MA fraction is F≈0,50–0,55, whereas at high conversion it increases to F≈0,65–0,70. At the same time, the styrene fraction decreases to F≈0,35–0,40, while the TDMA fraction remains relatively stable at F≈0,10–0,12. For all ternary systems studied, the values calculated using the kinetic model show a high degree of agreement with the experimental results, with a maximum deviation not exceeding ±0.02–0.04. The overall agreement (within ±0.03 accuracy) confirms the validity of the selected mathematical approach and the adequacy of the kinetic model. The model enables reliable prediction of terpolymer composition evolution and demonstrates that, by adjusting the TDMA–St–MA monomer ratios, it is possible to tailor the final structure and properties of the terpolymers. Furthermore, the obtained results provide a robust experimental basis for determining reactivity ratios.

Determination of reactivity ratios and adequacy of the kinetic model: Figure 3 presents the experimental data points of terpolymer composition in the TDMA–St–MA system along with the values calculated using the kinetic model, shown in a ternary diagram. In accordance with kinetic equations (11–13), Figure 3(a) illustrates the model results calculated based on binary reactivity ratios, while Figure 3(b) shows the model predictions obtained using ternary reactivity ratios, both compared with the experimental data.



3-Figure. Experimental and calculated (model-based) terpolymer composition for the TDMA/St/MA system: (a) binary reactivity coefficients, (b) ternary reactivity coefficients

According to the results shown in Figure 3(a), the values calculated based on the binary model exhibit significant deviations from the experimental data points,

ISSN 3030-3907

indicating that the binary approach is insufficient to fully describe the terpolymer composition in ternary systems. In contrast, the results presented in Figure 3(b) demonstrate that the model based on ternary reactivity ratios shows a much closer agreement with the experimental data. The maximum deviation between the model predictions and experimental results does not exceed ±0.03, confirming the improved accuracy of the ternary approach. These findings indicate that the mutual reactivity of monomers in the TDMA–St–MA system cannot be fully described solely by pairwise interactions, and the presence of a third monomer significantly affects the kinetic parameters. Thus, the comparison of experimental and calculated terpolymer compositions in the TDMA–St–MA system demonstrates that the ternary reactivity ratio model (based on Eq. 14) provides a more accurate representation of the system than the binary model.

TDMA-St-MA

$$r_{12}\frac{k_{TDMA}}{k_{St}}=\frac{k_{p1}}{k_{p12}}=\frac{k_{f1}}{k_{Sf12}}=0{,}994; \qquad r_{21}\frac{k_{St}}{k_{TDMA}}=\frac{k_{p2}}{k_{p21}}=\frac{k_{f2}}{k_{Sf21}}=1{,}621$$

$$r_{13}\frac{k_{TDMA}}{k_{MA}}=\frac{k_{p1}}{k_{p13}}=\frac{k_{f1}}{k_{Sf13}}=2{,}022; \qquad r_{31}\frac{k_{MA}}{k_{TDMA}}=\frac{k_{p2}}{k_{p31}}=\frac{k_{f2}}{k_{f31}}=0{,}343$$

$$r_{12}\frac{k_{MA}}{k_{St}}=\frac{k_{p1}}{k_{p32}}=\frac{k_{f1}}{k_{Sf32}}=0{,}994; \qquad r_{23}\frac{k_{St}}{k_{MA}}=\frac{k_{p2}}{k_{p31}}=\frac{k_{f2}}{k_{Sf31}}=0{,}315$$

The obtained results indicate that for the TDMA–styrene pair, the reactivity ratios were determined as $r_{12}\approx0.99$, suggesting nearly statistical copolymerization, while the chain end terminated with styrene exhibits higher reactivity toward TDMA. For the TDMA–MA pair, the values r_{13}va $r_{31}\approx0.34$ were obtained, indicating that a TDMA-ended chain has a high tendency to react with MA monomer, whereas an MA-ended chain shows lower reactivity toward TDMA. Similarly, for the styrene–MA pair, the reactivity ratios $r_{23}\approx$ indicate that a styrene-ended chain has a higher probability of reacting with MA, while an MA-ended chain exhibits lower reactivity toward styrene.

Based on these findings, the terpolymerization reaction can be described as follows:

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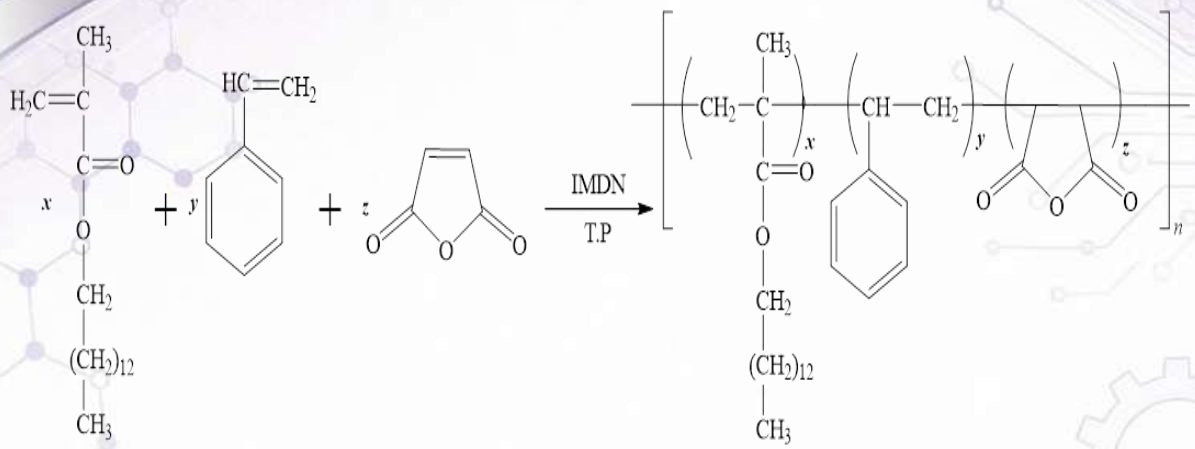


Figure 4. Terpolymerization reaction scheme

The mutual reactivity of TDMA–St–MA monomers is governed by a complex ternary kinetic mechanism. For the TDMA–styrene pair, the value $r_{12}=1$ indicates a nearly statistical distribution of monomers during chain growth, while $r_{21}>1$ reflects a higher tendency of styrene to be incorporated compared to TDMA, leading to an alternating arrangement of elastic (TDMA) and rigid (styrene) segments within the polymer chain. For the TDMA–MA pair, the observed ratios $r_{13}\gg1$ and $r_{31}\ll1$ indicate that maleic anhydride has a low tendency for homopolymerization; however, in the presence of TDMA, it is effectively incorporated into the terpolymer chain. This suggests that MA is incorporated primarily through reactions with other monomers and acts as a functional fragment within the polymer structure. For the styrene–MA pair, the values $r_{23}>1$ and $r_{32}<1$confirm the presence of a donor–acceptor mechanism, where styrene acts as a donor and maleic anhydride as an acceptor, resulting in the formation of partially alternating segments in the polymer chain.

The deviation of the binary model from the experimental results indicates that the presence of a third monomer in ternary systems significantly alters the kinetic constants. Therefore, a model that accounts for ternary reactivity ratios is required for an accurate description of the terpolymerization process. The high agreement of the ternary model with the experimental data (within ±0.03 accuracy) confirms its adequacy and demonstrates its capability to reliably predict terpolymer composition. Moreover, this approach enables simultaneous control of key material properties such as elasticity, viscosity, and functional performance of the resulting terpolymers.

CONCLUSION

The kinetic regularities of the terpolymerization process in the TDMA–styrene–maleic anhydride (TDMA–St–MA) system were comprehensively investigated, the monomer reactivity ratios were determined, and the adequacy of the developed kinetic model was validated against experimental data. It was

ISSN 3030-3907

established that an increase in the initiator (IMDN) concentration leads to a nearly linear increase in both the terpolymerization rate and monomer conversion. The initial stages of the process follow pseudo-first-order kinetics, highlighting the decisive role of active radical concentration in radical terpolymerization. The results obtained in the low conversion region (X_w = 0,02–0,09) indicate that the initial incorporation of monomers is close to the feed composition; however, slight deviations occur due to differences in reactivity ratios. TDMA and styrene exhibit higher reactivity and predominantly determine the terpolymer composition, whereas maleic anhydride, despite its low tendency for homopolymerization, is selectively incorporated into the polymer chain through a donor–acceptor mechanism.

Overall, the terpolymers formed in the TDMA–St–MA ternary system consist of statistically distributed and partially alternating segments, where TDMA contributes to elastic properties, styrene provides mechanical strength, and maleic anhydride introduces functional groups. Furthermore, controlling the terpolymerization process enables the design of functional terpolymer additives with targeted physicochemical properties. These findings provide a scientific basis for the synthesis of highly efficient terpolymer additives for fuel and lubricant applications.

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DEVELOPMENT OF DRILLING FLUID FORMULATIONS FOR WELLS IN DIFFICULT CONDITIONS BASED ON THE STUDY OF THE COMPOSITION OF CLAYS IN UZBEKISTAN

Sherzod Toshev Orziyevich
Bukhara state technical university, Bukhara, Uzbekistan
Khahramon Sharipov Qandiyorovich
Bukhara state technical university, Bukhara, Uzbekistan
Bobomurod Rakhimov Rustamovich
Bukhara state technical university, Bukhara, Uzbekistan
Abdukholik Kholmukhammadiev Mahammadi o‘g‘li
Termez state university of engineering and agrotechnology, Surkhandarya, Uzbekistan

Abstract. The article considers the scientific significance of the results of the study is to establish the chemical and mineralogical compositions and physico-chemical properties of bentonite compositions, as well as to identify the composition and properties of Navbakhor bentonites and Palygorskites and Shorsuv hydrosludes. The practical significance of the research results lies in the development of technology for producing clay compositions for drilling fluids based on local bentonites, palygorskites and hydrosludes.

Keywords: drilling mud, chemical and mineralogical composition, physico-chemical properties, composition of bentonites, composition of Navbakhor bentonites, properties of Navbakhor bentonites, palygorskite, hydrosludes, clay composition.

Annotatsiya. Maqolada tadqiqot natijalarining ilmiy ahamiyati bentonit kompozitsiyalarining kimyoviy va mineralogik tarkibi va fizik-kimyoviy xususiyatlarini aniqlash, shuningdek Navbaxor bentonitlari va Palygorskitlari va Shorsuv gidrosludiyalarining tarkibi va xususiyatlarini aniqlashdan iborat. Tadqiqot natijalarining amaliy ahamiyati mahalliy bentonitlar, palygorskitlar va gidroslyudalar asosida burg‘ulash suyuqliklari uchun loy kompozitsiyalarini ishlab chiqarish texnologiyasini ishlab chiqishdan iborat.

Kalit so‘zlar: burg‘ulash loyi, kimyoviy va mineralogik tarkibi, fizik-kimyoviy xossalari, bentonitlarning tarkibi, "Navbahor" bentonitlarining tarkibi, "Navbahor" bentonitlarining xossalari, palygorskit, gidroshlyuzlar, loy tarkibi.

Аннотация. В статье рассматривается научная значимость результатов исследования, заключающаяся в установлении химического и минералогического составов и физико-химических свойств бентонитовых композиций, а также в выявлении состава и свойств навбахорских бентонитов, палыгорскитов и шорсувских гидрошламей. Практическая значимость результатов исследований заключается в разработке

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технологии получения глинистых композиций для буровых растворов на основе местных бентонитов, палыгорскитов и гидрошламей.

Ключевые слова: буровой раствор, химико-минералогический состав, физико-химические свойства, состав бентонитов, состав навбахорских бентонитов, свойства навбахорских бентонитов, палыгорскит, гидрошламы, глинистый состав.

I. INTRODUCTION.

At the present stage of development of technologies for drilling wells and oil and gas production, the main attention is paid to improving the processes of deep drilling in complicated conditions, where salt formations, rocks of solid minerals, etc. are overcome. Under these conditions, the temperature in wells rises above 200°C and reservoir water contains a lot of salt, especially chloride. Such high mineralization of reservoir water destroys the stability of the drilling fluid, reduces its quality and thereby the efficiency of drilling operations. In addition, the unsatisfactory quality of the drilling mud leads to stoppage and emergency situations, which is more often observed when using clay solutions unstable to high temperatures and highly mineralized aqueous solutions. [1].

When drilling rotationally, a fluid flow constantly circulates in the well, which was previously considered only as a means for removing destruction products (sludge). Currently, it is perceived as one of the main factors ensuring the efficiency of the entire drilling process. When drilling operations are carried out, the liquid circulating in the well is commonly called-drilling mud or washing liquid.

Drilling mud, in addition to sludge removal, must perform other equally important functions aimed at efficient, economical, and safe execution and completion of the drilling process. For this reason, the composition of drilling fluids, the assessment of its properties, becomes the subject of a large volume of scientific and practical research and analysis [2].

During drilling, the equilibrium of the rocks composing the walls of the wells is disturbed. The stability of the walls depends on the initial strength characteristics of the rocks, their change over time under the influence of various factors. A big role here belongs to the flushing process and the flushing agent. The main task of flushing is to ensure an efficient well drilling process, which includes maintaining both the stability of the well walls and the core.

In conditions where the integrity of the rock is violated, mountain pressure plays an important role. In the barrel part of the well, it manifests itself both vertically and horizontally. Lateral pressure is a consequence of vertical pressure

ISSN 3030-3907

and causes tangential directions-contributing to the bulging of rocks, narrowing of the trunk and collapse. The magnitude of tangential stresses depends not only on the rock pressure, but also on the pressure of the washing liquid [3].

When drilling wells, the flushing fluid must circulate through a closed hydraulic circuit. Depending on the type of hydraulic circuit, all existing flushing systems are divided into two groups:

1) washing systems with solution output to the surface

2) flushing systems with downhole circulation.

Accordingly, drilling fluids must meet a number of requirements:

– perform the assigned functions;

– do not have a harmful effect on drilling tools and downhole motors (corrosion, abrasive wear, etc.):

– easy to pump and clean from sludge and gas;

– be safe for maintenance personnel and the environment;

– be convenient for cooking and cleaning;

– be affordable, inexpensive, allow for multiple use.

II. METHODS.

The creation of thermo and salt-resistant clay drilling fluids can be carried out in the following areas:

-creation of high-quality compositions of dispersed systems based on thermo and salt-resistant natural mineral raw materials;

-based on thermo salt-resistant reagents of stabilizers obtained by chemical and technological methods.

Of course, the predominant development of the first direction is considered promising and economically justified. Moreover, this does not exclude the need for work in the second direction.

As noted earlier, palygorskite minerals showed higher resistance to the aggression of electrolytes of reservoir waters and salt deposits than montmorillonite minerals. This made it possible to significantly reduce the cost of expensive chemical reagents in obtaining stable drilling fluids [4].

Known heat-resistant reagents-stabilizers (polyelectrolytes) obtained by hydrolysis of polyacrylonitrile and polyacrylamide or their copolymers greatly overestimate the cost of drilling fluids and hydrocarbon production in general. In practice, the following reagents-stabilizers are used to protect clay solutions from the coagulating action of electrolytes: condensed sulfite-alcohol bard (CSAB), carbosimethylcellulose (CMC), starch reagent (SR), cellulose sulfoesters, etc.

A common disadvantage of these stabilizers is their susceptibility to temperature influences. On the contrary, reagents such as HYPAN, RS-2, RS-3, K-

ISSN 3030-3907

4 and others are more resistant to thermal effects on clay solutions. The paper proposes a lignin-containing reagent for the treatment of drilling fluids and water-based buffer fluids [5]. A distinctive feature of this reagent from the known ones is that it contains lignin with a humidity of 20-44%, an alkaline agent is a product of condensation of JK cotton soapstock with silicic acid sodium, etc.

III. Results. From the table. 1 it can be seen that alkaline and alkaline-earth bentonites mainly differ in the contents of TiO_2, MgO, Na_2O, K_2O_2, etc. More significant differences in chemical composition are observed between bentonites and carbonate palygorskite, where the latter has significantly less Al_2O_3, SiO_2, MgO and more CaO. When bentonites are sealed with water, it penetrates into the interlayer space of montmorillonite, hydrates it and causes swelling. When further diluted with water, bentonites form a stable viscous suspension with pronounced thixotropic properties. These bentonites are considered to be good viscous-gelling agents and filtration reducers in the preparation of drilling fluids for drilling wells [6].

Today, formulations have been developed for obtaining padygorskite-containing drilling fluids that have low filtration and resistance to high downhole temperatures and electrolytes. This once again confirms the need for the right choice of mineral raw materials for the preparation of drilling fluids used in difficult drilling conditions.

Carbonate palygorskite of the Navbakhor deposit (Navoi region) is an aqueous magnesium aluminosilicate with the ideal formula R_5 [Si_8 O_2] $(OH)_2$, $(OH_2)_4$, $4H_2O$. The crystal structure of this palygorskite, which has a layered structure, resembles the structure of an amphibole and has zeolite-like channels of 6.4. 3.7 Å In size, two types of water are located in them: molecules that are freely placed and connected to the electronegative surface of the bases of tetrahedra, and molecules that have a connection with octahedral cations on the side walls of the channels. These molecules are removed from the latter at higher temperatures, as are the water molecules of zeolites [7].

Of course, if necessary, the formation of calcium bentonites into sodium ones can be performed by treating them with sodium salts. Today, in the Bukhara-Khiva and Ustyurt regions of Uzbekistan, drilling of oil and gas wells is carried out in saline formations. According to, it is advisable to use solutions for such drilling, mainly obtained using palygorskite clays (atapulgite), which are rich in CaO (Table 1).

ISSN 3030-3907

Table 1

The content of chemical compounds in the composition of bentonites and palygorskite of the Navbakhor deposit (Navoi region)

Name of connections	Compound content, % per absolute dry matter		
	Bentonites		Carbonate palygorskite (attapulgite)
	Alkaline	alkaline earth	
SiO_2	57,91	56,23	46,79
TiO_2	0,35	0,61	-
Al_2O_3	13,69	13,56	8,63
Fe_2O_3	%.10	6,50	-
MgO	1,84	3,76	2,74
CaO	0,48	0,69	10,08
Na_2O	1,53	0,98	-
K_2O	1,75	2,20	1,6
P_2O_3	0,43	0,92	1,99
SO_3	0,75	0,49	-
Fe_2O	-	-	3,41
P.P.P.	16,17	14,06	24,33
∑	99,98	99,95	99,75

The advantage of this reagent is that it is possible to use not only previously used brands of cotton and other types of lignins after pentose hydrolysis, but also more difficult-to-dissolve brands of lignins after hexose brews. Instead of the known stabilizing clay drilling fluids reagents CMC-600, K-4 and K-9, a composite polymer reagent is proposed, which consists mainly of caustic and soda ash and waste from the production of nitrogen fertilizers, which contains polyacrylamide [8].

The carbonate palygorskite of the Navbakhor deposit has more large fractions, compared with the alkaline and alkaline-earth bentonites of the same deposit (Table 2).

The results are presented in table 2.

Table 2

Dispersed composition and specific surface area of alkaline, alkaline-earth bentonites and carbonate palygorskite Navbakhor deposit and hydrosluidic clay Shorsuvskoye field

Name of clay	Content of fractions, %			Specific surface area 10^3 м^2/kg
	less than	less than 0,1 mm	less than 1,0 mm	

ISSN 3030-3907

	0,01 mm			
Alkaline bentonite of the Navbakhor deposit (ABND)	80,2	18,9	0,9	305
Alkaline earth bentonite of the Navbakhor deposit (AEBND)	81,6	17,7	0,7	310
Carbonate palygorskite of the Navbakhor deposit (CPND)	76,5	21,4	2,1	286
Hydrosluidic clay of the Shorsuv deposit (HCSD)	82,7	16,2	1,1	295

Table 2 shows that the largest specific surface area is found in alkaline-earth bentonite (310·103 m^2/kg) and vice versa, the smallest in carbonate palygorskite (286·103 m^2/kg).

In the table 3 the results of the study of the wetting heat and the amount of bound water are presented.

Table 3

Indicators of the heat of wetting and the amount of bound water in the clays of the Navbakhor and Shorsuv deposits

Name of clay	Wetting heat (Q), cal/g	Amount of bound water (A), %
Alkaline bentonite	25,8	33,54
Alkaline-earth bentonite	28,5	37,05
Carbonate palygorskite	19,5	25,35

It can be seen from Table 3 that the greater the value of the wetting heat of the clay, the greater the amount of bound water in it. The greatest heat of wetting and the amount of bound water is observed in alkaline-earth bentonite and vice versa the smallest in carbonate palygorskite at a density of bound water in = 1.3 g/cm^3.

The indicator of the amount of bound water makes it possible to judge the degree of hydrophilicity of the clay under study. Moreover, the alkaline and alkaline-earth bentonites of the Navbakhor deposit are more hydrophilic than the carbonate palygorskite of this object [9].

Palygorskite with a layered-ribbon crystal structure forms angular plank-like crystals with zeolite-like channels. It is known that in bentonite (montmorillonite) clays, water is absorbed not only by the outer surface, but also by the inner

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(interpackage) space. Therefore, Navbakhor bentonites are characterized by relatively higher values of wetting heat than carbonate palygorskite of this deposit.

The study of the swelling of bentonites and palygorskite of the Navbakhor deposit is important, especially at the stages of well wiring, because the drilled rock, peptising, can lead to an undesirable increase in the viscosity of the drilling mud. Therefore, reducing the amount of swelling of clays is one of the main tasks of obtaining effective drilling fluids. At the same time, the amount of bound water certainly depends on the type of clay, its mineralogical and chemical compositions, specific surface area, dispersion and others [10].

Table 4 presents the results of swelling analyses of selected clays of the Navbakhor deposit.

Table 4

Indicators of swelling of bentonites and carbonate palygorskite Navbakhor deposit and hydrosluidic clay Shorsuvskoye field (ShF)

Name of the swelling index	Bentonite		carbonate palygorskite	hydrosluidic clay ShF
	alkaline	alkaline-earth		
Degree of swelling (h), cm^3/g	1,398	1,425	1,235	1,321
Swelling time (τ), hour	762	776	675	689
Average swelling rate (ω_{cp}. 10^{-3}), cm^3/g. hour	1,720	1,735	1,689	1,578
Limiting shear stress (Pm), $g.s/cm^2$	125	121	127	122

From the table 4 it can be seen that the greatest water swelling is observed in alkaline-earth bentonite and vice versa, the least in carbonate palygorskite (atapulgite). Moreover, the average swelling is observed in the alkaline bentonite of the Navbakhor deposit [4].

Palygorskite-magnesium aluminosilicate forms the strongest suspension when replacing the exchange complex with magnesium cation, the most. Completely filling vacancies of broken bonds in places of crystal structure violations, especially in areas of destruction of zeolite-like channels.

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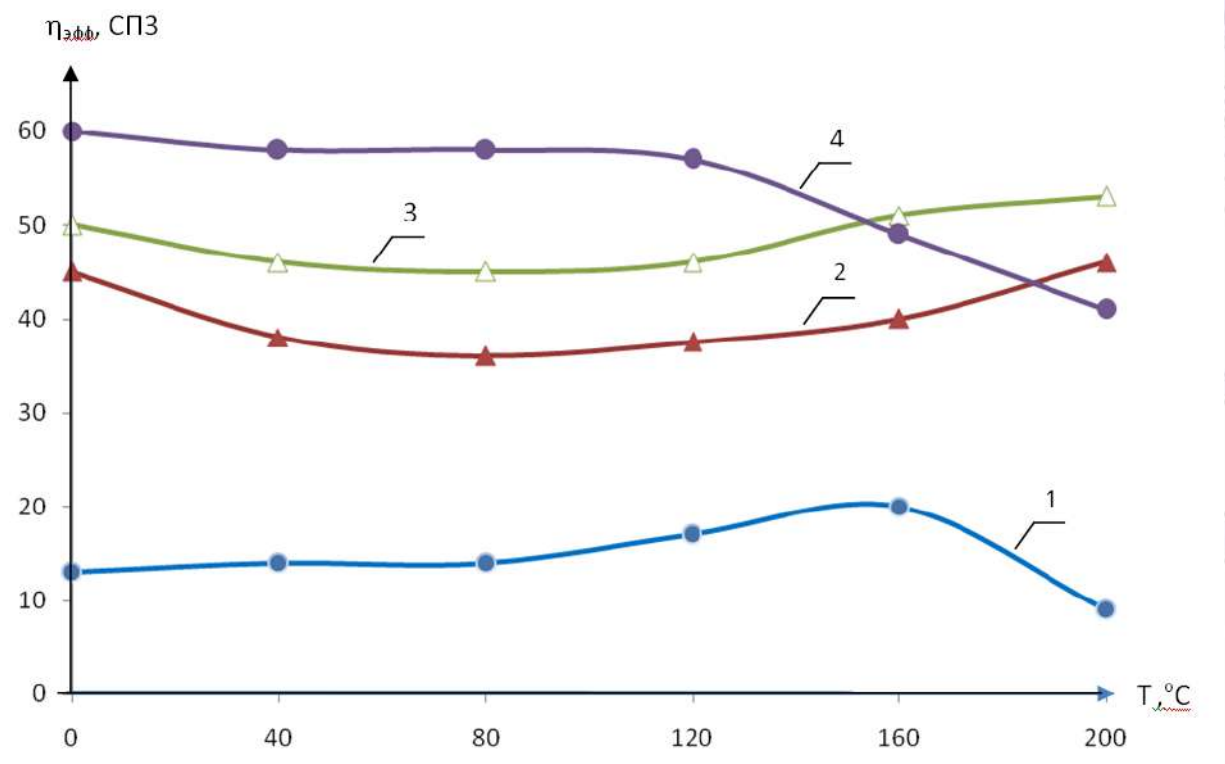


Figure 1. Change in the effective viscosity (η eff) of a 10% aqueous solution of CP NM depending on the temperature of its hydrothermal treatment: 1-without electrolyte; 2-with the addition of 10% NaCl; 3-with the addition of 20% NaCl; 4-with the addition of 30% NaCl.

When using a 50:50 ratio of the above-mentioned clays, the effective viscosity of the solution is higher than when they are used individually, and its decrease is observed after 170°C-180°C. This once again confirms the advantage of using a clay composition with the addition of palygorskite in producing a suspension for drilling deep, high-temperature wells.

With this in mind, we studied the change in the effective viscosity (η_{eff}) of a 10% aqueous solution of KP NM depending on its thermal treatment temperature and the addition of electrolyte with varying concentrations.

The results are presented in Figure 1.

Figure 1 shows that aqueous solutions of KP NM exhibit uniform changes in their effective viscosity curves up to 160°C. With further increases in temperature, the effect of NaCl concentration becomes more pronounced.

However, mixtures i.e. compositions of these types of clays of the Navbakhor field for obtaining drilling fluids have not been studied enough. In order to fill this gap, we studied a number of compositions obtained on the basis of clays from the Navbakhor deposit and others [11].

Thus, the conducted studies show that from these clays, depending on the purpose of the drilling fluids obtained, various compositions of them can be made. At the same time, it should be noted that the resulting compositions serve as the

ISSN 3030-3907

basis of clay drilling fluids and their treatment with chemical reagents allows to stabilize the quality indicators of the latter.

It is known that bentonites contain more than 70% of montmorillonite-a highly dispersed layered aluminosilicate, the crystal-chemical structure of which causes the presence of ion-exchange cations on its surface, which determine its chemical and physical properties as a mineral. The excessive negative charge compensating the exchange cations of the interlayer space of montmorillonite causes the high hydrophilicity of bentonites. When bentonites are sealed with water, it penetrates into the interlayer space of montmorillonite, hydrates it and causes swelling. Upon further dilution with water, bentonite forms a stable viscous suspension with pronounced thixotropic properties [12], These bentonites are considered good visco-gelling agents and filtration reducers in the preparation of drilling fluids for drilling wells.

IV. DISCUSSION.

Ca-clays bind water more strongly than Na-clays, in terms of the binding energy, i.e. by the heat of wetting, being more hydrophilic. However, they do not form diffuse double layers as thick as Na-clays, and therefore do not detect peptization of particles and give compact coagulation through the thinnest layers of water [13].

Carbonate palygorskite of the Navbakhor deposit has more large fractions, compared with alkaline and alkaline-earth bentonites of the same deposit (Table 2).

This means that the entire possible clay surface also interacts with water in this case, but this interaction is not accompanied by the release of particles and, consequently, a significant increase in their number per unit volume, as is observed in Na-clays. In the latter case, they are partially connected at the contact points much weaker, but their number, and therefore the number of contacts, is much greater [14]. In the limit, when the cation-exchange complex is completely replaced by a sodium ion, the diffuse ion forces are so developed that the peptization of particles and their stabilization in dilute suspensions are complete.

The results of the sedimentation analysis using the Sabanin-Robinson method showed that, according to their granulometric composition, all the clays of the Navbakhor deposit belong to fine-dispersed raw materials. Moreover, both bentonites have more small fractions than palygorskite [15].

The creation of thermo- and salt-resistant drilling fluids can be carried out in two main directions, partially complementing each other;

– creation of high-quality dispersed systems based on thermo- and salt-resistant natural mineral raw materials;

– based on thermo and salt-resistant reagents-stabilizers.

ISSN 3030-3907

Of course, it is advisable to preferentially develop the first direction as the most promising and economically profitable. Moreover, this does not exclude the possibility of carrying out work in the second direction, especially in the case of the use of washing fluids when drilling in salt deposits alternating with clay layers, where it is required to reduce the filtration of clay solutions to minimum values [16]. Of course, this can be achieved only by combining heat-resistant mineral raw materials and surfactants, i.e. by combining the two above-mentioned directions.

V. CONCLUSION.

It is known that the use of even high-quality montmorillonites (bentonites) does not allow efficient drilling in mineralized media without treatment with chemical reagents, which is many times higher than the cost of drilling fluids, and often leads to the impossibility of their operation due to coagulation of clay suspension by electrolytes. The use of palygorskite clays when drilling solid salt-bearing strata allows in some cases to do without expensive chemicals, which reduces the cost of drilling mud tenfold.

Long-term practice shows that ordinary clay minerals, even with chemical treatment, are not able to form dispersed systems stable in the presence of electrolytes in the hydrothermal regime. In this case, the use of padygorskite-containing drilling fluids allows for further drilling of difficult wells Such solutions have low filtration and are suitable for drilling salt deposits interspersed with clay layers. As can be seen, salt-resistant clay minerals do not significantly change the course of the deformation process in their dispersions when exposed to various electrolytes. Moreover, this is confirmed both with and without surfactant additives.

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DEVELOPMENT OF A TECHNOLOGY FOR THE PREPARATION OF LIGHT-DENSITY DRILLING MUD BASED ON THE STUDY OF THE COMPOSITION AND PROPERTIES OF LOCAL BENTONITES

Sherzod Toshev Orziyevich
Bukhara state technical university, Bukhara, Uzbekistan
Khahramon Sharipov Qandiyorovich
Bukhara state technical university, Bukhara, Uzbekistan
Abdukholik Kholmukhammadiev Mahammadi o‘g‘li
Termez state university of engineering and agrotechnology, Surkhandarya, Uzbekistan
Hamid Obidov Olimovich
Bukhara state technical university, Bukhara, Uzbekistan
Shakhnoza Tilloeva Faxritdinovna
Bukhara state technical university, Bukhara, Uzbekistan

Abstract. The article considers the scientific significance of the results of the study is to establish the chemical and mineralogical compositions and physico-chemical properties of bentonite compositions, as well as to identify the composition and properties of Navbakhor bentonites and Palygorskites and Shorsuv hydrosludes. The practical significance of the research results lies in the development of technology for producing clay compositions for drilling fluids based on local bentonites, palygorskites and hydrosludes.

Keywords: drilling mud, chemical and mineralogical composition, physico-chemical properties, composition of bentonites, composition of Navbakhor bentonites, properties of Navbakhor bentonites, palygorskite, hydrosludes, clay composition

Аннотация. В статье рассматривается научная значимость результатов исследования, заключающаяся в установлении химического и минералогического составов и физико-химических свойств бентонитовых композиций, а также в выявлении состава и свойств навбахорских бентонитов, палыгорскитов и шорсувских гидрошламей. Практическая значимость результатов исследований заключается в разработке технологии получения глинистых композиций для буровых растворов на основе местных бентонитов, палыгорскитов и гидрошламей.

Ключевые слова: буровой раствор, химико-минералогический состав, физико-химические свойства, состав бентонитов, состав навбахорских бентонитов, свойства навбахорских бентонитов, палыгорскит, гидрошламы, глинистый состав.

Annotatsiya. Maqolada tadqiqot natijalarining ilmiy ahamiyati bentonit kompozitsiyalarining kimyoviy va mineralogik tarkibi va fizik-kimyoviy xususiyatlarini aniqlash, shuningdek Navbaxor bentonitlari va Palygorskitlari va

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Shorsuv gidrosludiyalarining tarkibi va xususiyatlarini aniqlashdan iborat. Tadqiqot natijalarining amaliy ahamiyati mahalliy bentonitlar, paligorskitlar va gidroslyudalar asosida burg‘ulash suyuqliklari uchun loy kompozitsiyalarini ishlab chiqarish texnologiyasini ishlab chiqishdan iborat.

Kalit so‘zlar: burg‘ulash loyi, kimyoviy va mineralogik tarkibi, fizik-kimyoviy xossalari, bentonitlarning tarkibi, "Navbahor" bentonitlarining tarkibi, "Navbahor" bentonitlarining xossalari, palygorskit, gidroshlyuzlar, loy tarkibi

I. INTRODUCTION.

All over the world, work is being carried out on the exploration of oil and gas deposits, as well as their development and exploitation, taking into account the structure of wells and drilling depth. Therefore, it is of great importance to create new types of drilling fluids using local clay minerals, chemical reagents, and stabilizing additives from synthetic and natural materials. Of all types of drilling fluids, clay drilling fluids are used the most and in the largest volume. Currently, three groups of clay minerals deserve great attention in the drilling process: bentonite (montmorillonite, beidellite, nontronite, saponite, etc.), kaolinite (kaolinite, halloysite, nacrite, etc.) and hydromica (illite, brawnsite, etc.). From the point of view of preparing drilling fluids, montmorillonite and other bentonite materials have the best quality [1].

If the drilling fluid has sufficient stability and does not form sediment when used, but retains its properties, it can be used in the drilling process. However, excessive or insufficient aggregate stability also does not lead to good results. In the first case, excessive pressure is created during the pumping of drilling fluids into the well, and in the second case, the holding properties are weak. Thus, sedimentation instability must be completely eliminated, and aggregate instability must be adjusted within the necessary limits.

At the present stage of development of technologies for drilling wells and oil and gas production, the main attention is paid to improving the processes of deep drilling in complicated conditions, where salt formations, rocks of solid minerals, etc. are overcome. Under these conditions, the temperature in wells rises above 200°C and reservoir water contains a lot of salt, especially chloride [2]. Such high mineralization of reservoir water destroys the stability of the drilling fluid, reduces its quality and thereby the efficiency of drilling operations. In addition, the unsatisfactory quality of the drilling mud leads to stoppage and emergency situations, which is more often observed when using clay solutions unstable to high temperatures and highly mineralized aqueous solutions [3].

ISSN 3030-3907

When drilling rotationally, a fluid flow constantly circulates in the well, which was previously considered only as a means for removing destruction products (sludge). Currently, it is perceived as one of the main factors ensuring the efficiency of the entire drilling process. When drilling operations are carried out, the liquid circulating in the well is commonly called-drilling mud or washing liquid.

Drilling mud, in addition to sludge removal, must perform other equally important functions aimed at efficient, economical, and safe execution and completion of the drilling process. For this reason, the composition of drilling fluids, the assessment of its properties, becomes the subject of a large volume of scientific and practical research and analysis [4].

During drilling, the equilibrium of the rocks composing the walls of the wells is disturbed. The stability of the walls depends on the initial strength characteristics of the rocks, their change over time under the influence of various factors. A big role here belongs to the flushing process and the flushing agent. The main task of flushing is to ensure an efficient well drilling process, which includes maintaining both the stability of the well walls and the core [5].

In conditions where the integrity of the rock is violated, mountain pressure plays an important role. In the barrel part of the well, it manifests itself both vertically and horizontally. Lateral pressure is a consequence of vertical pressure and causes tangential directions-contributing to the bulging of rocks, narrowing of the trunk and collapse. The magnitude of tangential stresses depends not only on the rock pressure, but also on the pressure of the washing liquid.

When drilling wells, the flushing fluid must circulate through a closed hydraulic circuit. Depending on the type of hydraulic circuit , all existing flushing systems are divided into two groups:

1) washing systems with solution output to the surface
2) flushing systems with downhole circulation.

Accordingly, drilling fluids must meet a number of requirements:

– perform the assigned functions;
– do not have a harmful effect on drilling tools and downhole motors (corrosion, abrasive wear, etc.):
– easy to pump and clean from sludge and gas;
– be safe for maintenance personnel and the environment;
– be convenient for cooking and cleaning;
– be affordable, inexpensive, allow for multiple use.

II. METHODS.

ISSN 3030-3907

The creation of thermo and salt-resistant clay drilling fluids can be carried out in the following areas:

-creation of high-quality compositions of dispersed systems based on thermo and salt-resistant natural mineral raw materials;

-based on thermo salt-resistant reagents of stabilizers obtained by chemical and technological methods.

Of course, the predominant development of the first direction is considered promising and economically justified. Moreover, this does not exclude the need for work in the second direction.

As noted earlier, palygorskite minerals showed higher resistance to the aggression of electrolytes of reservoir waters and salt deposits than montmorillonite minerals. This made it possible to significantly reduce the cost of expensive chemical reagents in obtaining stable drilling fluids [6].

Known heat-resistant reagents-stabilizers (polyelectrolytes) obtained by hydrolysis of polyacrylonitrile and polyacrylamide or their copolymers greatly overestimate the cost of drilling fluids and hydrocarbon production in general. In practice, the following reagents-stabilizers are used to protect clay solutions from the coagulating action of electrolytes: condensed sulfite-alcohol bard (CSAB), carbosimethylcellulose (CMC), starch reagent (SR), cellulose sulfoesters, etc.

A common disadvantage of these stabilizers is their susceptibility to temperature influences. On the contrary, reagents such as HYPAN, RS-2, RS-3, K-4 and others are more resistant to thermal effects on clay solutions [7]. The paper proposes a lignin-containing reagent for the treatment of drilling fluids and water-based buffer fluids. A distinctive feature of this reagent from the known ones is that it contains lignin with a humidity of 20-44%, an alkaline agent is a product of condensation of JK cotton soapstock with silicic acid sodium, etc.

III. RESULTS.

From the table. 1 it can be seen that alkaline and alkaline-earth bentonites mainly differ in the contents of TiO_2, MgO, Na_2O, K_2O_2, etc. More significant differences in chemical composition are observed between bentonites and carbonate palygorskite, where the latter has significantly less Al_2O_3, SiO_2, MgO and more CaO. When bentonites are sealed with water, it penetrates into the interlayer space of montmorillonite, hydrates it and causes swelling. When further diluted with water, bentonites form a stable viscous suspension with pronounced thixotropic properties. These bentonites are considered to be good viscous-gelling agents and filtration reducers in the preparation of drilling fluids for drilling wells [8].

Carbonate palygorskite of the Navbakhor deposit (Navoi region) is an aqueous magnesium aluminosilicate with the ideal formula R_5 [Si_8 O_2] $(OH)_2$.

ISSN 3030-3907

$(OH_2)_4$, $4H_2O$. The crystal structure of this palygorskite, which has a layered structure, resembles the structure of an amphibole and has zeolite-like channels of 6.4. 3.7 Å In size, two types of water are located in them: molecules that are freely placed and connected to the electronegative surface of the bases of tetrahedra, and molecules that have a connection with octahedral cations on the side walls of the channels. These molecules are removed from the latter at higher temperatures, as are the water molecules of zeolites [9].

Of course, if necessary, the formation of calcium bentonites into sodium ones can be performed by treating them with sodium salts. Today, in the Bukhara-Khiva and Ustyurt regions of Uzbekistan, drilling of oil and gas wells is carried out in saline formations. According to, it is advisable to use solutions for such drilling, mainly obtained using palygorskite clays (atapulgite), which are rich in CaO (Table 1).

Table 1

The content of chemical compounds in the composition of bentonites and palygorskite of the Navbakhor deposit (Navoi region)

Name of connections	Compound content, % per absolute dry matter		
	Bentonites		Carbonate palygorskite (attapulgite)
	alkaline	alkaline earth	
SiO_2	57,91	56,23	46,79
TiO_2	0,35	0,61	-
Al_2O_3	13,69	13,56	8,63
Fe_2O_3	%.10	6,50	-
MgO	1,84	3,76	2,74
CaO	0,48	0,69	10,08
Na_2O	1,53	0,98	-
K_2O	1,75	2,20	1,6
P_2O_3	0,43	0,92	1,99
SO_3	0,75	0,49	-
Fe_2O	-	-	3,41
P.P.P.	16,17	14,06	24,33
∑	99,98	99,95	99,75

The advantage of this reagent is that it is possible to use not only previously used brands of cotton and other types of lignins after pentose hydrolysis, but also more difficult-to-dissolve brands of lignins after hexose brews. Instead of the known stabilizing clay drilling fluids reagents CMC-600, K-4 and K-9, a composite polymer reagent is proposed, which consists mainly of caustic and soda ash and

ISSN 3030-3907

waste from the production of nitrogen fertilizers, which contains polyacrylamide [10].

Stronger ion binding enhances protection. Thus, protection is enhanced in two ways: by increasing the number of charges and by chemically strengthening the protective ions on the surface of the dispersed phase particles. It is known that most organic compounds are soluble in water.

Compared to inorganic compounds, organic compounds have a somewhat higher molecular weight. In these substances, carbon atoms; form bonds for the six-membered nucleus of benzene and other analogous constituent particles. The dissolution of these substances occurs due to the free dissociation of the phenol hydroxyl (OH), alcohol (CH_2OH), carboxyl (COOH) groups in their composition [11].

To increase their hydrophilicity, sulfo groups (SO2OH) are introduced into many such substances. The hydrogen of all of the above groups is replaced by sodium. Dissociation occurs as a result of dissolution in water. In this case, sodium ions are considered cations, and the highly hydrophilic residues of the molecules of organic compounds are anions.

As a result of the large number of groups mentioned above, these anions have a large electric charge, and as a result, their adsorption on the particles of the dispersed phase provides a significant increase in electrical protection. In a number of such substances, chemical fixation is also observed on the surface of the particles of the dispersed phase [12]. This is also an increase in protection. And finally, adsorbing on the surface of the particles, these substances form a strong adsorption shell that prevents coagulation.

The carbonate palygorskite of the Navbakhor deposit has more large fractions, compared with the alkaline and alkaline-earth bentonites of the same deposit (Table 2). The results are presented in table 2.

Table 2

Dispersed composition and specific surface area of alkaline, alkaline-earth bentonites and carbonate palygorskite Navbakhor deposit and hydrosluidic clay Shorsuvskoye field

Name of clay	Content of fractions, %			Specific surface area 10^3 м^2/kg
	less than 0,01 mm	less than 0,1 mm	less than 1,0 mm	

ISSN 3030-3907

Alkaline bentonite of the Navbakhor deposit (ABND)	80,2	18,9	0,9	305
Alkaline earth bentonite of the Navbakhor deposit (AEBND)	81,6	17,7	0,7	310
Carbonate palygorskite of the Navbakhor deposit (CPND)	76,5	21,4	2,1	286
Hydrosluidic clay of the Shorsuv deposit (HCSD)	82,7	16,2	1,1	295

This adsorption shell structure is called a mechanical barrier. Thus, these organic substances combine three protective factors: a large number of electric charges, chemisorption, and the mechanical strength of the protective barrier. Such a shell is less effective in preventing the accumulation of negatively charged particles around it, protecting them from coagulation. Therefore, such protection is called strong protection. The preservation of certain given properties under various conditions, despite various degrading effects, is called “stabilization” [13].

Table 3

Indicators of the heat of wetting and the amount of bound water in the clays of the Navbakhor and Shorsuv deposits

Name of clay	Wetting heat (Q), cal/g	Amount of bound water (A), %
Alkaline bentonite	25,8	33,54
Alkaline-earth bentonite	28,5	37,05
Carbonate palygorskite	19,5	25,35

ISSN 3030-3907

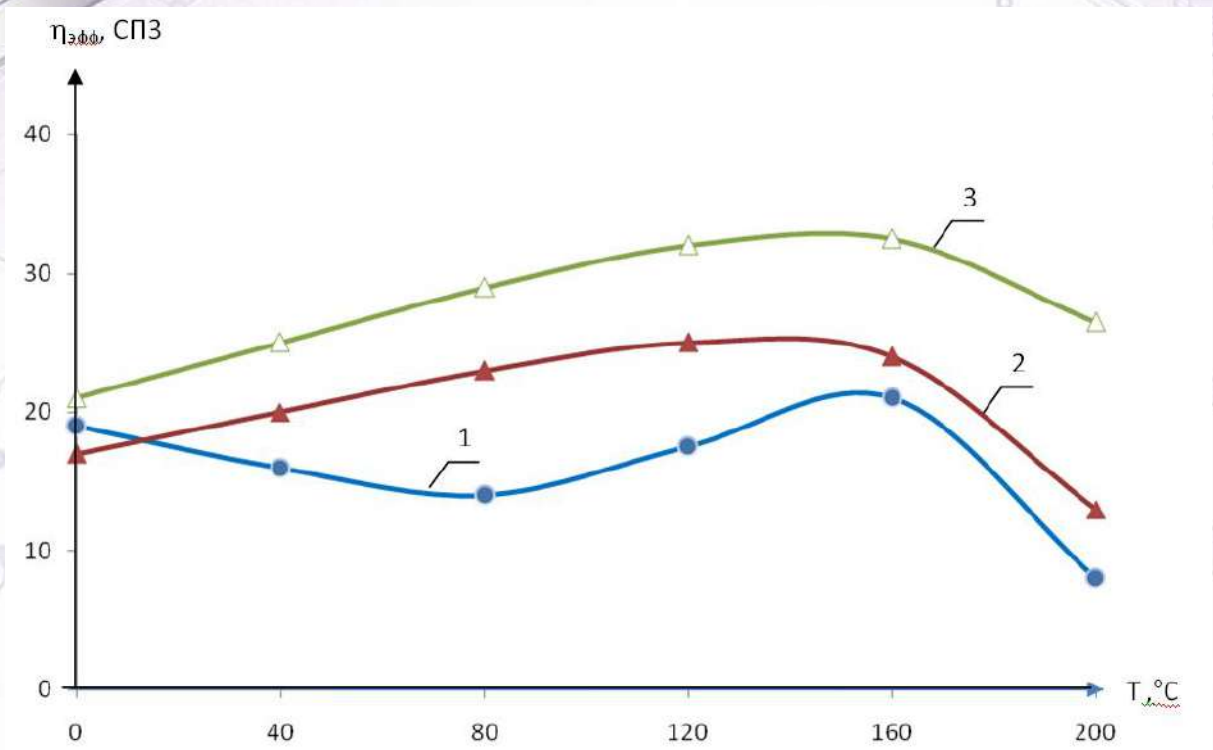


Figure 1. Change in the effective viscosity (η eff) of the clay solution depending on the temperature of its hydrothermal treatment: 1-for ShB NM; 2-for KP NM, 3-for the composition KP: SHB NM=50:50

Figure 1 shows that when using NM ShB and NM KP individually in a 10% aqueous suspension, their effective viscosity (ηeff) increases up to 1500C and then decreases significantly. This is explained by the fact that during hydrothermal treatment of NM ShB, a slight increase in its dispersion is observed and, simultaneously, a change in the submicroscopic region (from 69 to 105 Å) of heterogeneity occurs. Above 1500C, the number of crystals participating in the formation of coagulation structures decreases, which is reflected in a drop in the effective viscosity of the solution [14]. In the case of NM KP, elasticity and plasticity increase, as does the stability coefficient of the coagulation structure.

IV. DISCUSSION.

Substances that provide strong protection are called "stabilizers". Methods for preparing dispersed systems. There are two opposing methods for preparing dispersed systems. The first is dispersion, which is based on crushing large bodies to obtain a system of the required size. The second is condensation, which is based on increasing the size of particles of molecular size and forming a second dispersed phase [15].

Table 4

Indicators of swelling of bentonites and carbonate palygorskite Navbakhor deposit and hydrosluidic clay Shorsuvskoye field (ShF)

	Bentonite		

ISSN 3030-3907

Name of the swelling index	alkaline	alkaline-earth	carbonate palygorskite	hydrosluidic clay ShF
Degree of swelling (h), cm^3/g	1,398	1,425	1,235	1,321
Swelling time (τ), hour	762	776	675	689
Average swelling rate (ω_{cp}. 10^{-3}), cm^3/g. hour	1,720	1,735	1,689	1,578
Limiting shear stress (Pm), $g.s/cm^2$	125	121	127	122

Dispersion of an insoluble body differs from dispersion of a soluble body in that it is impossible to achieve the degree of molecular crushing. This is explained by two reasons. The first reason is determined by the stresses, moments of forces that destroy the body. In crushing devices, the magnitude of the forces is increased only up to a certain limit, therefore, the crushing must also be limited.

V. CONCLUSION.

The second reason is that with an increase in the specific surface area, the effect of the free interfacial energy increases. The attractive forces between the particles increase rapidly with grinding. As a result, the attraction of the particles to each other increases, and the particles coalesce and grow larger. This enlargement process causes an increase in the size of the dispersed phase particles. Simultaneously with the dispersion of the particles, their growth - particle condensation - begins. The smaller the particles, the more intense the condensation.

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INNOVATIVE DEVELOPMENTS TO IMPROVE CORE RECOVERY DRILLING EFFICIENCY IN WEAKLY CEMENTED FORMATIONS

Ravshanbek Narimov Anarmetovich
Associate Professor, *Tashkent State Technical University, Tashkent, Uzbekistan,*
Abdurasul Qayumov Shonazarovich
Associate Professor, *Tashkent State Technical University, Tashkent, Uzbekistan,*
Ozoda Akhmedova Baxronovna
Associate Professor, *Tashkent State Technical University, Tashkent, Uzbekistan,*
Abror Akhmedov Sayidmurod o‘g‘li
Senior Lecturer, Tashkent State Technical University, Tashkent, Uzbekistan,

Annotation. This study presents innovative core sampling tools and drilling head designs developed to improve core recovery in weakly cemented, fractured, and highly permeable formations. Traditional core barrels used in Uzbekistan often provide only 40–60% core recovery because of tool vibration, frequent lifting from the bottomhole, poor centering, and unsuitable drilling parameters. To address these issues, new cone-type, cylindrical, and PDC drilling heads, as well as a spring-loaded core catcher, were designed and tested under field conditions. Experimental studies were carried out in several oil and gas fields between 2017 and 2023 under different geological and technological conditions. The proposed tools improved core preservation and reduced core loss by minimizing the distance between the cutting head and the core catcher, reducing vibration, and ensuring stable core retention. Field tests showed that average core recovery increased from 73% in 2017–2018 to 84% in 2019–2020 and reached 94–100% after implementation of the improved designs. The developed equipment can replace imported core sampling systems, improve geological information quality, and reduce drilling costs.

Keywords: Core, innovative design, core barrel assembly, cylindrical drill bit, spring-loaded core catcher.

Annotatsiya. Ushbu tadqiqotda zaif sementlangan, singan va yuqori o‘tkazuvchan qatlamlarda yadrolarni qayta tiklashni yaxshilash uchun ishlab chiqilgan innovatsion yadro namunalarini olish asboblari va burg‘ulash boshlari dizaynlari keltirilgan. O‘zbekistonda qo‘llaniladigan an’anaviy yadro bochkalari ko‘pincha asbobning tebranishi, quduq tubidan tez-tez ko‘tarilishi, markazlashtirishning yomonligi va mos bo‘lmagan burg‘ulash parametrlari tufayli yadrolarni atigi 40–60% tiklaydi. Ushbu muammolarni hal qilish uchun konus tipidagi, silindrsimon va PDC burg‘ulash kallaklari, shuningdek, prujinali yadro ushlagichi ishlab chiqilgan va dala sharoitida sinovdan o‘tkazilgan. 2017 yildan 2023 yilgacha turli geologik va texnologik sharoitlarda bir nechta neft va gaz konlarida eksperimental tadqiqotlar o‘tkazildi. Taklif etilgan asboblar kesish

ISSN 3030-3907

boshi va yadro ushlagichi orasidagi masofani minimallashtirish, tebranishlarni kamaytirish va yadrolarni barqaror ushlab turishni ta'minlash orqali yadrolarni saqlashni yaxshiladi va yadro yo‘qotilishini kamaytirdi. Dala sinovlari shuni ko‘rsatdiki, o‘rtacha yadro tiklanishi 2017-2018 yillardagi 73% dan 2019-2020 yillarda 84% gacha oshdi va takomillashtirilgan dizaynlar joriy etilgandan keyin 94-100% ga yetdi. Ishlab chiqilgan uskunalar import qilingan yadro namunalarini olish tizimlarini almashtirishi, geologik axborot sifatini yaxshilashi va burg‘ulash xarajatlarini kamaytirishi mumkin.

Kalit so‘zlar: yadro, innovatsion dizayn, yadro bochkasini yig‘ish, silindrsimon burg‘ulash uchi, prujinali yadro ushlagichi.

Аннотация. В этом исследовании представлены инновационные инструменты для отбора керна и конструкции буровых головок, разработанные для улучшения извлечения керна из слабо сцементированных, трещиноватых и высокопроницаемых пластов. Традиционные колонковые барабаны, используемые в Узбекистане, часто обеспечивают извлечение керна лишь на 40-60% из-за вибрации инструмента, частого подъема из забоя скважины, плохого центрирования и неподходящих параметров бурения. Для решения этих проблем были разработаны и испытаны в полевых условиях новые буровые головки конусного, цилиндрического типа и PDC, а также подпружиненный керноуловитель. Экспериментальные исследования были проведены на нескольких нефтяных и газовых месторождениях в период с 2017 по 2023 год в различных геологических и технологических условиях. Предложенные инструменты улучшили сохранность керна и сократили потери керна за счет минимизации расстояния между режущей головкой и керноуловителем, снижения вибрации и обеспечения стабильного удержания керна. Полевые испытания показали, что среднее извлечение керна увеличилось с 73% в 2017-2018 годах до 84% в 2019-2020 годах и достигло 94-100% после внедрения усовершенствованных конструкций. Разработанное оборудование может заменить импортные системы отбора керна, повысить качество геологической информации и снизить затраты на бурение.

Ключевые слова: Керноуловитель, инновационная конструкция, колонковый ствол в сборе, цилиндрическое долото, подпружиненный керноуловитель.

INTRODUCTION.

Core sampling from prospective oil and gas reservoirs is of great importance during exploration and appraisal drilling because core material provides objective information about hydrocarbon presence and the reservoir properties of the rock, including porosity and permeability [1,2].

Core sampling from deep formations is carried out using a special tool known as a core barrel assembly, which is rotated by the drill string through the rotary drilling system.

Research aimed at developing innovative technologies that improve core recovery remains an important scientific and engineering task [3,4].

MATERIALS AND METHODS.

To provide scientific and technical support for field operations and improve core recovery, the authors developed a new core barrel assembly and drill bit design with several advantages over conventional systems. The internal diameter of the core tube was increased by 2 mm, which facilitates easier extraction of the recovered core sample. In addition, the distance between the collet and the openings of the drill bit, as well as between the collet and the core breaker, was minimized. As a result, the total recovered core length increases during retrieval and core preservation is improved. The proposed design can also operate effectively under the complex geological and mining conditions of oil and gas fields in Uzbekistan (Figures 1 and 2).

ISSN 3030-3907



Figure 1. Six-blade conical drill bit of the 6 LBK-MSZ type: 1 – core inlet opening; 2 – drilling fluid channels; 3 – carbide cutters; 4 – drill bit body.

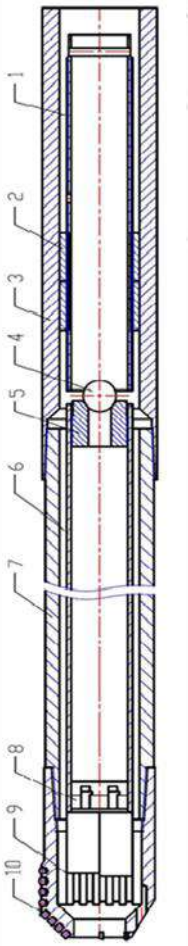


Figure 2. Core barrel assembly ("KOS") with a six-blade conical drill bit: 1 – adjusting screw; 2 – adjusting nut; 3 – upper sub; 4 – ball (Ø 50.8 mm); 5 – ball seat; 6 – core tube; 7 – body; 8 – lever-type core breaker; 9 – collet core holder; 10 – conical drill bit.

To determine the causes of low core recovery, an experimental study was conducted under field conditions. During drilling, a specific drilling mode was established at every 2-meter interval of the formation, and the core recovery results were recorded as the percentage of recovered core relative to the drilled interval. This study was conducted in the following wells:

1. Kokdumalak Field, Well No. 1P, interval 4725–4726 m. A 1 m interval was drilled with coring, and 0.25 m of core was recovered, corresponding to a recovery rate of 25%. The formation consisted of dark gray limestone with a brownish tint.

2. Shortak Field, Well No. 1, interval 2512–2515 m. A 3 m interval was drilled with coring, and 1.5 m of core was recovered, corresponding to a recovery

ISSN 3030-3907

rate of 50%. The formation consisted of terrigenous rocks of the XIX horizon belonging to the Lower–Middle Jurassic terrigenous formation.

3. Taldikuduk Field, Well No. 1, interval 2873–2874 m. A 1 m interval was drilled with coring, and 0.70 m of core was recovered, corresponding to a recovery rate of 70%. The formation consisted of dark brown, dense, slightly calcareous, fine-micaceous argillites. The rocks belong to the Lower–Middle Jurassic terrigenous formation.

4. Tuprokkala Field, Well No. 1, interval 1734–1736 m. A 2 m interval was drilled with coring, and 1.5 m of core was recovered, corresponding to a recovery rate of 75%. The formation consisted of brown to dark gray calcareous siltstone sandstones of the XII Cretaceous horizon.

5. Yerkin Field, Well No. 2, interval 1289–1290 m. A 1 m interval was drilled with coring, and 1 m of core was recovered, corresponding to a recovery rate of 100%. The formation consisted of medium- to fine-grained feldspar-quartz sandstone of the XIII Cretaceous horizon.

6. Sovligar Area, Well No. 4, interval 3605–3607 m. A 2 m interval was drilled with coring, and 1 m of core was recovered, corresponding to a recovery rate of 50%. The formation consisted of gray, thin-bedded, nodular limestone of the XV horizon of the Middle–Upper Jurassic carbonate formation.

7. Chakkakum Area, Well No. 4, interval 2190–2192 m. A 2 m interval was drilled with coring, and 1.5 m of core was recovered, corresponding to a recovery rate of 75%. The formation consisted of dark gray, nodular limestone with recrystallized shell detritus. The rocks belong to the XV-2 horizon of the Middle–Upper Jurassic carbonate formation.

8. Murodtepa Field, Well No. 4, interval 2801–2805 m. A 4 m interval was drilled with coring, and 3.5 m of core was recovered, corresponding to a recovery rate of 87.5%. The formation consisted of dark gray clayey siltstone interbedded with sandstone and argillite layers. The rocks belong to the XVIII horizon of the Lower–Middle Jurassic terrigenous formation.

9. Tumaris Field, Well No. 2, interval 1955–1957 m. A 2 m interval was drilled with coring, and 2 m of core was recovered, corresponding to a recovery rate of 100%. The formation consisted of gray to dark gray limestone with a nodular-oolitic, algal, and locally organogenic-detrital structure, containing bituminous material. The rocks belong to the XV-3 horizon of the Middle–Upper Jurassic carbonate formation.

10. Yangi Umid Area, Well No. 2, interval 2731–2732.7 m. A 1.7 m interval was drilled with coring, and 1.7 m of core was recovered, corresponding to a recovery rate of 100%. The formation consisted of black, silty, clayey, micaceous, bituminous limestone of the XV horizon of the Middle–Upper Jurassic carbonate

ISSN 3030-3907

formation. The average core recovery rate during 2017–2018 was 73%. A patent for the conical drill bit design was obtained as an industrial design under Patent No. SAP 01552 [5,6,7].

The author developed and manufactured a cylindrical drill bit of the MSZ type in sizes Ø187.3/80 mm and Ø139.7/60 mm (Figures 3 and 4), which was tested during 2019–2020 in the following wells:

1. Isavoy Area, Well No. 2, interval 3627–3628 m. A 1 m interval was drilled with coring, and 0.4 m of core was recovered, corresponding to a recovery rate of 40%. The formation consisted of clay belonging to the Middle Jurassic terrigenous formation.

2. Andakli Field, Well No. 2, interval 2515–2520 m. A 5 m interval was drilled with coring, and 4 m of core was recovered, corresponding to a recovery rate of 80%. The formation consisted of interbedded siltstones, argillites, and sandstones of the XVII horizon belonging to the Lower–Middle Jurassic terrigenous formation.

3. South Kulbeshkak Field, interval 2602–2606 m. A 4 m interval was drilled with coring, and 4 m of core was recovered, corresponding to a recovery rate of 100%. The formation consisted of terrigenous rocks of the XIX horizon belonging to the Lower–Middle Jurassic terrigenous formation.

4. Chordarboza Area, Well No. 3, interval 2861–2862 m. A 1 m interval was drilled with coring, and 1 m of core was recovered, corresponding to a recovery rate of 100%. The formation consisted of medium-grained limestone with interbeds of fine-grained limestone belonging to the Lower–Middle Jurassic terrigenous formation.

5. Dultatapa Area, Well No. 2, interval 1217–1218 m. A 1 m interval was drilled with coring, and 1 m of core was recovered, corresponding to a recovery rate of 100%. The formation consisted of argillite-like clay of the XII Cretaceous horizon.

6. South Kulbeshkak Field, Well No. 4, interval 2080–2083 m. A 3 m interval was drilled with coring, and 2 m of core was recovered, corresponding to a recovery rate of 66.6%. During coring, the following technological parameters were applied: rotor speed – 40 rpm, standpipe pressure – 20 atm, drill bit load – 2 t, and pump output – 10 L/s. The drilling mud parameters were: density – 1.10 g/cm³, Marsh funnel viscosity – 45 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation belonged to the XV-3 horizon of the Middle–Upper Jurassic carbonate formation.

7. Sulaimantepa Area, Well No. 1, interval 1661–1666 m. A 5 m interval was drilled with coring, and 4 m of core was recovered, corresponding to a recovery rate of 80%. During coring, the following technological parameters were applied:

ISSN 3030-3907

rotor speed – 45 rpm, standpipe pressure – 25 atm, drill bit load – 2 t, and pump output – 12 L/s. The drilling mud parameters were: density – 1.06 g/cm³, Marsh funnel viscosity – 60 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of clayey sandstone of the XV horizon belonging to the Middle–Upper Jurassic carbonate formation.

8. Shorkum Field, Well No. 2, interval 2471–2475 m. A 4 m interval was drilled with coring, and 3.5 m of core was recovered, corresponding to a recovery rate of 87.5%. During coring, the following technological parameters were applied: rotor speed – 50 rpm, standpipe pressure – 20 atm, drill bit load – 3–4 t, and pump output – 7–8 L/s. The drilling mud parameters were: density – 1.12 g/cm³, Marsh funnel viscosity – 41 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of dark gray, platy limestone of the XVII horizon belonging to the Lower–Middle Jurassic terrigenous formation.

9. Sulaimantepa Area, Well No. 1, interval 1772–1777 m. A 5 m interval was drilled with coring, and 4.5 m of core was recovered, corresponding to a recovery rate of 90%. During coring, the following technological parameters were applied: rotor speed – 45 rpm, standpipe pressure – 25 atm, drill bit load – 2.5 t, and pump output – 16 L/s. The drilling mud parameters were: density – 1.06 g/cm³, Marsh funnel viscosity – 60 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of limestone of the XV-1 horizon belonging to the Middle–Upper Jurassic carbonate formation.

10. Tumaris Area, Well No. 6, interval 2061–2065 m. A 5 m interval was drilled with coring, and 4 m of core was recovered, corresponding to a recovery rate of 80%. During coring, the following technological parameters were applied: rotor speed – 50 rpm, standpipe pressure – 20 atm, drill bit load – 3–4 t, and pump output – 16 L/s. The drilling mud parameters were: density – 1.12 g/cm³, Marsh funnel viscosity – 55 s, and fluid loss – 6 cm³/30 min. The formation consisted of gray limestone with dark gray and greenish-gray оттенками, a fine-grained structure, layered texture, and a dense, strong composition containing abundant carbonized black siltstone inclusions. The rocks belong to the Jurassic carbonate formation of the Callovian stage, XVa horizon.

ISSN 3030-3907



Figure 3. Cylindrical drill bit: 1 – core inlet opening; 2 – drilling fluid circulation channels; 3 – hard-alloy cutters; 4 – drill bit body.

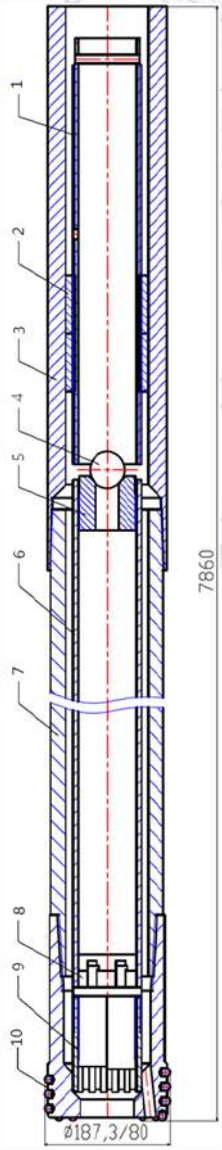


Figure 4. Core barrel assembly ("KOS") with a cylindrical drill bit: 1 – adjusting screw; 2 – adjusting nut; 3 – upper sub; 4 – ball (Ø 50.8 mm); 5 – ball seat; 6 – core tube; 7 – body; 8 – petal-type core catcher; 9 – collet holder; 10 – cylindrical drill bit.

Поддерживался технологический режим бурения, который составил: нагрузка на бурильную головку - 2-3т скорость вращения ротора - 35-50 об/мин, расход промывочный жидкость - 7-16 л/с. Средний вынос керна в 2019-2020 года составил 84% [8]. The teeth inserted into the cylindrical drill bit have a prismatic shape and are made of tungsten carbide alloy [9]. Core sampling assemblies and component parts were developed as import-substituting equipment

ISSN 3030-3907

for core recovery operations at oil and gas fields. To ensure more complete core recovery, we proposed an improved cylindrical drill bit and a spring-loaded core holder installed in combination with a collet-type core catcher.

Field tests demonstrated that the combined use of the core catcher and the spring-loaded core holder increased the core recovery rate (Figures 5 and 6).

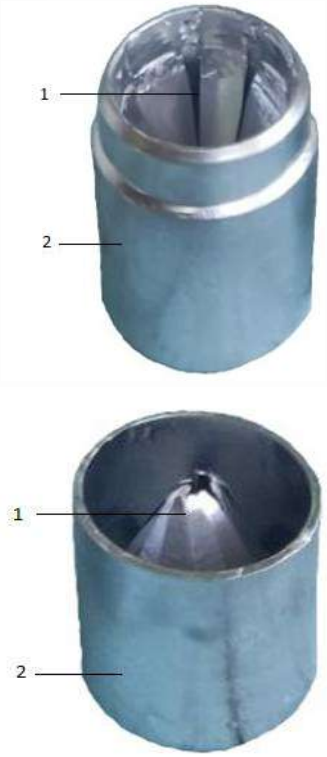


Figure 5. Spring-loaded core holder: 1 – spring-loaded core holder; 2 – body.

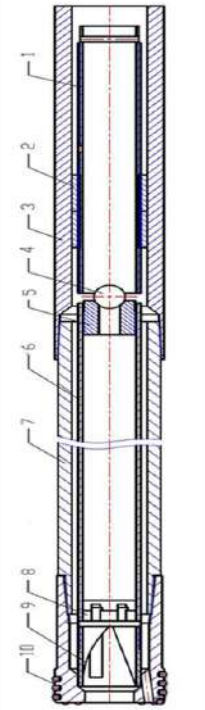


Figure 6. Core barrel assembly ("KOS") with an improved cylindrical drill bit and a spring-loaded core holder: 1 – adjusting screw; 2 – adjusting nut; 3 – upper sub; 4 – ball (Ø 50.8 mm); 5 – ball seat; 6 – core tube; 7 – body; 8 – lever-type core catcher; 9 – spring-loaded holder; 10 – cylindrical drill bit.

During coring operations, it is essential to prevent the drill bit from lifting off the bottomhole. Maintaining continuous contact with the formation ensures a high core recovery rate. Failure to comply with the prescribed drilling regime is one of the main causes of poor core recovery. In many cases, the cause is incorrectly attributed to the core barrel assembly, drill bit, or other equipment. Therefore, strict supervision by engineering and technical personnel is required to ensure compliance with the coring instructions [10,11].

1. Andakli Area, Well No. 6, interval 2071–2074 m. A 3 m interval was drilled with coring, and 2.50 m of core was recovered, corresponding to a recovery rate of 83.3%. During coring, the following technological parameters were applied:

ISSN 3030-3907

rotor speed – 45 rpm, standpipe pressure – 25 atm, drill bit load – 2–3 t, and pump output – 12 L/s. The drilling mud parameters were: density – 1.10 g/cm³, Marsh funnel viscosity – 60 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of limestone of the XV-1 horizon belonging to the Middle–Upper Jurassic carbonate formation.

2. Kattatepa Area, Well No. 2, interval 2153–2157 m. A 4 m interval was drilled with coring, and 3.5 m of core was recovered, corresponding to a recovery rate of 87.3%. During coring, the following technological parameters were applied: rotor speed – 45 rpm, standpipe pressure – 22 atm, drill bit load – 2–3 t, and pump output – 12 L/s. The drilling mud parameters were: density – 1.08 g/cm³, Marsh funnel viscosity – 55 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation belonged to the XV-3 horizon of the Middle–Upper Jurassic carbonate formation.

3. Temirkazgan Area, Well No. 1, interval 2485–2489 m. A 4 m interval was drilled with coring, and 4 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 60 rpm, standpipe pressure – 22 atm, drill bit load – 2–5 t, and pump output – 14 L/s. The drilling mud parameters were: density – 1.09 g/cm³, Marsh funnel viscosity – 55 s, fluid loss – 5 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of gray to dark gray, fine-grained, hard clay of the XVII horizon belonging to the Lower–Middle Jurassic terrigenous formation.

4. Kattatepa Area, Well No. 2, interval 2492–2495 m. A 3 m interval was drilled with coring, and 3 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 55 rpm, standpipe pressure – 22 atm, drill bit load – 3.5 t, and pump output – 14 L/s. The drilling mud parameters were: density – 1.08 g/cm³, Marsh funnel viscosity – 55 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation belonged to the XVII horizon of the Lower–Middle Jurassic terrigenous formation.

5. Chetkum Area, Well No. 1, interval 2392–2398 m. A 6 m interval was drilled with coring, and 6 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 45 rpm, standpipe pressure – 25 atm, drill bit load – 3.5 t, and pump output – 12 L/s. The drilling mud parameters were: density – 1.07 g/cm³, Marsh funnel viscosity – 48 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of gray limestone of the XV-a horizon belonging to the Middle–Upper Jurassic carbonate formation.

The implementation report is attached. The average core recovery rate in 2021 reached 94%.

ISSN 3030-3907

The recovery percentage increased significantly, especially in recent years. Following the implementation of the author's proposed design, core recovery improved and reached 80–100%.

The author developed a new core barrel assembly design with the following components: a spring-loaded core holder and PDC drill bits (polycrystalline diamond cutters) in sizes Ø187.3/80 mm, Ø158.7/67 mm, and Ø139.7/60 mm (Figures 7 and 8). Depending on the hardness, abrasiveness, degree of cementation, and looseness of the formations, drill bits of different sizes and with different numbers of blades may be used.

Based on the above, the following conclusions can be drawn:

1. The study identified the main causes of the low core recovery rate from Jurassic carbonate deposits.
2. These causes include both natural and technological factors:

- rock fracturing;
- high rock permeability;
- frequent lifting of the drill bit off the bottomhole to avoid tool sticking;
- non-compliance with the prescribed drilling regime, including excessive rotational speed and hoisting speed of the drill string, as well as uneven tool feed;
- an excessive distance between the core-forming opening of the drill bit and the lower end of the core catcher;
- the absence of a centralizer in the core barrel assembly.

This problem is addressed by a core barrel assembly consisting of a body made of thick-walled pipe, connected by a special tool joint thread to an upper sub. Inside the body, a core tube is installed; at the lower part, a spring-loaded core holder and a core catcher are mounted, both supported by a cylindrical drill bit. The distinguishing feature of this design is that the core holder is made of spring steel, the thickness of which is selected according to the rock hardness within the range of 0.25 to 0.40 mm (Table 1). The core holder is positioned at a height of L = 30 mm from the end face of the drill bit.

The reduced distance between the core holder and the end face of the drill bit ensures more efficient rock capture during coring, since the contact distance between the rock and the core tube is shortened. In addition, the inner part of the core holder is equipped with tongues arranged in the form of a cone or pyramid, operating on the principle of a check valve.

Table 1.

Classification-based correspondence of the spring-loaded core holder to rock types

ISSN 3030-3907

Category of coring difficulty	Rock type	Rock properties			Core receiving device with a spring-loaded core holder
		Hardness according to L. Schreiner	Abrasiveness according to L. Schreiner	Continuity according to B. Baidyuk	
	1	2	3	4	5
I.	Monolithic Slightly fractured, not eroded by drilling fluid, non-swelling, and not damaged by vibrations of the core sampling tool.	5.8	4.0	3.6	0.4 mm
		6.2	8.7	3.7	
II.	Medium- and low-porosity, interbedded, slightly eroded by drilling fluid, and only slightly damaged by vibrations of the core sampling tool.	3.1	1.9	3.4	0.30 to 0.35 mm
		4.0	2.5	3.3	
		4.7	3.4	3.1	
		5.8	4.0	2.9	
		7.4	9.0	2.8	
III.	Highly fractured, interbedded, eroded by drilling fluid,	4.4	3.1	1.9	0.25 mm
		5.1	5.2	1.8	

ISSN 3030-3907

	and damaged by vibrations of the core sampling tool.				
IV.	Loose, crushed and floating, swelling, highly porous, and soluble in drilling fluid.	1.6	1.9	1.4	0.25 mm

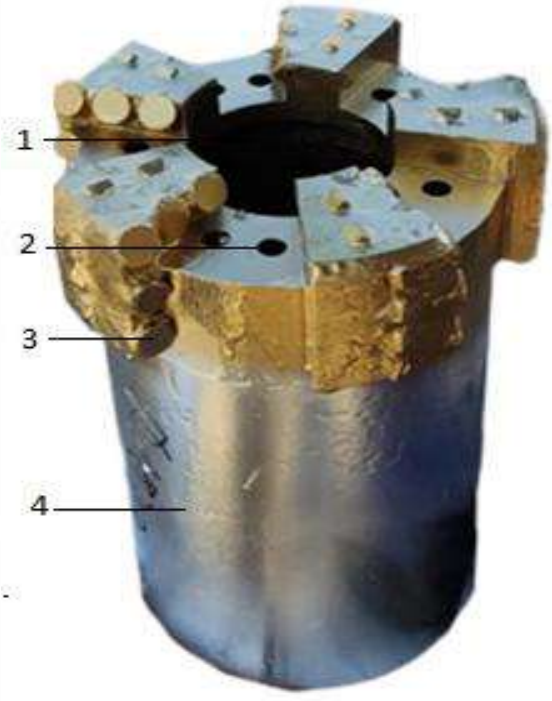


Figure 7. PDC-type drill bit: 1 – core inlet opening; 2 – drilling fluid circulation channels; 3 – polycrystalline diamond cutter; 4 – drill bit body.

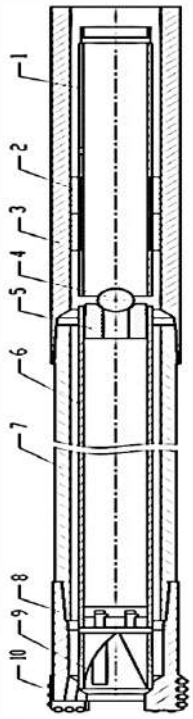


Figure 8. Core barrel assembly ("KOS") with a PDC-type drill bit: 1 – adjusting screw; 2 – adjusting nut; 3 – upper sub; 4 – ball (Ø 50.8 mm); 5 – ball seat; 6 – core tube; 7 – body; 8 – lever-type core catcher; 9 – spring-loaded holder; 10 – PDC-type drill bit.

ISSN 3030-3907

The specified core barrel assembly and its component parts were tested and implemented at wells operated by Alat NGRE LLC during 2022–2023 [12,13].

1. Well No. 11R of the Andakli Field, core interval 2367–2371 m. A 5 m interval was drilled, and 4 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 50 rpm, standpipe pressure – 20 atm, drill bit load – 4 t, and pump output – 8 L/s. The drilling mud parameters were: density – 1.12 g/cm³, Marsh funnel viscosity – 55 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of limestone.

2. Well No. 11R of the Andakli Field, core interval 2453–2458 m. A 5 m interval was drilled, and 5 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 60 rpm, standpipe pressure – 20 atm, drill bit load – 4 t, and pump output – 10 L/s. The drilling mud parameters were: density – 1.12 g/cm³, Marsh funnel viscosity – 55 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of limestone.

3. Well No. 11R of the Andakli Field, core interval 2547–2552 m. A 5 m interval was drilled, and 4 m of core was recovered, corresponding to a recovery rate of 80%. During coring, the following technological parameters were applied: rotor speed – 50 rpm, standpipe pressure – 20 atm, drill bit load – 4 t, and pump output – 8 L/s. The drilling mud parameters were: density – 1.12 g/cm³, Marsh funnel viscosity – 55 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1 mm. The formation consisted of limestone.

4. Chetkum Field, Well No. 4, core interval 2212–2218 m. A 6 m interval was drilled, and 6 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 60 rpm, standpipe pressure – 35 atm, drill bit load – 3 t, and pump output – 11 L/s. The drilling mud parameters were: density – 1.10 g/cm³, Marsh funnel viscosity – 51 s, fluid loss – 5 cm³/30 min, and mud cake thickness – 1.5 mm. The deposits belonged to Jurassic carbonate formations of the Oxfordian–Kimmeridgian stage, XV-2 horizon.

5. Kimmerekum Area, Well No. 1, core interval 2173–2178 m. A 5 m interval was drilled, and 5 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 60 rpm, standpipe pressure – 25 atm, drill bit load – 2.5 t, and pump output – 8–9 L/s. The drilling mud parameters were: density – 1.14 g/cm³, Marsh funnel viscosity – 58 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1.5 mm. The deposits belonged to Jurassic carbonate formations of the Oxfordian–Kimmeridgian stage, XV-2 horizon.

ISSN 3030-3907

6. Kimmerekum Area, Well No. 1, core interval 2545–2550 m. A 5 m interval was drilled, and 5 m of core was recovered, corresponding to a recovery rate of 100%. During coring, the following technological parameters were applied: rotor speed – 60 rpm, standpipe pressure – 32 atm, drill bit load – 4 t, and pump output – 11 L/s. The drilling mud parameters were: density – 1.14 g/cm³, Marsh funnel viscosity – 58 s, fluid loss – 6 cm³/30 min, and mud cake thickness – 1.5 mm. The deposits belonged to Jurassic terrigenous formations of the Bajocian–Bathonian stage, XVII horizon.

RESULTS.

Following the implementation of the author's proposed design, core recovery improved significantly and reached 80–100% (the implementation report is attached). In addition, the innovative developments were patented as Utility Model No. FAP 02137.

The application of these developments made it possible to improve both the quality and quantity of core recovery and to save foreign currency previously spent on purchasing imported core barrel assemblies and drill bits. The estimated annual savings amounted to USD 250,000.

There have been no complaints from the customers of the coring operations, namely the oil and gas exploration expeditions, and they are satisfied with the core recovery results achieved by the staff of IGIRNIGM.

The core recovery results for 2017–2023 are presented in graphical form.

Leading specialists of Alat NGRE LLC sent a formal review expressing gratitude to the author for the developed design, which increased core recovery to 90–100% and ensured preservation of the recovered core.

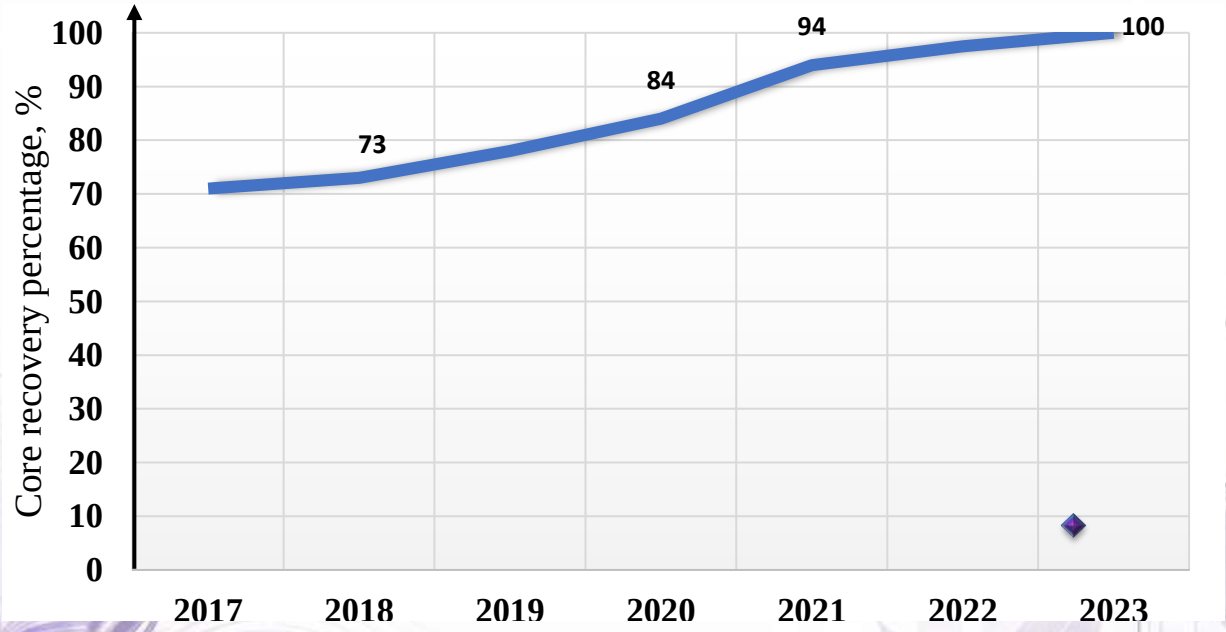


Figure.9. Results of Innovative Technologies Core Recovery Performance at the Fields of JSC "Uzbekneftegaz" in 2017–2023.

ISSN 3030-3907

CONCLUSION.

Core recovery and core analysis (rock samples) are of great importance for determining the hydrocarbon potential of oil and gas fields. Core sampling is carried out using a special device known as a core barrel assembly. To date, many types of core barrel assemblies of different designs and sizes have been developed. The performance and design quality of these assemblies are evaluated by the percentage of recovered core length relative to the drilled interval. Unfortunately, the average core recovery rate from wells in Uzbekistan is only 40–60%, which does not provide complete information about the structure of productive formations. Both natural and subjective factors influence this result. Under the geological conditions of Uzbekistan, loose and unconsolidated formations are relatively rare. In most cases, coring is carried out in sandy, clayey, and carbonate formations.

An analysis of coring operations shows that the unsatisfactory performance of core recovery from productive formations is mainly caused by subjective (human) factors. Core barrel assemblies are often not equipped with centralizers, resulting in excessive tool vibration. Due to concerns about tool sticking, the core barrel assembly is frequently lifted off the bottomhole. As a result, part of the core remains at the bottom and is subsequently ground up by the drill bit. In order to increase drilling speed, operators often raise the drill string rotation speed and drilling fluid flow rate beyond the required limits. The author conducted research to establish an optimal drilling regime for coring operations. Compliance with this drilling regime ensures core preservation and a high core recovery percentage. In addition, the author developed a new core barrel assembly with a body made of thick-walled pipes (16–24 mm) equipped with centralizers, which reduce vibration and bending. A spring-loaded core holder installed above the core catcher was also developed, and PDC drill bits equipped with polycrystalline diamond cutter teeth were introduced.

The end of the core tube was moved closer to the core-forming opening to a distance of 30 mm. It is also necessary to strengthen control over compliance with the prescribed drilling regime during coring operations. All of these innovations make it possible to achieve a core recovery rate of 80–100% and save foreign currency by eliminating the need to purchase imported coring equipment.

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INDUSTRIAL OPTIMIZATION OF ETHYLENE RECOVERY FROM PYROLYSIS GAS: YELLOW-OIL SEPARATION AND POLYMERIZATION INHIBITION

Ozoda Akhmedova Baxronovna
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
E-mail: zodamedova@gmail.com
Xujamberdi Toshboyev Mingyasharovich
Shurtan Gas Chemical Complex, Uzbekistan
Abdurasul Qayumov Shonazarovich
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
Ravshanbek Narimov Anarmetovich
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan

Abstract. This study presents an integrated approach to improving the efficiency of ethylene recovery from pyrolysis gas by optimizing key process parameters and mitigating “yellow oil” formation and polymerization-related equipment fouling. The effects of feedstock composition, conversion degree, temperature, steam dilution, and hydrocarbon residence time in the reaction zone were evaluated under laboratory and industrial conditions. Pyrolysis gas samples were analysed by gas chromatography at the central laboratory of the Shurtan Gas Chemical Complex. Laboratory results showed that the maximum ethylene content of 33.3% was achieved at 750–850 °C with a residence time of 6–12 s. The technological system was further improved by installing a 35 m³ vessel for separating “yellow oil” from the spent alkaline solution and applying a Petroflow polymerization inhibitor to the streams entering the reboiler and leaving the lower section of the column. The larger separation vessel reduced the required separation time to approximately 2 h, while inhibitor application limited undesirable polymerization and deposit formation. Following process optimization and equipment modification, the ethylene content increased from 32.65 to 33.466 mol%, corresponding to an absolute increase of 0.816 percentage points. The proposed measures also reduced product losses, minimized equipment fouling, and improved operational stability. These results demonstrate that combining process-parameter optimization, improved “yellow oil” separation, and polymerization inhibition provides a practical approach to enhancing industrial ethylene recovery from pyrolysis gas.

Keywords: gaz chemical compleks. monomer, polymerization, yellow oil, inhibitor, polyethylene, ethylene.

Аннотация. В данном исследовании представлен комплексный подход к повышению эффективности извлечения этилена из пиролизного газа путем оптимизации ключевых параметров процесса и уменьшения образования

“желтого масла” и загрязнения оборудования, связанного с полимеризацией. В лабораторных и промышленных условиях оценивалось влияние состава исходного сырья, степени конверсии, температуры, разбавления водяным паром и времени пребывания углеводородов в зоне реакции. Образцы пиролизного газа были проанализированы методом газовой хроматографии в центральной лаборатории Шуртанского газохимического комплекса. Лабораторные результаты показали, что максимальное содержание этилена в 33,3% было достигнуто при температуре 750-850°C и времени выдержки 6-12 с. Технологическая система была дополнительно усовершенствована за счет установки емкости объемом 35 м3 для отделения “желтого масла” от отработанного щелочного раствора и применения ингибитора полимеризации Petroflow к потокам, поступающим в ребойлер и выходящим из нижней секции колонны. Большая емкость для разделения сократила требуемое время разделения примерно до 2 часов, в то время как применение ингибиторов ограничило нежелательную полимеризацию и образование отложений. После оптимизации процесса и модификации оборудования содержание этилена увеличилось с 32,65 до 33,466 мол.%, что соответствует абсолютному увеличению на 0,816 процентных пункта. Предложенные меры также позволили снизить потери продукта, свести к минимуму загрязнение оборудования и повысить стабильность работы. Эти результаты демонстрируют, что оптимизация технологических параметров, улучшение отделения “желтого масла” и ингибирование полимеризации в сочетании обеспечивают практический подход к увеличению извлечения промышленного этилена из пиролизного газа.

Ключевые слова: газохимический комплекс. мономер, полимеризация, желтое масло, ингибитор, полиэтилен, этилен.

Annotatsiya. Ushbu tadqiqotda asosiy texnologik parametrlarni optimallashtirish va "sariq moy" hosil bo‘lishini va polimerizatsiya bilan bog‘liq uskunalarning ifloslanishini kamaytirish orqali piroliz gazidan etilenni qayta tiklash samaradorligini oshirishga kompleks yondashuv keltirilgan. Laboratoriya va sanoat sharoitida xomashyo tarkibi, konversiya darajasi, harorat, bug 'bilan suyultirish va uglevodorodlarning reaksiya zonasida qolish vaqtining ta'siri baholandi. Shurtan gaz-kimyo majmuasining markaziy laboratoriyasida piroliz gazi namunalari gaz xromatografiyasi usuli bilan tahlil qilindi. Laboratoriya natijalari shuni ko‘rsatdiki, 750–850 °C haroratda 6–12 s yashash vaqti bilan maksimal 33,3% etilen tarkibiga erishilgan. Texnologik tizim “sariq moy”ni sarflangan ishqoriy eritmadan ajratish uchun 35 m³ hajmli idish o‘rnatish va

ISSN 3030-3907

reboilerga kiradigan va ustunning pastki qismidan chiqadigan oqimlarga Petroflow polimerizatsiya inhibitori qo‘llash orqali yanada takomillashtirildi. Kattaroq ajratuvchi idish kerakli ajratish vaqtini taxminan 2 soatgacha qisqartirdi, inhibitorni qo‘llash esa kiruvchi polimerizatsiya va cho‘kma hosil bo‘lishini chekladi. Jarayonni optimallashtirish va uskunani o‘zgartirish natijasida etilen miqdori 32,65 dan 33,466 mol% gacha oshdi, bu mutlaq o‘sish 0,816 foiz punktga to‘g‘ri keladi. Taklif etilgan chora-tadbirlar, shuningdek, mahsulot yo‘qotishlarini kamaytirdi, uskunaning ifloslanishini minimallashtirdi va ish barqarorligini yaxshiladi. Ushbu natijalar shuni ko‘rsatadiki, jarayon parametrlarini optimallashtirish, "sariq moy" ni yaxshiroq ajratish va polimerizatsiya inhibisyonini birlashtirish piroliz gazidan sanoat etilenini qayta tiklashni yaxshilashga amaliy yondashuvni ta'minlaydi.

Kalit so‘zlar: gaz kimyo majmuasi. monomer, polimerizatsiya, sariq moy, ingibitor, polietilen, etilen.

INTRODUCTION.

Ethylene is one of the most important petrochemical monomers in the global chemical industry, serving as a fundamental building block for polymers such as polyethylene, ethylene glycol, polyvinyl chloride and various high-value chemicals. It is estimated that current world ethylene production capacities exceed 185 million tonnes per year, with a continuing growth trend driven by demand for plastics and derivatives in diverse industrial sectors [1].

Traditionally, ethylene is predominantly produced via steam cracking (pyrolysis) of hydrocarbon feedstocks, especially ethane, propane and naphtha fractions. In this high-temperature endothermic process, carbon–carbon bonds are cleaved to form low-molecular-weight olefins, with ethylene as the major product. However, conventional pyrolysis processes are energy intensive and produce a range of by-products that complicate downstream separation and reduce process selectivity.

The efficient separation of ethylene from pyrolysis gas streams remains a considerable challenge due to the thermodynamic similarity between ethylene and ethane, the presence of secondary hydrocarbons, and the formation of heavy by-products such as “yellow oils” and coke precursors. These by-products not only reduce ethylene yield but also contribute to equipment fouling, increased operational costs, and complex purification demands [2-3].

In recent years, researchers have sought innovative strategies to address these limitations. For example, novel adsorption-based separation methods using porous materials have been shown to improve ethylene/ethane selectivity and

ISSN 3030-3907

enable more energy-efficient downstream product purification. Other approaches explore the integration of membrane engineering and modular reactor designs to reduce overall energy consumption and enhance ethylene productivity in steam cracking processes.

In addition to conventional pyrolysis optimization, sustainable and carbon-neutral production pathways, including electrification of cracking furnaces and plasma-assisted mechanisms, have been proposed to mitigate greenhouse gas emissions and enhance environmental performance of ethylene plants.

Despite these advances, the optimization of pyrolysis operational parameters such as temperature profile, residence time, steam dilution, and reactor design still plays a pivotal role in maximizing ethylene output. Classical studies have shown that careful control of feedstock composition and reactor conditions can significantly influence product distribution and minimize unwanted side reactions.

In Uzbekistan and related regional contexts, experimental investigations into pyrolysis gas processing have focused on improving ethylene yield and reducing side-product formation through process modifications and inhibitor addition. These efforts aim to align industrial practice with global research trends while addressing local raw material characteristics and operational constraints.

Thus, this study builds upon established global research by targeting the enhancement of ethylene monomer production efficiency from pyrolysis gas through improved separation strategies, optimized reaction conditions, and mitigation of polymerization and by-product formation. The outcomes are intended to contribute both to scientific understanding and practical advances in the petrochemical sector [4-7].

EXPERIMENTAL RESEARCH.

Selection of Alternative (Optimal) Parameters for the Separation of Ethylene from Pyrolysis Gas. The selection of alternative (optimal) parameters for the process of separating ethylene from pyrolysis gas is a critical task. The amount of ethylene monomer released during the pyrolysis process is influenced by the following technological parameters [8-9]:

- composition of the feedstock supplied to pyrolysis;
- degree of conversion;
- temperature;
- saturated steam pressure;
- residence time of hydrocarbons in the reaction zone.

Composition of the feedstock supplied to pyrolysis. In the pyrolysis process, the yield of products per unit mass depends on the mass fraction of components in the feedstock. Product yields were determined using the example of: 1 – ethylene, 2 – propylene, and 3 – liquid-phase products. It was found that

ISSN 3030-3907

when the ethylene hydrocarbon content in the feedstock increased from 0 to 0.7, its share in the product composition increased from 0.17 to 0.50. Thus, the proportion of ethylene in the product relative to propylene increased by 1.2 to 2.1 times. At the same time, under these conditions, the formation of liquid-phase products decreased from 0.26 to 0.15 mass units.

Temperature. The dependence of pyrolysis product yields on temperature and time was analyzed. Under laboratory conditions, the residence time of the feedstock in the reaction zone was maintained within 6–12 seconds at temperatures of 500–550 °C, 550–650 °C, 650–750 °C, and 750–850 °C, and the results were summarized in a table. Based on the results, the maximum ethylene monomer yield of 33.3% was achieved at temperatures of 750–850 °C with a residence time of 6–12 seconds.

Industrial operation. In industrial conditions, the dependence of pyrolysis product yields on temperature and residence time was analyzed. According to the analysis, at temperatures of 650–750 °C, the residence time of the feedstock in the reaction zone was 0.7–1.0 seconds, whereas at 750–850 °C it was 0.3–0.5 seconds.

Saturated steam. In the process, saturation of the hydrocarbon feedstock supplied to pyrolysis with water steam was identified as one of the most important factors. It was determined that the optimal steam addition is 34–35% relative to the feedstock amount.

Residence time of hydrocarbons in the reaction zone. The residence time of the feedstock in the reaction zone is also a key parameter in the pyrolysis process. Studies were conducted by passing the feedstock through the reaction zone for up to 12 seconds at temperatures of 550–850 °C and analyzing the volume of ethylene monomer formed. In order to reduce coking of the pyrolysis furnace tubes, it was determined that maintaining a residence time of 6–12 seconds and a temperature range of 600–850 °C is optimal. According to the existing regulations, the residence time is up to 0.3 seconds and the temperature is 1000–1100 °C. Under such conditions, furnace tubes undergo intensive coking, leading to a decrease in product yield and a drop in pressure difference between the tubes [10-14].

Based on the above-mentioned parameters, laboratory analyses yielded the following positive results.

Table 1.

Dependence of pyrolysis product yields on temperature and residence time.

Products	Product output level			
	500-550 °C 6-1,2 s	**550-650 °C 6-12 s**	**650-750 °C 6-12 s**	**750-850 °C 6-12 s**
CH_4	15,6	16,6	16,8	16,7

ISSN 3030-3907

C_2H_4	23,0	25,9	29,3	33,3
C_3H_6	13,6	12,7	12,2	11,7
C_4H_6	2,2	3,8	4,2	4,8
C_5 and above	32,8	29,7	27,8	23,9
CH_4/ C_2H_4	0,678	0,641	0,575	0,501
C_3H_6/ C_2H_4	0,591	0,490	0,418	0,351

Saturation of the hydrocarbon feedstock supplied to the pyrolysis process with water steam is considered one of the most important factors, since a decrease in the partial pressure of hydrocarbons due to steam dilution leads to an increase in the yields of ethylene, 1,3-butadiene, and butenes. At the same time, the formation of aromatic hydrocarbons and methane is reduced, and the rate of secondary reactions directed toward the formation of high-molecular-weight compounds decreases, thereby ensuring a reduction in coke formation within the reactors. The indicators of feedstock saturation with water steam are presented in Table 2.

Table 2.

Degrees of Feedstock Saturation with Water Steam

	Ethane	**Butane**	**Light naphtha**	**Heavy naphtha**	**Gasoil**
Water Steam Saturation (relative to feedstock amount, %)	35	50	50-60	60-70	80-100

The presence of water steam reduces the rate of coke deposition on the inner surfaces of pyrolysis process tubes and prevents excessive increases in pressure and temperature. As a result, it becomes possible to extend the operating cycle between tube decoking operations. Therefore, saturating the feedstock subjected to pyrolysis with water steam leads to milder operating conditions of the process and makes it possible to increase the ethylene yield without reducing process selectivity [14-15].

RESEARCH RESULTS.

In order to further improve production efficiency, a method for reducing the formation of “yellow oil,” which is considered a globally relevant issue, was developed. As a result of the conducted studies, it was determined that the use of a storage vessel with a capacity of 35 m³ in the process of separating “yellow oil” makes it possible to reduce the time required to separate this type of oil from the alkaline solution in separators to up to 2.0 hours and to ensure the dissolution of “yellow oil” in the ethane–ethylene fraction. This method was subsequently implemented in industrial practice. As a result, in the separators used to separate

ISSN 3030-3907

the gas–liquid flow, the spent alkaline solution is effectively separated from the yellow oil.

The pyrolysis gas, purified from acidic gases and oils, is withdrawn from the top of the alkaline column under elevated pressure and fed to the demethanizer, where methane is separated; hydrogen is removed in the separators, and the ethane–ethylene fraction is then directed to the deethanizer column DA-1402.

The hydrocarbon 1,3-butadiene, formed as a result of the dimerization reaction of two acetylene molecules, is considered the primary representative of "yellow oils." The oil consists of a mixture of hydrocarbons with carbon numbers ranging from C_4 to C_{28}, with C_6–C_8 hydrocarbons constituting the major fraction. "Yellow oil" is an oily liquid that coats the surfaces of column trays, packings, demisters, compressor impellers, and molecular sieves, significantly reducing their activity and efficiency. Therefore, it is expedient to separate it from ethylene monomer as quickly and as completely as possible.

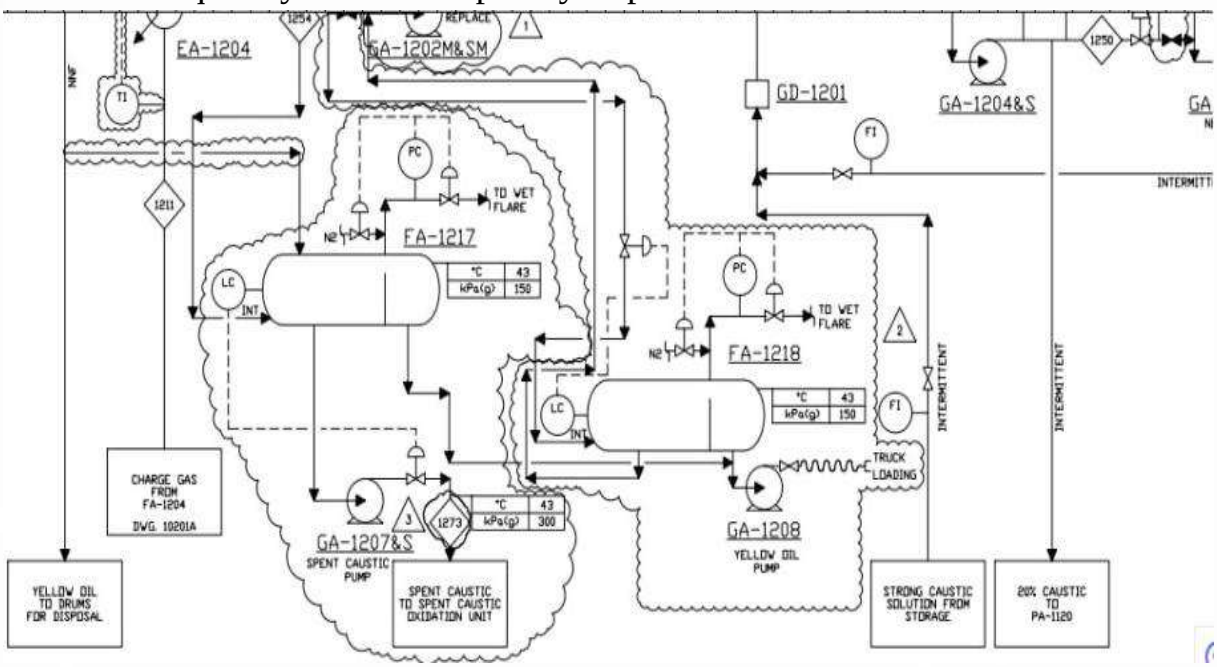


Figure 1. Method for Reducing the Formation of "Yellow Oil" during the Separation of Ethylene Monomer from Pyrolysis Gas

The selection and application of polymerization inhibitors is also an important factor in increasing the yield of ethylene monomer.

During the pyrolysis of hydrocarbons, two acetylene molecules undergo a dimerization reaction to form 1,3-butadiene, which is highly prone to polymerization. Even trace amounts of oxygen present in the pyrolysis feedstock convert butadiene into peroxides. This condition, under normal circumstances, significantly accelerates the onset of the polymerization reaction.

Thus, polymerization reactions occurring during the pyrolysis process are considered undesirable and must be minimized.

ISSN 3030-3907

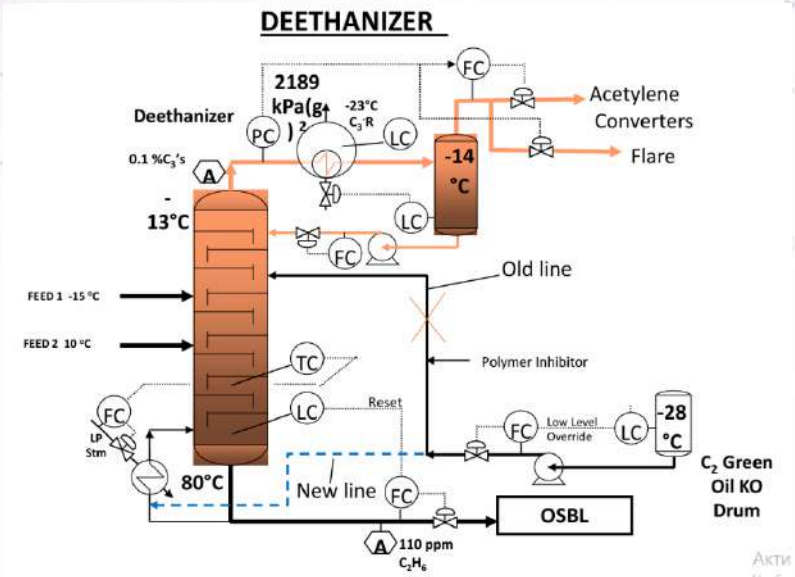


Figure 2. Application of Polymerization Inhibitors to Increase Ethylene Monomer Yield

To reduce the rate of polymerization reactions and minimize fouling of the reboiler, a polymerization inhibitor of the Petroflow brand was selected and recommended to be sprayed into the streams entering the reboiler of the product cube and into the flows leaving the lower part of the column. This method was implemented in industrial practice [16-18].

In general, it is advisable to add the inhibitor in amounts of 0.5–1.5% for these purposes.

Based on the selection of optimal parameters and upgraded process equipment, the pyrolysis process was organized, and the substances formed in the composition of pyrolysis gas were analyzed under laboratory conditions using gas chromatography.

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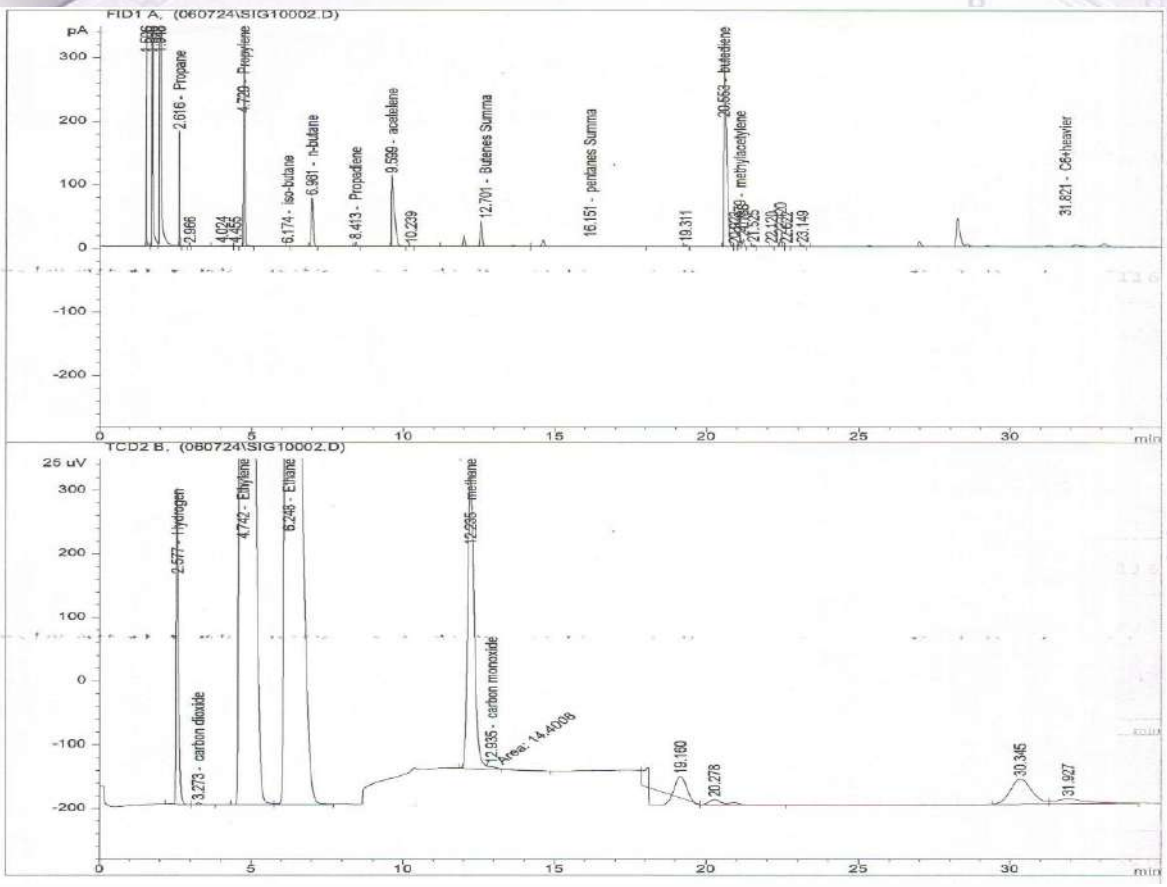


Figure 3. Chromatographic Analysis of Pyrolysis Gas Samples with Modified Furnace Operation (FID Detector)

Due to the fact that the thermal conductivity of many compounds is significantly lower than that of helium or hydrogen, when the analyzed gases reach the detector, the thermal conductivity of the detector decreases, generating a detectable signal [19-20].

The conducted study, based on the selected optimal parameters and modifications in the upgraded technological system, analyzed the ethylene monomer content (mol%) at the Shurtan Gas Chemical Complex central laboratory. The results are as follows: according to the standard regime, the initial ethylene monomer content was 32.65%. After optimizing technological parameters—such as feedstock composition, degree of conversion, temperature, saturated steam pressure, and hydrocarbon residence time in the reaction zone—the ethylene monomer content in the resulting pyrolysis gas increased to 33.32%. Further improvements in the technological system resulted in an increased monomer content of 33.466% [21-23].

Table 3.

Ethylene content (mol%) separated under modified conversion conditions in pyrolysis furnaces.

Compound Name	Ethylene Content under Modified	Ethylene Content According to Project

ISSN 3030-3907

	Conversion Conditions (mol%)	Documents and Regulations (mol%)
Hydrogen	38,304	32,92
Carbon monoxide (CO)	0,0049	0,11
Carbon dioxide (CO_2)	0,0069	0,03
Methane	4,539	3,56
Acetylene	0,32	0,23
Ethylene	**33,466**	**32,65**
Ethane	22,049	24,02
Iso-butane	0,000141	0,07
n-Butane	0,074	
Propadiene / Methylacetate	0,0095	0,2
Propylene	0,46	0,39
Butenes	0,066моль	0,06
Propane	0,0627	0,08
Butadiene / C_4 Acetylene	0,536	0,29
Methylacetylene	0,000193	-
C_6 Hydrocarbons	0,0959	0,06
Benzene	-	0,05
Toluene	-	0,01

Based on the modifications in the upgraded technological system, the ethylene monomer content was determined to be 33.466 mol%. The increase in ethylene content compared to the project value is calculated as:

$$F=33,466моль\%- 32,65моль\%=0,816\ моль\%$$

This shows that the technological improvements led to an increase of 0.816 mol% in ethylene monomer yield.

CONCLUSIONS.

This study analyzed innovative technologies and methods for improving the efficiency of ethylene monomer production from pyrolysis gas. Key process parameters, including feedstock composition, degree of conversion, temperature, saturated steam pressure, and hydrocarbon residence time in the reaction zone, were optimized. Proper adjustment of these parameters led to an increase in ethylene monomer content from 32.65 mol% to 33.466 mol%, representing an enhancement of 0.816 mol%.

Undesirable reactions, such as “yellow oil” formation and polymerization, negatively affect process efficiency. To address these issues, the feedstock was saturated with steam, the separation capacity for “yellow oil” was increased to

ISSN 3030-3907

35 m^3, and a Petroflow brand polymerization inhibitor was applied. These measures minimized product loss, reduced fouling of process equipment, and enhanced operational stability.

The results demonstrate that careful control of pyrolysis process parameters significantly improves both the yield and quality of ethylene monomer. Moreover, the developed methods for reducing “yellow oil” formation and polymerization have practical applicability in industrial-scale production, ensuring efficient operation of gas-chemical complexes.

Scientifically, this study contributes to the optimization of pyrolysis processes and modernization of separation equipment, providing a foundation for higher-yield ethylene production. These advancements can further support the production of high-molecular-weight polymers and petrochemical products in both national and international industrial contexts.

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VALORIZATION OF HIGH-SULFUR PETROLEUM FRACTIONS THROUGH THE SYNTHESIS OF ARENOTHIOPHENE-BASED CORROSION INHIBITORS

Ozoda Akhmedova Baxronovna
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
E-mail: zodamedova@gmail.com
Lobar Bozorova Sharipovna
Karshi state technical university, Karshi, Uzbekistan
Nazirila Maxmudov Nasimxanovich
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
Abdurasul Qayumov Shonazarovich
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
Mexriniso Axmedova Baxronovna
Bukhara state technical university, Bukhara, Uzbekistan
Sadriddin Fozilov Fayzullayevich
Bukhara state technical university, Bukhara, Uzbekistan
Dilbar Ergasheva Kuchkarovna
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
Fayzulla Raxmatullayev Nig‘matullayevich
Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan

Abstract. The growing exploitation of heavy and high-sulfur crude oils requires the development of efficient technologies for the utilization of sulfur-containing organic compounds present in petroleum fractions. In this study, arenothiophenes and their derivatives were isolated from the pre-bitumen fraction of high-sulfur crude oil and converted into functional sulfur-containing compounds through selective sulfonation and acylation reactions. The obtained products were structurally characterized and transformed into benzo[b]thiophene sulfonic acid derivatives and their corresponding sodium salts. Two key compounds, 3-butylbenzo[b]thiophene-2-sulfonic acid (BBT) and 5-acetyl-2-methylthiaine sulfoxide (AMTS), were evaluated as corrosion inhibitors for steel in aggressive acidic environments. Gravimetric corrosion tests conducted in hydrochloric and sulfuric acid solutions demonstrated that the synthesized inhibitors exhibit high protection efficiencies, reaching up to 99.8% depending on concentration and temperature. Quantum chemical analysis revealed that the inhibition efficiency is closely related to the electronic structure of the molecules, particularly the distribution of electron density around sulfur and oxygen atoms. These heteroatoms enable strong donor–acceptor interactions with the metal surface, leading to the formation of a stable protective adsorption layer. In addition, the synthesized arenothiophene derivatives exhibited surface-active properties and demonstrated the ability to generate stable foam systems, indicating their

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potential application as multifunctional petroleum-based chemical agents. The proposed technological approach provides a cost-effective and scalable pathway for the valorization of sulfur-rich petroleum fractions, enabling the production of new-generation corrosion inhibitors derived directly from crude oil components.

Keywords: oil, arenthiophene sulfo compounds, arenthiophene, benzothiophene, benzo[b]thiophene sulfoacid derivatives, sulfuric acid, corrosion inhibitor, surfactants.

Annotatsiya. Og‘ir va oltingugurt miqdori yuqori bo‘lgan xom neftdan foydalanishning ortib borishi neft fraksiyalarida mavjud bo‘lgan oltingugurt o‘z ichiga olgan organik birikmalardan foydalanishning samarali texnologiyalarini ishlab chiqishni talab qiladi. Ushbu tadqiqotda arenotiofenlar va ularning hosilalari oltingugurt miqdori yuqori bo‘lgan xom neftning bitumdan oldingi fraksiyasidan ajratib olindi va selektiv sulfonlash va asilatsiya reaksiyalari orqali funksional oltingugurt o‘z ichiga olgan birikmalarga aylantirildi. Olingan mahsulotlar strukturaviy jihatdan tavsiflandi va benzo[b]tiofen sulfan kislotasi hosilalariga va ularning natriy tuzlariga aylantirildi. Ikki asosiy birikma, 3-butilbenzo[b]tiofen-2-sulfonik kislota (BBT) va 5-atsetil-2-metiltiyain sulfoksid (AMTS) agressiv kislotali muhitda po‘lat uchun korroziya inhibitori sifatida baholandi. Xlorid va sulfat kislota eritmalarida o‘tkazilgan gravimetrik korroziya sinovlari sintez qilingan ingibitorlar yuqori himoya samaradorligiga ega ekanligini ko‘rsatdi, bu konsentratsiya va haroratga qarab 99,8% gacha yetadi. Kvant kimyoviy tahlil shuni ko‘rsatdiki, inhibisyon samaradorligi molekulalarning elektron tuzilishi, xususan, oltingugurt va kislorod atomlari atrofida elektron zichligining taqsimlanishi bilan chambarchas bog‘liq. Bu geteroatomlar metall yuzasi bilan kuchli donor-akseptor o‘zaro ta'sirga kirishib, barqaror himoya adsorbsion qatlam hosil bo‘lishiga olib keladi. Bundan tashqari, sintez qilingan arenotiofen hosilalari sirt-faol xususiyatlarga ega bo‘lib, barqaror ko‘pikli tizimlarni yaratish qobiliyatini namoyish etdi, bu ularning ko‘p funktsiyali neftga asoslangan kimyoviy moddalar sifatida qo‘llanilishi mumkinligini ko‘rsatadi. Taqdim etilgan texnologik yondashuv oltingugurtga boy neft fraksiyalarini baholashning tejamkor va kengaytiriladigan yo‘lini ta’minlaydi, bu esa to‘g‘ridan-to‘g‘ri xom neft komponentlaridan olingan yangi avlod korroziya ingibitorlarini ishlab chiqarish imkonini beradi.

Kalit so‘zlar: moy, arenthiophen sulfo birikmalari, arenthiophen, benzotiyofen, benzo[b]tiofen sulfo kislotasi hosilalari, sulfat kislota, korroziya inhibitori, sirt faol moddalar.

Аннотация. Растущая добыча тяжелой и высокосернистой нефти требует разработки эффективных технологий утилизации серосодержащих

органических соединений, присутствующих в нефтяных фракциях. В этом исследовании аренотиофены и их производные были выделены из предбитумной фракции сырой нефти с высоким содержанием серы и преобразованы в функциональные серосодержащие соединения с помощью реакций селективного сульфирования и ацилирования. Полученные продукты были структурно охарактеризованы и преобразованы в производные бензо[b]тиофенсульфоновой кислоты и соответствующие им натриевые соли. Два ключевых соединения, 3-бутилбензо[b]тиофен-2-сульфоновая кислота (ББТ) и 5-ацетил-2-метилтиаинсульфоксид (АМТС), были оценены в качестве ингибиторов коррозии стали в агрессивных кислых средах. Гравиметрические испытания на коррозию, проведенные в растворах соляной и серной кислот, показали, что синтезированные ингибиторы обладают высокой эффективностью защиты, достигающей 99,8% в зависимости от концентрации и температуры. Квантово-химический анализ показал, что эффективность ингибирования тесно связана с электронной структурой молекул, в частности с распределением электронной плотности вокруг атомов серы и кислорода. Эти гетероатомы обеспечивают сильные донорно–акцепторные взаимодействия с поверхностью металла, что приводит к образованию стабильного защитного адсорбционного слоя. Кроме того, синтезированные производные аренотиофена проявили поверхностно-активные свойства и продемонстрировали способность образовывать стабильные пенообразующие системы, что указывает на их потенциальное применение в качестве многофункциональных химических реагентов на основе нефти. Предлагаемый технологический подход обеспечивает экономически эффективный и масштабируемый путь повышения ценности нефтяных фракций, богатых серой, что позволяет производить ингибиторы коррозии нового поколения, получаемые непосредственно из компонентов сырой нефти.

Ключевые слова: нефть, арентиофенсульфосоединения, арентиофен, бензотиофен, производные бензо[b]тиофенсульфокислоты, серная кислота, ингибитор коррозии, поверхностно-активные вещества.

INTRODUCTION.

The continuous growth in global energy demand and the increasing complexity of hydrocarbon resources have intensified the need for advanced scientific approaches to petroleum processing and utilization. In particular, high-sulfur crude oils present significant technological and environmental challenges,

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primarily due to the presence of diverse sulfur-containing organic compounds that adversely affect processing efficiency, equipment durability, and product quality. Therefore, the development of effective strategies for the selective isolation and utilization of such compounds has become a priority in modern petrochemical research.

Ensuring the operational reliability and longevity of oil and gas processing equipment remains one of the most critical challenges in the industry. Corrosion, largely induced by reactive sulfur species, leads to substantial economic losses and safety risks. In this context, the design and synthesis of highly efficient corrosion inhibitors derived from petroleum feedstocks represent a promising and sustainable approach. The valorization of naturally occurring sulfur-containing compounds, particularly arenothiophenes, offers a dual benefit: mitigating corrosion processes while simultaneously enabling the rational utilization of complex hydrocarbon matrices [1].

Taking into account the analysis of these problems, scientists around the world have conducted numerous scientific studies and achieved significant results. Authors Shanke Liu, Hui Jin, Yan Yang, and Lijun Yu investigated the molecular dynamics of benzothiophene gasification during the hydrogen production process, where hydrogen generation and sulfur migration were studied. It was determined that an increase in the number of supercritical water molecules or an increase in reaction temperature enhances hydrogen formation and promotes the conversion of sulfur contained in organic compounds into inorganic sulfur. It was also shown that the gasification process of benzothiophene molecules in supercritical water consists of four stages, and the reaction mechanisms were described [2].

Zen He, Tony Bieremond, J. P. Gregory, Perre David, and J. Procter reported that benzothiophenes and their derivatives are among the most widely used key raw materials in medicinal chemistry. It was demonstrated that targeted syntheses can be effectively achieved through para-position coupling reactions of phenols with benzothiophene molecules [3].

Zili Guo, Renji Wang, Yunfei Liang, Gang Liu, and Pu Shouzi studied the synthesis and properties of photochromic hybrid diarylethenes containing benzothiophene and pyrrole molecules. Two photochromic diarylethenes incorporating hybrid structures of benzothiophene and pyrrole fragments were synthesized. Their structural characteristics and physicochemical properties were investigated. In addition, photochromic and luminescence processes were analyzed [4].

Omid Amiri, Farshad Beshkar, Sangar S. Ahmed, Ali Rafiei-Miandashti, Peshawa Mahmud, and Ahmad Anwar Dezael reported in their article the preparation of hierarchical flower-like $(Bi(Bi_2S_3)_9I_3)_{2/3}$ nanostructures, which act as

ISSN 3030-3907

powerful photocatalysts for benzothiophene desulfurization. The reaction time and temperature were optimized to synthesize porous flower-like $(Bi(Bi_2S_3)_9I_3)_{2/3}$ structures. The morphology, size, purity, and optical properties of the nanostructures were investigated using XRD, EDS, FESEM, and UV-Vis-DRS analyses to achieve the highest desulfurization efficiency [5].

Authors Wolfgang Bodlos, Sara Mattiello, Andrea Perinot, Roland Fischer, Luca Beverina, Mario Caironi, and Roland Resel reported that benzothieno-benzothiophene-type molecules belong to the most promising classes of organic small-molecule semiconductors to date. These compounds, which are easily synthesized and exhibit high stability, provide wide opportunities for obtaining semiconductor materials suitable for applications, particularly in thin-film transistors [6].

In their article entitled “Easy Synthesis of 3-Trifluoromethylthio-Substituted Thioflavones and Benzothiophenes via Radical Cyclization,” Lu Wang, Huaiyu Wang, Wuidong Meng, Xiu-Hua Hu, and Yangen Huang reported that radical cascade reactions have become one of the most efficient synthetic strategies for the construction of organosulfur heterocycles. Thioanisole derivatives can be widely applied in radical cyclization reactions, where the elimination of the methyl group enables the formation of thioflavone and benzothiophene skeletons [7].

Rohan Sharma and Manish Jain, in their article entitled “Removal of Benzothiophenes from Diesel (Jet) Fuel by Pervaporation: Evaluation of Mass Transfer Characteristics of Various Membranes and Dynamic Modeling of Mass Transfer,” evaluated the mass transfer properties of various membranes and compared their selective performance toward different sulfur-containing compounds. The pervaporation process for removing benzothiophenes from diesel and jet fuels was investigated [8].

Shuta Sakai, Kazuki Sato, and Kazuhiro Yoshida demonstrated that the synthesis reaction of [1]benzothiophene[2,3-b][1]benzothiophene (BTBT) from 1,1-diarylethylene can be accelerated by the addition of molecular iodine, and the incorporation of molecular iodine into the reaction significantly increases the synthesis rate [9].

Yun Zu, Linzhi Guan, Zhongsen Guo, Chengming Huang, and Yi Me analyzed the difficulties encountered in the deep purification of thiophene-containing sulfur compounds present in ultra-low-sulfur fuels (for example, <50 μg/g S). In this work, the authors aimed to overcome these difficulties by using CeAlSBA-15 materials synthesized with the incorporation of aluminum and cerium. It was noted that Ce-type and Al-type materials can be induced to achieve a high dispersion on the micro-mesoporous surface of CeAlSBA-15 [10].

Maria Schiel, Claudia Domini, and Gustavo Silvestre used benzothiophene

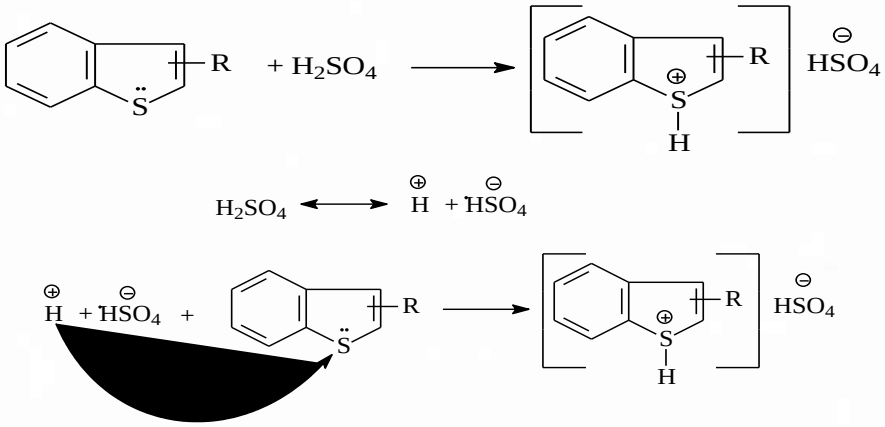
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derivatives for the extraction of metals from sedimentary rocks. In this study, a rapid and simple method for extracting metals from sedimentary samples was developed. It was emphasized that this method allows quick and easy acquisition of information about mobilizable metals present in sediment samples [11].

The novelty of this study lies in the development of an integrated method for the selective isolation of arenothiophenes from high-sulfur crude oil fractions and their subsequent transformation into functional corrosion inhibitors. Unlike conventional approaches that synthesize inhibitors from pure laboratory chemicals, the proposed method utilizes naturally occurring sulfur-containing petroleum components as a raw material. This approach not only improves the economic feasibility of inhibitor production but also provides a new strategy for the valorization of sulfur-rich petroleum fractions.

EXPERIMENTAL RESEARCH.

The synthesis of sulfonic acids and their corresponding salts derived from sulfur-containing organic compounds was investigated via the interaction of sulfuric acid with the residual fraction of crude oil obtained from the Northern Nishon oil fields of the Kashkadarya region. During the reaction, sulfur-containing compounds present in the crude oil interact with sulfuric acid through protonation mechanisms. As a result of this interaction, the sulfur atoms—possessing lone electron pairs—readily accept protons from the acid, leading to the formation of sulfonium-type complexes. These intermediates can be generally represented as follows:

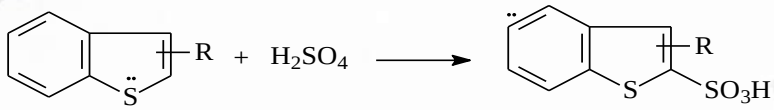


Subsequently, arenothiophenes were isolated in the form of their corresponding sulfonic acids. Within the formed complex, the coordination of the cation occurs due to the presence of a lone electron pair on the sulfur atom incorporated in the heterocyclic ring. This electron-rich sulfur center facilitates protonation and stabilization of the intermediate species, ultimately leading to the formation and isolation of arenothiophene sulfonic acids [12-14].

Kinetic studies of the interaction between alkyl-substituted arenothiophenes and sulfuric acid revealed that the reaction proceeds efficiently under equimolar

ISSN 3030-3907

conditions. It was established that, at a temperature of 45 °C, the process reaches a high yield within 2 hours, corresponding to the stoichiometric equivalence of the reacting components.



R = C_4H_9- (I) ; C_5H_{11}- (II); C_8H_{17}- (III);

Based on the above-described reaction pathway, a series of arenothiophene derivatives were synthesized, including 3-butylbenzo[b]thiophene-2-sulfonic acid (I), 4-pentylbenzo[b]thiophene-2-sulfonic acid (II), and 4-octylbenzo[b]thiophene-2-sulfonic acid (III).

The obtained sulfonic acids exhibited relatively low stability, which may be attributed to the structural features of the sulfonated heterocyclic system and the influence of alkyl substituents on the electron density distribution within the thiophene ring.

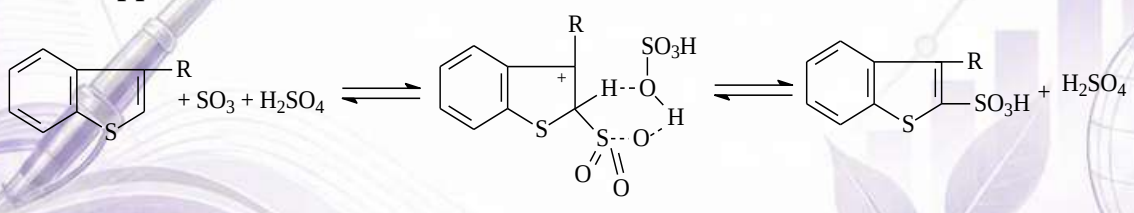
The elemental composition and analytical characteristics of the synthesized benzo[b]thiophene sulfonic acid derivatives are summarized in Table 1.

Table 1.

Elemental analysis characteristics of benzo[b]thiophene sulfonic acid derivatives.

Compound	M_r (г)	Empirical formula	Found, %			Calculated, %		
			C	H	S	C	H	S
I	270	$C_{12}H_{14}O_3S_2$	53,64 53,56	5,38 5,32	23,95 23,83	53,3	5,18	23,7
II	284	$C_{13}H_{16}O_3S_2$	55,16 55,08	5,82 5,74	22,67 22,61	54,9	5,63	22,5
III	326	$C_{16}H_{22}O_3S_2$	59,33 59,12	6,97 6,88	20,23 20,12	58,9	6,75	19,6

In this reaction, the sulfonation of sulfur-containing heterocyclic bicyclic polyaromatic compounds proceeds via an electrophilic substitution mechanism, predominantly occurring at the C-2 position of the heterocyclic ring. This regioselectivity can be attributed to the higher electron density at the 2-position of the thiophene ring, which enhances its susceptibility toward electrophilic attack under the applied reaction conditions.

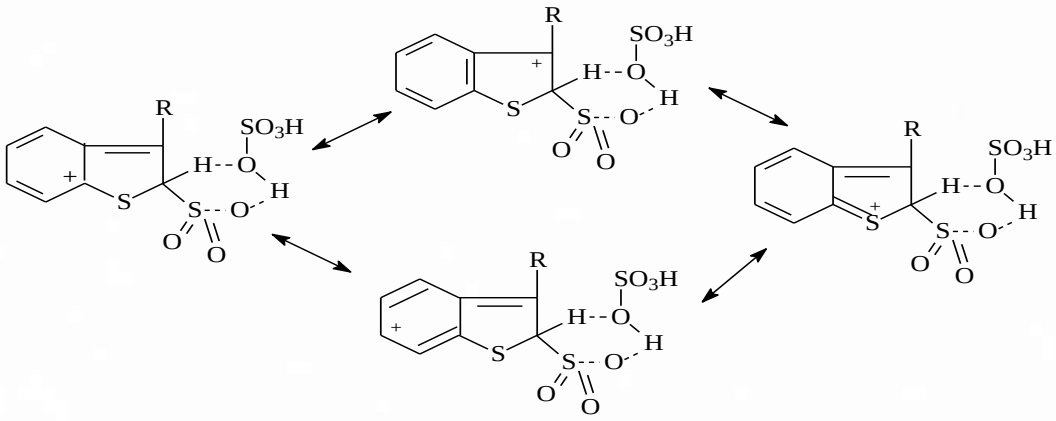


ISSN 3030-3907

In these compounds, the substitution of the hydrogen atom at the α-position relative to the sulfur atom by a sulfonic group is primarily обусловлено the electron-donating effect of the sulfur atom. Specifically, the lone pair electrons on the sulfur atom are delocalized into the π-system of the heterocyclic ring, resulting in an increased electron density at the α-carbon atoms, which makes these positions more reactive toward electrophilic attack.

According to the results of IR spectroscopic analysis and elemental analysis, it was established that the interaction between 3-alkyl arenothiophenes and sulfuric acid leads to the introduction of a single sulfonic group at the C-2 position of the heterocyclic ring. Based on these findings, the reaction can be classified as an electrophilic substitution process proceeding via an S_E2-type mechanism, with substitution occurring specifically at the second carbon atom of the heterocycle [15-17].

Furthermore, in the intermediate complex formed during this reaction, the positive charge is not localized but delocalized over several carbon atoms of the ring. This delocalization is stabilized through resonance structures, which significantly contributes to the overall stability of the intermediate species.

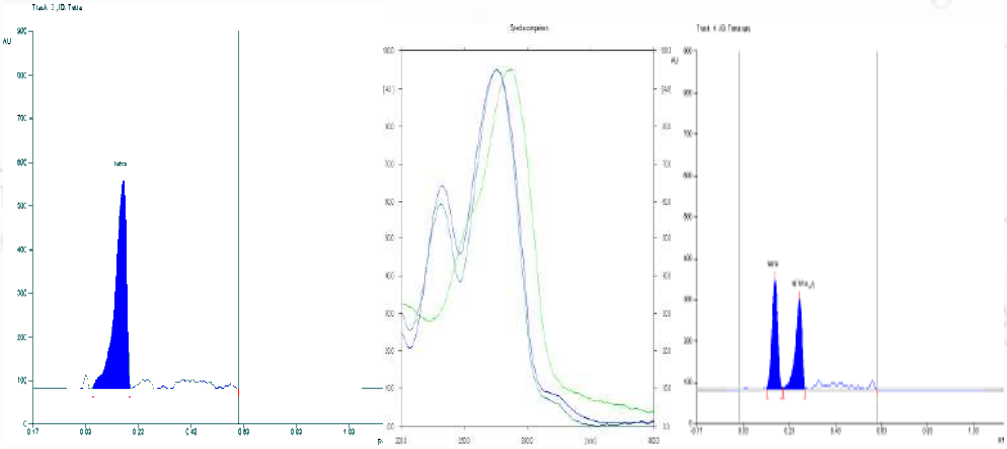


Practically, it is observed that during the sulfonation of arenothiophenes present in crude oil, other aromatic-ring-containing compounds may also undergo sulfonation. Additionally, unreacted arenothiophenes can be recovered in their pure form from the reaction mixture after neutralization with water or a basic solution.

For analytical characterization, a solution of the compounds in alcohol at a concentration of 1 mg/mL was prepared and analyzed using high-performance thin-layer chromatography (HPTLC). AL SIL G/UV plates (Whatman, Germany) were employed for the analysis. Sample application onto the plate was performed using a Linomat-5 automatic applicator (CAMAG, Switzerland), with an inter-track distance of 8 mm and track width of 3 mm, applying 3 µL per track. Chromatographic separation was achieved using a chloroform:benzene:methanol solvent system in a 2:2:0.5 ratio. The developed plate was scanned at a wavelength of 254 nm using a Scanner-3 device.

ISSN 3030-3907

The HPTLC data clearly indicate noticeable differences in the chromatogram of the reaction product (B) compared to the starting material (A), confirming successful sulfonation of the target arenothiophenes and allowing separation of residual unreacted compounds.

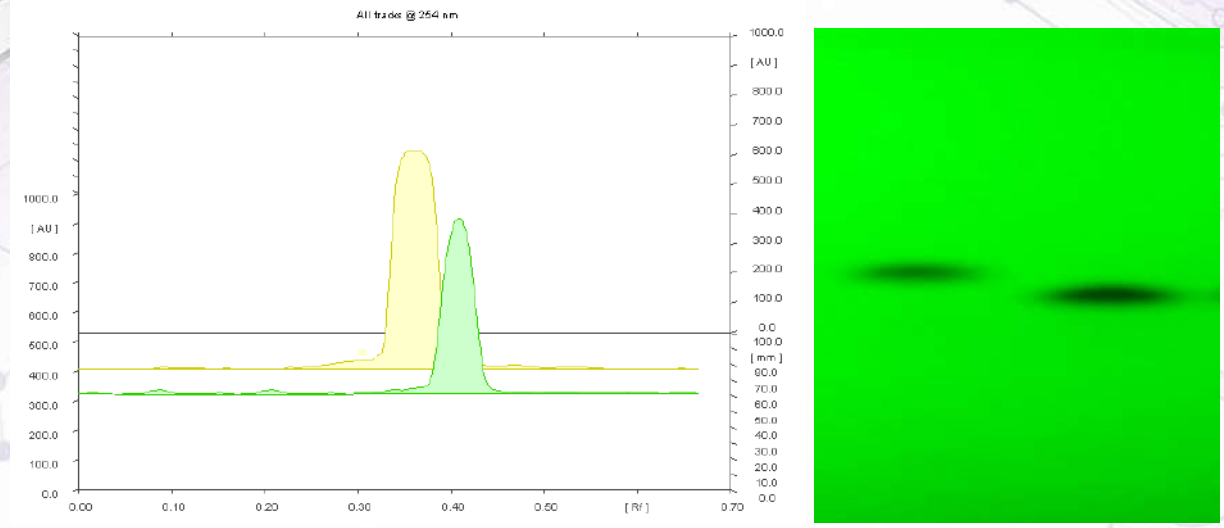


A B C

Figure 1. High-performance thin-layer chromatography (HPTLC) analysis of the sulfonation of arenothiophenes present in crude oil: starting material (A), sulfonation reaction product (B), UV spectrum of the reaction product (C).

Due to the inability to isolate the compounds obtained from the reaction mixture by recrystallization, the reaction product was further purified directly from the HPTLC plate using a preparative method. This approach allowed for the isolation of the sulfonated arenothiophenes in a sufficiently pure form for structural characterization. Figure 2. Analysis of the obtained sulfonated compounds using the chloroform:acetone:benzene (1:4:4) elution system and their corresponding UV–visible spectra. The chromatographic separation was performed under the specified solvent ratio to evaluate the purity and retention behavior of the sulfonated arenothiophenes. UV spectroscopy of the isolated fractions confirmed the presence of characteristic absorption bands corresponding to the sulfonic functional groups, providing evidence for successful sulfonation of the target compounds.

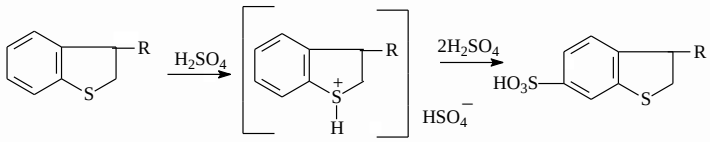
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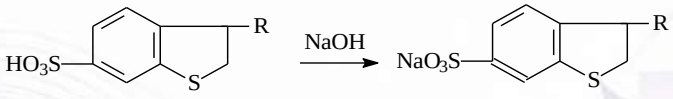
А **Б**

Figure 2. Analysis of sulfonated arenothiophene derivatives: UV–visible spectra of the sulfonated arenothiophene (A) and thin-layer chromatography analysis (B).

In the pre-bitumen fraction of crude oil, the content of dihydro derivatives of benzothiophenes is slightly higher compared to unsubstituted benzothiophenes. By reacting equivalent molar amounts of the sulfonating agent and sulfuric acid, the corresponding sulfonium salts of the target compounds can be formed. The isolation of benzothiophenes and their derivatives from crude oil and petroleum fractions, which belong to the sulfide fraction, is based on this methodology. Therefore, unlike the sulfonation of benzothiophenes, the separation of 2,3-dihydrobenzo[b]thiophenes was carried out using a slightly higher proportion of sulfuric acid to ensure efficient conversion to the sulfonated derivatives.



The identification of the obtained benzothiophene sulfonic acids and their salts is challenging due to their lack of well-defined melting points, which complicates their separation. Direct sulfonation was performed on arenothiophenes containing four or more carbon atoms in the side chain. The resulting sulfonic acid products were not sufficiently crystalline or stable. Therefore, immediately after the reaction, the crude reaction mixture was treated with a 20% aqueous solution of sodium hydroxide to convert the sulfonic acids into their corresponding sodium salts, which were then isolated in a stable form.



R= C_5H_{11}- (IV); C_8H_{17}- (V)

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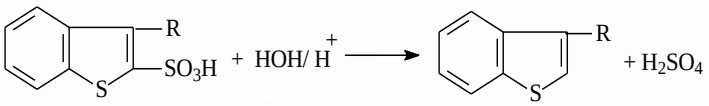
The sodium salts of the sulfonic acids have the following molecular formulas: $C_{13}H_{17}O_3S_2Na$ and $C_{16}H_{23}O_3S_2Na$. These compounds can be assigned to the general homologous series $C_nH_{2n-9}O_3S_2Na$. The identification of the obtained sulfonic acids and their sodium salts is rather challenging due to their lack of well-defined melting points.

Table 2

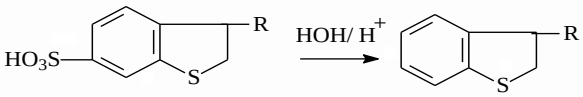
Elemental analysis data for sodium salts of 2,3-dihydrobenzo[b]thiophene-5-sulfonic acids

Compound	M_r (g)	Empirical formula	Found, %			Calculated, %		
			C	H	S	C	H	S
IV	308	$C_{13}H_{17}O_3S_2Na$	51,12 50,98	5,96 5,74	21,12 20,98	50,64	5,51	20,77
V	350	$C_{16}H_{23}O_3S_2Na$	55,44 55,23	6,93 6,66	18,78 18,46	54,85	6,57	18,28

To obtain concentrated organosulfur compounds, the previously prepared sulfonic acids were heated in a 25% sulfuric acid solution. The sulfonic acids underwent hydrolytic decomposition at 105–110 °C. The resulting organosulfur compounds were subsequently distilled off in an azeotropic form with the aid of water vapor.



R = - C_5H_{11} (VI); - C_8H_{17} (VII)



R = - C_5H_{11} (VIII); - C_8H_{17} (IX)

The obtained organosulfur aromatic compounds correspond to the following general formulas: $C_{13}H_{16}S$ and $C_{16}H_{22}S$, which can be included in the homologous series $C_nH_{2n-10}S$. Additionally, the general formulas of their dihydro derivatives are $C_{13}H_{18}S$ and $C_{16}H_{24}S$, which can be included in the homologous series $C_nH_{2n-8}S$.

Table 3

Elemental analysis data of benzo[b]thiophene derivatives

Compound	M_r (g)	Empirical formula	Found, %			Calculated, %		
			C	H	S	C	H	S
VI	204	$C_{13}H_{16}S$	76,73 76,68	7,96 7,91	16,02 15,78	76,5	7,84	15,68
VII	246	$C_{16}H_{22}S$	79,24	9,23	13,48	78,04	8,94	13,00

ISSN 3030-3907

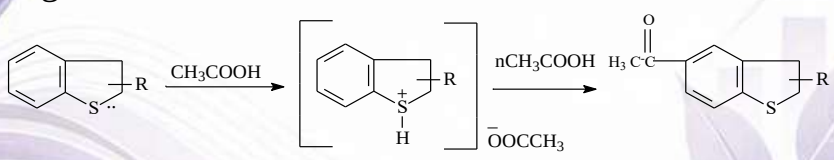
			79,13	9,16	13,26			
VIII	206	$C_{13}H_{18}S$	76,23 75,89	9,21 9,16	31,38 31,24	75,72	8,73	31,06
IX	248	$C_{16}H_{24}S$	77,93 77,52	9,97 9,84	26,03 25,94	77,41	9,67	25,80

To obtain sulfur-containing compounds and their salts, the thio-cyclic structures were initially treated with 80% sulfuric acid to remove the thio-cycles, followed by treatment with 90% sulfuric acid. The yield of sulfonic acids after two successive treatments with 80% sulfuric acid was relatively low (2.7%). Subsequent treatment of the thio-cycle-free fraction with 90% sulfuric acid increased the yield of sulfur-containing aromatic compounds to 13%.

For the compositional and structural analysis of the purified sulfur-containing organic compound concentrates, the products were fractionated under reduced pressure. The first fraction was distilled at 180–230 °C, the second at 230–280 °C, and the third at 280–330 °C. The remaining fraction above 330 °C constituted the residue. The results indicated that more than half of each of the first three fractions consisted of thio-mono-cyclic compounds. As the distillation temperature increased, the proportion of thio-bicyclic compounds in the fractions also increased. From the first to the third fraction, the content of dialkyl- and alkyl-cyclic sulfides decreased, whereas the proportion of thiophene and arenethiophene compounds increased from 8% to 18%.

The content of saturated sulfides (thio-cycles) in the concentrate is influenced by the hydrocarbon chain length. With increasing chain length, the solubility of sulfonic acids in the saturated sulfides increases, which facilitates the selective separation of sulfides containing fewer carbon atoms in the aromatic ring during dilution of the sulfuric acid layer. Sulfonic acids with long alkyl substituents remain in the sulfides and are retained in the sulfur-containing concentrate [18-20].

Additionally, the separation of arenethiophenes from the pre-bitumen fraction of crude oil via acylation was studied. The reactions of bi-cyclic sulfur-containing aromatic compound concentrates with acetic acid were also investigated. The separation of arenethiophenes using acetic acid followed the same procedure as described for sulfuric acid. It was established that treatment of the sulfur-containing aromatic compound concentrates with acetic acid at 115–120 °C for 1 hour in excess led to the formation of the corresponding acylated sulfur-containing aromatic derivatives.



ISSN 3030-3907

The obtained complex compound was subsequently treated with an excess of acetic acid, leading to the formation of the corresponding 5-acetyl-2,3-dihydro- and 5-acetylbenzo[b]thiophene derivatives. During the reaction, the reaction mixture was stirred and mixed with gasoline at 60 °C. Under these conditions, other by-products present in the concentrate dissolved in gasoline and transferred into the solvent, whereas the acetylated derivatives remained insoluble and were separated from the mixture.

The average empirical formulas of the isolated acetylated derivatives from the sulfur-containing aromatic compound concentrate were determined as $C_{18}H_{24}SO$ and $C_{18}H_{26}SO$, which can be incorporated into the following homologous series: $C_nH_{2n-10}SO$. The average molecular mass of these compounds was found to be 288.0–290.0 g/mol, with a refractive index of $n^{20D} = 1.5795$.

Table 4

Elemental analysis data of 2,3-dihydrobenzo[b]thiophene acetyl derivatives

Compound	M_r (g)	Empirical formula	Found, %			Calculated, %		
			C	H	S	C	H	C
X	288	$C_{18}H_{24}SO$	75,51 75,33	8,74 8,46	11,48 11,27	75,00	8,33	11,11
XI	290	$C_{18}H_{26}SO$	74,93 74,72	9,57 9,14	11,43 11,24	74,48	8,96	11,03

Obtaining Surface-Active Agents from Arenothiophenes. To investigate the application of arenothiophene sulfonic acid concentrates (ASC) as surface-active agents and to evaluate their practical significance, several experimental procedures were conducted. For this purpose, a measured amount of arenothiophene sulfonic acids was taken, and an aqueous solution of 28% sodium carbonate was added. The pH of the resulting solution was monitored using litmus paper to ensure controlled neutralization.

Table 5

Foaming properties of arenothiophene sulfonic acid concentrates

Solution composition	Foam color	Foam stability (min)	Foam height (cm)
Sodium carbonate + ASC	Pale yellow	13	11
Urea + ASC	Yellow	Unstable	1
Monoethanolamine + ASC	Whitish	18	5
Triethanolamine + ASC	Did not foam	—	—
Triethylamine + ASC	Did not foam	—	—

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The reaction mixture was neutralized by gradually adding water until a neutral pH was achieved. Subsequently, the resulting mixture was thoroughly stirred, resulting in a light yellow coloration. Additional water was then added to the mixture and it was mixed again to ensure homogeneity. This process led to the formation of a stable foam in the vessel, with a measured height of 11 cm, and the foam's stability persisted for approximately 13 minutes.

Similar experiments were carried out using aqueous solutions of monoethanolamine, triethanolamine, and triethylamine. The resulting data were summarized in Table 5.

The chemical treatment of the high sulfur residual fraction of crude oil generates various oil-derived products, which, together with the hydrocarbon components, effectively inhibit the intensive acidic corrosion of metallic equipment in oil wells. Additionally, these products can serve as solvents for high-molecular-weight components that accumulate or adsorb on the surfaces of the reservoir rocks, as well as agents to enhance the recovery of residual oil from the well.

RESEARCH RESULTS.

Application of 3-Butylbenzo[b]thiophene-2-sulfonic Acid (BBT) and 5-Acetyl-2-Methylthiaine Sulfoxide (AMTS) as Corrosion Inhibitors.

The sulfur-containing compounds 3-butylbenzo[b]thiophene-2-sulfonic acid (BBT) and 5-acetyl-2-methylthiaine sulfoxide (AMTS), isolated from crude oil, were evaluated as corrosion inhibitors for metals in acidic media. The inhibition efficiency of the compounds was determined using a gravimetric method. The aggressive environment consisted of 20% hydrochloric acid (HCl) and 30% sulfuric acid (H_2SO_4). Experiments were conducted at temperatures of 25 °C and 75 °C for 6 hours [21].

The test specimens were St.2 steel plates with dimensions of 100 mm height, 20 mm thickness, and 15 mm width. Inhibitor solutions were prepared at concentrations of 250, 500, and 1000 mg/L, and the corrosion inhibition was assessed gravimetrically by measuring the weight loss of the metal samples.

The obtained inhibition efficiency values of BBT and AMTS at 25 °C and 75 °C in 20% hydrochloric acid are summarized in Tables 7 and 8.

6-jadval.

25 °C va 75 °C da 20% HCl tarkibidagi BBT va AMTS ning korroziyani inhibe qilish samaradorligi

Compound	**Concentration (mg/L)**	At 25 °C		At 75 °C:	
		Corrosion rate,	Protection efficiency, (Z),	Corrosion rate, K_{g/m^2s}	Protection efficiency, (Z),

ISSN 3030-3907

		K_{g/m^2s}	%		%
BBT	250	-	-	-	-
	500	-	-	-	-
	1000	9,0	55	3,88	75
AMTS	250	2,1	90,5	3,59	76
	500	1,5	92,5	2,89	81
	1000	1,3	94	1,97	85

Table 7.

Inhibition Efficiency of BBT and AMTS Inhibitors at 25 °C and 75 °C in 30% Sulfuric Acid

Compound	**Concentration (mg/L)**	At 25 °C		At 75 °C:	
		Corrosion rate, K_{g/m^2s}	Protection efficiency, (Z), %	Corrosion rate, K_{g/m^2s}	Protection efficiency, (Z), %
ББТ	250	-	-	-	-
	500	-	-	-	-
	1000	12,5	62	577	59
АМТС	250	2,1	93	33	97,5
	500	1,5	94,7	3,9	99,7
	1000	1,3	96,0	1,8	99,8

The observed differences in inhibition efficiency among the applied compounds can be attributed to their molecular composition and structure. In the case of BBT, the molecular structure indicates that upon interaction with the acidic medium, the molecule becomes positively charged. This results in physical adsorption on the metal surface through electrostatic attraction between the charged inhibitor species and the negatively charged sites on the steel, thereby providing primary corrosion protection.

Moreover, the lone pair electrons on the sulfur atom and the π-electrons of the aromatic ring in BBT allow for chemisorptive interaction with vacant d-orbitals of the metal, leading to additional corrosion inhibition via chemical adsorption.

In comparison, the superior inhibition performance of AMTS can be explained by the presence of the acetyl functional group in its molecular structure. Beyond the lone electrons on the sulfur atom, the lone pair electrons of the carbonyl oxygen participate as functional groups, further interacting with the metal surface to enhance corrosion protection. Additionally, the methyl group attached to the heterocyclic ring and the sulfur atom increases the electron density of the aromatic

ISSN 3030-3907

core, enhancing the π-electron cloud of the ring and thus strengthening the adsorption on the steel surface.

Figures 3 and 4 schematically illustrate the physical and chemical adsorption mechanisms of BBT and AMTS on the steel surface, respectively, highlighting how molecular structure governs inhibition efficiency.

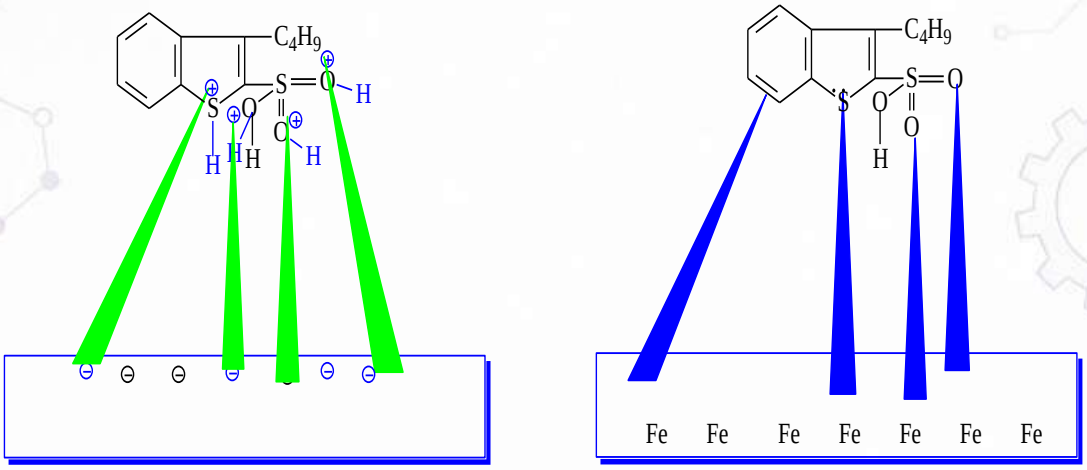


Figure 3. Mechanism of physical and chemical adsorption of BBT inhibitor on the steel surface.

The figure illustrates how BBT molecules interact with the metal substrate via two primary pathways. Firstly, physical adsorption occurs due to electrostatic attraction between the positively charged inhibitor molecules (resulting from protonation in acidic medium) and negatively charged sites on the steel surface. Secondly, chemical adsorption (chemisorption) arises from the donation of lone pair electrons on the sulfur atom and π-electrons from the aromatic ring to the vacant d-orbitals of the metal, forming coordinate covalent bonds. This dual adsorption mechanism ensures enhanced protection against acidic corrosion.

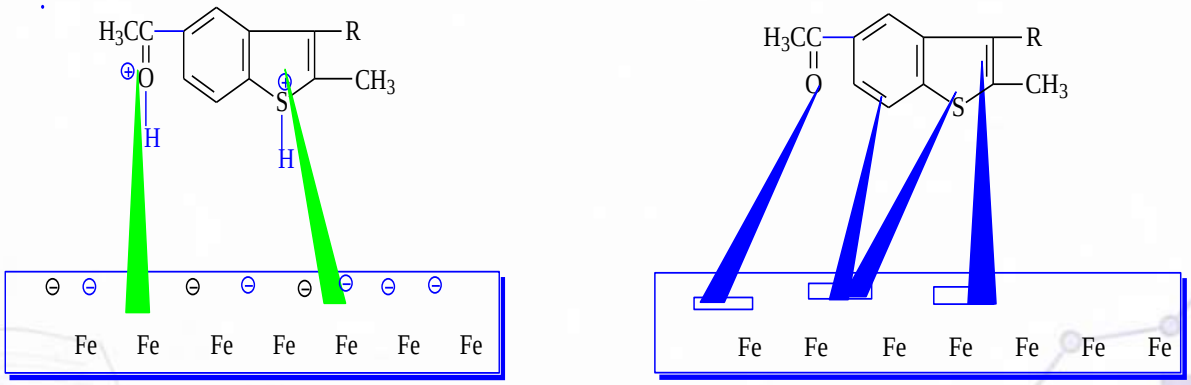


Figure 4. Mechanism of physical and chemical adsorption of AMTS inhibitor on the steel surface.

The figure demonstrates the adsorption behavior of AMTS molecules on the steel substrate. Physical adsorption occurs due to electrostatic interactions between the protonated AMTS molecules in acidic medium and negatively charged sites on the steel surface. Chemical adsorption (chemisorption) is facilitated by the lone pair

ISSN 3030-3907

electrons of the sulfur atom and the carbonyl oxygen atom, as well as π-electrons of the aromatic ring, interacting with the vacant d-orbitals of the metal. Additionally, the methyl group attached to the heterocyclic ring enhances electron density in the aromatic core, increasing the efficiency of π-electron donation to the metal. This synergistic adsorption mechanism significantly improves corrosion inhibition performance compared to BBT.

At present, quantum chemistry serves as the theoretical foundation for all branches of chemistry. It has become an essential tool for addressing complex scientific problems and elucidating the mechanisms of chemical reactions. By applying quantum chemical methods, it is possible to calculate the electronic states of molecules, electron density distribution, potential energy surfaces of reactions, phase barriers during rearrangements, and various spectroscopic parameters.

Currently, quantum chemical calculations are widely employed to evaluate the corrosion inhibition efficiency of organic inhibitors. In many cases, during acidic corrosion, the metal surface acquires a positive charge. Organic inhibitors adsorb onto the metal surface through electron-rich functional groups within their molecular structure. The inhibitor molecule can donate electrons to vacant d-orbitals of the metal and simultaneously accept electrons from the metal orbitals into its empty orbitals, forming coordinate (dative) bonds.

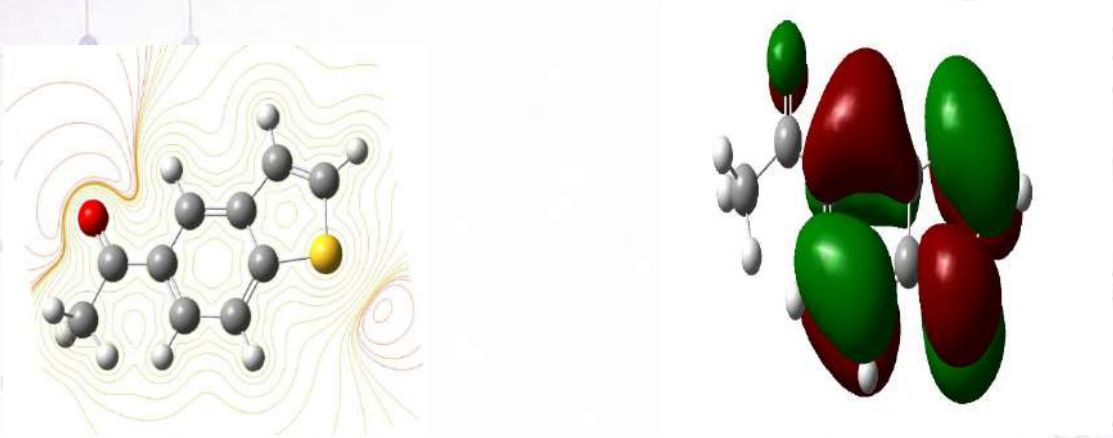
In analyzing atomic orbital energies, the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) are particularly significant. The HOMO reflects the electron-donating ability of the molecule, while the LUMO indicates its capacity to accept electrons. Consequently, the higher the HOMO energy of an organic molecule, the easier it is for electrons to be transferred to the vacant d-orbitals of the metal, thereby enhancing its anticorrosive activity.

Moreover, the electron distribution within the molecule is influenced by the effective charges of constituent atoms and the total system energy. Calculation of these energetic parameters provides insight into the stability of the molecule. Figures 5 and 6 illustrate the electron density distribution across functional groups and atoms of BBT and AMTS inhibitor molecules (regions of high electron density are shown in red).

Analysis of the effective atomic charges indicates that the highest electron densities in BBT and AMTS molecules are localized around the oxygen and sulfur atoms. The wavefunction and nonplanar molecular configuration of the inhibitors ensure that the positively charged metal surface is covered by donor–acceptor interactions and electrostatic attraction. Both BBT and AMTS inhibitors are multifunctional, with electron density distributed across the entire molecule. These

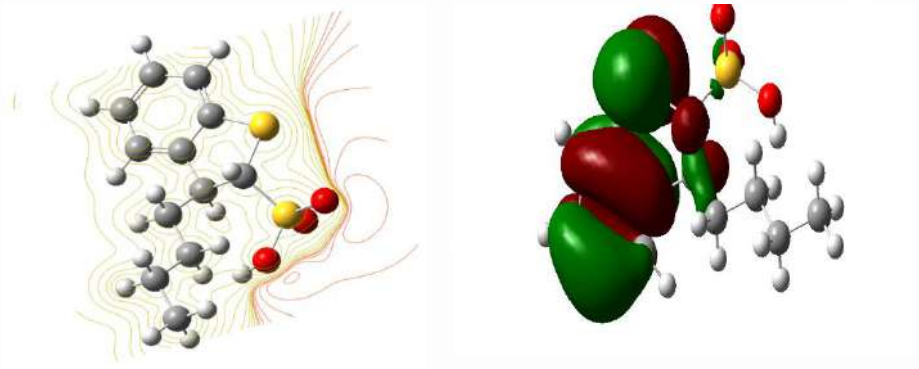
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features allow the inhibitors to effectively "shield" the metal surface, thereby exhibiting significant corrosion inhibition performance.



A **B**

Figure 5. Distribution of electron density in the AMTS inhibitor molecule by functional groups: (A) overall electron density distribution; (B) electron density distribution based on HOMO–LUMO orbitals.

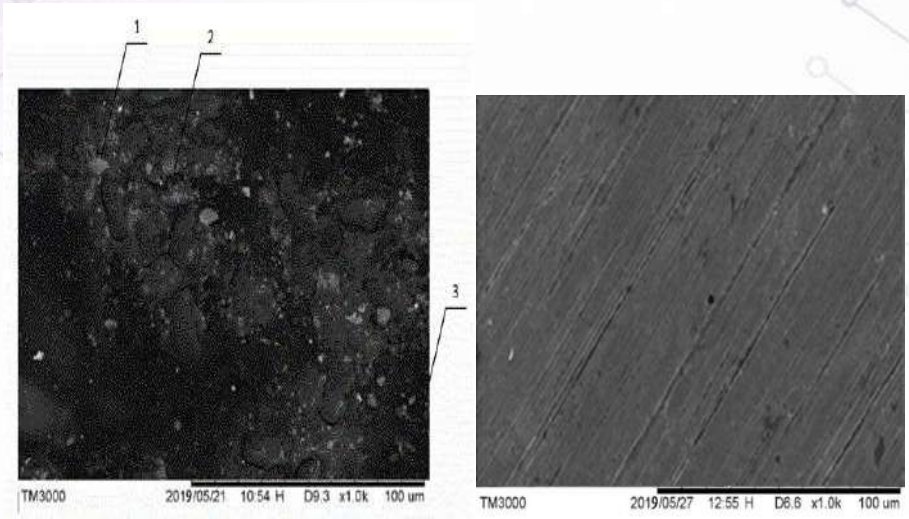


A **B**

Figure 6. Distribution of electron density in the BBT inhibitor molecule by functional groups: (A) overall electron density distribution; (B) electron density distribution based on HOMO–LUMO orbitals.

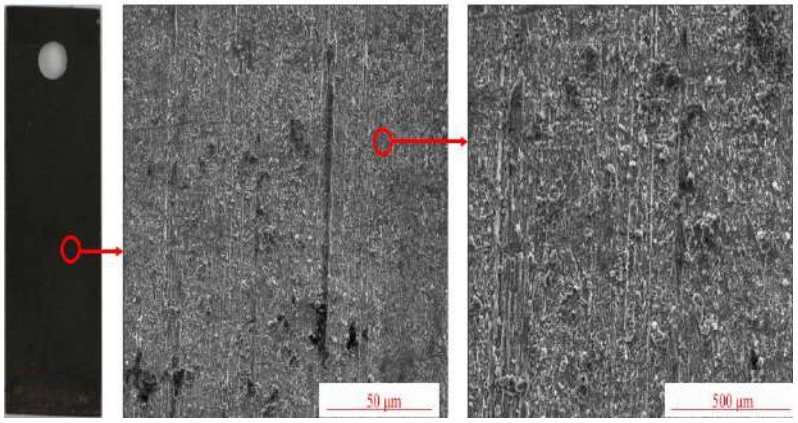
To validate the effectiveness of the inhibitors used as corrosion inhibitors, Figure 7 presents SEM micrographs of the steel St.20 samples: (A) steel sample in the inhibitor-free environment, showing 1-localized corrosion, 2-corrosion cracking, and 3-general corrosion; (B) steel sample in the presence of the inhibitor solution. Additionally, Figure 8 illustrates the concentration-dependent inhibition efficiency of the steel samples in working solutions containing the inhibitor at 250, 500, and 1000 mg/L.

ISSN 3030-3907

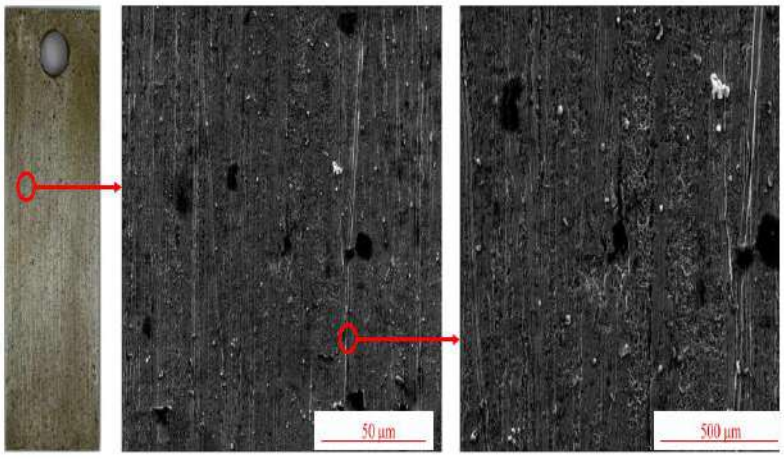


A B

Figure 7. SEM micrographs of steel St.20 samples: (A) steel in the absence of inhibitor showing 1-localized corrosion, 2-corrosion cracking, and 3-general corrosion; (B) steel in the presence of inhibitor solution.



A



B

ISSN 3030-3907

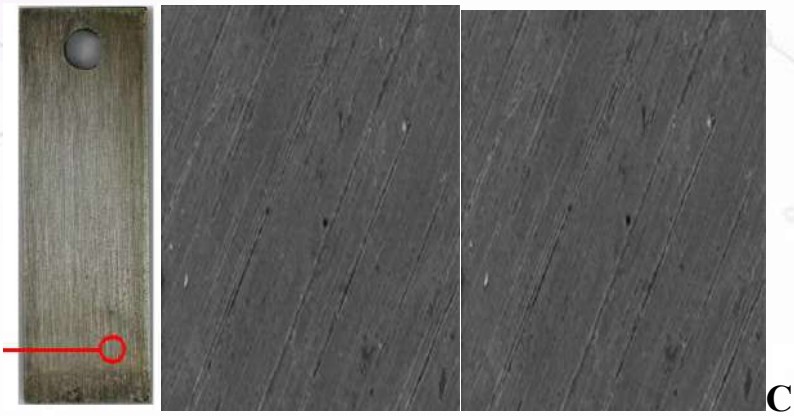

C

Figure 8. SEM micrographs of steel St.20 samples in inhibitor solutions at concentrations of: (A) 250 mg/L, (B) 500 mg/L, and (C) 1000 mg/L.

As can be observed from the micrographs, the steel samples were effectively protected against corrosion by the inhibitor solutions at all tested concentrations. In contrast, the steel sample immersed in the inhibitor-free system exhibited numerous cracks and localized corrosion on the surface. In the samples exposed to inhibitor-containing solutions, these cracks were absent, and no signs of corrosion were detected, indicating the high efficiency of the inhibitors in protecting the steel surface.

Figure 6 presents the schematic flow diagram for the processing of the pre-bitumen fraction of crude oil.

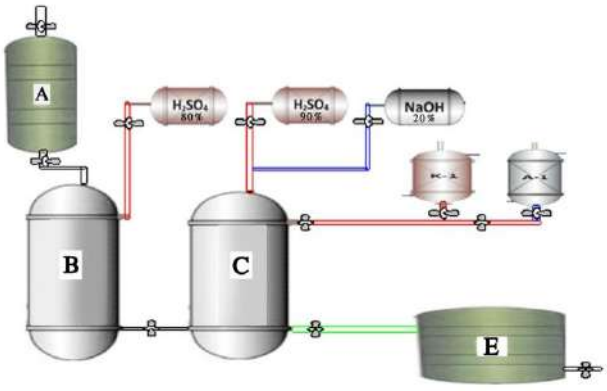


Figure 6. Schematic process flow diagram for the treatment of the pre-bitumen fraction of crude oil: A – bitumen-kerosene fraction; B – reactor; C – crude oil fractionation tank; K – tank for mono-thiocyclanes; A – tank for bi-thiocyclanes; E – tank for storing the resulting composition.

The bitumen-kerosene fraction of crude oil from tank A is fed into the treated reactor B. A measured amount of 80% sulfuric acid solution from the sulfuric acid tank is periodically added to reactor B, and the mixture is processed twice for 2 hours each cycle. The processed stream is then sent to tank C, where it is fractionated. The first fraction, distilled at 230–280 °C, is collected in tank K-1, while the second fraction, distilled at 280–330 °C, is collected in tank A-1. Analysis

ISSN 3030-3907

revealed that tank K-1 predominantly contains mono-thiocyclanes, whereas tank A-1 is enriched with bi-thiocyclanes [22-23].

In the residual fraction above 330 °C, the content of arenethiophene compounds increases from 8% to 18%. This residual fraction is treated for 2 hours with 90% sulfuric acid solution. Subsequently, a 20% alkaline solution is added to the treated fraction, and the mixture is stirred for 1 hour to convert the sulfonic acids into their sodium salts. Finally, the sodium salts of arenethiophenes from tank C are collected as the product in tank E.

CONCLUSIONS.

This study presents a comprehensive approach to the isolation, transformation, and application of arenothiophene derivatives obtained from the pre-bitumen fraction of high-sulfur crude oil. The developed methodology based on selective sulfonation and acylation reactions enabled the efficient extraction and modification of sulfur-containing bicyclic aromatic compounds. Structural and analytical investigations confirmed the successful formation of benzo[b]thiophene sulfonic acid derivatives and their corresponding salts, demonstrating the feasibility of converting complex petroleum fractions into valuable functional compounds.

Experimental studies revealed that the synthesized compounds, particularly 3-butylbenzo[b]thiophene-2-sulfonic acid (BBT) and 5-acetyl-2-methylthiaine sulfoxide (AMTS), exhibit significant corrosion inhibition efficiency in aggressive acidic environments. The inhibition performance was strongly influenced by inhibitor concentration and temperature, with AMTS demonstrating superior protection due to the presence of both sulfur and carbonyl functional groups capable of forming stable adsorption interactions with the metal surface.

Quantum chemical analysis provided further insight into the inhibition mechanism, indicating that the distribution of electron density, HOMO–LUMO energy characteristics, and donor-acceptor interactions between the inhibitor molecules and the metal surface play a crucial role in corrosion protection. The combined presence of heteroatoms and aromatic π-electron systems facilitates both physical adsorption and chemisorption processes, resulting in the formation of a stable protective layer on the steel surface.

In addition to their anticorrosive properties, the synthesized arenothiophene sulfonic acid derivatives demonstrated notable surface-active characteristics, indicating their potential application as foaming and dispersing agents in petroleum technologies. This multifunctional behavior significantly broadens the practical value of the obtained compounds for oil and gas processing operations.

Overall, the proposed approach offers a technologically feasible and economically attractive pathway for the valorization of high-sulfur crude oil

ISSN 3030-3907

fractions, transforming problematic sulfur-containing components into valuable industrial products. The obtained results contribute to the development of petroleum-based corrosion inhibitors and highlight new opportunities for sustainable utilization of complex hydrocarbon resources in modern petrochemical technologies.

Statements All authors declare that they have no conflict of interest.

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SYNTHESIS AND TRIBOLOGICAL EVALUATION OF LUBRICITY ADDITIVES FOR EURO-5 DIESEL FUEL BASED ON LOCAL SECONDARY RAW MATERIALS

Ozoda Baxronovna Akhmedova
Tashkent State Technical University named after Islam Karimov University Street 2, Tashkent 100095, Uzbekistan
Email: zodamedova@gmail.com
Hasan Sadriddinovich Fozilov
Bukhara State Technical University K. Murtazayev Street 15, Bukhara 200117, Uzbekistan
Abdurasul Shonazarovich Qayumov
Tashkent State Technical University named after Islam Karimov University Street 2, Tashkent 100095, Uzbekistan
Ra'no Asadova Dilmurodovna
Tashkent State Technical University named after Islam Karimov University Street 2, Tashkent 100095, Uzbekistan

Abstract. The reduction of sulfur content in modern diesel fuels significantly deteriorates their lubricity properties, leading to increased wear of fuel system components. Therefore, the development of effective lubricity-enhancing additives has become an important task for the production of environmentally friendly diesel fuels. In this study, a technology for obtaining lubricating additives based on higher fatty alcohols synthesized from locally available secondary raw materials was developed. Higher fatty alcohols (C_{12}–C_{17}) were produced through the oxidation of low-molecular-weight polyethylene and paraffinic hydrocarbons in the presence of boric acid at temperatures of 165–170 °C. The yield of the target products reached 35–40%. The obtained compounds were characterized using FTIR and GC–MS methods, confirming the formation of alcohol-containing structures. The synthesized additives were introduced into diesel fuel, and their lubricity performance was evaluated according to the ASTM D6079 (HFRR) method. The addition of 0.0163 wt.% of the additive reduced the wear scar diameter from 520 μm to 400–460 μm at 60 °C, meeting the requirements of Euro-5 diesel fuel standards. The proposed technology enables the utilization of local secondary resources and provides an effective alternative to imported commercial lubricity additives for the production of environmentally friendly low-sulfur diesel fuels.

Keywords: petroleum, diesel fuel, higher fatty alcohols (HFA), low-molecular polyethylene (LMPE), boric acid, lubricating additive, lubricity property, sulfur, fractional composition, viscosity.

Annotatsiya. Zamonaviy dizel yoqilg'ilaridagi oltingugurt miqdorini kamaytirish ularning moylash xususiyatlarini sezilarli darajada yomonlashtiradi, bu esa yonilg'i tizimi komponentlarining eskirishini oshiradi. Shuning uchun

ISSN 3030-3907

moylash qobiliyatini oshiruvchi samarali qo‘shimchalarni ishlab chiqish ekologik toza dizel yoqilg‘ilarini ishlab chiqarish uchun muhim vazifaga aylandi. Ushbu tadqiqotda mahalliy ikkilamchi xom ashyolardan sintez qilingan yuqori yog‘li spirtlar asosida moylovchi qo‘shimchalar olish texnologiyasi ishlab chiqildi. Yuqori molekulyar yog‘li spirtlar (C12–C17) past molekulyar og‘irlikdagi polietilen va parafin uglevodorodlarni bor kislotasi ishtirokida 165–170 °C haroratda oksidlash orqali ishlab chiqarilgan. Maqsadli mahsulotlarning hosildorligi 35-40% ga yetdi. Olingan birikmalar FTIR va GC–MS usullari yordamida tavsiflanib, tarkibida alkogol bo‘lgan tuzilmalar hosil bo‘lishini tasdiqladi. Sintez qilingan qo‘shimchalar dizel yoqilg‘isiga kiritildi va ularning moylash xususiyatlari ASTM D6079 (HFRR) usuli bo‘yicha baholandi. Qo‘shimchaning 0,0163 og‘irlik foizi qo‘shilishi 60 °C haroratda eskirish chandig‘i diametrini 520 mkm dan 400–460 mkm gacha qisqartirdi va bu Evro-5 dizel yoqilg‘isi standartlari talablariga javob beradi. Taklif etilayotgan texnologiya mahalliy ikkilamchi resurslardan foydalanish imkonini beradi va ekologik toza kam oltingugurtli dizel yoqilg‘isi ishlab chiqarish uchun import qilinadigan tijorat moylash qo‘shimchalariga samarali muqobil bo‘ladi.

Kalit so‘zlar: neft, dizel yoqilg‘isi, yuqori yog‘li spirtlar (HFA), past molekulyar polietilen (LMPE), bor kislotasi, moylash qo‘shimchasi, moylash xususiyati, oltingugurt, fraksiyonel tarkibi, yopishqoqlik.

Аннотация. Снижение содержания серы в современных дизельных топливах значительно ухудшает их смазывающие свойства, что приводит к повышенному износу компонентов топливной системы. Поэтому разработка эффективных присадок, повышающих смазывающие свойства, стала важной задачей для производства экологически чистых дизельных топлив. В ходе данного исследования была разработана технология получения смазочных присадок на основе высших жирных спиртов, синтезированных из местного вторичного сырья. Высшие жирные спирты (C12–C17) были получены путем окисления низкомолекулярного полиэтилена и парафиновых углеводородов в присутствии борной кислоты при температурах 165-170°C. Выход целевых продуктов достигал 35-40%. Полученные соединения были охарактеризованы методами FTIR и GC–MS, подтверждающими образование спиртосодержащих структур. Синтезированные присадки были введены в дизельное топливо, и их смазывающие свойства были оценены в соответствии с методом ASTM D6079 (HFRR). Добавление 0,0163 мас.% присадки уменьшило диаметр следов износа с 520 мкм до 400-460 мкм при температуре 60°C, что соответствует требованиям стандартов на дизельное топливо Евро-5.

ISSN 3030-3907

Предлагаемая технология позволяет использовать местные вторичные ресурсы и является эффективной альтернативой импортным коммерческим смазочным присадкам для производства экологически чистых дизельных топлив с низким содержанием серы.

Ключевые слова: нефть, дизельное топливо, высшие жирные спирты (HFA), низкомолекулярный полиэтилен (LMPE), борная кислота, смазочная присадка, смазывающие свойства, сера, фракционный состав, вязкость.

INTRODUCTION.

At present, the production of diesel fuels with improved environmental characteristics and reduced contents of sulfur and aromatic hydrocarbons is of considerable importance.

This is because, during combustion, sulfur-containing and aromatic hydrocarbons generate toxic gases and, due to incomplete combustion, exert a greater negative impact on the environment. From an environmental perspective, research aimed at reducing such impacts is therefore highly relevant. However, decreasing the sulfur content in diesel fuel adversely affects its lubricity properties, which may result in non-compliance with standard requirements. In such cases, lubricity-improving additives are introduced into diesel fuel at low concentrations in order to bring its lubricity characteristics into conformity with the applicable standards.

Currently, in the Republic of Uzbekistan, diesel fuels are produced at oil refineries as well as at the Uzbekistan GTL plant. High-quality diesel fuel with reduced sulfur content is produced as a finished product by blending diesel fuel streams manufactured at oil refineries and the Uzbekistan GTL plant. During the production process, lubricity-improving additives imported from foreign countries and purchased in foreign currency are added to the fuel. The use of such additives inevitably affects the production cost of the fuel.

Based on a review of the literature, the composition of lubricity-improving additives and the availability of domestic resources in the country were studied. A comparative analysis of studies conducted by researchers who synthesized additives for improving the lubricity of diesel fuels was carried out. Lubricity-enhancing additives for diesel fuels are generally synthesized through the catalytic hydrogenation of esters of higher fatty alcohols [1]. Higher fatty alcohols are also produced through hydroformylation of higher α-olefins, the use of aluminum-containing catalysts, and oxidation of alkanes with atmospheric oxygen.

ISSN 3030-3907

Studies on the synthesis of lubricity-enhancing additives have shown that not the fractional composition of the fuel but rather parameters such as the content of sulfur-containing compounds and the flow properties of the fuel play a decisive role. Only after establishing the significance of these factors did the development and synthesis of lubricity-improving additives begin to advance rapidly [2].

At present, diesel fuels produced at petroleum refineries commonly contain lubricity-improving additives based on polymers, oligomers, copolymers, and non-polymeric compounds. One class of additives that significantly influence the lubricating properties of diesel fuel includes polyolefins and their derivatives. Among them is low-molecular-weight branched polyethylene (LMWPE), a by-product formed during the production of high-pressure low-density polyethylene. Experimental studies have demonstrated that the addition of 0.1–1.0% LMWPE can reduce the wear scar diameter of diesel fuel to approximately 360 μm [3]. In the Republic of Uzbekistan, this low-molecular-weight polyethylene is generated as a secondary product at the Shurtan Gas Chemical Complex. This creates an opportunity for its targeted utilization as a raw material for the production of lubricity-improving additives.

In general, it can be concluded that the effectiveness of lubricity-enhancing additives increases with the length of the saturated linear hydrocarbon radical present in their structure, which significantly improves the lubricating properties of diesel fuels [4].

Based on the analysis of the lubricity-enhancing additives described above and the evaluation of their properties, it was considered appropriate to develop a synthesis method using locally available raw materials. To address this problem, scientific research was carried out focusing on the utilization of secondary raw material resources available in the country. Particular attention was given to the development and implementation of technologies for processing these resources and converting them into effective lubricating additives. The research aimed to obtain additives that are economically viable, environmentally safe, and capable of significantly improving the lubricating properties of diesel fuels. The results of the study demonstrate the feasibility of producing efficient and low-cost lubricity-enhancing additives from locally available feedstocks while simultaneously promoting sustainable utilization of secondary resources [5].

In this context, low-molecular-weight polyethylene (LMWPE), which is formed as a secondary industrial by-product during polyethylene production, can be considered a promising and economically attractive raw material for the synthesis of lubricity-improving additives. Through controlled oxidation in the presence of boric acid, LMWPE can be converted into higher fatty alcohols containing long hydrocarbon chains and polar hydroxyl groups. Such molecular

ISSN 3030-3907

structures are expected to adsorb effectively on metal surfaces and form a protective lubricating film, thereby reducing friction and wear in fuel injection systems. Therefore, the aim of this study is to synthesize higher fatty alcohol-based additives from LMWPE waste and to evaluate their effectiveness in improving the lubricity of Euro-5 diesel fuel using the ASTM D6079 HFRR test method.

LITERATURE REVIEW ON LUBRICITY-IMPROVING ADDITIVES

A literature review on additives that improve the lubricity properties of diesel fuel was conducted.

Additives based on ethylene-propylene (EP) copolymers and ethylene-propylene-diene (EPDM/EPDS) copolymers, as well as their derivatives, have also been widely applied in diesel fuels at concentrations of 1.0–5.0%. It has been observed that products obtained through thermal and thermo-oxidative degradation of dicyclopentadiene exhibit significantly higher lubricity-enhancing activity compared with conventional EP and EPDS additives.

The effect of the DAKS-D composite lubricity-enhancing additive for diesel fuel has also been investigated. This additive is synthesized through the production of alcohols from carboxylic acids followed by the formation of compositions with nitrogen-containing compounds. Research results indicate that pure carboxylic acids cannot be effectively used as additives for diesel fuels because they have little influence on the wear scar diameter across the fuel volume. However, composite additives containing higher fatty alcohols and nitrogen-containing compounds exhibit a synergistic effect, improving both lubricity and stability of petroleum products [6-8].

The influence of esters derived from triglycerides of higher fatty acids and vegetable oils on the lubricity and sedimentation stability of diesel fuel has also been investigated. Esters synthesized from polyoxyalkylene glycols containing C_{10}–C_{30} carbon atoms with molecular masses ranging from 200 to 2000 were obtained at temperatures of 200–340 °C and were shown to increase the viscosity and lubricity of diesel fuels. Additives synthesized from higher fatty acids and stearic acid improved the lubricating properties of diesel fuels when added in an amount of 0.1%, lowering the pour point by 2–5 °C.

To enhance fuel fluidity and lubricity, esters based on trimethylolpropane, trimethylolethane, and pentaerythritol have been employed. Studies on ester-based additives have shown that concentrations of 0.01–0.03% reduce the wear scar diameter to approximately 450 μm. Esters obtained through esterification of pentaerythritol with oxystearic acid at concentrations of 0.1–0.3% reduced the wear scar diameter of summer diesel fuel from –13 °C to –40 °C, while for dewaxed winter diesel fuel the wear scar diameter decreased from 570 μm to 360 μm [9].

ISSN 3030-3907

Compounds with molecular masses of 12 000–15 000, obtained from the reaction of aliphatic acid chlorides containing C_{12}–C_{18} carbon atoms with dextrin, have also been shown to improve both viscosity and lubricity of diesel fuel.

Condensation-type additives with lubricity-enhancing properties have been synthesized based on monoaliphatic alcohols containing C_{10}–C_{30} carbon atoms and malic acid, and their effectiveness in improving diesel fuel lubricity has been experimentally confirmed [10,11].

Esters obtained from higher fatty alcohols ($C_8H_{17}OH$, $C_{15}H_{31}OH$, $C_{16}H_{33}OH$) with molecular masses ranging from 300 to 1200, together with polyhydric alcohols such as glycerol, ethylene glycol, diethylene glycol, and triethylene glycol, and adipic acid, have also been investigated. When added in amounts of 0.1–1.0%, these esters reduce the wear scar diameter to 460 μm, meeting the requirements of the Euro-5 standard, while simultaneously improving the operational and environmental characteristics of diesel fuels.

To enhance both fuel fluidity and lubricity, additives containing esters of linear carboxylic acids with N-hydroxyl groups (C_6–C_{12}) have also been used. Nitrogen-containing compounds such as triethanolamine, diethanolamine, methyldiethanolamine, ethyldiethanolamine, butyldiethanolamine, and diisopropanolamine, as well as derivatives of lauric, palmitic, and stearic acids, have been applied as components of such additives [12,13].

Low-molecular-weight compounds containing dialkylcyanamide groups with C_4–C_{16} carbon atoms have been synthesized by condensation of potassium cyanamide with haloalkyls in a dimethylformamide medium. When added at a concentration of 0.03%, these compounds demonstrated lubricity-enhancing properties in diesel fuel. Nitrogen-containing additives of this class effectively reduce the wear scar diameter.

EXPERIMENTAL RESEARCH.

At present, in production plants, the fractional composition of diesel fuels is lightened in order to improve their low-temperature properties. This leads to a reduction in viscosity. As viscosity decreases, the lubricity properties of diesel fuel also deteriorate [14].

To investigate the influence of fractional composition and viscosity on the lubricating properties of diesel fuels, low-sulfur diesel fuels containing up to 0.07 wt.% sulfur were selected for the study.

The experimental results showed that for diesel fuel samples 1 and 2, in which 50% and 96% distillation temperatures were within the ranges of 262–274 °C and 350–360 °C, respectively, the wear scar diameter was found to be 430–450 μm.

ISSN 3030-3907

A decrease in the distillation temperature of diesel fuel led to an increase in the wear scar diameter. As shown in Table 1. sample 4, characterized by a fractional composition with final boiling temperatures of 182–276 °C for the 50% and 96% fractions, exhibited a wear scar diameter of 610 μm, which corresponds to conditions close to dry friction.

This behavior is mainly attributed to the higher sulfur content in sample 4 (0.022 wt.%) compared with samples 1 and 2. For these fuels, the wear scar diameters were observed to be 870 μm and 835 μm, respectively. When the sulfur content of the fuel reached 0.03 wt.%, the wear scar diameter reached its minimum value of 430 μm.

The physicochemical properties of the investigated diesel fuels are presented in Table 1.

Table 1.

Main physicochemical properties of diesel fuels.

Fuel sample	Fractional composition, °C		Sulfur content, wt.%	Kinematic viscosity at 20 °C, mm²/s	Wear scar diameter, μm
	50%	96%			
1	193	322	0,010	1,84	870
2	222	296	0,015	2,19	835
3	255	351	0,020	3,74	520
4	182	276	0,022	1,53	610
5	**262**	**360**	**0,030**	**4,22**	**430**
6	274	350	0,040	5,49	450
7	204	262	0,070	1,88	520
8	269	334	0,080	4,94	545

Thus, the influence of fractional composition and sulfur content on the lubricating properties of diesel fuel can be clearly observed in samples 3 and 7, where both fuels exhibit the same wear scar diameter of 520 μm. In sample 7, the sulfur content is 0.07 wt.%, whereas in sample 3 it is 0.02 wt.%. Compared with sample 3, sample 7 is characterized by a lighter fractional composition and lower kinematic viscosity.

It can therefore be concluded that the lubricating properties of diesel fuels are not determined solely by their physicochemical and operational characteristics. Rather, they are also significantly influenced by factors such as the fractional composition of the fuel, its viscosity, and the sulfur content present in the fuel. At present, since diesel fuel fraction corresponding specifically to Sample 5 has been reprocessed at the Bukhara Oil Refinery, subsequent studies were carried out using a sample of this composition. [15].

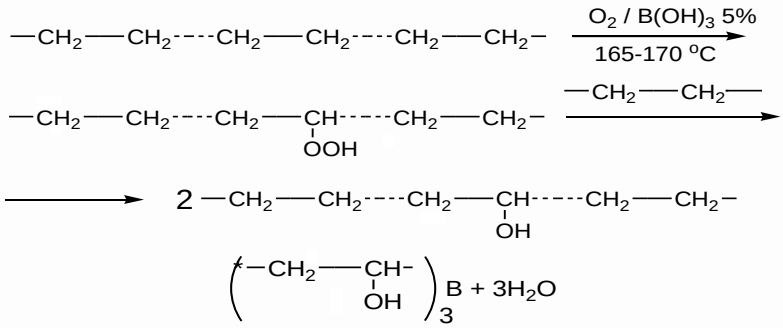
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As a constituent of diesel fuel, the petroleum hydrocarbon fraction boiling within the range of 262 °C to 360 °C is separated as an individual fraction, and its sulfur content is reduced by means of hydrotreating technology. In this fraction, the sulfur content generally amounts to approximately 0.03%. At present, it is brought to the finished-product stage by blending with diesel fuel produced at the Uzbekistan GTL plant, which contains virtually no sulfur. This, in turn, leads to a further deterioration of the lubricity properties of the fuel.

Therefore, when producing diesel fuel that meets the requirements of O‘z DSt 1134:2018, particularly Euro-5 and Euro-6 standards, the addition of lubricity-improving anti-wear additives is of particular importance.

Globally, such problems are addressed by adding additives based on higher fatty alcohols (HFA) to diesel fuel.

Considering the importance of higher fatty alcohols in various fields, it is appropriate to review and compare the raw materials and methods used for their synthesis. In this study, higher fatty alcohols were synthesized based on low-molecular polyethylene (LMPE), which is a secondary waste product of the Shurtan Gas Chemical Complex.



A total of 100 g of low-molecular polyethylene (LMPE) was charged into the reactor, after which a gas mixture of nitrogen and 3.0–4.5% oxygen was supplied from a cylinder, and 5 g of boric acid was added. The temperature was raised to 165–170 °C, and the reaction was carried out at this temperature for 2–3 hours. Oxygen supply was ensured using a sparger. The flow rates of air and nitrogen were monitored using a rheometer (Figure 1).

The flow rate of the oxidizing gas was maintained at 70 L/h per batch of LMPE. During the oxidation process, the gases leaving the reactor were vented to the atmosphere [23].

Condensed droplets of the reaction mixture were returned to the reactor, while the aqueous condensate was collected in a water trap. The separated higher fatty alcohols were purified, and unreacted hydrocarbons were distilled off under vacuum.

As a result of oxidation, alcohols containing the same number of carbon atoms as the initial hydrocarbons were obtained. These products were mainly

ISSN 3030-3907

secondary alcohols, in which the hydroxyl group is attached at different positions along the carbon chain. The residue consisted mainly of boric acid esters, which formed a brown mass that solidified even at room temperature. The yield of the target product was 38–39%.

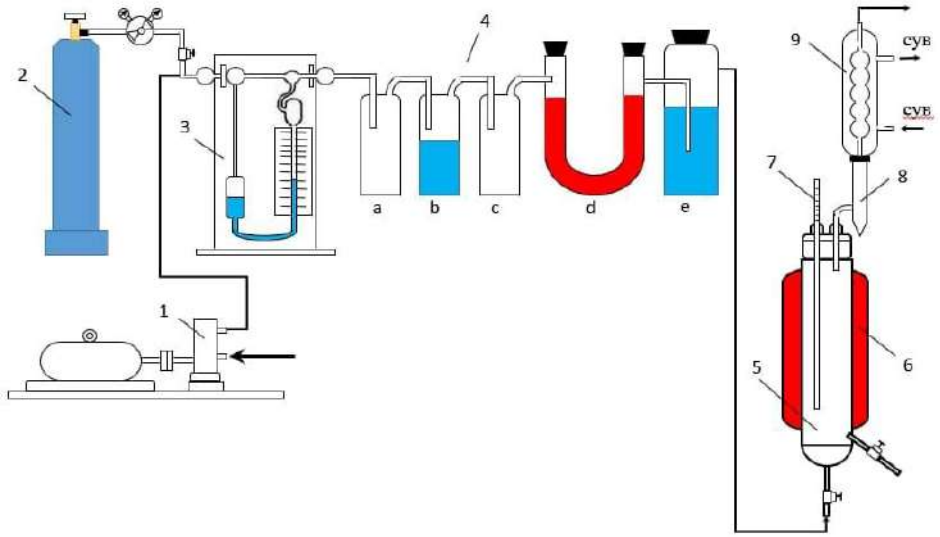


Figure 1. Schematic diagram of the laboratory setup for producing higher fatty alcohols by oxidation of LMPE: 1 – air sparger, 2 – nitrogen cylinder, 3 – rheometer, 4 – $CaCl_2$ dryer, 5 – reactor, 6 – heater, 7 – thermometer, 8 – Dean–Stark apparatus, 9 – reflux condenser.

The maximum oxidation efficiency of LMPE, i.e., the highest conversion, is achieved in the fourth hour of oxidation of low-molecular-weight polyethylene. By the fifth hour of synthesis, the amount of formed hydroxyl groups remains constant [24].

RESEARCH RESULTS.

The rate of formation of higher fatty alcohols depends on the temperature of the oxidation process of normal paraffinic hydrocarbons by molecular oxygen from air in the presence of boric acid. When paraffins obtained from local secondary raw materials are oxidized with atmospheric oxygen at 120–170 °C in the presence of boric acid and without a catalyst, the rate of increase in the number of hydroxyl groups decreases by 8–10 times (Figure 2).

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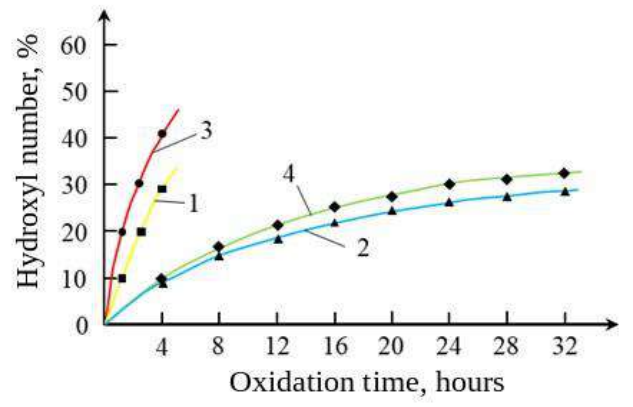


Figure 2. Time dependence of the formation of hydroxyl and ether groups during the catalyst-free oxidation of paraffinic hydrocarbons in the presence of boric acid at different temperatures: 1 – number of hydroxyl groups formed in paraffin oxidized at 170 °C; 2 – number of hydroxyl groups formed from paraffinic hydrocarbons oxidized at 120 °C; 3 – number of ether groups formed in paraffin oxidized at 170 °C; 4– number of ether groups formed in paraffin oxidized at 120 °C

If the temperature is reduced below 120 °C, the oxidation process slows down significantly; however, the ratio of alcohols to carbonyl compounds in the oxidation products, equal to 1:1.27, remains almost unchanged.

Therefore, in order to ensure the rapid accumulation of large amounts of primary oxidation products and maintain a high process rate, it is recommended to use a variable-temperature regime for paraffin oxidation. In this regime, the initial oxidation temperature should be 120–125 °C, after which, depending on the intensity of the process, the temperature should be decreased by 2–5 °C per hour to obtain higher fatty alcohols of the highest quality.

The oxidation of paraffinic hydrocarbons with oxygen from air is a heterogeneous process. Its rate is affected by temperature, the concentrations of hydrocarbons and oxygen, and the rate of oxygen diffusion into the liquid phase. Under the conditions of the oxidation process, the concentration of paraffin in the oxidized mixture does not have a significant effect on the oxidation rate. However, the concentration of dissolved oxygen affects both the degree of oxidation and the quality of the products formed. In the liquid-phase oxidation of paraffins to higher fatty alcohols, the rate of oxygen absorption is not constant throughout the process, and the maximum absorption rate varies depending on the operating regime.

During catalyst-free oxidation, the higher the temperature in the range of 120–160 °C, the greater the amount of absorbed oxygen. In this case, oxygen is consumed mainly for the formation of other oxygen-containing products rather than alcohols. When purified paraffin is oxidized on a large scale without a catalyst at 125–105 °C, oxygen absorption begins before the formation of the first carbonyl

ISSN 3030-3907

products and reaches a maximum corresponding to the highest rate of alcohol formation (Figure 4.2, curve 1).

During the oxidation of a mixture of fresh and recycled paraffins at a ratio of 1:2, oxygen absorption begins immediately and proceeds intensively. It reaches its maximum 3–4 hours after the start of the reaction, which also corresponds to the period of the highest accumulation rate of alcoholic products (curve 2). However, the amount of absorbed oxygen does not exceed 20% of the oxygen supplied with air for oxidation.

When the same mixture is oxidized after the preliminary addition of 0.2% boric acid, oxygen uptake begins intensively from the very start of the process. The curve of the oxygen absorption rate passes through a sharp maximum and then rapidly decreases (curve 3). The maximum amount of oxygen absorbed from air is four times higher than that observed during catalyst-free oxidation and reaches 80%. During 20 hours, alcohol accumulation continues at a constant rate of 2.0–2.3% per hour.

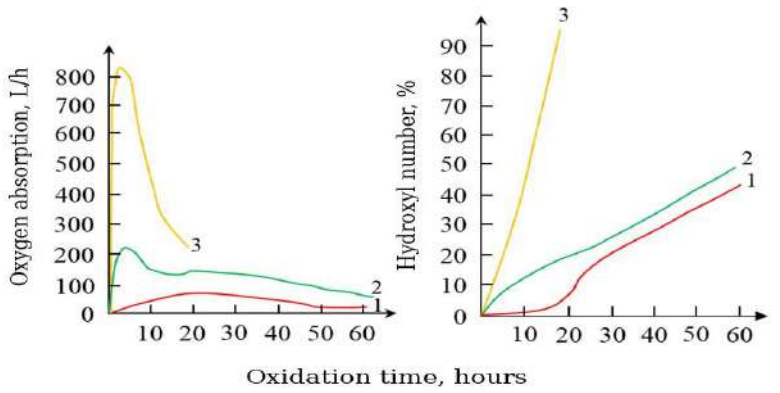


Figure 3. Changes in the amount of absorbed oxygen and the hydroxyl number of the oxidate during the oxidation of paraffins in the presence of various additives: 1 - initial paraffin; 2 - initial paraffin + recycled paraffin; 3 - initial paraffin + recycled paraffin + boric acid.

During catalyst-free oxidation, only approximately one-third of the absorbed oxygen is consumed for the formation of acidic products, while the remaining portion is used for the formation of other oxygen-containing compounds. In the presence of active soluble boric acid, the major part of the absorbed oxygen, up to 80.5%, is consumed for the formation of alcohols.

Therefore, during a rapid reaction in the presence of active boric acid, it is very important to ensure the supply of the required amount of oxygen to the oxidizing hydrocarbons.

In the production of synthetic fatty alcohols in oscillating columns, the supply of oxygen to paraffin molecules oxidized in the liquid phase is primarily determined by its diffusion rate. The amount of oxygen transferred by diffusion per

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unit reaction volume, **k**, is a function of the linear velocity of air in the column, **w**, and the average oxygen concentration in it, **c**:

$$k = f(w, s)$$

The average oxygen concentration in the gas phase depends on the height of the oxidizing product layer: the smaller the reactor, the higher this concentration becomes. Practical data show that variations in oxygen concentration depending on the size of the apparatus are not of major significance, since only 40–45% of oxygen is consumed during oxidation, and in some cases approximately 20%.

The linear velocity of air determines both the value of the oxygen transfer rate constant and the size of the interfacial contact area between the phases. Therefore, it is a decisive factor in creating optimal conditions for supplying oxygen to the oxidized paraffin molecules.

The relationship between the oxidation reaction rate and the air flow velocity in an oscillating column was demonstrated using paraffin oxidation as an example and was confirmed during the oxidation of soft paraffin to higher fatty alcohols (Table 4.1). In order to establish a rapidly proceeding liquid-phase oxidation process and scale it up to other production capacities, it is necessary to maintain the linear air velocity in oscillating columns at the level determined during the modeling process. The specific air consumption does not play a significant role [136, pp. 1056–1060].

Under laboratory conditions, when carrying out the liquid-phase oxidation process, the degree of air dispersion is of great importance, especially when comparing air supply through a simple tube and through a porous glass filter. However, in apparatuses where the height of the sparger zone is relatively small compared with the total volume, the degree of air dispersion plays only a minor role, since small bubbles coalesce into larger bubbles in the main volume of the oxidized mass.

Thus, during the liquid-phase oxidation of paraffin in the presence of active boric acid, it is necessary to ensure a sufficient supply of atmospheric oxygen in order to obtain high-quality higher fatty alcohols. This can be achieved by maintaining a linear air velocity of approximately 0.1 m/s in equipment of any size. With a significant increase in the linear air velocity, the ratio of the reaction products remains unchanged; however, the amount of exhaust gases leaving with the air increases sharply.

ISSN 3030-3907

Table 2.

Dependence of the oxidate characteristics on the linear air velocity during the oxidation of paraffinic hydrocarbons

Column / Scale	Loading, t	Linear air velocity, m/s	Specific air consumption, $m^3/(t \cdot h)$	Duration, h	Hydroxyl number, mg KOH/g		
					Hydroxyl number, mg KOH/g	Ester number, mg KOH/g	Carbonyl number, mg KOH/g
Industrial scale	30,2	0,095	59,0	8,5	68,6	56,5	4,9
Pilot scale	0,1	0,015	60,0	4,3	69,9	48,6	2,6
Pilot scale	0,1	0,094	382,0	8,3	69,2	54,6	4,1
Laboratory scale	$2 \cdot 10^{-4}$	0,093	60,0	0,0	23,1	35,2	1,0
Laboratory scale	$2 \cdot 10^{-4}$	0,094	1725,0	6,3	70,2	54,3	5,1

Increasing the oxygen content in air up to pure oxygen affects the reaction rate; however, it does not change the ratio of the components and does not affect the composition of the final products during the bubbling process. Improvement of oxygen diffusion conditions due to an increase in pressure does not significantly increase the degree of oxidation, although the solubility of atmospheric oxygen is almost proportional to pressure and may negatively affect product quality.

The most promising method for intensifying paraffin oxidation in the liquid phase is to create new and more favorable conditions for interaction with atmospheric oxygen by sharply increasing and continuously renewing the gas–liquid contact surface. This considerably increases the rate of oxygen absorption. For this purpose, foam-type apparatuses, hollow mixers, and similar devices can be used. In the foam regime, the nature of bubble motion is determined not by Archimedes' forces, as in conventional bubbling, but by the kinetic energy of the gas, which ensures instantaneous renewal of the bubbling surface. In practice, to create a foam regime, the gas velocity in the free cross-section of the apparatus should be within the range of 0.8–4.0 m/s. Despite the high gas velocity, foam apparatuses have low hydraulic resistance and a simple design; however, they require large operating volumes. The main factor determining the efficiency of an oxidation apparatus is its productivity per unit volume. Therefore, any increase in the volume of the foam apparatus compared with a conventional bubbling

ISSN 3030-3907

apparatus must be compensated by a corresponding increase in the overall rate of the oxidation reaction. Prolonged exposure of the oxidation products to high temperature and oxygen has a negative effect on their composition.

Thus, during oxidation, cleavage occurs at various positions of the LMPE molecules, resulting in a mixture of fatty acids containing different numbers of carbon atoms. The resulting mixture is then distilled through a column with a dephlegmator to separate it into narrow fractions. The initial fraction, based on its characteristics, resembles the acid obtained from coconut oil. The composition and properties of the first and second fractions are presented in Table 3.

Table 3.

Composition of the first fraction (C_{10}–C_{16})

Fractions	HFA content, wt %
C_{10} until	4,51–6,42
C_{10}–C_{11}	22,0–26,5
C_{12}–C_{13}	47,3–48,6
C_{14}–C_{16}	30,2–34,0
C_{16} above	17,6–21,5

The infrared (IR) spectrum of the higher fatty alcohols obtained by oxidation of low-molecular polyethylene (LMPE) was recorded using a Shimadzu IRAffinity-1S Fourier Transform Infrared (FTIR) spectrophotometer in the 300–4000 cm^{-1} range. The experiment was conducted under standard conditions: atmospheric pressure (762 mmHg), temperature of 25 °C, and relative humidity of 45%.

In the IR spectrum of the higher fatty alcohols obtained from oxidized LMPE:

- The absorption band at 1712.19 cm^{-1} corresponds to the C=O stretching of saturated aliphatic aldehydes.
- Absorption bands at 2848.86 cm^{-1}, 2914.44 cm^{-1}, and 2956.87 cm^{-1} are characteristic of C–H stretching vibrations in alkyl chains.
- The band at 1463.97 cm^{-1} corresponds to C–H bending vibrations.
- Bands at 1377.17 cm^{-1} and 1332.88 cm^{-1} are associated with the planar deformation vibrations of primary alcohol O–H bonds.
- Absorption bands at 1193.94 cm^{-1}, 1124.5 cm^{-1}, and 1074 cm^{-1} are characteristic of the O–H stretching vibrations of secondary alcohols.
- Bands at 719.45 cm^{-1} and 621.08 cm^{-1} indicate the presence of 14 and 12 $–CH_2$ groups, respectively.

This analysis confirms the presence of both primary and secondary hydroxyl groups in the synthesized higher fatty alcohols and provides detailed information about their molecular structure.

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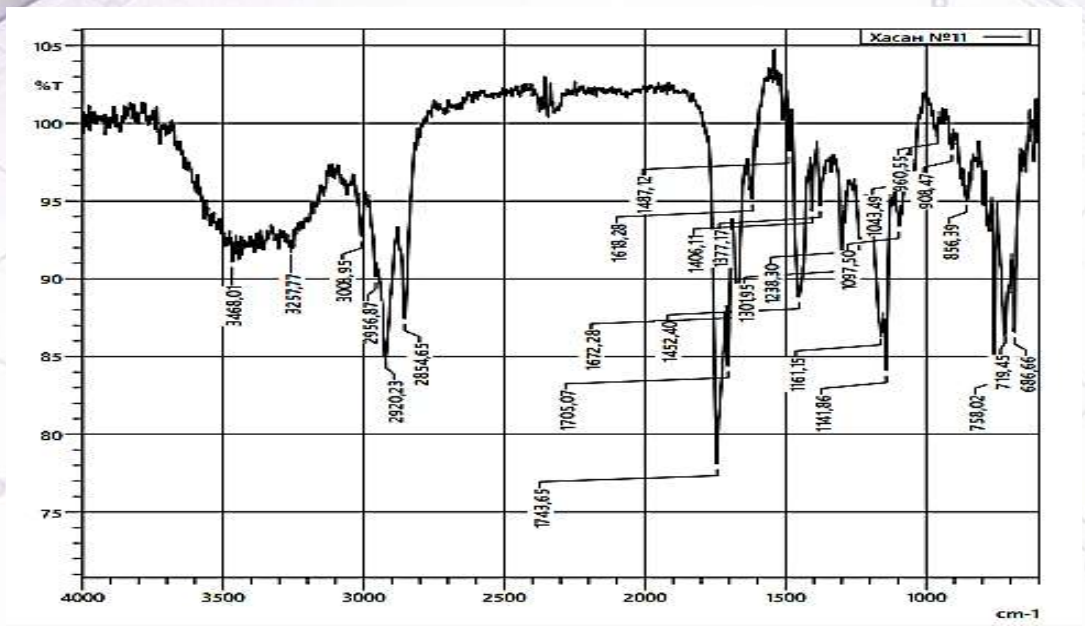


Figure 4. IR spectrum of higher fatty alcohols obtained by oxidation of low-molecular polyethylene (LMPE).

Higher fatty alcohols (extracts and ester oils) obtained from local secondary industrial raw materials via oxidation were analyzed using a gas chromatography–mass spectrometry (GC–MS) system Agilent 5975C inert MSD/7890A GC (Agilent Technologies) (Figure 6).

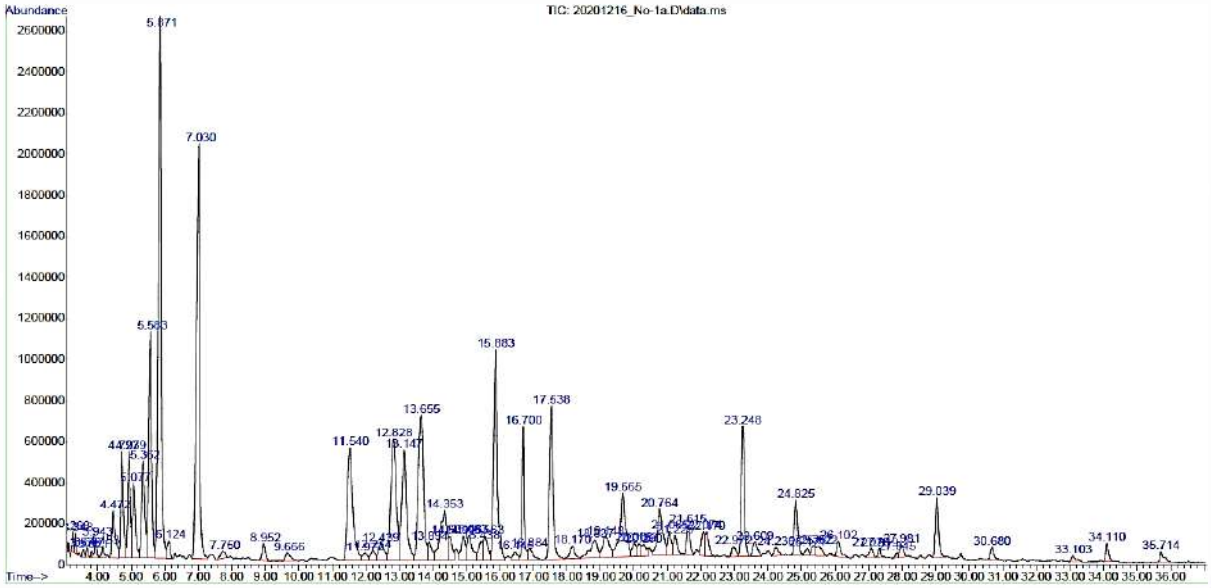


Figure 5. GC–MS analysis of higher fatty alcohols obtained by oxidation of low-molecular polyethylene (LMPE).

The analysis of the components present in the mixture was carried out using a quartz capillary column Agilent HP-INNOWax (30 m × 250 μm × 0.25 μm). The temperature program was set as follows: 60 °C (10 min), then increased at 4 °C/min to 220 °C (10 min), followed by heating at 1 °C/min to 240 °C (20 min).

ISSN 3030-3907

The injected sample volume was 0.2 mL (in hexane), while the flow rate of the mobile phase was 1.1 mL/min (H_2). The injector temperature was maintained at 250 °C.

The EI–MS spectra were recorded within the m/z range of 10–550 a.m.u. The identification of the components was performed by comparing the obtained mass spectra with data from the W9N11.L, W8N05ST.L, and NIST08 spectral libraries. The results of the chromatographic–mass spectrometric analysis are presented in Table 4.

Table 4.

Chromatographic–mass spectrometric analysis of compounds obtained from the oxidation of low-molecular-weight polyethylene.

№	Components	R_f, min	Content, %
1	n-Dodecane	**4,470**	**1,20**
2	Oxalic acid, hexyl L-menthyl ester	**4,725**	**2,00**
3	Oxalic acid, heptadecyl L-menthyl ester	**4,939**	**1,94**
4	1,4-Dimethyl-2-(2-methylpropyl)cyclohexane, (1alpha,2beta,5alpha)-	**5,075**	**1,70**
5	1-Ethyl-2,4-dimethylcyclohexane	**5,360**	**2,47**
6	(Z)-2-Dodecene	**5,585**	**4,87**
7	1,1,3-Trimethyl-3-(2-methylprop-2-enyl)cyclopentane	**5,870**	**11,49**
8	Hexylcyclohexane (1-cyclohexylhexane)	**7,028**	**10,20**
9	2-(Hydroxymethyl)-3-butyl-5-methylfuran	**11,539**	**4,50**
10	4-Butoxy-2,3-dicyanophenyl 4-butylcyclohexane-1-carboxylate	**12,827**	**4,81**
11	1,5-Diethyl-2,3-dimethylcyclohexane	**13,147**	**3,99**
12	Methyl 1-ethylcyclohexane-1-carboxylate	**13,658**	**5,79**
13	1,1,3-Trimethylcyclohexane	**14,352**	**2,60**
14	(E)-3-Tetradecene	**15,883**	**5,67**
15	2-Decanone (methyl octyl ketone)	**16,702**	**1,97**
16	Octylcyclohexane (1-cyclohexyloctane)	**17,539**	**4,24**
17	4-Butoxy-2,3-dicyanophenyl 4-hexylcyclohexane-1-carboxylate	**18,839**	**1,01**
18	Cyclotetradecane	**19,148**	**1,07**
19	1,2-Dodecanediol	**19,664**	**2,87**
20	2,3-Dicyano-4-(pentyloxy)phenyl 4-hexylcyclohexane-1-carboxylate	**20,762**	**1,86**
21	1-Propyltridecyl dichloroacetate	**23,249**	**2,96**

ISSN 3030-3907

22	Decylcyclohexane (1-cyclohexyldecane)	**24,828**	**1,48**
23	(E)-5-Octadecene	**29,036**	**1,35**

The chromatographic–mass spectrometric analysis of higher fatty alcohols obtained from the oxidation of low-molecular-weight polyethylene and paraffin is presented in Table 5. The results show that the yield of higher fatty alcoh,ols formed during the oxidation process was significant and efficient [25,26].

Since 2026, the requirements for producing Euro-5 grade diesel fuel at petroleum refineries have been strengthened. According to the GOST standards, the sulfur content in such fuels must not exceed 10 mg/kg, while the hydrocarbon composition must also comply with the established regulatory specifications. The use of this type of fuel provides several operational advantages. During engine operation, noise and vibration levels are reduced, engine starting becomes easier, and fuel consumption decreases. In addition, this fuel is designed to reduce the wear rate of engine components, thereby extending the service life of engine parts. Furthermore, Euro-5 diesel fuel is considered environmentally safer, as the lower concentrations of hydrocarbons and sulfur significantly reduce the emission of harmful combustion products into the atmosphere.

A lubricity-improving additive was synthesized based on higher fatty alcohols obtained by the oxidation of low-molecular-weight polyethylene. The effectiveness of this additive was evaluated in accordance with the ASTM D6079 standard. According to the results of the study, the addition of this additive at a concentration of 0.0163 wt.% to diesel fuel obtained by the compounding method at the Bukhara Oil Refinery reduced the wear scar diameter at 60 °C to a level not exceeding 460 μm, in compliance with the standard requirement. This indicates that the additive introduced at this concentration is sufficient to ensure the lubricity requirements established for Euro-5 diesel fuel.

Currently, the lubricity of diesel fuels worldwide is commonly evaluated using the HFRR (High Frequency Reciprocating Rig) method, which measures the high-frequency reciprocating motion of a ball against a stationary plate immersed in the fuel. The results obtained from this device are widely accepted as an international standard for assessing diesel fuel lubricity [29].

Table 5

Results of BNKIZ tests of lubricating additives for diesel fuels

Sample designation	Additive content, %	Lubricity by ASTM D6079, wear scar diameter at 60 °C, μm (should not exceed 460 μm according to the standard)

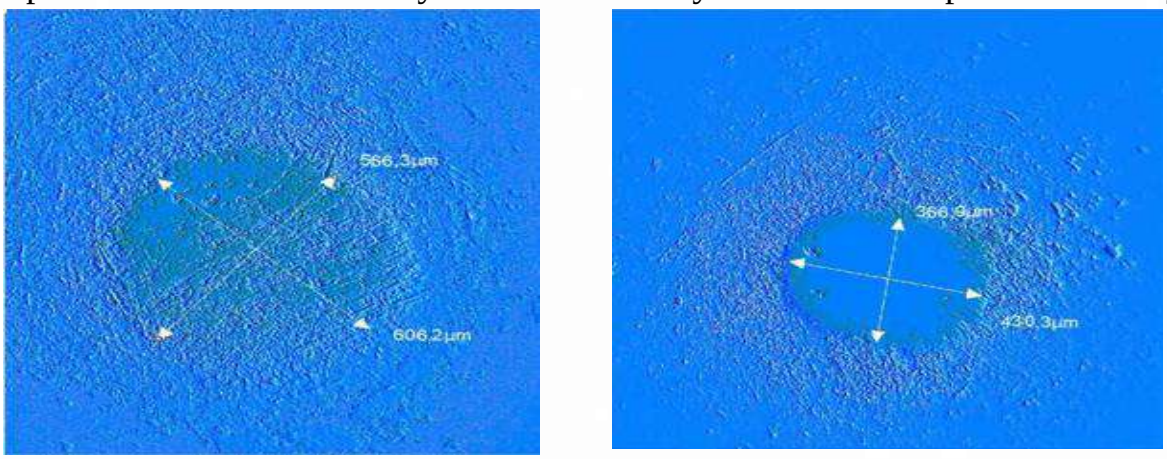
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Euro-5 diesel fuel without additive	-	520
Euro-5 diesel fuel with additive	0.0163	460

Research on the effect of the synthesized higher fatty alcohols on the lubricity properties of diesel fuel was continued. In this study, the optimal concentration of the additive was determined based on the lubricity requirements for Euro-5 diesel fuel according to the ASTM D6079 method. If the wear scar diameter exceeds 460 μm, the lubricating performance of the fuel is considered non-compliant with the standard requirements.

Currently, worldwide, the lubricity of diesel fuels is most often assessed using the HFRR method (High-Frequency Reciprocating Rig), in which a ball slides against a plate in the fuel at high frequency. The HFRR test is recognized by professionals as the standard method for evaluating the lubricating properties of diesel fuels [30].

Images of the wear scar diameter on the steel balls, obtained using a digital microscope (ToupCam model), are presented in Figure 5. The images compare samples with and without the synthesized lubricity additive developed in this study.



a) *b*)

Figure 6. Wear scar marks on the steel ball obtained in pure diesel fuel without additives (a) and in diesel fuel containing 0.0163 vol.% additive (b).

The physicochemical properties of diesel fuel containing 0.0163 wt.% of a lubricity additive synthesized from higher fatty alcohols (C_{12}–C_{17}) were comprehensively analyzed (Table 6).

Table 6.

Main characteristics of diesel fuel complying with Euro-5 requirements

Parameter	**Value**
Cetane number, not less than	51
For Class 1	49

ISSN 3030-3907

Cetane index, not less than	46
Density at 15 °C, kg/m³	820–845
Density at 15 °C for Class 1, kg/m³	800–845
Polycyclic aromatic hydrocarbons, wt.%, not more than	11
Sulfur content in fuel, mg/kg, not more than	10
Flash point (closed cup), °C, not lower than	55
Carbon residue on 10% distillation residue, wt.%, not more than	0.30
Ash content, wt.%, not more than	0.01
Water content, mg/kg, not more than	200
Total contamination, mg/kg, not more than	24
Copper strip corrosion (3 h at 50 °C), class	Class 1
Oxidation stability, g/m³, not more than	25
Lubricity: wear scar diameter at 60 °C, μm, not more than	**460**
Kinematic viscosity at 40 °C, mm²/s	2.0–4.5
Kinematic viscosity at 40 °C for Class 1, mm²/s	1.5–4.0

Thus, the synthetic higher fatty alcohols proposed in this study demonstrated superior lubricating performance compared with existing anti-wear additives, which makes it possible to obtain low-sulfur, environmentally friendly diesel fuels [31].

CONCLUSIONS.

In this study, a technology for obtaining lubricity-enhancing additives for diesel fuels based on locally available secondary raw materials was developed. Higher fatty alcohols (C_{12}–C_{17}) were synthesized through the oxidation of low-molecular-weight polyethylene (LMPE) and paraffinic hydrocarbons in the presence of boric acid at temperatures of 165–170 °C. Under the selected reaction conditions, the yield of the target products reached 35–40%, confirming the effectiveness of the proposed synthesis method.

Chromatographic–mass spectrometric (GC–MS) analysis demonstrated that the obtained products consist of a mixture of higher fatty alcohols and oxygen-containing compounds, confirming the successful oxidation of the initial hydrocarbons. The synthesized higher fatty alcohols were subsequently applied as lubricity additives for diesel fuel.

Experimental results showed that the addition of 0.0163 wt.% of the synthesized additive to diesel fuel significantly improved its lubricating properties. According to the ASTM D6079 method, the wear scar diameter at 60 °C decreased from 520 μm for untreated diesel fuel to approximately 400–460 μm after the addition of the additive, which fully satisfies the requirements of Euro-5 standards.

ISSN 3030-3907

The obtained results demonstrate that the synthesized additives based on higher fatty alcohols exhibit higher lubricity efficiency compared with several commercial anti-wear additives. In addition, the proposed technology utilizes local secondary raw materials, including industrial polymer waste, which contributes to resource efficiency, cost reduction, and environmental sustainability. Therefore, the developed lubricity-enhancing additive can be considered a promising alternative to imported commercial additives and may be successfully applied in domestic oil refineries for the production of environmentally friendly low-sulfur diesel fuels with improved operational and tribological properties.

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MODERN APPROACHES TO IMPROVING THE EFFICIENCY OF GAS PURIFICATION FROM ACIDIC COMPONENTS

Shaxnoza Akhmedova Utkirovna
Bukhara State Technical University
Ozoda Akhmedova Baxronovna
Tashkent State Technical University, Associate Professor,
Abdurasul Qayumov Shonazarovich
Tashkent State Technical University, Associate Professor

Abstract. The article presents scientific research on the preparation and application of compositions with the necessary concentration of activators and inhibitors in the absorbent to reduce the corrosion rate and enhance the complete absorption of acidic components from gases. The effectiveness of a new absorption composition containing diethylolamine (DEA), hexamine, and carbohydrazide in purifying gases from acidic components has been determined. According to the studies conducted, the activation of absorbents with activators allows for more complete absorption of acidic components from gases, reduces the formation of heat-resistant salts, thereby reducing the corrosion observed in devices and preventing excessive accumulation in the absorber.

Keywords: gas chromatography, composite absorbent, diethylamine (ДЭА), hexamine ($C_6H_{12}N_4$), carbohydrazide ($OC(N_2H_3)$), carbon dioxide (CO_2), hydrogen sulfide (H_2S), carbon sulfide (COS), carbon disulfide (CS_2), mercaptans (RSH), thiophenes (C_4H_4S).

Аннотация. В статье представлены научные исследования по приготовлению и применению композиций с необходимой концентрацией активаторов и ингибиторов в абсорбенте для снижения скорости коррозии и повышения полноты поглощения кислых компонентов из газов. Определена эффективность новой абсорбционной композиции, содержащей диэтилоламин (ДЭА), гексамин и карбогидразид, при очистке газов от кислых компонентов. Согласно проведенным исследованиям, активация абсорбентов активаторами позволяет добиться более полного поглощения кислых компонентов из газов, уменьшает образование термостойких солей, тем самым уменьшая коррозию, наблюдаемую в устройствах, и предотвращая чрезмерное накопление в абсорбере.

Ключевые слова: газовая хроматография, композитный абсорбент, диэтиламин (DЭА), гексамин (C6H12N4), карбогидразид (OC(N2H3)), диоксид углерода (CO2), сероводород (H2S), сульфид углерода (COS), сероуглерод (CS2), меркаптаны (RSH), тиофены (C4H4S).

Annotatsiya. Maqolada korroziya tezligini pasaytirish va gazlardan kislotali komponentlarning to‘liq so‘rilishini kuchaytirish uchun changni yutish

ISSN 3030-3907

vositasida aktivatorlar va ingibitorlarning kerakli konsentratsiyali kompozitsiyalarni tayyorlash va qo‘llash bo‘yicha ilmiy tadqiqotlar keltirilgan. Tarkibida dietilolamin (DEA), geksamin va karbogidrazid bo‘lgan yangi absorbsion kompozitsiyaning gazlarni kislotali komponentlardan tozalashdagi samaradorligi aniqlandi. O‘tkazilgan tadqiqotlarga ko‘ra, absorbentlarni aktivatorlar bilan faollashtirish gazlardan kislotali komponentlarni to‘liqroq singdirish imkonini beradi, issiqlikka chidamli tuzlarning hosil bo‘lishini kamaytiradi, shu bilan qurilmalarda kuzatiladigan korroziyani kamaytiradi va absorberda ortiqcha to‘planishning oldini oladi.

Kalit so‘zlar: gaz xromatografiyasi, kompozit absorbent, dietilamin (RSH), geksamin (C6H12N4), karbogidrazid (oC(N2H3)), karbonat angidrid (CO2), vodorod sulfidi (H2S), uglerod sulfidi (cos), uglerod disulfidi (CS2), merkaptanlar (RSH), tiofenlar (c4h4s).

1. INTRODUCTION.

At present, due to the rapid development of industry and manufacturing, it has become evident that the direct combustion of hydrocarbon gases is an inefficient use of resources. Modern trends in the oil and gas industry focus on the deep processing of gases to obtain valuable products, which in turn ensures the efficient utilization of raw materials considered highly economically advantageous and meets contemporary requirements [1].

Like any other raw material, hydrocarbon gases cannot be used directly — their application requires preliminary purification, processing, and separation into fractions using appropriate technologies [2–3].

Globally, during the purification of hydrocarbon gases from acidic components, alkanolamine-based absorbents play a leading role. Aqueous solutions of diethanolamine (DEA) of various concentrations are considered particularly effective and are widely used for the removal of acidic compounds, especially hydrogen sulfide, from gases. However, gas compositions also contain other acidic components such as carbon dioxide (CO_2), carbonyl sulfide (COS), carbon disulfide (CS_2), mercaptans (RSH), and thiophenes [4–5].

2. MATERIALS AND RESEARCH METHODS.

At present, in order to enhance the complete absorption of acidic components from gases, scientific research aimed at developing and applying compositions consisting of mixtures of activators, corrosion inhibitors, and antifoaming additives within absorbents is of great importance.

Activators added to alkanolamine absorbents include hexamine, piperazine, methanol, phenol, ethanolamine, arsenic acid, glycine, and substituted amines. Corrosion inhibitors that slow down the corrosion rate include carbohydrazide, glycols (MEG/TEG), methyldiethanolamine (MDEA), as well as mixtures of

ISSN 3030-3907

glycols (MEG/TEG) with tertiary amines. The introduction of these components into the absorbent further enhances its absorption capacity and stability, reduces concentration losses, and decreases corrosion rates and excessive foaming in the absorber [15].

The study began with an analysis of the composition of the raw gas supplied to the Shurtan Gas Chemical Complex. The composition of the feed gas was determined based on the average result of gas chromatographic analysis over one month. According to the obtained data, the CO_2 content was 3.36%, and H_2S — 0.093%. These indicators exceed the standard values established by the process regulations, which negatively affect the efficiency of amine absorption purification.

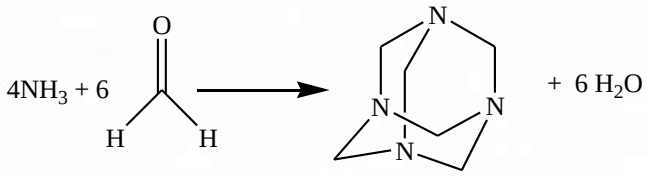
The gas purified at the Shurtan Gas Chemical Complex is subsequently directed as follows: the methane fraction of hydrocarbons is used as feedstock at the GTL (Gas-to-Liquid) plant to produce synthetic fuels, while the ethane fraction serves as raw material for polymer production within the complex itself. The purity of these gas compositions is of primary importance for their chemical and catalytic processing.

To improve the technical and economic performance of hydrocarbon gas purification processes from acidic components by reducing operating costs, a modified version of the absorption process using diethanolamine (DEA) was developed.

Accordingly, a composite absorbent was formulated based on industrially used diethanolamine (DEA) and activators such as hexamine and carbohydrazide.

Diethanolamine (DEA) — $NH(C_2H_2OH)_2$ — possesses the following physicochemical properties: it is a liquid ranging from colorless to yellowish in appearance, with a characteristic odor. It is well soluble in both water and fats. The hydrogen ion index (pH) is 11 at a concentration of 100 g/L in water at 20 °C. The density at 20 °C is 1.0959 g/cm³.

Hexamine (HMTA) — $C_6H_{12}N_4$ — is a white crystalline powder formed by the reaction of 4 moles of ammonia with 6 moles of formaldehyde [45; 48–62 pp.]. In terms of structural organization, the compound resembles adamantane, which gives it high thermal stability and chemical resistance.

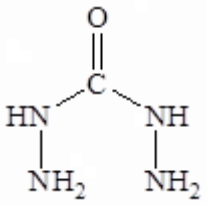


Based on toxicological assessments of hexamine exposure, it has been established that under various application methods, no long-term health risks have been identified, and the current level of exposure to the substance is considered

ISSN 3030-3907

safe. Hexamine functions as a corrosion inhibitor, preventing hydrogen-induced corrosion of equipment.

Carbohydrazide (hydrazine, 1,3-diaminourea; carbonyl dihydrazide) — molecular formula $CO(NHNH_2)_2$ — is a white crystalline powder with a purity of 98.0%. It is typically used as a 10% aqueous solution with a pH of 8.45. Carbohydrazide is highly soluble in water and alcohol and is applied as a corrosion inhibitor, particularly in systems where water and elevated temperatures are present.



An experimental setup was prepared, with its parameters adapted to industrial operating conditions. The process of gas absorption purification was carried out using various composite absorbents. Tests were conducted with seven samples, during which the purified gas and the saturated absorbent were collected in separate containers for subsequent analysis (Table 1) [16–18].

Table 1.

Composition of absorbent mixtures based on DEA, hexamine, and carbohydrazide for the purification of gases from acidic components

№	Name of absorbent	Water content in the composition, %	Concentration of components, %		
			DEA	Hexamine	Carbohydrazide
1	DEA, Sample 1 (for comparison)	70	30	-	-
2	Sample 2 with DEA	67,975	30	2	0,025
3	Sample 2 with DEA	65,975	30	4	0,025
4	Sample 2 with DEA	65,975	32	2	0,025
5	Sample 2 with DEA	63,975	32	4	0,025
6	Sample 2 with DEA	63,975	34	2	0,025
7	Sample 2 with DEA	61,975	34	4	0,025

ISSN 3030-3907

When preparing the above-mentioned absorbent composition, the selection of chemical reagents was primarily based on the local origin of raw materials, their degree of efficiency, as well as on the shortcomings observed in the existing technological scheme.

3. RESULTS AND ANALYSIS

To ensure the efficient performance of the diethanolamine (DEA) absorbent in the process of gas absorption purification, regular laboratory analyses are carried out. This is necessary because, under the influence of process parameters — such as pressure, temperature, environment, chemical reagents, and gas composition — chemical changes may occur in the absorbent, causing it to lose its functional properties.

Taking this into account, the following studies were conducted on DEA-based absorbent compositions used for the purification of natural gases from CO_2 and H_2S:

- determination of carbon dioxide (CO_2) content;
- determination of hydrogen sulfide (H_2S) mass in saturated and regenerated diethanolamine solutions by titration;
- determination of the amount of acid–thermally stable salts;
- determination of the foaming tendency of the absorbents;
- determination of concentration;
- determination of H_2S content in DEA;
- measurement of the pH value of DEA;
- determination of DEA turbidity;
- determination of DEA viscosity.

These analyses made it possible to evaluate the physicochemical stability of the absorbent, the efficiency of its performance, and the changes in its properties during operation and regeneration. The amount of carbon dioxide in the DEA composition samples was determined using an Orsat apparatus (INV 12147) in accordance with Enterprise Standard 39.2-36-201 / ASTM D-513.

Based on the obtained results, it can be concluded that an increase in diethanolamine concentration and the addition of an activator lead to a higher degree of carbon dioxide removal. However, a further increase in activator concentration does not have a significant effect on the amount of absorbed carbon dioxide. The composition containing 2% activator and 32% DEA concentration differed from the others in that during regeneration, minimal absorbent concentration losses were observed [19–21].

ISSN 3030-3907

Table 2.

Results of Determining the CO_2 Content in Saturated DEA Solutions in Various Units of Measurement

No	Samples	mg	wt.%	g/L	mole %	mole/ L	mole/mole DEA
	CO_2 Indicator According to Orsat		CO_2	CO_2	CO_2	CO_2	CO_2
1	DEA, Sample 1 (for comparison)	82,0	5,783	64,429	3,324	1,464	0,495
2	Sample 2 with DEA	83,0	5,848	64,429	3,342	1,482	0,499
3	Sample 2 with DEA	84,0	5,929	65,214	3,388	1,501	0,503
4	Sample 2 with DEA	91,0	6,418	70,592	3,392	1,625	0,505
5	Sample 2 with DEA	91,0	6,418	70,592	3,392	1,625	0,505
6	Sample 2 with DEA	91,4	6,446	70,900	3,399	1,642	0,498
7	Sample 2 with DEA	91,9	6,475	71,219	3,423	1,660	0,499

The main issue lies in the degree of CO_2 absorption by the absorbent, while the analysis of the absorption degree with the activator was compared and illustrated in the graph (Figure 1).

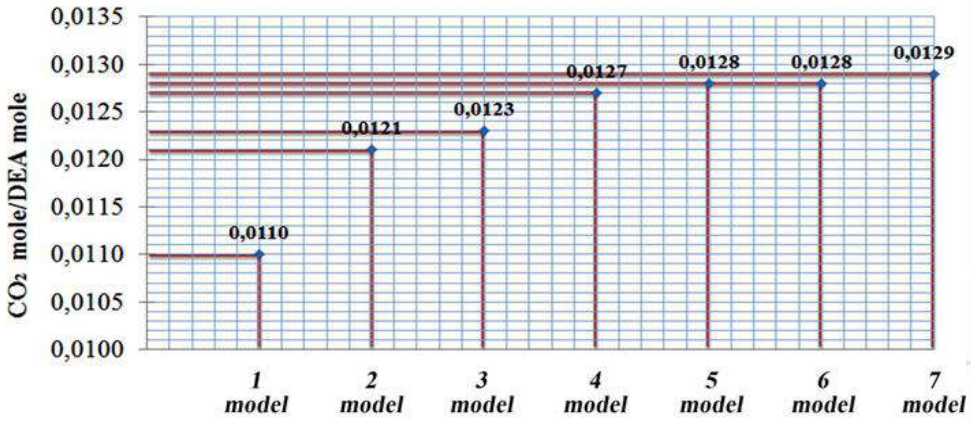


Figure 1. Degree of CO_2 Absorption by Saturated DEA Samples, CO_2 mole/mole DEA

Sample No. 1 represented the DEA solution used at the plant without the addition of any activators. According to the results obtained for Sample No. 1 and other composite samples, in compositions with an increased concentration of

ISSN 3030-3907

diethanolamine and the addition of an activator, the degree of carbon dioxide absorption increased.

Another characteristic feature of amines is the concentration of carbon dioxide remaining in the DEA composition after regeneration. In practice, a decrease in DEA concentration is observed with each regeneration cycle. To maintain the required concentration in the technological process, regular addition of fresh amine solution is provided. In composite absorbents containing an activator (Sample No. 4), such losses were significantly reduced.

The carbon dioxide content in the desorbed (regenerated) composite DEA samples was also determined and calculated by laboratory methods in various units, similar to the saturated amine solutions (Table 3).

Table 3.

Determination of Carbon Dioxide Content in Desorbed Composite DEA Samples in Various Units of Measurement

No.	Samples	mg	wt.%	g/L	mole %	mole/L	mole/mole DEA
	CO_2 Indicator According to Orsat		CO_2	CO_2	CO_2	CO_2	CO_2
1	DEA, Sample 1 (for comparison)	5,9	0,219	2,121	0,114	0,052	0,017
2	Sample 2 with DEA	5,8	0,214	2,161	0,117	0,051	0,016
3	Sample 2 with DEA	5,5	0,202	2,161	0,117	0,049	0,016
4	Sample 2 with DEA	5,3	0,194	2,157	0,113	0,047	0,014
5	Sample 2 with DEA	5,3	0,193	2,153	0,112	0,047	0,015
6	Sample 2 with DEA	5,3	0,193	2,153	0,112	0,047	0,014
7	Sample 2 with DEA	5,4	0,196	2,158	0,113	0,048	0,014

The amount of carbon dioxide in the desorbed DEA composition sample indicates that the absorbent has been regenerated.

Analyses showed that the carbon dioxide content in the regenerated absorbent samples was lower compared to the control sample. It was found that the added activator influences the rapid and efficient absorption and subsequent release of acidic components by the amine (Figure 2).

ISSN 3030-3907

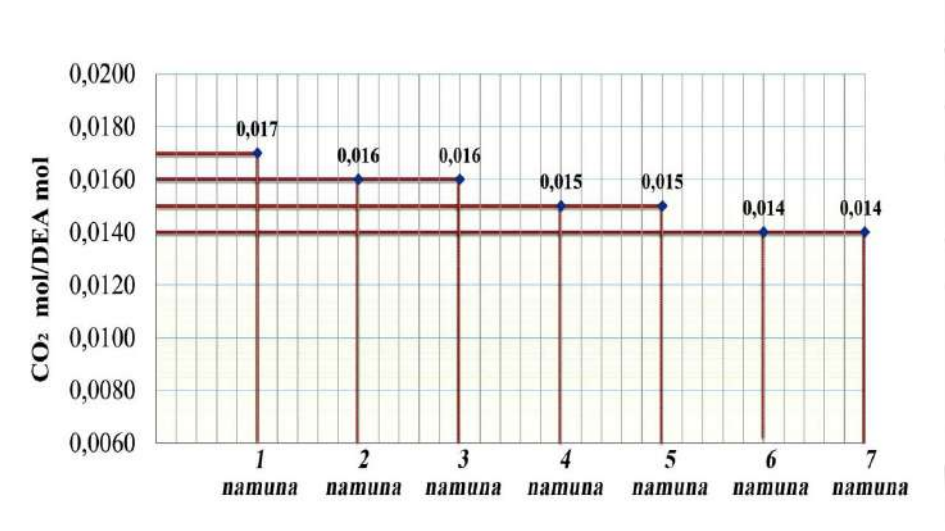


Figure 2. CO_2 Content in Regenerated DEA Composition Samples, CO_2 mole/mole DEA

The essence of the analysis lies in comparing the absorbent's capacity based on its hydrogen sulfide absorption performance. After repeated regeneration of the absorbent, analyses were conducted to determine the amount of hydrogen sulfide remaining in its composition.

The next key indicator is the determination of the hydrogen sulfide content. It can be observed that the absorption capacity of the absorbent compositions containing activators toward H_2S also increased. This is evident from the results obtained for Sample No. 4.

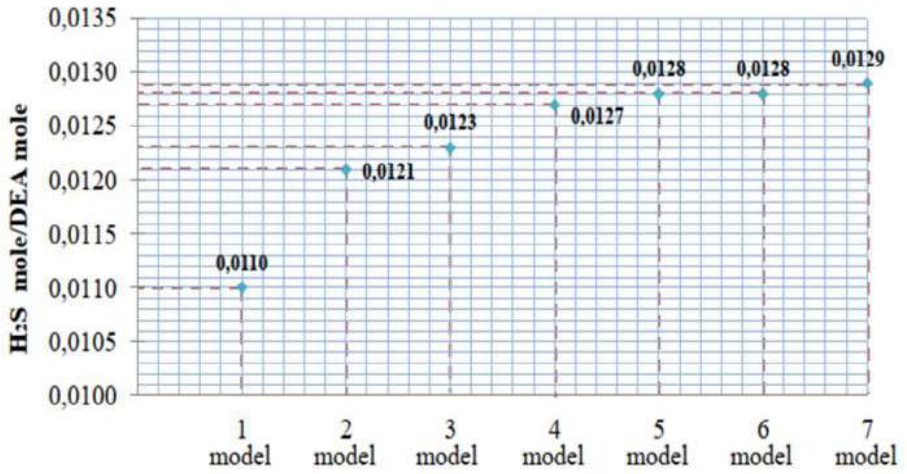


Figure 3. Amount of Absorbed H_2S by Saturated DEA Samples, H_2S mole/mole DEA

The determination of hydrogen sulfide content in the regenerated DEA samples was carried out using the above-mentioned method. However, during the analysis of regenerated DEA, the amine samples were diluted as follows: 10 ml of DEA was mixed with 40 ml of water, after which the resulting 50 ml solution was titrated (Table 5).

Table 5.

ISSN 3030-3907

Determination of H_2S Content in Desorbed (Regenerated) DEA Composition Samples in Various Quantities

No.	Samples	mg	wt.%	g/L	mole %	mole/L	mole/mole DEA
	H_2S titrator indicator		H_2S	H_2S	H_2S	H_2S	H_2S
1	DEA, Sample 1 (for comparison)	10,3	0,071	0,0074	0,0071	0,003	0,00062
2	Sample 2 with DEA	9,7	0,067	0,0070	0,0056	0,003	0,00059
3	Sample 2 with DEA	8,7	0,061	0,0062	0,0051	0,002	0,00053
4	Sample 2 with DEA	8,5	0,058	0,0061	0,0043	0,002	0,00052
5	Sample 2 with DEA	8,4	0,058	0,0060	0,0042	0,002	0,00051
6	Sample 2 with DEA	8,3	0,057	0,0059	0,0042	0,002	0,00050
7	Sample 2 with DEA	8,3	0,057	0,0059	0,042	0,002	0,00050

From the analyses determining the amount of hydrogen sulfide remaining in the absorbent after repeated regeneration, it can also be seen that the desorption process has improved (Figure 3.4).

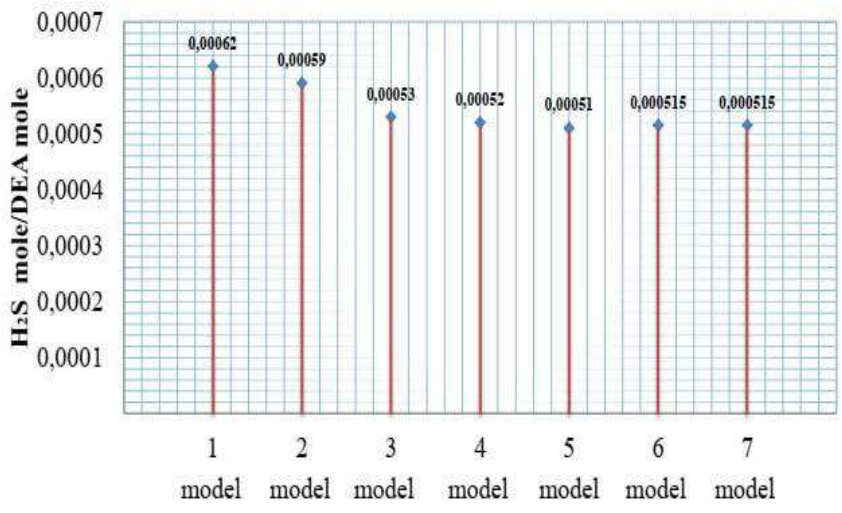


Figure 4. Amount of Residual H_2S in Regenerated DEA Samples, H_2S mol/mol DEA

The titrator readings and the obtained results also showed a decrease in the H_2S content in the DEA composition samples. This was particularly evident in Sample No. 3 and subsequent ones.

ISSN 3030-3907

Determination of Thermally Stable Salts in the Absorbents

Thermally stable salts are components formed during the absorption process as a result of the interaction between the absorbent and acidic components, which are not decomposed or removed during desorption (regeneration).

The study was carried out only for the desorbed DEA samples. The amount of thermally stable salts in the DEA samples was calculated using data on the sample density and the volume of alkali consumed for titration (Table 6) [22–23].

Table 6.

Content of Thermally Stable Salts in Regenerated DEA Samples

No.	Absorbent Samples	Sample Density, g/cm³	V, Volume of Alkali Used for Titration, mL	Content of Thermally Stable Salts in DEA Samples, wt.%
1	DEA, Sample 1 (for comparison)	1,055	5,9	0,1118
2	Sample 2 with DEA	1,062	5,8	0,1092
3	Sample 3 with DEA	1,068	5,5	0,1030
4	**Sample 4 with DEA**	**1,073**	**5,4**	**0,1006**
5	Sample 5 with DEA	1,075	5,4	0,1004
6	Sample 6 with DEA	1,077	5.3	0,0984
7	Sample 7 with DEA	1,079	5,4	0,0955

The content of thermally stable salts in the desorbed DEA samples decreased compared to the initial control sample. This is clearly illustrated in the following graph (Figure 5).

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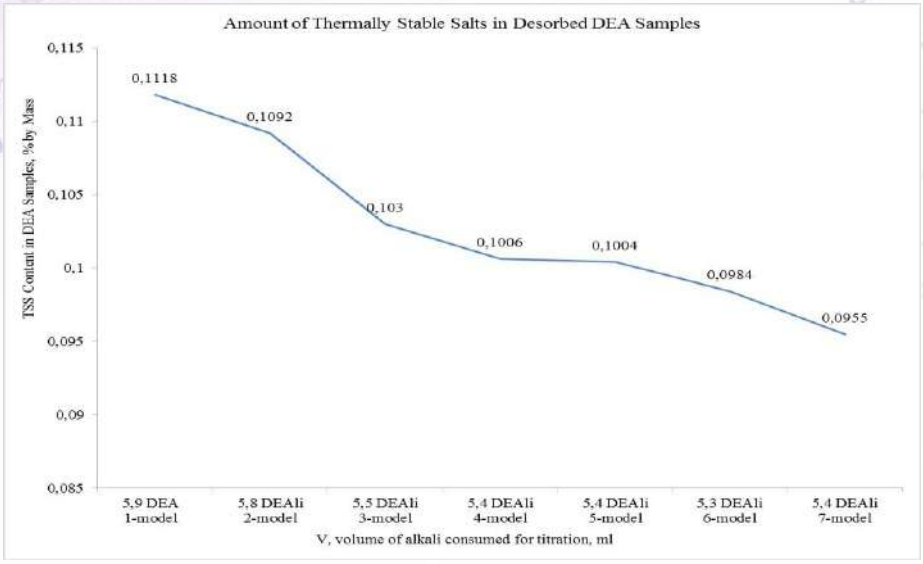


Figure 5. Content of Thermally Stable Salts in Regenerated DEA Samples

The results showed that the amount of thermally stable salts in the desorbed DEA samples decreased compared to the initial control sample.

With an increase in the amount of thermally stable salts, excessive foaming of DEA is observed, which leads to the entrainment of the absorbent into the gas stream and an increase in amine consumption. To prevent this, the foaming tendency of the amine solutions was measured in accordance with Enterprise Standard 39.2-22-2008.

Table 7.

Characteristics for Evaluating the Foaming Properties of the Absorbent

No.	Composition Samples	Foam Height, mm	Foaming Ability	Foam Collapse Time, s	Foam Stability
1	DEA, Sample 1 (for comparison)	52	Average	33	Average
2	Sample 2 with DEA	46	Average	19	Average
3	Sample 3 with DEA	45	Average	18	Average
4	**Sample 4 with DEA**	38	Average	13	Low
5	Sample 5 with DEA	39	Average	11	Low
6	Sample 6 with DEA	39	Average	14	Low

ISSN 3030-3907

7	Sample 7 with DEA	31	Average	15	Average

The foaming characteristics of the absorbent were determined for the regenerated absorbent. It was found that the additives introduced into the DEA did not have any significant negative effect on this property.

The concentrations of the composite DEA samples after the absorption process were determined through analysis. The concentration (%) was measured by the titrimetric method in accordance with the "Huntsman Gas Treating Team, Field Test Method" [112; pp. 96–98].

Based on the obtained results, the concentrations of the saturated and desorbed DEA samples were determined (Table 8).

Table 8

Concentrations of Saturated and Desorbed DEA Samples

No.	Absorbent Samples	Measured Mass of Absorbent	Volume of 0.5 N HCl Solution Used for Titration	**Concentration of Saturated DEA Samples**	Measured Mass of Absorbent	Volume of 0.5 N HCl Solution Used for Titration	**Concentration of Desorbed DEA Samples**
1	DEA, Sample 1 (for comparison)	1,020	5,23	27,19	1,018	5,63	29,32
2	Sample 2 with DEA	1,021	5,39	27,99	1,013	5,65	29,57
3	Sample 3 with DEA	1,015	5,35	27,98	1,009	5,63	29,58
4	**Sample 4 with DEA**	**1,014**	**5,91**	**30,90**	**1,023**	**6,17**	**31,98**
5	Sample 5 with DEA	1,017	5,75	29,98	1,011	6,09	31,94
6	Sample 6 with DEA	1,019	5,98	31,12	1,025	6,55	33,88
7	Sample 7 with DEA	1,022	6,35	32,94	1,006	6,41	33,78

The concentration analysis of the composite DEA samples made it possible to compare, using graphs, the losses of saturated and desorbed diethanolamine samples (Figure 6).

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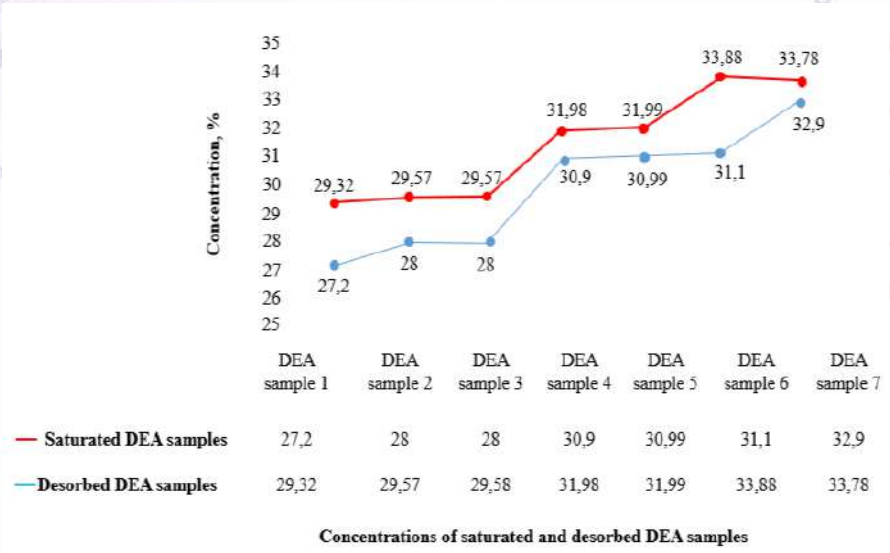


Figure 6. Change in the Concentration of Saturated and Desorbed DEA Samples

The effect of activators on reducing absorbent concentration was studied. According to the results, increasing the activator concentration does not have a significant effect on absorbent losses. Sample No. 4, with the addition of 2% activator, showed that its concentration was almost equal to the initial DEA concentration (32%).

Such parameters of the diethanolamine samples as color, turbidity, viscosity, and content of mechanical impurities were also studied.

Table 9.

Indicators of Saturated and Regenerated DEA Samples: Color, Turbidity, pH, and Mechanical Impurity Content

No.	Name	Blurriness, color	Turbidity, mg/L	pH value	Mechanical Impurities, mg/L
Saturated DEA Samples					
1	DEA, Sample 1 (for comparison)	Прозрачно-зелёный	0,69	9,7	0,84
2	Sample 2 with DEA	Прозрачно-зелёный	0,69	10,1	0,76
3	Sample 3 with DEA	Прозрачно-зелёный	0,67	10,2	0,72
4	**Sample 4 with DEA**	Прозрачно-зелёный	0,65	10,1	0,63
5	Sample 5 with DEA	Прозрачно-зелёный	0,65	10,2	0,62

ISSN 3030-3907

6	Sample 6 with DEA	Прозрачно-зелёный	0,64	10,1	0,62
7	Sample 7 with DEA	Прозрачно-зелёный	0,64	10,2	0,61
Regenerated DEA Samples					
1	DEA, Sample 1 (for comparison)	Transparent green	0,56	11,0	0,70
2	Sample 2 with DEA	Transparent green	0,54	11,1	0,56
3	Sample 3 with DEA	Transparent green	0,53	11,2	0,55
4	**Sample 4 with DEA**	Transparent green	0,54	11,1	0,47
5	Sample 5 with DEA	Transparent green	0,54	11,2	0,46
6	Sample 6 with DEA	Transparent green	0,54	11,1	0,46
7	Sample 7 with DEA	Transparent green	0,54	11,2	0,45

It was found that the additives introduced into the DEA did not have a negative effect on these properties.

The conducted studies showed that activation of absorbents with activators promotes more complete absorption of acidic components from gases, reduces the formation of thermally stable salts, which in turn decreases equipment corrosion and prevents excessive foaming in the absorber. In addition, experiments demonstrated that even with a decrease in absorbent concentration in the technological process, losses were reduced due to the use of activators.

The absorption process was carried out using a composite absorbent consisting of a mixture of diethanolamine (32%), hexamine (2%), and carbohydrazide (0.025%). The gas mixture purified during absorption with this composite absorbent—recognized as the most effective—was analyzed by gas chromatography (Figure 10).

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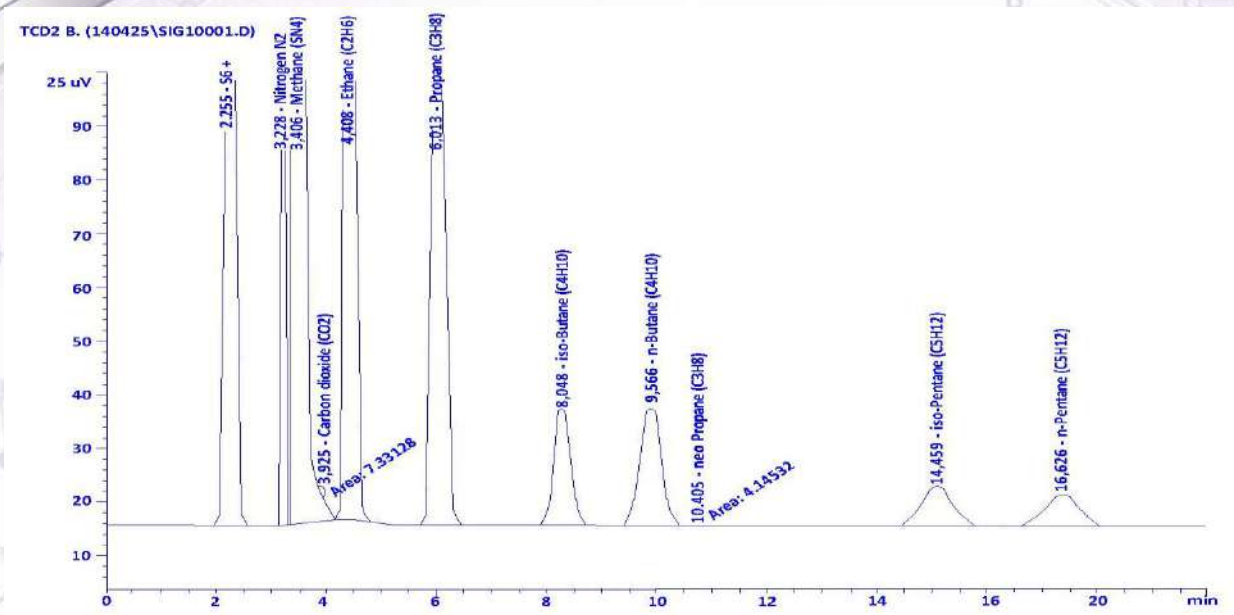


Figure 7. Gas Chromatographic Spectrum of the Gas Composition Purified Using the Composite Absorbent

As a result of the study of the purified gas mixture by gas chromatography, it was found that the methane content was up to 92.483%, ethane — up to 4.297%, propane — up to 1.151%, a mixture of n-butane and iso-butane — up to 0.501%, a mixture of n-pentane, iso-pentane, and neo-pentane — up to 0.137%, and hydrocarbons heavier than hexane — up to 0.493%. The analysis showed that the content of the acidic component, carbon dioxide (CO_2), was up to 0.0057%. The amount of hydrogen sulfide (H_2S) was so low that it could not be detected by the gas chromatograph.

During the natural gas purification process using amine treatment, the analysis results after absorption with the standard absorbent — diethanolamine (DEA) used at the plant — and the composite absorbent were compared (Table 10).

Table 10.

Comparative Analysis of Gas Chromatographic Results of Natural Gas Samples

No.	Substance Name	Concentration of Untreated Gas, mole %	Concentration of Gas Purified at the Plant, mole %	Concentration of Gas Purified with Sample No. 4, mole %
1	Methane (CH_4)	89,83	92,548140	92,483560
2	Ethane (C_2H_6)	4,08	4,258207	4,297052
3	Propane (C_3H_8)	0,93	1,057069	1,151073
4	n-Butane (C_4H_{10})	0.24	0,272238	0,257529

ISSN 3030-3907

5	iso-Butane (C_4H_{10})	0.22	0,236912	0,244604
6	n-Pentane (C_5H_{12})	0,13	0,130925	0,010134
7	iso-Pentane (C_5H_{12})		0,127161	0,127495
8	C_6+	0,31	0,512006	0,492785
9	**Carbon dioxide CO_2**	**3,36**	**0,010134**	**0,005739**
10	Hydrogen sulfide **H_2S**	**0,093**	-	-
11	Nitrogen N_2	0,757	0,847208	0,836577
	Total:	**100,0000**	**100,0000**	**100,0000**

The research results showed that the use of absorbent compositions in the absorption process reduces equipment corrosion rates and lowers the energy consumption required for amine regeneration.

In conclusion, the industrial-scale tests demonstrated positive results for Sample No. 4. It was found that the amount of acidic components decreased by half compared to the absorbent used at the plant.

The content of very low amounts of sulfur compounds in the purified gas was determined by spectrophotometric methods. However, due to the extremely low concentration of hydrogen sulfide (H_2S) in the purified gas mixture, quantitative determination was challenging. Nevertheless, trace amounts of H_2S (in ppm) were measured according to GOST 22387.2–2021 using a specialized "Lambda 20" spectrometer under laboratory conditions.

Table 11.

Results of the Analysis of Very Low Levels of Sulfur Compounds in Purified Gas

Description	Formula Symbol	Unit of Measurement	Indicator
Mass of mercaptan sulfur in the analyzed volume of absorbent solution, determined from calibration results	m	mkg	15,5
Volume of gas measured by the gas meter for the test	V	dm^3	6

ISSN 3030-3907

Correction factor for converting the volume of the analyzed gas to standard measurement conditions (temperature 20 °C, pressure 101.325 kPa)	K	-	0,92
Conversion factor from micrograms to grams	100	-	100
Concentration of all sulfur-containing compounds in the gas (H_2S, R-SH, COS)	**X**	**g/m^3**	**0,0028**

The analysis results showed that the sulfur compound content in the purified gas, according to the spectrophotometric method, is 0.0028 g/m^3 [119]. A comparison of this value with the gas purified using the plant's standard absorbent (0.0057 g/m^3 of sulfur compounds) showed that the amount was reduced by half. The use of such an absorbent composition ensures the absence of undesirable chemical reactions in subsequent stages of hydrocarbon gas processing in technological units.

4. CONCLUSIONS.

The introduction of a new composite absorbent through a pump into the existing process is important, as it does not require significant modifications to the technology. The use of an absorbent with the new composition allows the achievement of the following positive effects in the system:

1. The amount of thermally stable salts formed as a result of irreversible reactions between the absorbent and acidic gases is reduced.

2. The introduction of an activator increases the rate and degree of carbon dioxide absorption.

3. The addition of an inhibitor and the reduction in the formation of thermally stable salts decrease the corrosion rate of equipment.

4. The reduction of corrosion products, decreased formation of thermally stable salts, and the use of activators prevent excessive foaming of the absorbent in the absorber.

5. During previous cases of excessive foaming, alkanolamine was observed to enter the purified gas. Improved process performance prevents the absorbent from entering the gas stream, thereby reducing diethanolamine losses.

6. Under the influence of activators, the surface tension of the solution is reduced, allowing the absorbent to capture only acidic gases. When the absorbent enters the expander, the amount of released gas is minimized.

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DETERMINATION OF THE PRESSURE GRADIENT ALONG THE WELLBORE IN GAS–LIQUID WELLS

Nazarov Azizbek Ulugbekovich
General Director of GRDC LLC, Tashkent, Republic of Uzbekistan
E-mail: azizbek.nazarov@saneq.com.

Sunnatov Muxiddin Saloxiddinovich
Doctor of Philosophy (PhD) in Geological and Mineralogical Sciences, Senior Researcher, Deputy Chairman of the Management Board – Head of the Department of Geology and Field Development, O'ZLITINEFTGAZ JSC; ORCID: 0009-0009-1594-215X
E-mail: m.sunnatov@liting.uz.

Shin Aleksey
Senior Researcher, Department of Gas-Dynamic and Gas-Condensate Studies and Oil and Gas Production Enhancement
E-mail: a.shin@liting.uz.

Ozoda Akhmedova Baxronovna
Islam Karimov Tashkent State Technical University
E-mail: zodamedova@gmail.com

Abstract. Accurate determination of bottomhole pressure is a critical task in the analysis and optimization of gas and gas-condensate well performance. In wells operating under liquid loading conditions, conventional methods based on wellhead or annular pressure often fail to provide sufficient accuracy due to the complex nature of multiphase flow and the impact of liquid accumulation in the wellbore. This leads to distortions in well testing interpretation and reduces the efficiency of engineering decisions. This study proposes a statistical approach to estimating bottomhole pressure in gas–liquid wells using multiple linear regression analysis. The model is developed based on field data obtained from gas hydrodynamic well testing, including downhole pressure measurements acquired with electronic gauges. Key operational and physical parameters were considered, such as gas flow rate, condensate-to-gas ratio, water-to-gas ratio, fluid density, tubing length and geometry, as well as temperature conditions. As a result, a regression equation was derived that allows accurate prediction of bottomhole pressure. Comparison with conventional methods showed that the average error is reduced by more than two times. The high coefficient of determination ($R^2 = 0.96$) confirms the adequacy and statistical significance of the model. It is demonstrated that liquid accumulation and operating conditions significantly affect the pressure gradient distribution along the wellbore. The proposed approach can be effectively applied in reservoir engineering practice and integrated into digital field development management systems.

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Keywords: bottomhole pressure, gas–liquid well, pressure gradient, liquid loading, multiple linear regression, gas-condensate wells, well testing, multiphase flow, tubing, reservoir engineering.

Annotatsiya. Quduq tubidagi bosimni aniq aniqlash gaz va gaz-kondensat quduqlari ish faoliyatini tahlil qilish va optimallashtirishda muhim vazifadir. Suyuq yuklanish sharoitida ishlaydigan quduqlarda quduq boshi yoki halqali bosimga asoslangan an'anaviy usullar ko‘pincha ko‘p fazali oqimning murakkab tabiati va quduq tubida suyuqlik to‘planishining ta'siri tufayli etarli darajada aniqlikni ta'minlay olmaydi. Bu quduqlarni sinovdan o‘tkazishni talqin qilishda buzilishlarga olib keladi va muhandislik qarorlari samaradorligini pasaytiradi. Ushbu tadqiqotda ko‘p chiziqli regressiya tahlilidan foydalangan holda gaz-suyuqlik quduqlaridagi tubdagi bosimni baholash uchun statistik yondashuv taklif etiladi. Model gaz gidravlik quduqlarini sinovdan o‘tkazish natijasida olingan dala ma'lumotlari, jumladan, elektron o‘lchagichlar yordamida olingan quduqdagi bosim o‘lchovlari asosida ishlab chiqilgan. Gaz oqimining tezligi, kondensat-gaz nisbati, suv-gaz nisbati, suyuqlik zichligi, quvur uzunligi va geometriyasi, shuningdek harorat sharoitlari kabi asosiy operatsion va fizik parametrlar ko‘rib chiqildi. Natijada, quduq tubidagi bosimni aniq bashorat qilish imkonini beruvchi regressiya tenglamasi ishlab chiqildi. An'anaviy usullar bilan taqqoslash shuni ko‘rsatdiki, o‘rtacha xato ikki martadan ko‘proq kamayadi. Aniqlanishning yuqori koeffitsienti ($R^2 = 0,96$) modelning adekvatligi va statistik ahamiyatini tasdiqlaydi. Suyuqlikning to‘planishi va ish sharoitlari quduq bo‘ylab bosim gradientining taqsimlanishiga sezilarli ta'sir ko‘rsatishi ko‘rsatilgan. Taklif etilgan yondashuvni suv omborlarini loyihalash amaliyotida samarali qo‘llash va konlarni rivojlantirishni boshqarishning raqamli tizimlariga integratsiya qilish mumkin.

Kalit so‘zlar: quduq tubidagi bosim, gaz-suyuqlik qudug‘i, bosim gradienti, suyuqlik yuklanishi, ko‘p chiziqli regressiya, gaz-kondensat quduqlari, quduqlarni sinovdan o‘tkazish, ko‘p fazali oqim, quvurlar, rezervuar muhandisligi.

Аннотация. Точное определение забойного давления является важнейшей задачей при анализе и оптимизации работы газовых и газоконденсатных скважин. В скважинах, работающих в условиях загрузки жидкостью, традиционные методы, основанные на измерении устьевого или кольцевого давления, часто не обеспечивают достаточной точности из-за сложной природы многофазного потока и влияния накопления жидкости в стволе скважины. Это приводит к искажениям при интерпретации результатов испытаний скважин и снижает эффективность инженерных решений. В

ISSN 3030-3907

данном исследовании предлагается статистический подход к оценке забойного давления в газожидкостных скважинах с использованием множественного линейного регрессионного анализа. Модель разработана на основе полевых данных, полученных в результате газогидродинамических испытаний скважин, включая измерения забойного давления, полученные с помощью электронных датчиков. Были рассмотрены ключевые эксплуатационные и физические параметры, такие как расход газа, соотношение конденсата и газа, соотношение воды и газа, плотность жидкости, длина и геометрия трубопровода, а также температурные условия. В результате было получено уравнение регрессии, позволяющее точно прогнозировать забойное давление в скважине. Сравнение с традиционными методами показало, что средняя ошибка уменьшается более чем в два раза. Высокий коэффициент детерминации (R2 = 0,96) подтверждает адекватность и статистическую значимость модели. Показано, что накопление жидкости и условия эксплуатации существенно влияют на распределение градиента давления вдоль ствола скважины. Предложенный подход может быть эффективно применен в практике разработки месторождений и интегрирован в цифровые системы управления разработкой месторождений.

Ключевые слова: забойное давление, газожидкостная скважина, градиент давления, загрузка жидкостью, множественная линейная регрессия, газоконденсатные скважины, испытания скважин, многофазный поток, насосно–компрессорные трубы, разработка месторождений.

INTRODUCTION.

Determination of bottomhole pressure is one of the key tasks in the analysis and control of gas and gas-condensate well operating conditions. In routine well operation, annular pressure is widely used to calculate bottomhole pressure. However, as demonstrated by Korotaev Yu.P. [1], when the tubing shoe is submerged in liquid, the surface annular pressure does not provide the accuracy required for determining bottomhole pressure either while the well is flowing through the production tubing or after the well has been shut in.

A number of methods are currently available for determining bottomhole pressure in wells operating with liquid entrainment, including methods based on the wellhead pressure measured in the tubing [1,2,4–6]. However, under the conditions encountered in gas–liquid wells in Uzbekistan's fields, these methods often yield substantially different results, thereby reducing the reliability of gas-well test calculations.

ISSN 3030-3907

Improving the accuracy of pressure determination along the wellbore is of considerable practical importance. Errors in pressure estimation distort well productivity characteristics, lead to incorrect selection of operating conditions, and reduce the efficiency of gas gathering and treatment systems [3]. Accordingly, the development of more accurate methods for calculating bottomhole pressure with due consideration of the specific features of gas–liquid flow is an important and timely task.

In recent years, methods of mathematical statistics have been increasingly applied in the oil and gas industry because they make it possible to account for the combined effects of various factors on well-performance parameters [7–9]. The use of such methods offers opportunities for developing empirical models suitable for integration into digital field-development management systems and for automating well-condition monitoring.

The pressure gradient in the wellbore of gas–liquid wells is affected by a complex set of factors, including gas production rate, gas and liquid densities, condensate–gas and water–gas ratios, production-tubing length, the wellbore temperature profile, the distance from the tubing shoe to the perforated interval, the thickness of the completed interval, and the gas velocity at the tubing shoe [1,2,5,6].

In the present study, methods of mathematical statistics were used to determine the pressure gradient in the production-tubing string of wells operating with liquid entrainment (water and condensate). The study was based on the results of gas-dynamic well tests involving downhole pressure measurements performed with electronic pressure gauges.

RESEARCH METHODOLOGY AND RESULTS.

To determine the pressure gradient and bottomhole pressure in the wellbore of gas–liquid wells, methods of mathematical statistics based on multiple regression analysis were applied.

The source database comprised the results of gas-dynamic well tests obtained from downhole pressure measurements using electronic pressure gauges. The analysis included data from wells operating with liquid entrainment (water and condensate) at a water–gas ratio (WGR) of at least 1 cm^3/m^3.

Based on the analysis of experimental data and the application of linear regression, an empirical correlation was derived for determining bottomhole pressure while accounting for the principal geological, engineering, and operating parameters of the well. The proposed approach improves the accuracy of pressure calculations under gas–liquid-flow conditions and may be used to analyze and optimize well operating modes.

Table 1 presents the data obtained from these investigations. At the first stage, the source data were systematized and preprocessed.

ISSN 3030-3907

The following variables, which characterize well operating conditions and fluid properties, were considered as independent variables: gas production rate (Q_g); condensate–gas ratio (CGR); water–gas ratio (WGR); water density (ρ_w); gas relative density ($\bar{\rho}_g$); ratio of static pressure to wellhead pressure (P_{st}/P_{wh}); average wellbore temperature (T_{avg}); production-tubing length (L_{tub}); distance from the tubing shoe to the uppermost perforation (h_{tub}); gas velocity at the tubing shoe ($V_{tub,shoe}$); length of the perforated interval (l); and bottomhole pressure (P_{bh}), which was taken as the dependent variable.

To improve the reliability of the results, the original dataset was filtered. Data with extreme parameter values—specifically, WGR ≥ 200 cm³/m³ and CGR ≥ 500 cm³/m³—were excluded from the analysis. This ensured greater homogeneity of the statistical sample and improved model stability.

The data were processed using multiple linear regression, which made it possible to establish a quantitative relationship between bottomhole pressure and the combined set of governing factors.

As a result, the following empirical equation was obtained for determining bottomhole pressure:

$$P_{bh} = -113.131 + 0.000785Q_g - 0.06496\text{CGR} - 0.014501\text{WGR} - 0.81683\rho_w - 1.55137(P_{st}/P_{wh}) + 284.3685\bar{\rho}_g + 0.151057T_{avg} - 0.01402L_{tub} - 0.07703h_{tub} - 14.2639V_{tub,shoe} + 0.002707l. \quad (1)$$

The resulting correlation accounts for both the technological parameters of well operation and the physicochemical properties of the fluids, thereby providing a more accurate description of two-phase (gas–liquid) flow conditions in the wellbore.

Analysis of the coefficients in Equation (1) shows that bottomhole pressure is most strongly affected by the gas relative density, the ratio of static pressure to wellhead pressure, and the gas velocity at the tubing shoe. The water–gas and condensate–gas ratios, which characterize the liquid-phase content of the flow, also exert a substantial influence.

To evaluate the applicability of the developed model, the calculated bottomhole-pressure values were compared with those obtained using existing methods. The comparative analysis showed that the proposed correlation provides closer agreement with actual measurements, particularly when the flow contains a substantial liquid phase.

RESULTS AND DISCUSSION.

A comparison of bottomhole-pressure calculations obtained using the developed model and the conventional method [2] is presented in Figure 1.

ISSN 3030-3907

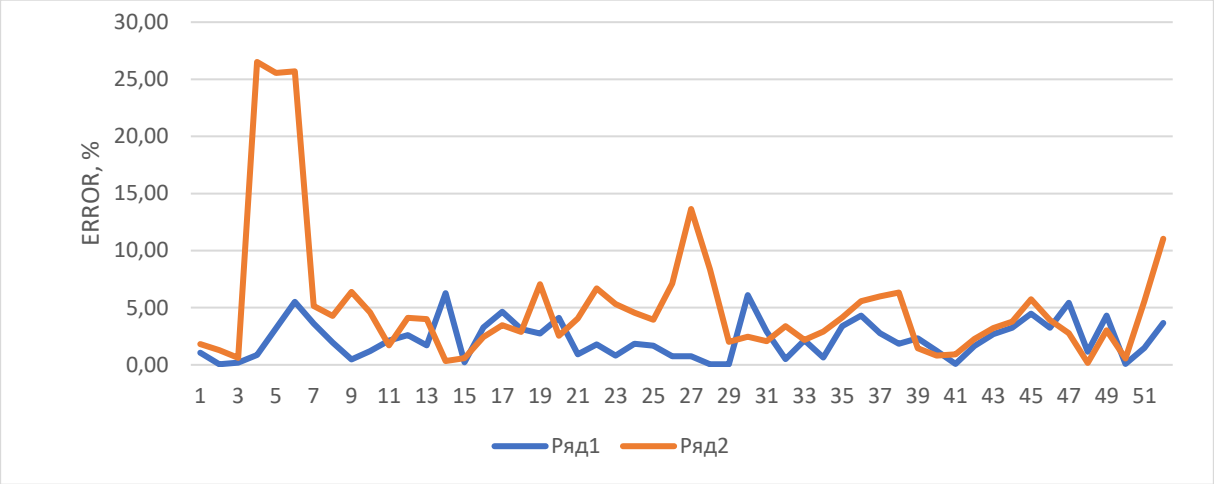


Fig. 1 - Comparison of bottomhole pressures calculated using the linear regression model and the method described in [2]

Error determined for the calculation performed using linear regression

Error determined for the calculation performed according to the procedure described in [2].

To assess the calculation accuracy, the root-mean-square deviation was calculated in accordance with [9,10] using the following equation, with the mean value replaced by the measured value:

$$"S"" = "\sqrt{\frac{\sum_{i=1}^{n}("P"_{meas}" - ""P"_{calc})^2}{"n-1"}}$$

where n is the number of measurements.

The results are presented in Table 2.

Table 1.

Initial data for the calculation and results of the calculation of the pressure in the wellbore operated with gas-liquid flows

Field, well	$P_{bh,meas}$,	Q_g, m³/d	CGR,	WGR,	ρ_w,	P_{st}/P_{wh}	Relative gas	T_{avg}, K	L_{tub}	h_{tub},	$V_{sh,tub}$,	l	$P_{bh,calc}$, regression,	Error, %	$P_{bh,calc}$,	Error, %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
West Kukcha 2	78.44	38207	20.10	0.00	0.00	1.10	0.6177	338.6	2072.29	9.85	2.22	41	79.28	-1.06	79.87	1.82
	77.55	51894	18.50	4.16	1.005	1.14	0.6177	339.6	2072.29	9.85	3.05	41	77.59	-0.06	78.55	1.29

ISSN 3030-3907

	76.67	58065	16.53	4.41	1.005	1.17	0.6177	340.1	2072.29	9.85	3.46	41	76.82	-0.20	77.13	0.60
Kalandar 1	81.04	28689	14.08	0.00	0.00	2.09	0.6196	334.1	2076.15	2.85	1.57	51	80.35	0.85	59.55	26.52
	75.08	34973	94.36	51.47	1.025	2.25	0.6196	335.1	2076.15	2.85	2.07	51	72.67	3.20	55.89	25.56
	67.57	38510	51.93	75.31	1.025	2.53	0.6196	335.6	2076.15	2.85	2.56	51	71.30	-5.52	50.21	25.69
Chandyr 19	86.62	69121	5.90	3.12	1.003	1.06	0.6152	339.4	2063.15	14.85	3.59	57	83.49	3.61	91.08	5.15
	86.17	101109	5.54	3.96	1.003	1.12	0.6152	340.4	2063.15	14.85	5.28	57	84.49	1.96	89.86	4.28
	85.32	133582	3.53	3.83	1.003	1.18	0.6152	341.9	2063.15	14.85	7.06	57	84.91	0.48	90.77	6.39
Chandyr 3	86.73	76342	3.51	3.96	1.035	1.21	0.6184	340.9	2080.25	2.75	3.95	40	85.68	1.21	90.71	4.59
	80.76	72397	5.69	12.18	1.035	1.39	0.6184	341.9	2080.25	2.75	3.95	40	82.48	-2.12	79.38	1.71
	80.9	98244	2.36	6.08	1.035	1.36	0.6184	342.9	2080.25	2.75	5.36	40	83.01	-2.60	84.23	4.12
	88.42	91310	5.78	6.31	1.035	1.22	0.6184	340.9	2080.25	2.75	4.68	40	86.91	1.71	91.95	3.99
Alat 1	101.11	44524	5.39	4.31	1.02	1.11	0.6498	345.14	2177.8	28.9	2.00	77.6	94.76	6.28	101.46	0.35
	94.93	66877	8.97	7.18	1.02	1.22	0.6498	345.64	2177.8	28.9	3.22	77.6	94.72	0.23	94.37	0.59

Continuation of Table 1.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

ISSN 3030-3907

Alat	88.71	82768	9.28	5.80	1.02	1.36	0.6498	346.14	2177.8	28.9	4.30	77.6	91.61	-3.26	86.54	2.45
	84.58	95935	8.76	6.25	1.02	1.49	0.6498	346.64	2177.8	28.9	5.23	77.6	88.52	-4.66	81.64	3.48
	89.41	82966	9.26	5.79	1.02	1.36	0.6498	346.64	2177.8	28.9	4.27	77.6	92.22	-3.14	86.82	2.90
Xisha, 1104	63.19	35631	2.02	9.43	1.007	1.18	0.6299	292.5	2395.9	29.8	2.68	36.5	61.45	2.75	58.73	7.06
	64.54	17398	1.38	9.66	1.007	1.08	0.6299	291.5	2395.9	29.8	1.28	36.5	67.19	-4.11	62.89	2.56
	63.72	26819	1.79	9.84	1.007	1.12	0.6299	292	2395.9	29.8	2.00	36.5	64.31	-0.92	61.13	4.06
	62.95	33968	2.12	9.89	1.007	1.18	0.6299	292.5	2395.9	29.8	2.57	36.5	61.81	1.80	58.74	6.69
	63.81	26243	1.37	7.32	1.007	1.13	0.6299	291	2395.9	29.8	1.96	36.5	64.33	-0.81	60.41	5.33
Xisha, 1102	72.31	39511	1.09	18.83	1.006	1.10	0.6299	359.9	2395.9	61.1	2.61	63	73.64	-1.85	69.01	4.56
	72.67	37497	3.52	9.92	1.006	1.09	0.6299	360.1	2395.9	61.1	2.47	63	73.90	-1.69	69.8	3.95

ISSN 3030-3907

	72.03	4948 0	3.88	13.58	1.0066	1.16	0.6299	359.8	2395.9	61.1	3.29	63	71.48	0.76	66.9	7.12
	71.5	5084 6	2.83	27.85	1.0066	1.27	0.6299	359.5	2395.9	61.1	3.41	63	70.95	0.76	61.74	13.65
	71.66	4634 0	4.66	16.06	1.0066	1.17	0.6299	359.6	2395.9	61.1	3.10	63	71.70	-0.06	65.67	8.36
Xiji, 1	68.37	4758 0	7.57	10.09	1.0188	1.14	0.62	350.45	2362.3	18.7	3.35	54	68.40	-0.05	66.99	2.02
	70.55	1921 7	6.24	5.93	1.0188	1.08	0.62	347.45	2362.3	18.7	1.31	54	74.87	-6.12	68.81	2.47
	70.48	3269 2	7.34	8.81	1.0188	1.09	0.62	348.95	2362.3	18.7	2.23	54	72.53	-2.90	69.02	2.07
	69.52	4333 2	8.31	13.29	1.0188	1.13	0.62	348.95	2362.3	18.7	2.99	54	69.87	-0.50	67.16	3.39
	68.76	5406 7	7.99	12.43	1.0188	1.17	0.62	350.45	2362.3	18.7	3.78	54	67.28	2.15	67.25	2.20
	69.13	4374 3	8.78	13.72	1.0188	1.14	0.62	349.45	2362.3	18.7	3.04	54	69.58	-0.65	67.12	2.91
Xisha, 1	57.76	2891 5	1.66	1.66	1.005	1.32	0.6284	336.42	2326.9	125.3	2.40	31	59.72	-3.39	55.37	4.14

ISSN 3030-3907

	57.3	33264	5.80	1.44	1.005	0.00	0.6284	338.42	2326.9	125.3	2.78	31	59.77	-4.31	54.11	5.57

Table 1 (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Xisha, 1	57.2	38134	7.84	15.03	1.005	1.30	0.6284	337.42	2326.9	125.3	3.19	31	55.62	2.77	53.77	6.00
	57.39	30134	7.17	3.98	1.005	1.30	0.6284	334.42	2326.9	125.3	2.51	31	58.44	-1.83	53.76	6.33
Chandyr, 5	74.5	71385	4.15	5.04	1.002	1.09	0.6157	339.255	2109	-18	4.36	32	76.23	-2.32	75.59	1.46
	74.36	81496	3.78	5.20	1.002	1.12	0.6157	339.755	2109	-18	4.99	32	75.27	-1.23	74.97	0.82
	73.98	89731	4.10	5.35	1.002	1.15	0.6157	338.755	2109	-18	5.52	32	73.91	0.09	74.66	0.92
Xisha, 1103	77.61	27436	2.62	7.00	1.01	1.23	0.63511	342.7	2416.8	57.2	1.65	40	76.32	1.66	75.84	2.28
	77.17	45116	4.26	15.96	1.01	1.27	0.63511	344.7	2416.8	57.2	2.73	40	75.09	2.70	74.68	3.23
	74.92	60869	3.94	19.71	1.01	1.34	0.63511	346.7	2416.8	57.2	3.79	40	72.48	3.26	72.09	3.78
	72.32	70257	4.10	22.20	1.01	1.46	0.63511	347.2	2416.8	57.2	4.54	40	69.08	4.48	68.16	5.75

ISSN 3030-3907

	73.5	58309	4.12	22.64	1.01	1.37	0.6351	346.7	2416.8	57.2	3.75	40	71.12	3.24	70.61	3.93
Chandyr, 12	100.17	86470	9.01	3.40	1.003	1.06	0.6099	342.84	2080.25	-23.25	3.86	75	94.71	5.45	102.95	2.78
	99.77	128289	6.56	3.83	1.003	1.11	0.6099	343.84	2080.25	-23.25	5.75	75	100.91	-1.14	99.94	0.17
	99	151832	9.58	5.86	1.003	1.18	0.6099	343.84	2080.25	-23.25	6.86	75	103.26	-4.30	96.01	3.02
Chandyr, 17	76.76	62616	6.64	2.68	1.002	1.04	0.6163	335.4	2063.19	10.81	3.70	63	76.83	-0.09	76.33	0.56
	77.01	89472	5.36	8.99	1.002	1.11	0.6163	337.1	2063.19	10.81	5.26	63	75.87	1.48	72.71	5.58
	76.56	112759	4.26	11.62	1.002	1.22	0.6163	335.7	2063.19	10.81	6.68	63	73.75	3.67	68.1	11.05

Table 2

Error in Bottomhole Pressure Determination

Metric	According to Method [1]	Regression Model
Minimum, %	0.17	0.05
Maximum, %	26.52	6.28
Mean, %	5.14	2.26
RMSD, %	5.78	2.27

Additional statistics: $R^2 = 0.96$; $F_{calc} = 84.30$; $F_{tab} = 2.04$

The analysis demonstrates that the regression model reduces the mean error by more than a factor of two and the root-mean-square deviation (RMSD) by a factor of 2.6. Furthermore, the number of cases with an error exceeding 5% is significantly reduced.

ISSN 3030-3907

Under certain well operating conditions, deviations are observed due to liquid accumulation. For Well No. 1 at the Alat field (Fig. 2), a liquid column was identified above the downhole gauge.

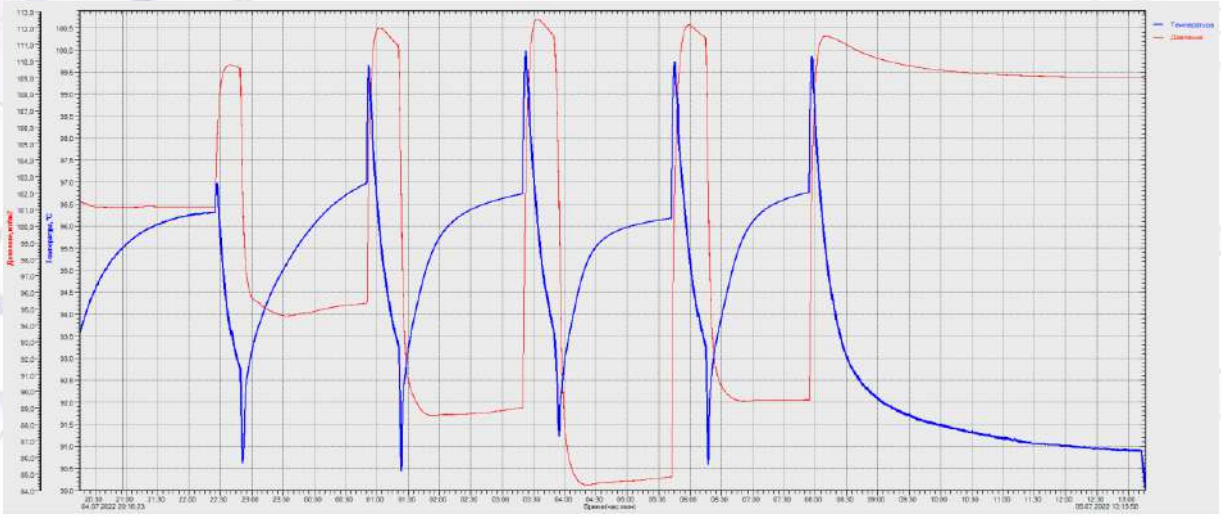


Fig. 2. Variation in downhole pressure-gauge readings at a depth of 2,245.48 m in the Alat-1 well (6 mm, 8 mm, 10 mm, 12 mm, 10 mm, and pressure buildup test)

It was established that an insufficient gas flow rate results in incomplete liquid removal, thereby affecting calculation accuracy. Additional analysis [11,12,13] (Fig. 3) confirms the influence of hydrodynamic conditions.

When the ratio of the calculated pressure gradient to the pressure gradient attributable to the weight of the gas column ranges from 1.01 to 1.09, the error is 5.45–6.12%.

Thus, the developed calculation equation provides higher accuracy in determining bottomhole pressure under gas–liquid flow conditions and can be used to optimize well operating modes and support the digitalization of field-development processes.

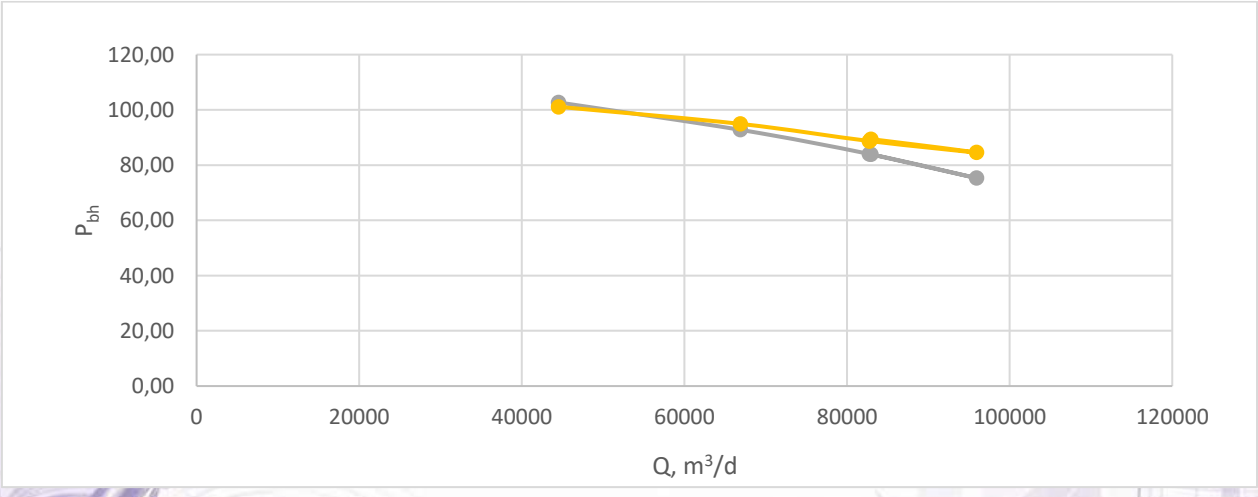


Fig. 3. Well indicator diagram; *yellow line*—indicator curve, *gray line*—characteristic curve

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Scientific novelty: The following new scientific findings were obtained in this study:

– a regression-based calculation equation was developed for determining bottomhole pressure in gas–liquid wells, accounting for the combined effects of the technological and physicochemical parameters of well operation;

– quantitative relationships were established for the effects of the water–gas ratio, condensate–gas ratio, and tubing-string parameters on the pressure gradient under two-phase flow conditions;

– the feasibility of applying mathematical statistics to improve the accuracy of bottomhole-pressure calculations for wells operating with liquid carryover was substantiated;

– the conditions associated with increased calculation error were identified, specifically liquid accumulation in the wellbore and an insufficient liquid-lifting velocity;

– it was demonstrated that the proposed calculation equation substantially reduces the error in bottomhole-pressure determination compared with standard methods.

CONCLUSIONS: It was established that the use of standard methods for calculating bottomhole pressure under gas–liquid flow conditions results in substantial errors, particularly when the liquid-phase content is significant.

A calculation equation based on multiple linear regression was developed for determining bottomhole pressure. The equation accounts for the principal well-operating parameters, including gas flow rate, water–gas ratio, condensate–gas ratio, and tubing-string characteristics.

The proposed calculation equation was shown to provide higher accuracy than the conventional method: the mean error was reduced by more than a factor of two, while the root-mean-square deviation was reduced by a factor of 2.6.

The relative gas density, the ratio of static pressure to wellhead pressure, and the gas velocity at the tubing shoe were found to have the greatest effect on the accuracy of bottomhole-pressure determination.

The increase in calculation error is associated with liquid accumulation in the wellbore at an insufficient gas-flow velocity, as confirmed by the results of downhole measurements.

The statistical significance of the developed calculation equation is confirmed by the high coefficient of determination ($R^2 = 0.96$) and by the calculated Fisher criterion exceeding its tabulated value.

The proposed calculation equation can be used to interpret gas-hydrodynamic well-test data, optimize well operating modes, and develop digital systems for monitoring and managing gas and gas-condensate field development.

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ANGREN KO‘MIRINI ORTOFOSFAT KISLOTA YORDAMIDA KIMYOVIY FAOLLASHTIRISH NATIJASIDA STRUKTURAVIY O‘ZGARISHLARNI SKANERLOVCHI ELEKTRON MIKROSKOPIYA ASOSIDA TAHLILI

Aslanova Feruza Ilxomovna
Qo‘qon DU III bosqich tayanch doktoranti
Boymatov Ismoiljon Mamatkulovich
Qo‘qon DU Kimyo va ekologiya kafedrasi dotsenti
E-mail: ism8585@mail.ru

Annotatsiya Mazkur ishda Angren ko‘mirini ortofosfat kislota (H_3PO_4) yordamida kimyoviy faollashtirish natijasida yuz beradigan strukturaviy va kimyoviy o‘zgarishlar skanerlovchi elektron mikroskopiya (SEM) va energiya-dispersiv rentgen spektroskopiya (EDS) usullari yordamida o‘rganildi. 5 %, 10 % va 15 % li eritmalarda faollashtirilgan namunalar qiyosiy tahlili natijasida mineral qo‘shimchalarning kamayishi, uglerod miqdorining ortishi hamda kislorod tutuvchi funksional guruhlarning hosil bo‘lishi aniqlandi. SEM natijalari g‘ovaklikning rivojlanishi va mikrostrukturaviy transformatsiyalarni ko‘rsatdi. Tadqiqot natijalariga ko‘ra, 10 % li H_3PO_4 eritmasi optimal faollashtirish sharoiti sifatida belgilandi.

Kalit so‘zlar: angren ko‘miri, kimyoviy faollashtirish, ortofosfat kislota, adsorbent, skanerlovchi elektron mikroskopiya, SEM, EDS tahlil, g‘ovaklik, mikrostrukturaviy o‘zgarishlar, funksional guruhlar, sorbsiya xossalari, oqova suvlarni tozalash.

Annotation. In this work, structural and chemical changes caused by chemical activation of Angren coal using orthophosphatic acid (H_3PO_4) were studied using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) methods. A comparative analysis of samples activated in 5%, 10%, and 15% solutions revealed a decrease in mineral additives, an increase in carbon content, and the formation of oxygen-containing functional groups. The SEM results showed the development of porosity and microstructural transformations. According to the study results, a 10% H_3PO_4 solution was determined as the optimal activation condition.

Keywords. angrenium, chemical activation, orthophosphatic acid, adsorbent, scanning electron microscopy, SEM, eds analysis, porosity, microstructural changes, functional groups, sorption properties, wastewater treatment.

Аннотация. В данной работе структурные и химические изменения, возникающие в результате химической активации Ангренового угля с помощью ортофосфатной кислоты (НКРОК), изучались с помощью

методов сканирующей электронной микроскопии (SEM) и энергодисперсионной рентгеновской спектроскопии (EDS). Сравнительный анализ образцов, активированных в растворах 5%, 10% и 15%, показал уменьшение содержания минеральных добавок, увеличение содержания углерода и образование кислородсодержащих функциональных групп. Результаты СЭМ показали развитие пористости и микроструктурные преобразования. На основании результатов исследования оптимальным условием активации был определен 10%-ный раствор H_3PO_4.

Ключевые слова. Ангреновый уголь, химическая активация, ортофосфатная кислота, адсорбент, сканирующая электронная микроскопия, SEM, EDS анализ, пористость, микроструктурные изменения, функциональные группы, сорбционные свойства, очистка сточных вод.

KIRISH.

Adssorbentlarni faollashtirish natijasida uning tarkibidagi qo‘shimchalar chiqarib yuborilishi natijasida uning sorbsiya xossalari ortishiga olib keladi. Ko‘mirlarni kislotali (H_3PO_4) muxitda faollash natijasida uning tarkibidagi mineral moddalar chiqarib yuborilishi bilan bir-qatorda unda qo‘shimcha organik (COH, va COOH) funksional gurux xosil bo‘lib, ko‘mirning sirt yuzadagi faolligi ham bir necha bor ortishiga olib keladi. Shu usulda faollab olingan ko‘mir adsorbentlar yordamida oqova suvlar tozalanganda, ular oqova suv tarkibidagi qutbli va qutbsiz birikmalardan bir vaqtda tozalash imkonini beradi.

Shu maqsadda Angren ko‘mirini ortofosfat kislota bilan faollashning maqbul sharoitlarini aniqlash uchun uning elektron mikroskopdagi natijalari taxlil qilindi. Hozirgi vaqtda skanerlovchi elektron mikroskopiya materialshunoslik va materiallarni tadqiqot qilishda ilg‘or va zamonaviy qurilma hisoblanadi.

MATERIAL VA METODLAR Namunalarni SEM tahliliga tayyorlash bosqichi alohida e’tibor bilan amalga oshirildi. Ma’lumki, ko‘mir asosli materiallar dielektrik xususiyatga ega bo‘lib, elektron nur ta’sirida ularning yuzasida elektrostatik zaryadlanish hodisasi yuzaga kelishi mumkin. Bu esa tasvir sifatining pasayishiga, signal shovqinining ortishiga va mikrostrukturaviy elementlarning noto‘g‘ri talqin qilinishiga olib keladi. Shu sababli namuna yuzasining elektr zaryadlanishini minimallashtirish hamda ikkilamchi elektronlar signalining barqarorligini ta’minlash maqsadida namunalar tok o‘tkazuvchi uglerodli yopishqoq lenta ustiga joylashtirildi.

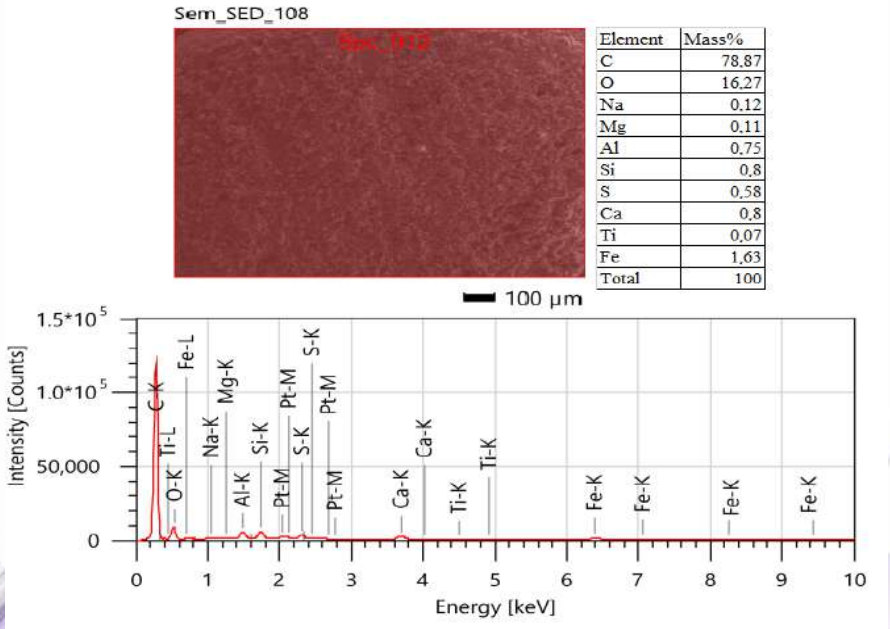
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Mikrostrukturaviy tadqiqotlar JSM-6610LV skanerlovchi elektron mikroskopida amalga oshirildi. Ushbu qurilma yuqori aniqlikdagi tasvir olish imkonini berib, namunalarning sirt morfologiyasi, g‘ovak tuzilmasi, mikro va mezog‘ovaklarning shakllanish darajasi hamda faollashtirish jarayonida yuz bergan destrukturatsiya yoki rekristallanish elementlarini aniqlashga xizmat qildi.

Olingan SEM tasvirlari asosida ortofosfat kislotaning konsentratsiyasi ortishi bilan ko‘mir sirtida g‘ovaklikning rivojlanishi, strukturaning bo‘shashuvi va yangi reaktiv markazlarning hosil bo‘lish jarayonlari qiyosiy tahlil qilindi. Shu tariqa, faollashtirish darajasi va sirt morfologiyasi o‘rtasidagi o‘zaro bog‘liqlik aniqlanib, Angren ko‘mirini kimyoviy faollashtirishning maqbul konsentratsion sharoitlarini belgilash uchun ilmiy asos yaratildi.

NATIJA VA MUHOKAMALAR. Angren ko‘mirining namunalarini ortofosfat kislota yordamida kimyoviy faollashtirish uchun (faollashtirilmagan) namuna hamda 5 %, 10 % va 15 % li kislota eritmalarida ishlov berilgan namunalar kompleks ravishda tadqiq qilindi. Tadqiqot jarayonida namunalar tarkibidagi strukturaviy o‘zgarishlar, g‘ovaklik darajasi, sirt morfologiyasi va disperslik xususiyatlari skanerlovchi elektron mikroskopiya (SEM) usuli yordamida batafsil o‘rganildi.

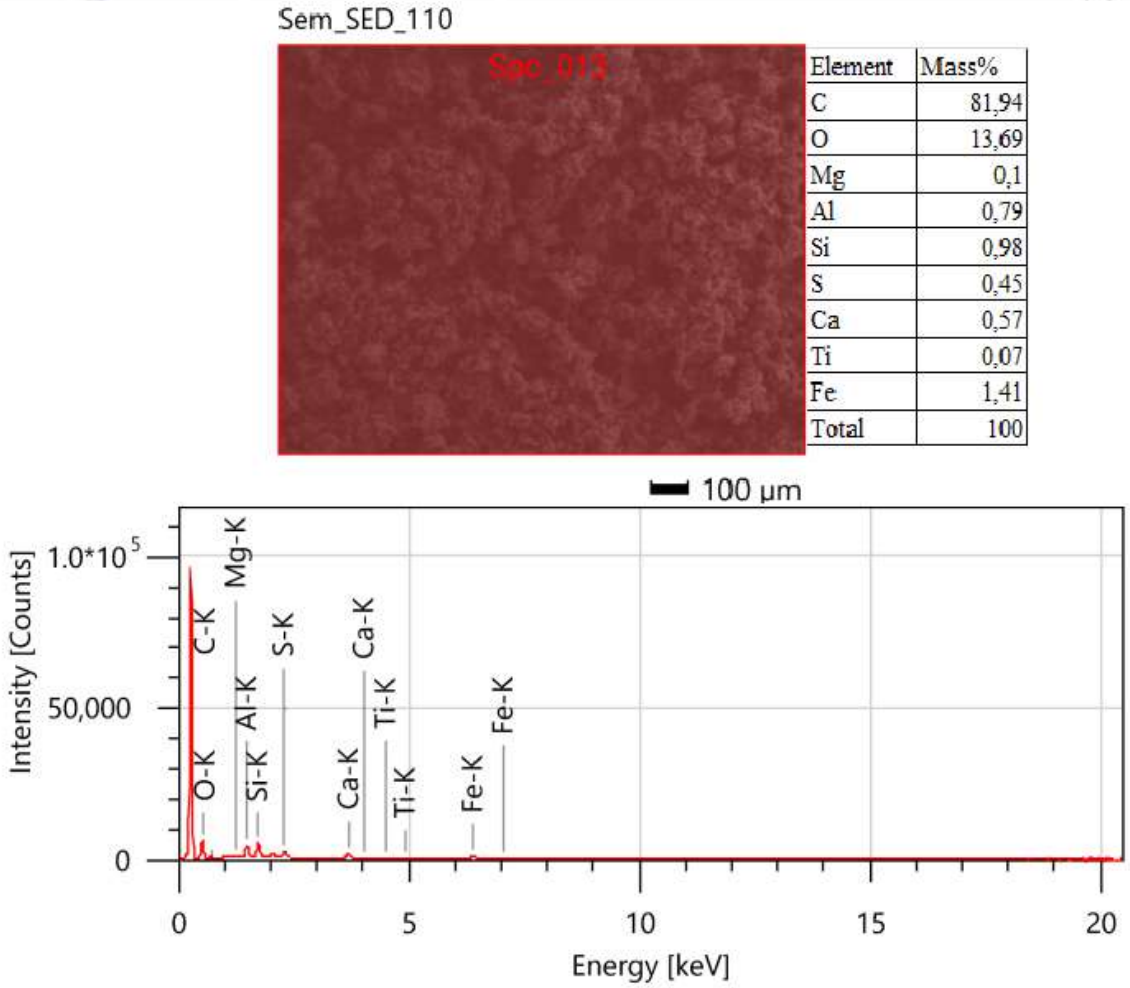
Qurilma **INCAx-act** energiya-dispersiv rentgen spektrometri (EDS) bilan jihozlangan bo‘lib, u Oxford Instruments tomonidan ishlab chiqarilgan. Mazkur tizim yordamida namunalar yuzasida tanlangan mikrosohalarda element tarkibi va ularning nisbiy miqdoriy taqsimoti aniqlanib, lokal kimyoviy tahlil amalga oshirildi.



1-rasm. Angren ko‘mirining (2BBK) ning elektron mikroskopdagi tasviri va element tarkibi

ISSN 3030-3907

Angren ko‘mirining elektron mikroskop yordamida o‘tkazilgan elementar tahlili uning murakkab va ko‘p komponentli tarkibga ega ekanligini yaqqol namoyon etdi. Tadqiqot natijalariga ko‘ra, namunada 78,87% uglerod, 16,27% kislorod, 0,12% natriy, 0,11% magniy, 0,75% alyuminiy, 0,8% kremniy, 0,58% oltingugurt, 0,8% kalsiy, 0,07% titan va 1,6% temir mavjudligi aniqlandi. Ushbu ko‘rsatkichlar ko‘mirning nafaqat organik, balki sezilarli darajada mineral komponentlarga ham boy ekanligini tasdiqlaydi. Mazkur natijalar tabiiy Angren ko‘mirida minerallik darajasi yuqori ekanligi haqidagi ilmiy xulosalarni yana bir bor asoslab beradi.



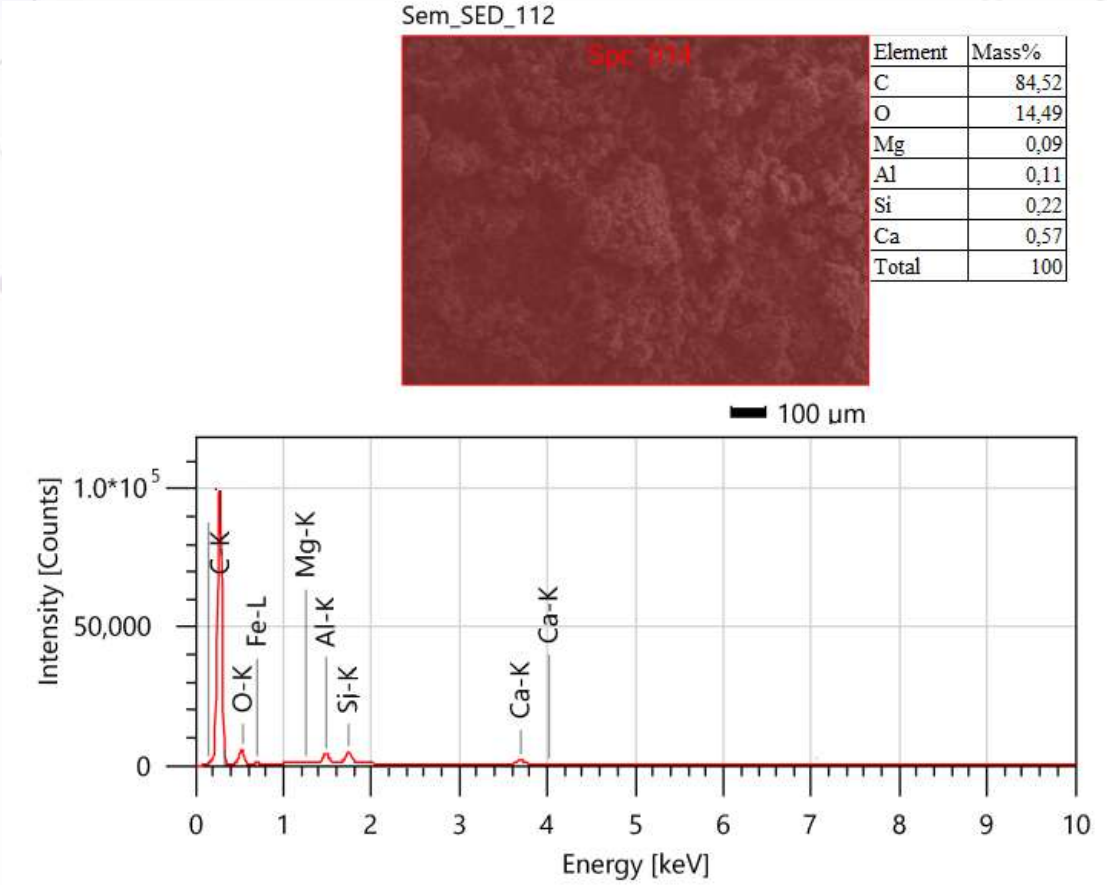
Element	Mass%
C	81,94
O	13,69
Mg	0,1
Al	0,79
Si	0,98
S	0,45
Ca	0,57
Ti	0,07
Fe	1,41
Total	100

2-rasm. Angren ko‘mirining (An-1) 5 % li H_3PO_4 eritmasi yordamida faollangan adsorbentning mikroskopdagi tasviri va element tarkibi

Angren ko‘mirini ortofosfat kislotaning 5% li eritmasi bilan faollash natijasida olingan namunaning elementar tahlili esa tarkibiy o‘zgarishlar yuz berganligini ko‘rsatadi. Faollashtirilgan namunada uglerod miqdori 81,94% gacha oshgan. Bu holat kislota bilan ishlov berish jarayonida mineral qo‘shimchalarning bir qismi eritmaga o‘tganligi va natijada uglerodning nisbiy ulushi ortganligini faniqlandi. Shuningdek dastlabki tabiiy ko‘mir namunasi bilan taqqoslanganda quyidagi asosiy o‘zgarishlar kuzatiladi: natriy kislota bilan ishlov berish natijasida

ISSN 3030-3907

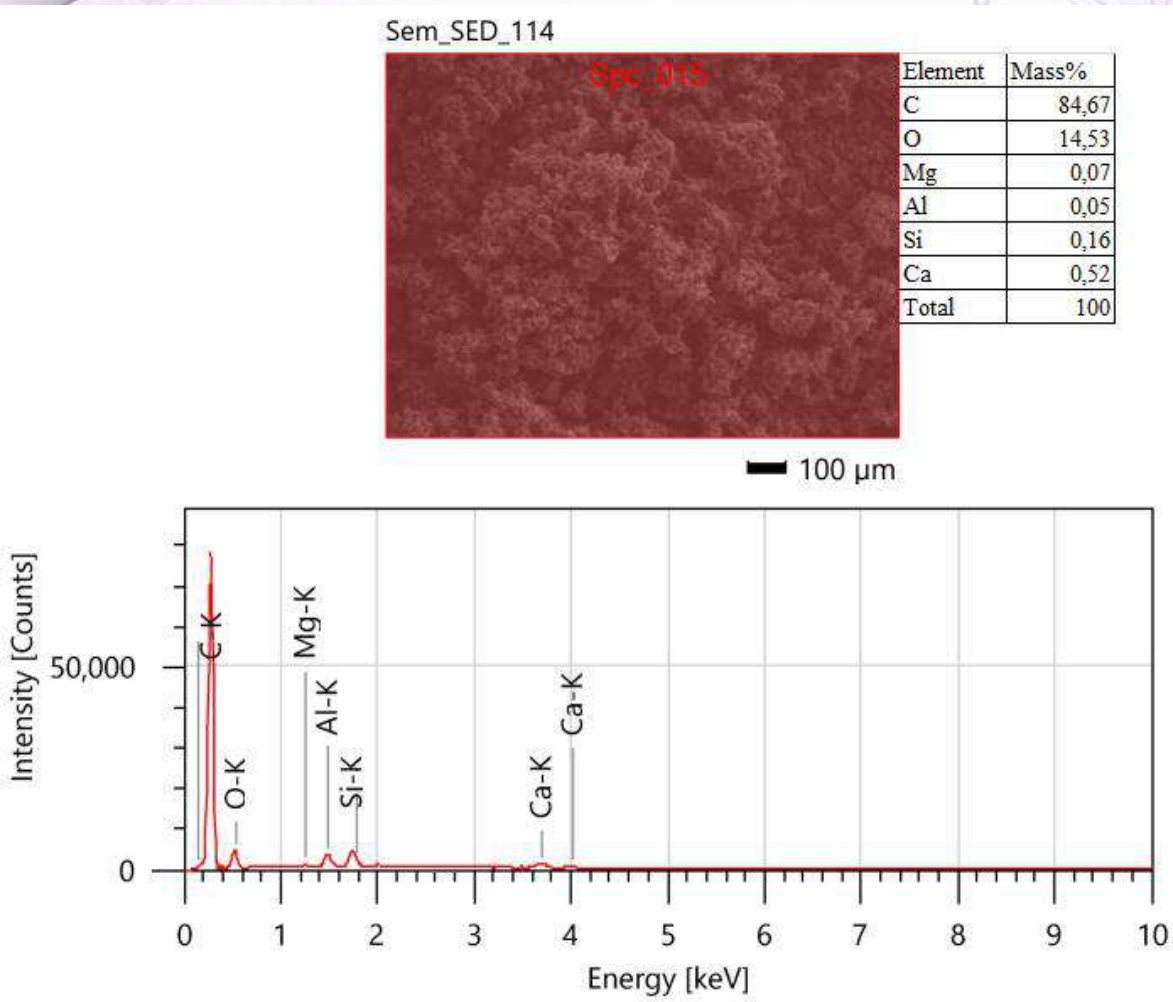
natriy to‘liq chiqarib yuborilgan, Alyuminiy 0,75%dan 0,79% ga va kremniy 0,8% -0,98% ortdi bu boshqa elementlarning kamayishi natijasida, oltingugurt 0,58% - 0,45% ga, kalsiy 0,8% 0,57% ga va temir 1,6% -1,41% ga kamaygan bu ularning birikmalarining kislota bilan reaksiyaga kirishganini bildiradi.



3-rasm. Angren ko‘mirining (An-3) 10 % li H_3PO_4 eritmasi yordamida faollangan adsorbentning mikroskopdagi tasviri va element tarkibi

Angren ko‘mirini 10% li ortofosfat kislotaning eritmasi bilan faollash natijasida olingan namunaning elementar tahlili olindi. Faollashtirilgan namunada uglerod miqdori 84,52% gacha va kislorodning massa ulishi 14.49% gacha oshgan. Kislorod miqdorining ortishidan namunani ortofosfat kislota bilan ishlov berish jarayonida uning tarkibidagi ma’lum miqdorda uglerod oksidlanishi natijada uning tarkibida COH va COOH guruxlar miqdori ortishidan dalolat beradi. Bu esa uglerodning azotli organik birikmalar (metil va dimetil amin)bilan faollash imkoniyatini oshiradi. Shuningdek, alyuminiy 0,11% gacha, magniy 0.09% gacha, kremniy 22% gacha, kalsiy 0,57% ga kamaygan.

ISSN 3030-3907



4-rasm. Angren ko‘mirining (An-3) 15 % li H_3PO_4 eritmasi yordamida faollangan adsorbentning mikroskopdagi tasviri va element tarkibi

Angren ko‘mirini ortofosfat kislota (H_3PO_4) eritmalari yordamida kimyoviy faollashtirish jarayonida 15 % li eritma bilan ishlov berilgan namunaning elektron mikroskopik element tahlili natijalari 10 % li eritma bilan faollashtirilgan namuna ko‘rsatkichlari bilan qiyosiy o‘rganildi. Tahlil natijalariga ko‘ra, sorbsiya xususiyatlarini belgilovchi asosiy elementlar — uglerod (C) va kislorod (O) miqdorida mos ravishda C ≈ 0,15 % va O ≈ 0,04 % farq aniqlangan. Mazkur tafovutlar juda kichik qiymatni tashkil etib, tajriba xatoliklari chegarasiga yaqin bo‘lgani sababli namunalar orasida sezilarli strukturaviy yoki kimyoviy farq mavjud emasligini ko‘rsatadi.

Ma’lumki, faollashtirilgan ko‘mirning adsorbsion xossalari asosan uning element tarkibi, g‘ovaklik darajasi, sirt maydoni hamda kislorod tutuvchi funksional guruhlar miqdori bilan belgilanadi. Yuqoridagi natijalar shuni ko‘rsatadiki, 15 % li ortofosfat kislota eritmasi qo‘llanilganda hosil bo‘lgan namunaning sorbsiya ko‘rsatkichlari 10 % li eritma bilan olingan namunaga nisbatan amaliy jihatdan ustunlik bermaydi.

ISSN 3030-3907

XULOSA texnologik jarayonning iqtisodiy samaradorligini, ya’ni reaktiv sarfi, energiya tejamkorligi hamda ishlab chiqarish tannarxini inobatga olgan holda, Angren ko‘mirini ortofosfat kislota bilan faollashtirishda 10 % li eritmadan foydalanish eng maqbul sharoit sifatida tavsiya etiladi. Mazkur konsentratsiya yuqori sorbsiya xususiyatlarini saqlab qolgan holda, qo‘shimcha reaktiv sarfini kamaytirish va jarayonni iqtisodiy jihatdan optimallashtirish imkonini beradi.

Ko‘mirni ortofosfat kislota yordamida faollanganda uning tarkibidagi mineral ko‘shimchalar chiqib ketishi va uning sirtidagi kislorodli funksional guruhlar xosil bo‘lishi natijasida adsorbentlarda qo‘shimcha g‘ovakliklar hosil bo‘ladi. Buning natijasida ko‘mir g‘ovaklar o‘lchami kichiklashadi. Bunda mezog‘ovaklarning miqdori kamayib, mikrog‘ovaklar miqdori ortadi. Natijada adsorbentlar g‘ovaklari radiusi qisqaradi. Ushbu xulosalar yuqoridagi elektron mikroskopda olingan natijalar asosida o‘z tasdiqini topgan.

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GLYUTEN VA O‘SIMLIK OQSILI KOMPOZITLARINING BO‘KISH XUSUSIYATLARI VA YUQORI HARORATLI SILJITISH TA’SIRIDA FIBRILLYAR STRUKTURA SHAKLLANISH QONUNIYATLARI

Sobuddinov Sohibjon Mahmudjonovich
Namangan davlat texnika universiteti Doktorant
Qanoatov Xayrullo Murodillayevich
Namangan davlat texnika universiteti texnika fanlari doktori, dotsent
Dadamirzayev Muzaffar Habibullayevich
Namangan davlat texnika universiteti texnika fanlari nomzodi, dotsent

Annotatsiya. Maqolada glyuten va o‘simlik oqsillari asosidagi kompozision tizimlarning bo‘kish xususiyatlari hamda yuqori haroratli siljitish ta’sirida fibrillyar struktura shakllanish qonuniyatlari tadqiq etilgan. Glyutenning uzluksiz oqsil fazasi sifatidagi roli, o‘simlik oqsillari bilan mexanik o‘zaro ta’siri va suvni yutish jarayonidagi strukturaviy o‘zgarishlar tahlil qilingan. Shuningdek, yuqori harorat va siljish ta’sirida oqsillarning denaturatsiyasi, agregatlanishi va qayta tashkillanishi natijasida anizotrop va fibrillyar struktura hosil bo‘lish mexanizmlari baholangan. Olingan natijalar glyuten–o‘simlik oqsili kompozisiyalarining bo‘kish darajasi, mexanik xususiyatlari va strukturalanish qobiliyati o‘rtasidagi o‘zaro bog‘liqlikni aniqlash hamda o‘simlik oqsillari asosida go‘sht o‘rnini bosuvchi mahsulotlar uchun maqbul teksturaviy xususiyatlarni shakllantirish imkonini beradi.

Kalit so‘zlar: glyuten, soya oqsili izolyati, no‘xat oqsili izolyati, loviya oqsili izolyati, o‘simlik oqsillari, oqsil kompozitlari, bo‘kish koeffitsiyenti, mexanik o‘zaro ta’sir, termomexanik ishlov berish, yuqori haroratli siljitish, fibrillyar struktura, tolasimon tuzilma, uzluksiz glyuten tarmog‘i, strukturaviy anizotropiya, fibrillanish.

Аннотация. В статье исследованы закономерности набухания композиционных систем на основе глютена и растительных белков, а также формирования фибриллярной структуры под воздействием высокотемпературного сдвигового воздействия. Проанализированы роль глютена как непрерывной белковой фазы, его механическое взаимодействие с растительными белками и структурные изменения в процессе поглощения воды. Кроме того, оценены механизмы формирования анизотропной и фибриллярной структуры в результате денатурации, агрегации и структурной перестройки белков под воздействием высокой температуры и сдвиговых деформаций. Полученные результаты позволяют установить взаимосвязь между степенью набухания, механическими свойствами и способностью к структурообразованию

ISSN 3030-3907

глютен–растительных белковых композиций, а также создать оптимальные текстурные характеристики мясных аналогов на основе растительных белков.

Ключевые слова: глютен, изолят соевого белка, изолят горохового белка, изолят фасолевого белка, растительные белки, белковые композиты, коэффициент набухания, механическое взаимодействие, термомеханическая обработка, высокотемпературный сдвиг, фибриллярная структура, волокнистая структура, непрерывная глютеновая сеть, структурная анизотропия, фибрилляция.

Abstract. This study investigates the swelling behavior of composite systems based on gluten and plant proteins, as well as the mechanisms underlying fibrillar structure formation under high-temperature shear treatment. The role of gluten as a continuous protein phase, its mechanical interactions with plant proteins, and structural changes during water absorption were analyzed. In addition, the mechanisms of anisotropic and fibrillar structure formation resulting from protein denaturation, aggregation, and structural rearrangement under high-temperature and shear deformation conditions were evaluated. The obtained results make it possible to establish the relationship between the degree of swelling, mechanical properties, and structuring ability of gluten–plant protein composites, as well as to develop optimal textural characteristics for meat analogues based on plant proteins.

Keywords: gluten, soy protein isolate, pea protein isolate, bean protein isolate, plant proteins, protein composites, swelling coefficient, mechanical interaction, thermomechanical treatment, high-temperature shearing, fibrillar structure, fibrous structure, continuous gluten network, structural anisotropy, fibrillationg.

KIRISH.

So‘nggi yillarda o‘simlik oqsillari asosida go‘sht o‘rnini bosuvchi mahsulotlarni yaratishga bo‘lgan ilmiy va amaliy qiziqish sezilarli darajada ortib bormoqda. Bunday mahsulotlarning iste’mol xususiyatlarini belgilovchi asosiy ko‘rsatkichlardan biri go‘sht to‘qimasiga xos bo‘lgan yo‘nalgan va tolasimon strukturaning shakllanishidir. Yuqori namlikli ekstruziya va boshqa termomexanik strukturaviy ishlov berish usullari o‘simlik oqsillarini fibrillyar strukturaga aylantirishning istiqbolli texnologik yondashuvlari sifatida qaralmoqda [1]. Bunda oqsil tarkibi, komponentlarning o‘zaro ta’siri, namlik, harorat va siljitish sharoitlari hosil bo‘ladigan strukturaning morfologik hamda reologik xususiyatlarini belgilovchi muhim omillar hisoblanadi.

ISSN 3030-3907

O‘simlik oqsillari orasida soya, no‘xat va loviya oqsillari yuqori funksional xususiyatlari hamda oziq-ovqat mahsulotlarida qo‘llash imkoniyatlari bilan alohida ahamiyatga ega. Biroq ushbu oqsillarning mustaqil holda yetarlicha shakllanga tolasimon struktura hosil qilish qobiliyati ularning oqsil tarkibi, fazaviy holati va termomexanik ishlov sharoitlariga bog‘liq. Shu sababli turli o‘simlik oqsillarini strukturani shakllantiruvchi boshqa biopolimerlar, xususan, glyuten bilan kombinatsiyalash orqali kompozit tizimlarning strukturaviy xususiyatlarini boshqarish muhim ilmiy-amaliy yo‘nalishlardan biri hisoblanadi [2,3]. Zamonaviy tadqiqotlarda ham glyutenning o‘simlik oqsillari bilan kompozisiyalarda fibrillyar struktura va tekstura shakllanishiga sezilarli ta’sir ko‘rsatishi qayd etilgan.

Glyutenning strukturaviy xususiyatlari uning gidratatsiyalangan holatda uzluksiz polimer tarmog‘ini shakllantirish qobiliyati bilan bevosita bog‘liq. Bunday tarmoqning mavjudligi glyuten va glyuten bo‘lmagan oqsil fazalari o‘rtasida mexanik o‘zaro ta’sir yuzaga kelishiga, natijada kompozit tizimning deformatsiyalanishi va bo‘kish xususiyatlarining o‘zgarishiga olib kelishi mumkin [4]. Shu nuqtai nazardan, bo‘kish jarayonini o‘rganish kompozit gelning ichki strukturaviy tashkil topishi va uning komponentlari o‘rtasidagi mexanik bog‘liqlikni baholash uchun muhim vosita bo‘lib xizmat qiladi.

Mazkur masalaning yana bir muhim jihati shundaki, glyuten–o‘simlik oqsili tizimlarida bo‘kish xususiyatlari va siljitish ta’sirida hosil bo‘ladigan tolasimon struktura o‘rtasidagi o‘zaro bog‘liqlik hali to‘liq aniqlangan emas. Ayniqsa, glyutenning turli o‘simlik oqsillari bilan mexanik o‘zaro ta’siri oqsil manbasiga bog‘liq holda qanday o‘zgarishi, glyuten konsentratsiyasining bo‘kish va fibrillanish jarayonlariga ta’siri hamda tolasimon struktura hosil bo‘lishi uchun qanday strukturaviy shartlar zarurligi alohida ilmiy qiziqish uyg‘otadi [5]. Hozirgi tadqiqotlar ham yuqori harorat, bosim va siljitish ta’sirida oqsil komponentlarining qayta tashkil topishi natijasida murakkab molekulyar va strukturaviy o‘zgarishlar yuz berishini ko‘rsatmoqda, biroq fibrillyar strukturaning shakllanish mexanizmi barcha tizimlar uchun bir xil darajada tushuntirilgan emas.

Shu munosabat bilan, ushbu tadqiqotning maqsadi glyutenning soya oqsili izolyati (SOI), no‘xat oqsili izolyati (NOI) va loviya oqsili izolyati (LOI) bilan hosil qilgan kompozisiyalarining bo‘kish xususiyatlarini o‘rganish, glyuten va glyuten bo‘lmagan oqsil fazalari o‘rtasidagi mexanik o‘zaro ta’sir qonuniyatlarini aniqlash hamda yuqori haroratli siljitish ta’sirida tolasimon (fibrillyar) struktura shakllanishining asosiy strukturaviy va texnologik omillarini baholashdan iborat Glyuten saqlovchi aralashmalar yuqori haroratli siljitish qurilmasida termomexanik ishlov berilgandan so‘ng ularning bo‘kish xususiyatlari ham o‘rganildi. Mazkur tadqiqotning asosiy maqsadi siljitish ta’sirida shakllangan struktura bilan materialning bo‘kish xususiyatlari o‘rtasidagi bog‘liqlikni aniqlash

ISSN 3030-3907

hamda termomexanik ishlov berish sharoitlarining bo‘kish jarayoniga ta’sirini baholashdan iborat bo‘ldi. Olingan natijalar shuni ko‘rsatdiki, siljitish ta’sirida termomexanik ishlov berilgan bir fazali SOI va NOI gellarining absolyut bo‘kish koeffitsiyenti ishlov berilmagan namunalarga nisbatan yuqoriroq qiymatlarni namoyon etdi. Bunga qarama-qarshi ravishda, LOI gellarida siljitish ta’siridan keyin absolyut bo‘kish koeffitsiyentining pasayishi kuzatildi. Biroq, ishlov berilgan va ishlov berilmagan namunalar o‘rtasidagi absolyut bo‘kish koeffitsiyenti farqi umumiy holda katta bo‘lmaganini ta’kidlash lozim.

Siljitish ta’sirida ishlov berilgan SOI va NOI gellarining nisbiy bo‘kish koeffitsiyenti glyuten miqdorining ortishi bilan izchil ravishda kamayib bordi. Mazkur tendensiya siljitish ta’sirisiz tayyorlangan namunalarda kuzatilgan natijalar bilan ham mos keladi. Ushbu o‘xshashlik siljitish ta’sirida yuzaga kelgan strukturaviy o‘zgarishlarga qaramay, glyutenning SOI va NOI oqsil fazalarining bo‘kish jarayoniga ko‘rsatadigan ta’siri saqlanib qolishini ko‘rsatadi.

Bo‘kish koeffitsiyentining pasayish darajasi nisbatan kamroq bo‘lganiga qaramay, olingan natijalar glyutenning SOI va NOI oqsil fazalariga ko‘rsatadigan mexanik ta’siri o‘xshash xarakterga ega ekanligini ko‘rsatadi. Siljitish ta’sirida termomexanik ishlov berilgan namunalarda glyuten ta’sirining nisbatan sustroq namoyon bo‘lishi glyuten fazasida anizotrop strukturaning shakllanishi bilan izohlanishi mumkin [6]. Mazkur anizotrop struktura glyuten va glyuten bo‘lmagan oqsil fazalari o‘rtasidagi mexanik o‘zaro ta’sir xarakterini o‘zgartirishi hamda natijada glyuten bo‘lmagan oqsil fazasining yo‘nalishga bog‘liq, ya’ni anizotrop bo‘kish xususiyatini namoyon etishiga olib kelishi mumkin. Biroq, mazkur tadqiqot doirasida anizotrop bo‘kishning bevosita mavjudligi eksperimental jihatdan aniqlanmadi. Shu sababli, ushbu izoh ehtimoliy mexanizm sifatida qaralishi lozim. Kuzatilgan farqlarning yana bir ehtimoliy sababi ishlov berish haroratlaridagi tafovut bilan bog‘liq bo‘lishi mumkin. Biroq, bu omilning bo‘kish jarayoniga ta’sirini alohida baholash uchun qo‘shimcha eksperimental tadqiqotlar talab etiladi. LOI gellarida glyuten konsentratsiyasining bo‘kish xususiyatlariga ta’siri SOI va NOI gellarida kuzatilgan qonuniyatdan farq qildi. Xususan, LOI tarkibida glyuten miqdorining ortishi bilan bo‘kish koeffitsiyentining ham ortib borishi kuzatildi. Bunday farq, avvalo, siljitish ta’sirida ishlov berilgan LOI namunalarida yuzaki qatlamning hosil bo‘lishi bilan bog‘liq bo‘lishi mumkin. SOI va NOI namunalarida bunday strukturaviy qatlam kuzatilmadi.

LOI namunalarida hosil bo‘lgan yuzaki qatlam namunaning ichki qismiga nisbatan zichroq va qattiqroq bo‘lib, suvning material ichiga kirib borishi hamda namunaning hajmiy kengayishini mexanik jihatdan cheklagan. Shu bilan birga, glyuten konsentratsiyasining ortishi bilan mazkur yuzaki qatlamning shakllanish darajasi kamayib bordi. Natijada, glyuten miqdori past bo‘lgan, xususan, toza LOI

ISSN 3030-3907

namunasida bo‘kish koeffitsiyentining qiymati yuzaki qatlamning cheklovchi ta’siri ostida eng katta darajada o‘zgargan deb dastlabki hulosa qilish mumkin. Demak, LOI gellarida kuzatilgan bo‘kish xususiyatlarining o‘ziga xosligi nafaqat glyuten konsentratsiyasi, balki termomexanik ishlov jarayonida yuzaga keladigan yuzaki strukturaviy qatlamning shakllanishi bilan ham bog‘liq bo‘lishi mumkin.

Yuzaki qatlamning ta’siri doimiy xarakterga ega bo‘lmaganligi sababli, uning bo‘kish jarayoniga ta’sirini glyuten konsentratsiyasining ta’siridan alohida ajratib baholash imkoniyati mavjud bo‘lmadi. Bundan tashqari, nisbiy bo‘kish koeffitsiyenti glyuten qo‘shilmagan boshlang‘ich namunaning bo‘kish koeffitsiyentiga nisbatan hisoblangan. Shu sababli, LOI gellarida olingan natijalarni SOI va NOI gellarida kuzatilgan natijalar bilan bevosita miqdoriy jihatdan taqqoslash to‘g‘ri emas.

Shunga qaramay, SOI va NOI gellari bo‘yicha olingan eksperimental natijalar siljitish ta’sirida termomexanik ishlov berilgandan keyin ham glyuten va glyuten bo‘lmagan oqsil fazalari o‘rtasidagi mexanik o‘zaro ta’sir saqlanib qolishini ko‘rsatadi. Demak, siljitish jarayonida yuzaga keladigan strukturaviy o‘zgarishlar mazkur o‘zaro ta’sirni to‘liq bartaraf etmaydi, balki uning namoyon bo‘lish xarakteri va darajasiga ta’sir ko‘rsatishi mumkin. Bu holat glyuten–o‘simlik oqsili kompozitlarining bo‘kish xususiyatlarini baholashda nafaqat oqsil tarkibini, balki termomexanik ishlov natijasida shakllangan strukturaviy holatni ham hisobga olish zarurligini ko‘rsatadi.

Uzluksiz glyuten tarmog‘ining shakllanishi bilan tolasimon (fibrillyar) tuzilmaning hosil bo‘lishi o‘rtasidagi bog‘liqlikni aniqlash maqsadida LOI, NOI va SOI oqsillarining glyuten bilan turli nisbatdagi aralashmalari yuqori haroratli siljitish qurilmasida termomexanik ishlov berildi. Tajribalarda bo‘kish xususiyatlarini o‘rganish uchun tayyorlangan aralash gellarda qo‘llanilgan kompozisiyalar aynan o‘sha tarkibiy nisbatlarda ishlatildi. Glyuten konsentratsiyasi umumiy oqsil massasiga nisbatan massaviy ulush (%) ko‘rinishida ifodalandi.

Siljitish ta’sirida shakllangan tolasimon tuzilmani baholash uchun olingan gel namunalari siljish yo‘nalishiga parallel yo‘nalishda egildi va hosil bo‘lgan sinish yuzasi vizual jihatdan tahlil qilindi. Bunda, avvalo, sinish yuzasida tolalarning mavjudligi hamda ularning siljish yo‘nalishiga nisbatan joylashuvi baholandi. Mazkur yondashuv avvalgi tadqiqotlarda qo‘llanilgan strukturaviy baholash metodikasiga o‘xshash bo‘lib, natijalar 1-rasmda keltirilgan.

Glyutensiz, ya’ni toza LOI, NOI va SOI xamirlarini siljitish ta’sirida qayta ishlash natijasida vizual jihatdan bir jinsli gel strukturalari hosil bo‘ldi. Biroq, ushbu namunalarning sinish yuzalarida siljish yo‘nalishi bo‘ylab shakllangan fibrillyar strukturalar kuzatilmadi. Bu holat mazkur oqsil izolyatlarining o‘z-

ISSN 3030-3907

o‘zidan siljitish ta’siri ostida aniq yo‘nalgan makrostrukturani shakllantirish qobiliyati cheklanganligini ko‘rsatadi.

Kompozisiyaga 16,7 % miqdorda glyuten qo‘shilganda LOI va SOI namunalari strukturasida sezilarli o‘zgarish kuzatilmadi. NOI–glyuten kompozisiyasida esa namuna egilgandan keyin nisbatan g‘adir-budur sinish yuzasi hosil bo‘ldi, biroq unda ham siljish yo‘nalishi bo‘ylab orientatsiyalangan struktura yoki aniq fibrillyar tuzilma aniqlanmadi. Demak, ushbu glyuten konsentratsiyasida aralashma strukturasining makroskopik darajada yo‘nalgan shakllanishi hali yetarli darajada namoyon bo‘lmagan. Glyutenning massaviy ulushi 33,3 % gacha oshirilganda LOI va NOI kompozisiyalarida siljish yo‘nalishi bo‘ylab ma’lum darajada orientatsiyalangan strukturalarning shakllanishi kuzatildi. Shunga qaramay, ushbu bosqichda aniq shakllangan tolasimon (fibrillyar) struktura hosil bo‘lmadi. Ayni glyuten konsentratsiyasida SOI–glyuten kompozisiyasida esa umuman yo‘nalgan struktura kuzatilmadi. Ushbu natijalar glyuten konsentratsiyasining ortishi bilan kompozit gel strukturasining siljitish oqimiga javobi oqsil turiga qarab farqlanishi mumkinligini ko‘rsatadi.

Barcha uch turdagi oqsil kompozisiyalarida tolasimon (fibrillyar) tuzilmaning shakllanishi glyutenning massaviy ulushi kamida 50,0 % ga yetgandagina kuzatildi. Bu natija kompozitsiyada fibrillyar strukturaning shakllanishi uchun glyutenning yetarli darajada yuqori konsentratsiyada bo‘lishi muhim ekanligini ko‘rsatadi. Glyutenning 50,0 % massaviy ulushida LOI–glyuten kompozisiyasida hosil bo‘lgan alohida tolalar NOI–glyuten va SOI–glyuten kompozisiyalarida kuzatilgan tolalarga nisbatan qalinroq bo‘ldi. Shu bilan birga, glyutenning massaviy ulushi 100,0 % ga yaqinlashishi bilan uchala oqsil kompozisiyasida ham hosil bo‘lgan tolalarning diametri izchil ravishda kamayib bordi. Demak, glyuten konsentratsiyasining o‘zgarishi nafaqat tolasimon strukturaning hosil bo‘lish imkoniyatini, balki shakllangan tolalarning morfologik xususiyatlarini, xususan, ularning qalinligini ham o‘zgartiradi.

Olingan natijalar shuni ko‘rsatadiki, glyuten kompozitsiyaning asosiy struktura hosil qiluvchi komponenti sifatida tolasimon tuzilmaning shakllanishida hal qiluvchi ahamiyatga ega. Biroq, tolalar diametrining LOI, NOI va SOI ishtirokidagi kompozisiyalarda turlicha bo‘lishi ikkilamchi oqsil fazasining tabiati ham shakllanayotgan fibrillyar strukturaning morfologik xususiyatlariga ta’sir ko‘rsatishi mumkinligini ko‘rsatadi (1-rasm).

ISSN 3030-3907

Glyutenning massa ulushi (massa/massa, %)	LOI + glyuten (loviya oqsili izolyati)		NOI + glyuten (no'xat oqsili izolyati)		SOI + glyuten (soya oqsili izolyati)	
	Namuna ko'rinishi	Tolaning ulushi, %	Namuna ko'rinishi	Tolaning ulushi, %	Namuna ko'rinishi	Tolaning ulushi, %
0 %		0 %		0 %		0 %
17,8 %		7,8 %		7,8 %		6,0 %
34,3 %		13,3 %		13,3 %		11,0 %
51,0 %		19,0 %		19,0 %		16,0 %
67,6 %		26,6 %		26,6 %		21,6 %
100 %		37,5 %		37,5 %		37,5 %
	Glyutenning massa ulushi ortishi					

Izoh: Namunalar yuqori haroratli siljitish qurilmasida ishlov berligan. Raqamlar tolasimon tuzilma ulushini (%) ifodalaydi.

1-rasm Glyuten miqdorini ortishi bilan gyuten va o'simlik oqsili kompozitsiyalarida tolasimon tuzilma miqdorining o'zgarishi

1-rasm. LOI–glyuten, NOI–glyuten va SOI–glyuten aralashmalari siljitish qurilmasida strukturalangandan keyin hosil bo'lgan makrotuzilmalarning rasmlari. Chap ustunda umumiy oqsil tarkibidagi glyutenning massa ulushi (%) keltirilgan bo'lib, rasmlardagi raqamlar namunalarning haqiqiy glyuten konsentratsiyasini (%) ifodalaydi. Siljitish qurilmasi 140 °C haroratda, 30 ayl/min (39 s^{-1}) siljitish tezligida 15 daqiqa davomida ishlatilgan. Har bir struktura ikki marta tayyorlangan (n = 2). Rasmlarda namunaning tashqi 4 sm qismiga xos bo'lgan aloxida makrotuzilmalar aks ettirilgan. Har bir namunaning kengligi 5-6 sm oraliqni tashkil etadi

Ushbu tadqiqotda glyutenning soya oqsili izolyati (SOI), no'xat oqsili izolyati (NOI) va loviya oqsili izolyati (LOI) bilan hosil qilgan kompozisiyalarining bo'kish xususiyatlari hamda yuqori haroratli siljitish qurilmasida strukturalanish qonuniyatlari o'rganildi. Dastlab, bir fazali SOI, NOI va LOI gellari muvozanat holatigacha bo'ktirilib, olingan eksperimental ma'lumotlar asosida glyuten saqlovchi aralash gellarning bo'kish xususiyatlari nazariy jihatdan baholandi. Nazariy baholashda glyuten va glyuten bo'lmagan oqsil fazalari o'rtasida mexanik o'zaro ta'sir mavjud emas, degan faraz qabul qilindi. Ushbu yondashuvga ko'ra, kompozitsiyada glyuten konsentratsiyasining ortishi bilan glyuten bo'lmagan oqsil fazasining bo'kish koeffitsiyenti ham ortishi kutilgan edi. Biroq, eksperimental natijalar mazkur nazariy taxminni tasdiqlamadi. Aksincha, olingan ma'lumotlar glyuten va glyuten bo'lmagan oqsil fazalari

ISSN 3030-3907

o‘rtasida mexanik o‘zaro ta’sir mavjudligini ko‘rsatdi va ushbu o‘zaro ta’sir kompozit gelning bo‘kish darajasining pasayishi bilan namoyon bo‘ldi.

Turli oqsil manbalari uchun absolyut bo‘kish koeffitsiyentlari o‘zaro farq qilgan bo‘lsa-da, ikkilamchi, ya’ni glyuten bo‘lmagan oqsilning bir fazali gellari bo‘yicha me’yorlashtirilgandan keyin, oqsil manbasidan qat’i nazar, bo‘kish jarayonida deyarli bir xil umumiy qonuniyat kuzatildi (1-rasm). Bu natija glyutenning turli o‘simlik oqsillari bilan o‘zaro ta’siri faqat ma’lum bir oqsil turiga xos emasligini va ushbu ta’sirning umumiy strukturaviy qonuniyatga ega bo‘lishi mumkinligini ko‘rsatadi.

SOI va glyuten kompozisiyalari bo‘yicha olingan natijalar asosida mazkur mexanik o‘zaro ta’sirni glyutenning uzluksiz tarmoq strukturasini shakllantirishi bilan izohlash mumkin. Bunday tarmoq glyuten bo‘lmagan oqsil fazasining deformatsiyalanishi va bo‘kishiga mexanik jihatdan qarshilik ko‘rsatishi natijasida kompozit tizimning umumiy bo‘kish darajasini cheklashi mumkin. Shu nuqtai nazardan, tajribada kuzatilgan bo‘kish koeffitsiyentining kamayishi glyuten konsentratsiyasining ortishi bilan ortadigan strukturaviy mexanik cheklanishning mavjudligini ko‘rsatadi. Kuzatilgan umumiy qonuniyat glyutenning nafaqat soya oqsili, balki no‘xat va loviya oqsili izolyatlari bilan ham o‘xshash mexanik o‘zaro ta’sirga kirishishi mumkinligini ko‘rsatadi. Biroq, mazkur xulosani barcha o‘simlik oqsillariga umumlashtirish uchun qo‘shimcha eksperimental tadqiqotlar talab etiladi. Shu sababli, ushbu natijalar glyuten va o‘simlik oqsili tizimlarida kuzatiladigan mexanik o‘zaro ta’sirning umumiy xususiyatlarini aniqlash uchun muhim ilmiy asos sifatida qaralishi mumkin.

Polimer tarmog‘ining deformatsiyalanish xususiyatlarini qo‘shimcha tahlil qilish natijalari van der Sman tomonidan tavsiflangan qonuniyatlarga yaqin ekanligi aniqlandi. Mazkur moslik glyuten tarmog‘ining deformatsiyalanish xususiyatlari va uning turli oqsil fazalari bilan mexanik o‘zaro ta’siri o‘rtasida umumiy qonuniyat mavjudligini ko‘rsatadi. Shunday qilib, olingan natijalar glyutenning turli o‘simlik oqsillari bilan hosil qilgan kompozisiyalarida mexanik o‘zaro ta’sirning o‘xshash xarakterga ega ekanligi haqidagi ilmiy farazni qo‘llab-quvvatlaydi.

Shuningdek, olingan ikkita umumlashtirilgan egri chiziq natijalari glyuten va o‘simlik oqsili kompozitlarida turli oqsil manbalari qo‘llanilgan taqdirda ham strukturaning shakllanish jarayoni o‘xshash umumiy qonuniyatlarga bo‘ysunishini ko‘rsatdi. Mazkur natija turli oqsil tizimlarida kuzatilgan strukturaviy o‘zgarishlar glyutenning umumiy strukturaviy xususiyatlari bilan bog‘liq bo‘lishi mumkinligini ko‘rsatadi. Biroq ushbu umumiy qonuniyatning fundamental sabablarini aniqlash hamda uning turli oqsil tizimlari uchun umumiyligini baholash uchun qo‘shimcha eksperimental tadqiqotlar talab etiladi.

ISSN 3030-3907

Olib borilgan tadqiqotning dastlabki nazariy qarashlariga ko‘ra, glyuten ma’lum bir kritik konsentratsiyaga yetgandan so‘ng uzluksiz tarmoq hosil qilishi va shu sababli ushbu kritik chegaradan yuqori konsentratsiyalarda bo‘kish koeffitsiyentining keskin pasayishi kutilgan edi. Biroq eksperimental natijalar bunday keskin chegaraviy o‘zgarishni ko‘rsatmadi. Aksincha, glyuten konsentratsiyasining ortishi bilan bo‘kish koeffitsiyentining taxminan chiziqli ravishda kamayishi kuzatildi va bu tendensiya glyutenning nisbatan past konsentratsiyalaridayoq namoyon bo‘ldi. Mazkur natija dastlabki gipotezani to‘liq qo‘llab-quvvatlamaydi hamda glyuten va glyuten bo‘lmagan oqsil fazalari o‘rtasidagi mexanik o‘zaro ta’sir glyutenning faqat yuqori konsentratsiyalarida emas, balki nisbatan past miqdorlarida ham yuzaga kelishi mumkinligini ko‘rsatadi.

Yuqori haroratli siljitish qurilmasida olib borilgan tajribalar esa glyuten kompozitsiyaning asosiy komponenti bo‘lgan holatlarda, ya’ni uning massaviy ulushi kamida 50,0 % ga yetganda, SOI, NOI va LOI bilan fibrillyar (tolasimon) tuzilmalar hosil bo‘lishi mumkinligini ko‘rsatdi . Bu natija glyutenning kompozitsiyada nafaqat bo‘kish jarayoniga ta’sir qiluvchi komponent, balki siljitish ta’sirida yo‘nalgan va tolasimon strukturaning shakllanishini ta’minlovchi asosiy strukturaviy komponent sifatidagi rolini ham ko‘rsatadi.

Mazkur natijalar avvalgi tadqiqotlarda SOI va NOI ning glyuten bilan aralashmalarida glyutenning massaviy ulushi 50,5 % bo‘lganda fibrillyar tuzilmalar hosil bo‘lishi qayd etilgani bilan mos keladi. Shu bilan birga, ayrim tadqiqotlarda siljitish ta’sirida ishlov berilgan SOI–glyuten gellarida glyutenning nisbatan past, ya’ni 20,0 % dan yuqori konsentratsiyalarida ham tolalar hosil bo‘lishi kuzatilgan. Biroq mazkur natijalarni ushbu tadqiqot natijalari bilan bevosita taqqoslashda eksperimental sharoitlardagi farqlarni hisobga olish zarur. Xususan, avvalgi tadqiqotlarda boshlang‘ich quruq modda miqdori 30,0 % va ishlov berish harorati 95 °C ni tashkil etgan bo‘lib, bu ko‘rsatkichlar mazkur tadqiqotdagi ishlov berish sharoitlaridan sezilarli darajada farq qiladi. Shu sababli, fibrillyar strukturaning hosil bo‘lish chegarasidagi farqni faqat glyuten konsentratsiyasi bilan izohlash mumkin emas, balki jarayonning termik va fizik sharoitlari ham muhim omil sifatida qaralishi lozim.

So‘nggi yillarda olib borilgan reologik tadqiqotlar shuni ko‘rsatdiki, NOI yoki SOI ning glyuten bilan kompozisiyalariga 120–140 °C harorat oralig‘ida siljitish ta’sirida termomexanik ishlov berilganda, glyuten uzluksiz yoki ikki uzluksiz fazali strukturani shakllantirishi mumkin. Bunda kompozit materialning yakuniy strukturaviy tashkil topishi, avvalo, ishlov berish sharoitlari va qo‘llanilayotgan xom ashyoning xususiyatlariga bog‘liq ekanligi aniqlangan. Demak, bir xil tarkibli oqsil kompozisiyalarida ham termomexanik ishlov berish

ISSN 3030-3907

parametrlarining o‘zgarishi strukturaning fazaviy tashkil topishiga va natijada materialning makrostrukturaviy xususiyatlariga sezilarli ta’sir ko‘rsatishi mumkin.

Hozirgi kunga qadar siljitish oqimi ta’sirida tolasimon (fibrillyar) strukturalarning shakllanish mexanizmi to‘liq aniqlanmagan. Polimer tizimlarida bunday strukturalarning hosil bo‘lishini tushuntirish uchun eng ko‘p qo‘llaniladigan gipotezalardan biri ikki fazali tizimning siljitish oqimi ta’sirida deformatsiyalanishi va keyinchalik qattiqlashishiga asoslanadi. Ushbu gipotezaga ko‘ra, tizimning dispers fazasi siljitish ta’sirida deformatsiyalanadi va oqim yo‘nalishi bo‘ylab ma’lum darajada joylashadi. Natijada materialda strukturaviy va mexanik anizotropiya yuzaga keladi.

Mazkur yondashuv doirasida SOI dispers faza sifatida qaralib, uning siljitish oqimi ta’sirida deformatsiyalanishi va yo‘nalishi tolasimon strukturaning shakllanishiga asosiy hissa qo‘shishi mumkin, deb hisoblanadi. Biroq, siljitish ta’sirisiz tayyorlangan SOI va glyuten aralash gellarida glyutenning uzluksiz tarmoq hosil qilib, SOI zarrachalarini o‘z ichiga qamrab olishi ushbu an’anaviy talqinni murakkablashtiradi. Ya’ni, bunday tizimda faqat bitta dispers fazaning mavjudligi emas, balki glyutenning ham uzluksiz tarmoq sifatida shakllanishi ehtimoli mavjud. Shu sababli, ikki uzluksiz tarmoqdan tashkil topgan strukturaviy holat tolasimon strukturaning faqat dispers fazaning deformatsiyalanishi va joylashuviga asoslangan an’anaviy gipoteza bilan to‘liq izohlanmaydi. Bu holat glyuten va o‘simlik oqsili kompozisiyalarida fibrillyar strukturaning shakllanish mexanizmi yanada murakkab ekanligini va uni tushuntirishda kompozitsiyaning fazaviy tashkil topishi hamda glyuten tarmog‘ining strukturaviy roli ham hisobga olinishi zarurligini ko‘rsatadi.

Olingan natijalar shuni ko‘rsatdiki, glyuten bo‘lmagan oqsil fazasining mavjudligi tolasimon (fibrillyar) strukturalarning shakllanishi uchun majburiy shart emas. Bunga ikkinchi oqsil komponenti qo‘shilmagan, ya’ni faqat glyuten asosidagi tizimda ham tolasimon strukturalarning hosil bo‘lgani yetarli asos bo‘la oladi. Mazkur natija fibrillyar strukturaning shakllanishida glyuten bo‘lmagan oqsil fazasi yagona yoki majburiy strukturaviy omil emasligini ko‘rsatadi. Gidratatsiyalangan glyutenni ikki fazali tizim sifatida ko‘rib chiqish mumkin. Bunda glyutenin va gliadin fazalari mos ravishda tizimning ikki tarkibiy fazasini tashkil etadi. Shunday qilib, gidratatsiyalangan glyutenning o‘zi ham dispers va uzluksiz fazalardan tashkil topgan tizim uchun zarur bo‘lgan strukturaviy shartlarni ta’minlashi mumkin. Bu holat ikkinchi oqsil komponenti mavjud bo‘lmagan sharoitda ham gidratatsiyalangan glyutendan tolasimon strukturalar hosil bo‘lishini izohlashga imkon beradi.

Bundan tashqari, sanoatda ishlab chiqariladigan glyuten tarkibida ma’lum miqdorda kraxmal qoldiqlari mavjud bo‘lishi mumkin. Mazkur kraxmal qoldiqlari

ISSN 3030-3907

ham tizimda ikkinchi faza vazifasini bajarishi ehtimoldan xoli emas. Tajriba natijalari ikkinchi biopolimer nisbatan kam miqdorda, ya'ni 50,0 % gacha qo'shilganda ham tolasimon strukturalarning shakllanishi saqlanib qolishini ko'rsatdi. Biroq glyuten kompozitsiyaning asosiy uzluksiz komponenti bo'lmay qolganida, tolasimon strukturalarning shakllanishi kuzatilmadi.

Shu asosda, glyuten saqlovchi kompozisiyalarda tolasimon strukturalarning shakllanishida asosiy strukturaviy rolni aynan glyuten bajaradi, degan xulosaga kelish mumkin. Bunda ikkinchi biopolimer komponenti, avvalo, kompozitsiyaning to'ldiruvchi fazasi sifatida ishtirok etadi. Shu bilan birga, uning miqdorini o'zgartirish strukturaviy xususiyatlarni boshqarish nuqtai nazaridan amaliy ahamiyatga ega. Tadqiqot natijalariga ko'ra, ikkinchi biopolimer miqdorini o'zgartirish orqali hosil bo'ladigan tolalarning qalinligi hamda tolasimon strukturaning rivojlanish darajasini, ya'ni fibrillanish darajasini boshqarish mumkin.

Shuningdek, tolasimon strukturalarning shakllanishi faqat kompozitsiyaning tarkibiy nisbatlari bilan belgilanmay, balki termomexanik ishlov berish sharoitlariga ham bevosita bog'liq. Xususan, ishlov berish harorati va siljitish davomiyligi fibrillyar strukturaning shakllanish darajasiga ta'sir qiluvchi muhim texnologik parametrlar hisoblanadi. Shu sababli, amaliy texnologik jarayonda mazkur parametrlarni maqbul qiymatlarda tanlash va barqaror boshqarish muhim ahamiyat kasb etadi.

Umuman olganda, tadqiqot natijalari glyuten saqlovchi kompozisiyalarda tolasimon struktura shakllanishining asosiy strukturaviy asosi uzluksiz glyuten tarmog'ining hosil bo'lishi bilan bog'liqligini ko'rsatadi. Demak, glyutenning kompozitsiyada uzluksiz tarmoq hosil qilishi fibrillyar strukturaning shakllanishi uchun muhim va zarur strukturaviy shartlardan biri sifatida qaralishi mumkin.

XULOSA.

Olib borilgan tadqiqotlar natijasida glyutenning soya oqsili izolyati (SOI), no'xat oqsili izolyati (NOI) va loviya oqsili izolyati (LOI) bilan hosil qilgan kompozisiyalarining bo'kish xususiyatlari hamda yuqori haroratli siljitish ta'sirida strukturalanish qonuniyatlari aniqlandi. Bir fazali oqsil gellari va kompozit tizimlarni taqqoslash glyuten va glyuten bo'lmagan oqsil fazalari o'rtasida mexanik o'zaro ta'sir mavjudligini ko'rsatdi. Ushbu ta'sir glyuten konsentratsiyasining ortishi bilan bo'kish koeffitsiyentining kamayishida namoyon bo'ldi.

Turli oqsil manbalarining absolyut bo'kish koeffitsiyentlari farq qilgan bo'lsa-da, me'yorlashtirilgandan so'ng SOI, NOI va LOI tizimlarida deyarli bir xil umumiy qonuniyat kuzatildi. Bu glyutenning turli o'simlik oqsillari bilan mexanik o'zaro ta'siri o'xshash strukturaviy asosga ega bo'lishi mumkinligini ko'rsatadi. Yuqori haroratli siljitishdan keyin ham SOI va NOI tizimlarida mazkur mexanik

ISSN 3030-3907

ta’sir saqlanib qoldi. Yuqori haroratli siljitish qurilmasidagi tajribalar barcha uch turdagi oqsil bilan fibrillyar strukturalar glyutenning massaviy ulushi kamida 50,0 % bo‘lganda shakllanishini ko‘rsatdi. Glyuten miqdori hosil bo‘ladigan tolalarning qalinligi va fibrillanish darajasiga ham ta’sir ko‘rsatdi. Glyuten kompozitsiyaning asosiy uzluksiz komponenti bo‘lmagan holatda esa fibrillyar struktura hosil bo‘lmadi. Shuningdek, glyuten bo‘lmagan ikkilamchi oqsil fazasi fibrillyar struktura hosil bo‘lishining majburiy sharti emasligi aniqlandi. Ikkinchi oqsil komponentisiz gidratatsiyalangan glyuten tizimida ham tolasimon strukturalar hosil bo‘ldi. Ikkilamchi biopolimer miqdorini o‘zgartirish orqali tolalarning qalinligi va fibrillanish darajasini boshqarish mumkinligi aniqlandi.

Umuman olganda, glyuten saqlovchi kompozisiyalarda fibrillyar struktura shakllanishining asosiy strukturaviy omili glyutenning uzluksiz tarmoq hosil qilish qobiliyatidir. Ikkilamchi oqsil yoki biopolimer komponenti esa asosan to‘ldiruvchi faza sifatida ishtirok etib, hosil bo‘ladigan strukturaning morfologik xususiyatlarini modulyatsiya qilishi mumkin. Shu sababli, glyuten va ikkilamchi komponent miqdorini boshqarish fibrillyar strukturaning kerakli xususiyatlarini shakllantirishning istiqbolli usuli hisoblanadi. Fibrillyar strukturaning shakllanishi, shuningdek, termomexanik ishlov berish sharoitlariga ham bog‘liq bo‘lib, ishlov berish harorati va siljitish davomiyligini maqbul darajada tanlash muhim ahamiyatga ega. Olingan natijalar glyuten–o‘simlik oqsili kompozisiyalarining strukturaviy xususiyatlarini boshqarish va ularni o‘simlik oqsillari asosidagi tolasimon oziq-ovqat mahsulotlari, jumladan, go‘sht o‘rnini bosuvchi yarimfabrikatlar olish texnologiyasida qo‘llash uchun ilmiy asos bo‘lib xizmat qiladi.

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ISSN 3030-3907

INGLIZ BALLADALARI VA O‘ZBEK QAHRAMONLIK EPOSI AN’ANALARI

Mahmudova Nilufar Maqsudovna
Mustaqil izlanuvchi
E-mail: mahmudovanilufar800@gmail.com

Annotatsiya. Ushbu maqola o‘zbek va ingliz she’riyatida urush motivining tipologik transformatsiyasi va badiiy talqinini qiyosiy-tahliliy yo‘sinda o‘rganishga bag‘ishlangan. Maqola Erkin Vohidovning “Nido” (1970-yillar) hamda Carol Ann Duffyning “War Photographer” (1985) she’rlari materiallari asosida olib borildi. Mazkur poetik matnlar forma, leksik-semantik qatlam, obrazlar tizimi, emotsional tonalilik, xronotop va ideologik xabar nuqtayi nazaridan qiyoslanib tahlil qilindi. Maqolada urushning individual va kollektiv xotiradagi badiiy reprezentatsiyasi, poetik subyekt pozitsiyasi, guvohlik va befarqlik fenomeni, shuningdek, “xotira – unutish”, “shahidlik – deformatsiya (aberratsiya)” kabi binar semantik modellar ochib berildi. O‘zbek she’riyatida urush motivi milliy fojea, ma’naviy qarz va umumiy xotira kontekstida talqin etilsa, ingliz poeziyasida u posttravmatik tajriba, axloqiy distansiya va o‘quvchi mas’uliyati masalalari orqali ifodalanishi ko‘rsatib berildi.

Kalit so‘zlar: urush motivi, o‘zbek she’riyati, ingliz she’riyati, tipologik transformatsiya, badiiy tasvir.

Аннотация. Данная статья посвящена сравнительно-аналитическому изучению типологической трансформации и художественной интерпретации мотива войны в узбекской и английской поэзии. Исследование проведено на материале стихотворений Эркина Вахидова «Нидо» (1970-е годы) и Кэрол Энн Даффи «Военный фотограф» («War Photographer», 1985). Указанные поэтические тексты были подвергнуты сопоставительному анализу с точки зрения формы, лексико-семантического уровня, системы образов, эмоциональной тональности, хронотопа и идеологического послания. В статье раскрываются художественная репрезентация войны в индивидуальной и коллективной памяти, позиция поэтического субъекта, феномены свидетельствования и безразличия, а также бинарные семантические модели «память — забвение», «жертвенность — деформация (аберрация)». Показано, что в узбекской поэзии мотив войны интерпретируется в контексте национальной трагедии, нравственного долга и общей исторической памяти, тогда как в английской поэзии он выражается через призму посттравматического опыта, этической дистанции и ответственности читателя.

ISSN 3030-3907

Ключевые слова: мотив войны, узбекская поэзия, английская поэзия, типологическая трансформация, художественный образ.

Annotation. This article is devoted to a comparative and analytical study of the typological transformation and artistic interpretation of the war motif in Uzbek and English poetry. The research is based on the poetic texts “Nido” (1970s) by Erkin Vohidov and “War Photographer” (1985) by Carol Ann Duffy. These poems are examined comparatively from the perspectives of form, lexico-semantic structure, imagery system, emotional tonality, chronotope, and ideological message.The article explores the artistic representation of war in individual and collective memory, the position of the poetic subject, the phenomena of witnessing and indifference, as well as binary semantic models such as “memory–forgetting” and “martyrdom–distortion (aberration).” It is demonstrated that in Uzbek poetry the war motif is interpreted within the framework of national tragedy, moral responsibility, and shared historical memory, whereas in English poetry it is articulated through post-traumatic experience, ethical distance, and the reader’s responsibility.

Keywords: war motif, Uzbek poetry, English poetry, typological transformation, artistic imagery.

KIRISH.

Ingliz xalq og‘zaki ijodida balladalar muhim o‘rin tutadi. Balladalar asosan xalq orasida og‘zaki ravishda tarqalgan she’riy asarlar bo‘lib, ularda tarixiy voqealar, sevgi, sadoqat, jangovar jasorat va turli ijtimoiy hodisalar tasvirlanadi. Ingliz balladalari sodda syujet, takroriy misralar va ohangdorlik bilan ajralib turadi. Ular odatda kuylab ijro etilgan va xalq orasida avloddan-avlodga o‘tib kelgan.

O‘zbek xalq og‘zaki ijodida esa qahramonlik eposlari muhim o‘rin egallaydi. Qahramonlik eposlari xalqning tarixiy xotirasi, orzu-umidlari va milliy qadriyatlarini aks ettiradi. Bu eposlarda jasur qahramonlarning vatanni himoya qilishi, adolat uchun kurashi, xalq manfaatini himoya qilishi tasvirlanadi. Masalan, “Alpomish”, “Go‘ro‘g‘li” kabi eposlar o‘zbek xalqining qahramonlik an’analarini namoyon etadi.

Ingliz balladalari bilan o‘zbek qahramonlik eposlari o‘rtasida ayrim o‘xshashliklar mavjud. Har ikkisi ham xalq og‘zaki ijodiga mansub bo‘lib, tarixiy voqealar va qahramonlik ruhini aks ettiradi. Shuningdek, ular og‘zaki ijro an’anasi orqali avloddan-avlodga yetib kelgan.

Shu bilan birga, ular o‘rtasida farqlar ham mavjud. Ingliz balladalari ko‘proq qisqa hajmli, sodda syujetli va lirik-dramatik xarakterga ega bo‘lsa, o‘zbek qahramonlik eposlari keng syujetli, ko‘p qismli va epik tasvirlarga boy bo‘ladi.

ISSN 3030-3907

Eposlarda qahramonlarning hayoti, sarguzashtlari va kurashlari batafsil bayon qilinadi.

Urush adabiyotda eng universal va chuqur mazmunga ega bo‘lgan mavzulardan biridir. Chunki u insoniyatning og‘ir sinovlar davridagi holatini va tajribasini aks ettiradi. Urush faqat shaxslar va xalqlar hayotiga o‘lim ta’sir ko‘rsatmaydi, balki madaniyatlar va sivilizatsiyalar qadriyatlari hamda e’tiqodlariga ham zarba beradi. Urush adolat va axloq, jasurlik va qo‘rqoqlik, sadoqat va xiyonat, muhabbat va nafrat tushunchalariga qarshi turadi. Shuningdek, urush yozuvchi va san’atkorlarning ifoda va ijodiy yaratish jarayonlariga ilhom baxsh etadi. Ular so‘z va tasvir vositasi orqali urush haqiqatlari va urush kayfiyatlarini aks ettiradilar. Urushga tanqidiy munosabat bildirib, unga qarshi chiqadilar, urush qurbonlarini yodga olib, ular uchun motam tutadilar va tinchlikka umid qiladilar.

ADABIYOTLAR TAHLILI. Jahon adabiyotida urush mavzusi insoniyat uchun eng og‘riqli va dolzarb masalalardan biri sifatida ko‘plab adiblar ijodida o‘z aksini topgan. O‘zbek adabiyotida ham, ingliz adabiyotida ham urushning inson ruhiyatiga, jamiyat hayotiga ko‘rsatgan ta’siri turli badiiy vositalar orqali yoritilgan. Bu jihatdan o‘zbek shoiri Erkin Vohidovning “Nido” she’ri hamda britaniyalik shoir Carol Ann Duffyning War Photographer she’ri urush fojiasini tasvirlashda muhim adabiy namunalar hisoblanadi.

Erkin Vohidovning Nido she’rida urush insoniyat boshiga solgan musibatlar, inson qalbidagi iztirob va faryod badiiy tasvirlar orqali ifodalangan. Shoir she’rda urush oqibatida vayron bo‘lgan taqdirlar, ota-onasiz qolgan bolalar, iztirobga to‘la inson qalbini tasvirlab, insoniyatni tinchlikni asrashga chorlaydi. “Nido” asari o‘z mohiyatiga ko‘ra inson qalbidan chiqqan og‘riqli hayqiriq, ya’ni urushga qarshi norozilik ifodasi sifatida namoyon bo‘ladi. She’rda lirizm, kuchli emotsional ohang va ramziy obrazlar orqali tinchlik g‘oyasi ilgari suriladi.

Erkin Vohidovning “Nido” dostoni Ikkinchi jahon urushi oqibatlarini bevosita shoirning shaxsiy xotirasi va oilaviy fojeasi orqali ifodalashi bilan xarakterlanadi. Tadqiqotchilar dostonda shoirning urushda halok bo‘lgan otasi Cho‘yanboy Vohidov xotirasi, farzandning ota mehriga bo‘lgan ehtiyoji hamda urush sabab yuzaga kelgan yetimlik va ayriliq motivlari markaziy o‘rin tutishini qayd etadi.[3]

“Nido”dagi urush oddiy tarixiy hodisa sifatida emas, balki inson taqdirini o‘zgartiruvchi fojiaviy kuch sifatida namoyon bo‘ladi. Urush frontdagi jang manzaralaridan ko‘ra, uning inson qalbida qoldirgan izlari orqali ochiladi. Ayniqsa,

[3] Hamrayev I.A. “erkin vohidovning "Nido" dostoning g'oyaviy va badiiy ahamiyati” *«MODERN SCIENCE AND RESEARCH» VOLUME 4 / ISSUE 3 / UIF:8.2 / MODERNSCIENCE.UZ*

ISSN 3030-3907

ota va farzand o‘rtasidagi ayriliq urushning eng og‘riqli oqibati sifatida talqin qilinadi. Shu jihatdan dostonning poetik markazida “urush – ayriliq – xotira – sog‘inch” semantik zanjiri shakllanadi.

Dostondagi xotira individual bo‘lsa-da, uning mazmuni kollektiv xarakterga ega. Bir bolaning otasini yo‘qotishi butun bir avlodning urush tufayli yetim qolishi, ayollarning beva bo‘lishi va oilalarning parokanda bo‘lishi bilan umumlashadi. Demak, Vohidov poetikasida individual xotira milliy xotira darajasiga ko‘tariladi.

Carol Ann Duffyning “War Photographer” she’rida esa urush voqealari bevosita jang maydonidan emas, balki urushni suratga oluvchi fotograf nigohi orqali tasvirlanadi. She’r qahramoni urush hududlarida olingan suratlarni tartibga solayotgan paytda boshidan kechirgan ruhiy kechinmalarini eslaydi. Fotograf obyektivi orqali urushning dahshatli manzaralari — vayronagarchilik, insonlarning iztirobi va o‘lim tasvirlari namoyon bo‘ladi. Shoira urushning inson ruhiyatiga qoldiradigan jarohatlarini chuqur psixologik tasvirlar orqali ochib beradi.

Carol Ann Duffy esa 2009–2019-yillarda Buyuk Britaniyaning davlat shoiri bo‘lgan va “War Photographer” (“Urush fotografi”) she’rini jangovar fotosuratchi-do‘stlariga atab yozgan. Ikkala shoir ham urushni turli pozitsiyasidan va turli badiiy uslublarda o‘rganadilar, ammo ular har ikkalasi jangovar dahshatlar va azoblarni, shuningdek urushga bevosita jalb qilinmagan kishilarning befarqligi va ajralishini aks ettiradilar. Maqolada har ikkala shoirning poetik vositalardan tasvir, isti’ora, reministseniya, takror, qofiya, ironiya va sarkazm orqali xabarlarni kuchaytirish va ta’sirchanlikka erishish usullari tahlil qilinadi. Shuningdek, urush haqiqati bilan tinchlikdagi bexabarlilik orasidagi kontrast va urushning shaxsiy-ijtimoiy jihatlari yaqinlarni yo‘qotish, zo‘ravonlik guvohi bo‘lish travmalari, guvoh yoki ishtirokchi bo‘lish ikkilamchiligi muhokama qilinadi. Ushbu tahlil ikkala she’rning o‘quvchini urush oqibatlari va sabablari haqida o‘ylashga, shuningdek o‘z roli va mas’uliyati masalasiga qaytishga chaqirish ekanini isbotlaydi.

Erkin Vohidovning “Nido” (Nido) va Carol Ann Duffyning “War Photographer” (“Jangovar fotograf”) she’rlarini solishtirish usuliga asoslangan. Erkin Vohidov sovet rejimi davrida xalqining qiynalib o‘tgan hayoti, Ikkinchi jahon urushi oqibatlari haqida yozgan. “Nido” she’ri jangda jon bergan otiga bag‘ishlangan marosimiy qasida sifatida yozilgan; asarda ingliz mamlakatidagi tinch qishloq hayoti bilan chet eldagi urush dahshatlari orasidagi ziddiyat aks etadi. Carol Ann Duffy 2009-yilda Ingliz davlat shoirlari lavozimiga saylangan birinchi ayol shoir. “War Photographer” asari u o‘rtoqlaridan jangovar fotosuratchilar Don McCullin va Philip Jones Griffithsga bag‘ishlangan. She’r fotografning kasbiy burchi va shaxsiy hissiyotlari o‘rtasidagi muvozanat, shuningdek urush rasmlarini iste’mol qiluvchi o‘quvchilarning befarqligini ko‘rsatadi.

ISSN 3030-3907

Asarlarni forma, til, tasvir va ulguriydagi xabarlari jihatidan tahlil qilamiz. **Forma jihatdan** har ikkala she’r to‘rtta banddan iborat, lekin “Nido”da qofiya sxemi va vazn o‘zgaruvchan, “War Photographer”da esa ABBCDD tartibidagi barqaror qofiya va iambik pentametr saqlangan. Bu “Nido”ning ifodali-impulsiv, “War Photographer”ning nazoratli-strukturali uslubda yozilganini ko‘rsatadi. **Til jihatdan** har ikkala asar sodda va bevosita so‘zlar bilan yozilgan, ammo “Nido”da “otajon”, “yolg‘izim”, “qo‘zim” kabi o‘zbekcha leksik birliklar ishlatilib, yaqinlik va madaniy identifikatsiya hosil qilinadi. Erkin Vohidov. “Nido” *Parcha* (boshlanishi, 1-bayit):

“Otajon, yolg‘izim, qo‘zim, jonim,
Sizning ko‘ksingizni teshgan qora o‘q
Qalbimni o‘rtamoqda so‘ngsiz armonim,
O‘sha olis yurtda qon kechib hozir…” [1]

Izoh: Ota shaxsiga qaratilgan sanoatli murojaat (“yolg‘izim, qo‘zim”) o‘zbek xalq she’riyatiga xos endearment-formulalaridir. “Qora o‘q” metaforasi o‘limning aniqligini, “songsiz armon” pleonazmi esa g‘amning chegarasizligini kodlaydi. “Olis yurt” so‘zi sovet janglarida halok bo‘lgan otaning chet elda qabrini anglatib, urushning mehnat qishlog‘iga yetgan masofasini ko‘rsatadi.

“War Photographer”da “spools”, “solutions”, “supplement” kabi texnik atamalar fotografning kasbiy hayoti va uning emotsional ajralishini anglatadi.

“In his darkroom he is finally alone
with spools of suffering set out in ordered rows.
The only light is red and softly glows,
as though this were a church and he a priest…”[4]

Izoh: “Spools of suffering” – alliteratsiya va metaforsintez orqali yorug‘likka chiqmagan aziyatlarning material (plastik rulon) ko‘rinishiga keltirilishi; bu fotografning professional ob’ektivini shaxsiy qayg‘u bilan almashtiradi. “Church / priest” similesi jang rasmlarini “baptise” qilish, ya’ni ularni muqaddas xotira sifatida saqlash niyatini bildiradi. **Tasvir jihatdan** har ikkala she’r urush ta’sirini berish uchun jonli va zid tasvirlardan foydalanadi. “Nido”da “Sizning ko‘ksingizni teshgan qora o‘q”, “Qalbimni o‘rtamoqda so‘ngsiz armonim”, “O‘sha olis yurtda qon kechib hozir” kabi isti’oralar shoirning g‘am va yo‘qot hissini beradi. “War Photographer”da “as though this were a church and he a priest”, “to fields which don’t explode beneath the feet”, “a hundred agonies in black and white” kabi sinoqli tasvirlar fotografning axloqiy ziddiyatini va olamlar farqini ta’kidlaydi. Duffy, Carol Ann. “War Photographer”

[4] Vohidov, Erkin. Tanlangan asarlar. – Toshkent: G‘afur G‘ulom, 2020.

ISSN 3030-3907

Parcha (3-stanza):
“A hundred agonies in black and white
from which his editor will pick out five or six
for Sunday’s supplement.
The reader’s eyeballs prick
with tears between the bath and pre-lunch beers.” [5]

Izoh: “A hundred agonies in black and white” – partitiv soni (“hundred”) va rang kontrasti orqali ko‘plikdagi og‘riqning matritsaga (fotografik nega) sig‘ishi; oxirgi satrda “bath – pre-lunch beers” kundalik ritmi urush rasmi qo‘zg‘atgan “tezda o‘tadigan ko‘z yoshi” ni kontrastlaydi. Bu postmodern “consumption of trauma” fenomenini qoralaydi.

Kayfiyat (ton): Har ikkala asar g‘amgin va g‘azabli kayfiyatda yozilgan, ammo “Nido” shaxsiy-emotsional, “War Photographer” esa ajralgan-ironik uslubda bajarilgan. “Nido” otasiga bo‘lgan muhabbat, urushga nisbatan nafrat va umidsizlikni bildiradi. “War Photographer” fotografning bechoralik, aybdorlik hissini va o‘quvchilarning befarqligiga nisbatan sinizmni ochib beradi. **Xabar (mazmuniy xulosa):** Har ikkala she’r antiharbiy g‘oya va inson azobini anglatadi, lekin “Nido” vatanparvarona va optimistik, “War Photographer” esa tanqidiy va pessimistik yondashuvda yozilgan. “Nido” otaning jasurligi va xalqining hurriyat kurashini yuksak tutadi, kelajak avlodi uchun yaxshiroq umid qiladi. “War Photographer” esa fotografning ishinig maqsad va samarasini so‘rab, jamiyatning befarqligini ochib beradi.

Ikki asarda poetik subyektning farqi

Ikki ijodkor urushni turli poetik subyektlar orqali tasvirlaydi.

1-Jadval

Mezon	**Erkin Vohidov – “Nido”**	**Carol Ann Duffy – “War Photographer”**
Poetika subyekti	Urush qurboni va uning xotirasini tashuvchi farzand	Urush guvohi – fotograf
Urush bilan munosabat	Bevosita oilaviy va milliy fojiaviy xotira	Bilvosita guvohlik va professional faoliyat
Asosiy hissiyot	Sog‘inch, iztirob, ayriliq	Travma, aybdorlik, ruhiy begonalashuv
Xotira turi	Individual → kollektiv	Individual → global
Urush obrazi	Milliy fojea	Global insoniy muammo

[5] Duffy, Carol Ann. *Selected Poems*. – London: Penguin, 2018.

ISSN 3030-3907

Asosiy konflikt	Farzand va yo‘qotilgan ota o‘rtasidagi ruhiy bog‘liqlik	Fotograf, urush qurbonlari va befarq auditoriya o‘rtasidagi axloqiy konflikt
Asosiy g‘oya	Urush xotirasini unutmaslik	Urush dahshatini ko‘rish va unga befarq bo‘lmaslik

Bu qiyosdan ko‘rinadiki, Vohidovda poetik subyekt **urushning bevosita qurboni xotirasini davom ettiruvchi shaxs** sifatida ko‘rinsa, Duffyda u **urushni ko‘rgan va boshqalarga yetkazishga urinayotgan guvoh** sifatida namoyon bo‘ladi.

Eng muhim nazariy nuqtalardan biri — **“xotira – unutish”** qarama-qarshiligini ikki asar asosida ochib berishdir.

“Nido”da xotira — axloqiy majburiyat. Ota xotirasini saqlash orqali farzand nafaqat o‘zining shaxsiy tarixini, balki urushda halok bo‘lgan butun avlod xotirasini asraydi. Shuning uchun xotira bu yerda **ma’naviy qarz** vazifasini bajaradi.

Duffy she’rida esa muammo boshqacharoq. Fotograf yuzlab azob-uqubatlarni suratga oladi, biroq gazeta muharriri ulardan faqat bir nechtasini nashrga tanlaydi. O‘quvchilar esa suratlarni qisqa muddatli hissiy ta’sir bilan qabul qiladilar.

Natijada urush qurbonlarining individual fojeasi ommaviy axborot vositasida qisqartiriladi, tanlanadi va iste’mol qilinadigan axborotga aylanadi. Bu holat **xotiraning ommaviy axborot vositalari orqali deformatsiyalanishi** masalasini yuzaga chiqaradi.

Demak:

“Nido”: xotira → saqlash → avlod → milliy xotira

“War Photographer”: xotira → tasvir → ommaviy axborot → befarqlik → unutish.

Har ikkala she’r urush dahshatlari va uning inson ruhiyatiga bergan oqibatlarini kuchli va ta’sirchan ifodalaydi. Ular sodda til, jonli tasvir, zid muhit kabi umumiy xususiyatlarga ega, lekin forma, kayfiyat va xabar jihatidan farq qiladi. “Nido” shaxsiy va emotsional, “War Photographer” esa professional va ironik uslubda yozilgan. “Nido” vatanparvar ruhda va optimistik, “War Photographer” tanqidiy va pessimistik yondashuvda bajarilgan. Har ikkala she’r o‘quvchi nuqtai-nazariga va afzalliklariga ko‘ra o‘ziga xos foyda va kamchiliklarga ega.

Qiyosiy tahlil shuni ko‘rsatdiki, ikki asarda “xotira – unutish”, “guvohlik – befarqlik”, “shahidlik – deformatsiya” kabi binar semantik modellar urush

ISSN 3030-3907

motivining tipologik transformatsiyasini belgilovchi muhim poetik mexanizmlardir. Vohidovda urush xotirasi milliy-tarixiy va ma’naviy mazmun kasb etsa, Duffyda u global insoniy fojiaga, individual travma va jamiyatning axloqiy mas’uliyati muammosiga aylanadi.

Shunday qilib, milliy poetik tafovutlarga qaramay, “Nido” va “War Photographer” asarlarini birlashtiruvchi umumiy jihat — urushning jang maydoni bilan chegaralanmasligi, uning inson xotirasi va ruhiyatida davom etuvchi fojiaviy hodisa sifatida talqin qilinishidir. Mazkur asarlar urushni yodda saqlash, uning qurbonlarini unutmaslik va tinchlikning insoniyat uchun fundamental qadriyat ekanligini anglashga xizmat qiladi. Shu nuqtayi nazardan, urush motivining ikki milliy adabiyotdagi tipologik transformatsiyasi universal insoniy qadriyatlar va milliy tarixiy xotiraning o‘zaro uyg‘unligini namoyon etadi.

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ISSN 3030-3907

AYOLLAR KUNDALIK POYABZALINING QULAYLIGINI OSHIRISH: YANGI KONSTRUKTORLIK-TEXNOLOGIK YECHIMLAR TAHLILI

Uzoqova Laylo Polvonovna
Buxoro davlat texnika universiteti "Yengil sanoat muhandisligi va dizayni" kafedrasi
E-mail.: laylo.uzakova@mail.ru
Avezova Anoraxon Azimovna
Buxoro davlat texnika universiteti "Yengil sanoat muhandisligi va dizayni" kafedrasi
E-mail.anorakhon.avezova@gmail.com

Annotatsiya. Maqolada ratsional poyabzal tushunchasi, uning shakllanish tarixi va zamonaviy holati xorijiy olimlarning ilmiy ishlari asosida tahlil qilingan. Ratsional poyabzal g'oyasi o'zi yangilik bo'lmasa-da, uning komfortlilik darajasini yanada oshirish maqsadida qo'llanilishi mumkin bo'lgan zamonaviy konstruktorlik, materialshunoslik va raqamli loyihalash yechimlari o'rganilgan. Tadqiqot natijasida ayollar ratsional poyabzali uchun taklif etilayotgan ilmiy yangilik - individual antropometrik ma'lumotlarga asoslangan moslashuvchan konstruksiya, gibrid material tizimi va bosimni boshqaruvchi "aqlli" taglik detali elementlarini birlashtirgan kompleks yondashuv sifatida shakllantirilgan.

Kalit so'zlar: ratsional poyabzal, komfortlilik, ergonomika, antropometriya, 3D skanerlash, gibrid materiallar, aqlli taglik detaili.

Аннотация. В статье проанализированы концепция рациональной обуви, история ее формирования и современное состояние на основе научных работ зарубежных ученых. Хотя идея рациональной обуви не нова, в ней изучены современные конструкторские, материаловедческие и цифровые проектные решения, которые могут быть использованы для дальнейшего повышения ее комфорта. В результате исследования было сформировано научное новшество, предлагаемое для рациональной женской обуви, гибкая конструкция, основанная на индивидуальных антропометрических данных, гибридной материальной системе и комплексном подходе, объединяющем элементы «умного» детали низа обуви управляющей давления.

Ключевые слова: рациональная обувь, комфорт, эргономика, антропометрия, 3D сканирование, гибридные материалы, "smart" стелька.

Abstract. The article analyzes the issue of improving the convenience of everyday women's shoes from the point of view of the concept of rational shoes. The formation of the concept of rational footwear, its ergonomic, anthropometric, hygienic and biomechanical requirements are generalized on the basis of scientific works of foreign and domestic researchers. Instead of a radical change in the concept of rational shoes in modern conditions, the prospects for its improvement with individual anthropometric data, 3D scanning and digital

ISSN 3030-3907

design, hybrid materials, modular design and sensor pressure control elements are considered.

Keywords: rational shoes, everyday shoes, amenities, ergonomics, anthropometry, paws, 3D scanning, hybrid materials, modular design, smart insole, biomechanics.

KIRISH.

Zamonaviy poyabzal sanoatining rivojlanish tendensiyalari mahsulotning tashqi ko‘rinishi va modaga mosligini ta’minlash bilan cheklanmay, uning inson organizmiga ta’siri, ergonomik xususiyatlari, uzoq muddatli foydalanishdagi qulayligi va gigiyenik ko‘rsatkichlariga ham katta e’tibor qaratishni talab etmoqda. Ayniqsa, kundalik poyabzal inson tomonidan kun davomida bir necha soat davomida foydalanilishi sababli uning konstruksiyasi oyoq panjasining anatomik tuzilishi va biomexanik harakatlariga maksimal darajada mos bo‘lishi kerak.

Poyabzal sanoatida “ratsional poyabzal” tushunchasi yangi tushuncha emas. Uning shakllanishida tibbiyot, ortopediya, gigiyena, antropometriya va ergonomika sohalarida olib borilgan tadqiqotlar muhim o‘rin tutgan.

Mazkur maqolaning maqsadi ayollar kundalik ratsional poyabzalining qulaylilik ko‘rsatkichlarini oshirishga xizmat qiluvchi zamonaviy konstruktorlik va texnologik yechimlarni tahlil qilish hamda ularni yagona kompleks tizimga birlashtirish imkoniyatlarini ilmiy jihatdan asoslashdan iborat.

Poyabzal konstruksiyasining qulayligini belgilovchi eng muhim omillardan biri uning oyoq panjasi shakli va o‘lchamlariga mosligidir. Oyoq panjasi murakkab anatomik-biomexanik tizim bo‘lib, uning uzunligi, eni, tovon qismining kengligi, kaft-gumbaz balandligi, barmoqlar joylashuvi va boshqa parametrlar individual xususiyatlarga ega.

I. Krauss va hammualliflari tomonidan olib borilgan tadqiqotlarda ayollar va erkaklar oyoq panjalari o‘rtasidagi morfologik farqlar o‘rganilgan. Tadqiqotlarda oyoq shaklining jinsga bog‘liq xususiyatlari mavjudligi, shu jumladan panjaning nisbiy kengligi, tovon qismi, gumbaz balandligi va ayrim proporsional ko‘rsatkichlarda sezilarli tafovutlar mavjudligi qayd etilgan [1].

Bu holat ayollar poyabzalini loyihalashda faqat oyoq uzunligi yoki standart to‘liqlik parametrlaridan foydalanish yetarli emasligini ko‘rsatadi. Bir xil uzunlikdagi ikki oyoq panjasi ko‘ndalang o‘lchamlar, gumbaz balandligi va tovon konfiguratsiyasi bo‘yicha farq qilishi mumkin.

Ayollar kundalik poyabzali uchun bu masala yanada muhim, chunki uning konstruksiyasiga estetik talablar ham bevosita ta’sir qiladi. Tor tumshuq, yuqori poshna, taglikning haddan tashqari qattiqligi yoki poyabzal ichki hajmining anatomik xususiyatlarga mos kelmasligi uzoq muddat foydalanilganda noqulaylikni kuchaytiradi. Shuning uchun zamonaviy ratsional poyabzal

ISSN 3030-3907

konstruksiyasini ishlab chiqishda antropometrik ma’lumotlarni chuqurroq differensiallashtirish zarur[2].

Raqamli texnologiyalarning rivojlanishi poyabzal loyihalash jarayoniga yangi yondashuvlarni olib kirdi. Oyoq panjasini 3D skanerlash orqali qisqa vaqt ichida uning uch o‘lchamli geometrik modelini hosil qilish mumkin.

An’anaviy antropometrik o‘lchashlarda oyoq uzunligi, eni, aylanasi va ayrim balandlik parametrlariga e’tibor berilsa, 3D skanerlash oyoq sirtining murakkab fazoviy shaklini ham raqamlashtirish imkonini beradi. Olingan ma’lumotlar asosida oyoq panjasining individual yoki tipologik modeli yaratilishi mumkin[3].

Bunday yondashuv individual buyurtma asosida poyabzal ishlab chiqarish bilangina cheklanmaydi. Aksincha, katta hajmdagi 3D antropometrik ma’lumotlar bazasini shakllantirish ommaviy ishlab chiqarish uchun ham anatomik jihatdan asoslangan yangi tipologik qoliplar qatorini yaratish imkonini beradi.

Haddan tashqari qattiq taglik oyoqning tabiiy bukilishiga qarshilik ko‘rsatishi mumkin. Juda yumshoq taglik esa tayanch barqarorligini kamaytirishi ehtimoli mavjud. Demak, optimal yechim materialning qattiqligi, elastikligi, qalinligi va taglik geometrik profilining o‘zaro muvofiqligini ta’minlashdan iborat.

Taglik profilini biroz yumaloqlashtirish yurish vaqtida oyoqning tovondan panjaning old qismiga o‘tishini yengillashtirishi mumkin. Bunday konstruktiv yechim tabiiy “dumalash” mexanizmini qo‘llab-quvvatlab, ayrim zonalarga tushadigan yukni qayta taqsimlash imkoniyatiga ega.

Poyabzalning qulayligini oshirishda material tanlash hal qiluvchi ahamiyatga ega. Biroq zamonaviy poyabzal uchun barcha zarur xususiyatlarni bir vaqtning o‘zida ta’minlaydigan yagona “ideal” material mavjud emas.

Shu sababli ayollar ratsional poyabzali uchun gibrid material tizimini qo‘llash maqsadga muvofiq.

Taklif etilayotgan tizimda poyabzalning har bir zonasi bajaradigan funksiyasiga qarab material tanlanadi. Ustki detalning oyoq bilan faol deformatsiyalanadigan zonalarida elastik va gigiyenik materiallardan, shakl barqarorligi zarur bo‘lgan zonalarda esa mustahkamroq materiallardan foydalanish mumkin.

Ichki detallarda namlikni boshqaruvchi va teri bilan kontaktda qulaylikni ta’minlovchi materiallardan foydalanish maqsadga muvofiq. Taglik tizimida esa zarba energiyasini yutuvchi ko‘pikli materiallar, tayanch barqarorligini ta’minlovchi nisbatan qattiq qatlamlar va yeyilishga chidamli tashqi qatlam birlashtirilishi mumkin[4].

Qayta ishlangan poliester va boshqa ikkilamchi xomashyolardan foydalanish ekologik barqarorlikni ta’minlash nuqtai nazaridan ham istiqbolli hisoblanadi. Zamonaviy tadqiqotlar poyabzal taglik materiallarining xizmat muddatini

ISSN 3030-3907

uzaytirish va ekologik ko‘rsatkichlarini yaxshilash yo‘nalishidagi texnologik imkoniyatlar mavjudligini ko‘rsatmoqda [5].

Kundalik poyabzal turli ekspluatatsion sharoitlarda foydalaniladi. Iste’molchi bir kun davomida uzoq yurishi, transportda harakatlanishi, ofisda uzoq vaqt o‘tirishi yoki zinapoyalardan foydalanishi mumkin. Bunday sharoitlarning har birida oyoqqa tushadigan yuk va qulaylik talablari farqlanadi.

Shu sababli poyabzalning ayrim funksional elementlarini almashtirish yoki sozlash imkonini beradigan modulli-transformer konstruksiya taklif etiladi.

Bunda ichki anatomik qo‘shimcha, amortizatsion modul yoki ayrim taglik elementlarini iste’molchining ehtiyoji va foydalanish sharoitiga qarab almashtirish imkoniyati yaratiladi.

So‘nggi yillarda rivojlanayotgan istiqbolli yo‘nalishlardan biri poyabzal ichki tagligiga sensorli elementlarni integratsiya qilishdir. Bunday “aqlli” pataklar oyoq panjasining tayanch yuzasidagi bosimini aniqlash, yurish parametrlarini kuzatish va to‘plangan ma’lumotlarni raqamli shaklda tahlil qilish imkoniyatini beradi.

O‘tkazilgan tahlillar shuni ko‘rsatadiki, zamonaviy poyabzal qulayligini oshirish bo‘yicha ilmiy ishlarda antropometriya, materialshunoslik, biomexanika, raqamli loyihalash va sensor texnologiyalari bo‘yicha katta hajmdagi natijalar mavjud.

Yuqorida bayon etilgan tahlil va nazariy asoslar natijasida ishning ilmiy yangiligi quyidagi holatlarda ifodalanadi:

1. Ayollar kundalik ratsional poyabzalini loyihalashda mahalliy antropometrik ma’lumotlar va oyoq panjasining 3D geometrik parametrlarini klasterlash asosida differensiallashtirilgan qolip o‘lchamlari tizimini shakllantirish taklif etildi.

2. Poyabzal detallarining funksional vazifalaridan kelib chiqib, tabiiy, ko‘pikli, namlikni boshqaruvchi va ekologik barqaror materiallarni maqsadli kombinatsiyalashga asoslangan gibrid material tizimining konseptual modeli ishlab chiqildi.

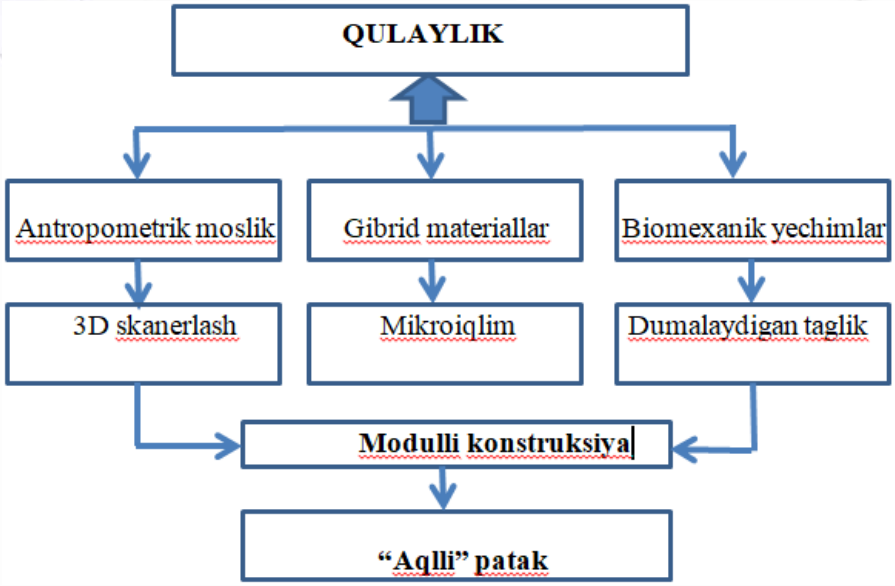
3. Turli ekspluatatsion sharoitlarga moslashtirish hamda poyabzalning xizmat muddatini uzaytirish maqsadida almashtiriladigan funksional elementlarga ega modulli-transformer konstruktiv yechim asoslandi.

4. Oyoq panjasidagi bosim taqsimotini aniqlash va poyabzalni individual sozlash uchun sensorli “aqlli” patakdan qayta aloqa elementi sifatida foydalanish imkoniyati taklif etildi.

5. Poyabzal ichki mikroiqlimini tartibga soluvchi passiv ventilyatsiya, biomexanik yukni optimallashtiruvchi taglik profili, individual anatomik moslik va

ISSN 3030-3907

sensorli nazoratni yagona ratsional poyabzal tizimida birlashtirish g‘oyasi shakllantirildi.



1-rasm. Ayollar kundalik poyabzali qulayligini shakllantiruvchi konstruktiv-texnologik omillarning o‘zaro bog‘liqlik sxemasi

Taklif etilayotgan ilmiy yondashuvning asosiy xususiyati alohida texnologik yangiliklarni yaratishdan ko‘ra, mavjud va istiqbolli yechimlarni ayollar kundalik poyabzalining qulayligini oshirish maqsadida o‘zaro bog‘langan yagona tizim sifatida shakllantirishdan iborat.

Modulli konstruksiya ayrim funksional elementlarni almashtirish orqali mahsulotning xizmat muddatini uzaytirishga yordam beradi. Sensorli elementlardan foydalanish esa oyoq panjasining yuklanishi to‘g‘risidagi obyektiv ma’lumotlarni olish va shu asosda konstruksiyani moslashtirish imkonini beradi.

Bunday yondashuv poyabzal ishlab chiqarish korxonalari uchun ham istiqbolli. Raqamli antropometrik ma’lumotlar bazasi va parametrik qolip modellarining yaratilishi kelajakda ommaviy ishlab chiqarish bilan individual moslashtirish o‘rtasidagi texnologik tafovutni kamaytirishi mumkin.

O‘tkazilgan ilmiy adabiyotlar va zamonaviy konstruktorlik-texnologik yechimlar tahlili ayollar kundalik poyabzalining komfortlilik darajasini oshirish ko‘p omilli vazifa ekanligini ko‘rsatdi.

Ratsional poyabzal konsepsiyasining asosiy tamoyillari ilmiy va amaliy jihatdan shakllangan bo‘lsa-da, zamonaviy raqamli texnologiyalar, yangi materiallar va sensorli tizimlarning rivojlanishi ushbu konsepsiyani yangi sifat bosqichiga olib chiqish imkoniyatini yaratmoqda.

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FASLLAR ALMASHINUVINING ODAM VA HAYVONLARDA GORMONAL FON (MELATONIN, KORTIZOL) VA FAOLLIK RITMIGA TA'SIRI

Dilfuzaxon Boqijon qizi Anvarjonova
Farg‘ona Davlat Universiteti magistranti
E-mail: anvarjonovadilfuza83@gmail.com

Annotatsiya. Maqolada yil davomida kun uzunligi va yorug‘lik rejimining o‘zgarishi odam hamda hayvon organizmidagi gormonal muvozanatga, xususan melatonin va kortizol miqdoriga qanday ta'sir ko‘rsatishi ko‘rib chiqiladi. Kun uzunligi ya’ni, fotoperiod bu epifiz bezida melatonin ishlanishini va buyrak usti bezi po‘stlog‘ida kortizol chiqishini yo‘naltiruvchi tabiiy soat vazifasini bajaradi. Bundan tashqari mazkur ishda odamlarda qish va yoz oylarida melatonin cho‘qqisining o‘zgarishi, tongi kortizol ko‘tarilishining fasl bo‘yicha tebranishi, shuningdek mavsumiy ko‘payuvchi hayvonlar fotoperiodik signalning gormonal boshqaruvga aylanish yo‘li tahlil qilingan. Yig‘ilgan ma'lumotlarga ko‘ra, kuz-qish oylarida qorong‘ulik uzayishi bilan melatonin ishlab chiqarilish muddati cho‘zilib, bu holat asab tizimi faolligi, uyqu-uyg‘onish tartibi va gonadotrop gormonlar sekretsiyasiga bilvosita ta'sir ko‘rsatadi. Odamlarda uchraydigan mavsumiy affektiv holat (SAD) aynan shu jarayon bilan izohlanadi.

Kalit so‘zlar: fotoperiod, melatonin, kortizol, sirkadian ritm, mavsumiy ritm, epifiz bezi, gipotalamus-gipofiz-buyrak usti o‘qi, hayvonlar fiziologiyasi.

Annotation. The article examines how changes in day length and light regime throughout the year affect the hormonal balance in the human and animal organisms, particularly the levels of melatonin and cortisol. Day length, i.e. the photoperiod, acts as a natural clock that directs the production of melatonin in the pineal gland and the release of cortisol from the adrenal cortex. In addition, this work analyses changes in the melatonin peak in humans during the winter and summer months, seasonal fluctuations of the morning cortisol rise, as well as the pathway by which the photoperiodic signal is converted into hormonal regulation in seasonally breeding animals. According to the collected data, with the lengthening of darkness in the autumn–winter months the duration of melatonin production is extended; this condition indirectly affects nervous-system activity, the sleep–wake cycle and the secretion of gonadotropic hormones. Seasonal affective disorder (SAD) observed in humans is explained precisely by this process.

Keywords: photoperiod, melatonin, cortisol, circadian rhythm, seasonal rhythm, pineal gland, hypothalamic–pituitary–adrenal axis, animal physiology.

Аннотация. В статье рассматривается, как изменение продолжительности дня и светового режима в течение года влияет на гормональный баланс в

ISSN 3030-3907

организме человека и животных, в частности на уровень мелатонина и кортизола. Продолжительность дня, то есть фотопериод, выполняет функцию природных часов, направляющих выработку мелатонина в эпифизе и выделение кортизола в коре надпочечников. Кроме того, в данной работе проанализированы изменения пика мелатонина у людей в зимние и летние месяцы, сезонные колебания утреннего подъема кортизола, а также путь преобразования фотопериодического сигнала в гормональную регуляцию у сезонно размножающихся животных. Согласно собранным данным, с удлинением темноты в осенне-зимние месяцы продлевается продолжительность выработки мелатонина; это состояние косвенно влияет на активность нервной системы, режим сна-бодрствования и секрецию гонадотропных гормонов. Сезонное аффективное расстройство (SAD), встречающееся у людей, объясняется именно этим процессом.
Ключевые слова: фотопериод, мелатонин, кортизол, циркадный ритм, сезонный ритм, эпифиз, гипоталамо-гипофизарно-надпочечниковая ось, физиология животных.

KIRISH.

Yer o‘z o‘qi atrofida va Quyosh atrofida aylanishi tufayli barcha tirik mavjudotlar davriy o‘zgarishlar ichida rivojlangan. Kun uzunligi, harorat va yorug‘lik kuchining yil bo‘yi almashinishi organizmning ichki gormonal tartibiga bevosita ta'sir qiladi. Ushbu jarayonning markazida melatonin va kortizol gormonlari turadi. Ular mos ravishda tungi tinchlik holati va kunduzgi faollik holatini belgilovchi asosiy biokimyoviy ko‘rsatkichlar hisoblanadi. Melatonin miya ichidagi epifiz bezida, asosan qorong‘i vaqtda hosil bo‘ladi va uning miqdori to‘g‘ridan-to‘g‘ri tun davomiyligiga qarab o‘zgaradi. Kunlar qisqarib, tunlar uzayganda (kuz va qish oylarida) melatonin ko‘proq va uzoqroq vaqt davomida ishlab chiqariladi, yoz oylarida esa aksincha qisqaradi. Aynan shu xususiyati tufayli melatonin nafaqat kunlik, balki yillik ritmlarni ham kodlab beruvchi o‘ziga xos "vaqt belgisi" rolini o‘ynaydi. Kortizol gipotalamus-gipofiz-buyrak usti bezi tizimi orqali chiqariladi, kuchlanish holati va energiya sarfi bilan bog‘liq bo‘lib, odatda tong paytida eng yuqori nuqtasiga yetadi. Bir necha tadqiqotlarda kortizolning bazal darajasi va kunlik profili fasllarga qarab farq qilishi qayd etilgan, biroq bu farq melatoninnikiga nisbatan kamroq izchil ko‘rinishga ega.

Hayvonot dunyosida, xususan ma'lum faslda ko‘payadigan turlarda kun uzunligi haqidagi axborot melatonin orqali reproduktiv tizimni ishga tushirish yoki to‘xtatish signaliga aylanadi. Bunday moslashuv naslning eng qulay vaqt ko‘pincha bahorda dunyoga kelishini ta'minlaydi.

ISSN 3030-3907

Xususan, mavzuning ahamiyati so‘nggi yillarda yanada ortdi deb ayta olamiz. Chunki, tungi sun'iy yoritish, kechqurun ekrandan tarqaladigan nur, smenali ish tartibi va vaqt mintaqalarini almashtirib safar qilish odamning tabiiy fotoperiodik moslashuvini izdan chiqarmoqda. Bunday buzilishlar yurak-qon tomir, endokrin va ruhiy kasalliklar rivojlanishida xavf omili sifatida tilga olinmoqda. Shu bilan bir qatorda, chorvachilik va parrandachilikda mahsuldorlikni fotoperiodik yo‘l bilan boshqarish iqtisodiy jihatdan foydali hisoblanadi, shu sababli mavzu fundamental fiziologiya bilan bir qatorda amaliy tibbiyot va agrar soha nuqtai nazaridan ham dolzarb.

MAQOLANING MAQSADI.

Fasllar almashinuvining inson va hayvon organizmidagi melatonin va kortizol darajasiga, shuningdek kunlik va mavsumiy faollik ritmiga ta'sirini mavjud ilmiy manbalar asosida tahlil qilish va qiyoslashdan iborat. Yuqorida belgilab olgan maqsadimizga erishish uchun quyidagi vazifalar belgilandi:

1. Odamda melatonin va kortizolning fasl bo‘yicha o‘zgarishini tavsiflash,
2. Hayvonlarda fotoperiod orqali gormonal boshqaruv yo‘lini ko‘rib chiqish,
3. Ikki guruh o‘rtasidagi o‘xshash va farqli tomonlarni aniqlash,
4. Olingan ma'lumotlarning tibbiyot va chorvachilikdagi amaliy qo‘llanilishini muhokama qilish.

ADABIYOTLAR SHARHI VA METODOLOGIYA.

Ushbu maqolamiz tavsifiy adabiyotlar sharhi sifatida tayyorlandi. Maqolada oldimizga qo‘yilgan maqsadimizga ko‘ra, maqolani tayyorlash jarayonida eksperimental yoki klinik tadqiqot o‘tkazilmadi. Balki mavzu bo‘yicha nashr etilgan ishonchli ilmiy ishlarni tizimli tanlab olib, ularni chuqurroq o‘rganib chiqdik. Shuningdek, manbalarni tanlashda manbaning nashr 2000–2026 yillar oralig‘ida chiqqan bo‘lishi, taqrizdan o‘tgan jurnalda bosilgan bo‘lishi, odam yoki umurtqali hayvonlar ustida o‘tkazilgan tadqiqot yoki sharh bo‘lishi va melatonin yoki kortizolning fasl omili bilan bog‘liqligini o‘rgangan bo‘lishi kabi mezonlarga tayandik. Ushbu mezonlar asosida jami sakkizta asosiy manba tanlandi. Ulardan oltitasi xalqaro resenzlanadigan jurnallardan, ikkitasi esa O‘zbekistonda nashr etiluvchi milliy tibbiyot jurnallaridan olingan. Milliy manbalardan biri “Биомедицина ва амалиёт журнали” - fundamental va amaliy tibbiyotga oid tadqiqotlarni, jumladan fiziologiya va endokrinologiya yo‘nalishidagi ishlarni yoritib boradi [7]; ikkinchisi - “Фундаментал ва клиник тиббиёт ахборотномаси” - Buxoro davlat tibbiyot instituti tomonidan chiqariladigan, klinik va fundamental tibbiyot mavzularini qamrab oluvchi nashr hisoblanadi [8]. Ularning maqolaga kirish orqali biz O‘zbekistonda ushbu yo‘nalishdagi ilmiy faoliyatning mavjudligini va milliy nashrlarni xalqaro adabiyot bilan bir qatorda

ISSN 3030-3907

ko‘rib chiqish zarurligini ko‘rsatib o‘tdik. Tadqiqot davomida yig‘ilgan ma’lumotlar to‘rtta asosiy yo‘nalishda guruhlandi:

- odamda melatoninning fasliy o‘zgarishi,
- odamda kortizol dinamikasi va sirkadian ko‘rsatkichlar,
- hayvonlarda fotoperiodik-reproduktiv boshqaruv,
- gormonal o‘zgarishlarning faollik ritmi va uyqu-uyg‘onish tartibiga ta’siri.

Tahlil jarayonida odam va hayvonlardagi o‘xshashliklar hamda farqlar alohida e’tiborga olindi. Shuningdek, geografik kenglik, jins va yosh kabi qo‘shimcha omillar ham hisobga olindi. Yuqorida aytib o‘tganimizdek, ishlarning metodologiyasi va gormonlarni aniqlash usullari bir xil bo‘lmagani sababli miqdoriy meta-tahlil o‘tkazilmadi. Va natijalar sifat jihatdan umumlashtirildi. Bunday yondashuv mavzuning hozirgi holatini nisbatan to‘liq va obyektiv ko‘rsatish, shuningdek olingan xulosalarning tibbiyot va chorvachilikdagi amaliy ahamiyatini aniqlash imkonini beradi.

NATIJALAR.

Odamda melatoninning fasl bo‘yicha o‘zgarishiga ham bog‘liq ekanligi aniqlandi. Misol sifatida ko‘rishimiz mumkinki, Shvetsiyada, 56° shimoliy kenglikda o‘tkazilgan bir yillik kuzatuvda ofis xodimlarining kunlik yorug‘lik ta'siri hamda so‘lagidagi melatonin va kortizol miqdori har oy o‘lchangan [1]. Tungi melatonin darajasi qishda yozga nisbatan sezilarli darajada yuqori chiqqan, ertalab soat 07:00 dagi ko‘rsatkich ham aynan qish oylarida balandroq bo‘lgan. Buning sababi oddiy: qishda tabiiy yorug‘lik kamayadi, tun esa uzayadi, natijada melatonin ko‘proq vaqt davomida ishlab chiqariladi. Yana bir tadqiqotda jins va fasl birgalikda yorug‘lik ta'sirida melatonin qanchalik bosilishiga hamda sirkadian fazaning siljishiga qanday ta'sir qilishi tekshirilgan [2]. O‘rta kengliklarda yoz oylarida yorug‘likka sezgirlik pasayib, sirkadian faza erta siljigan. Bundan tashqari, ayollarning yorug‘likka erkaklardan ko‘ra yuqoriroq sezgirligi qayd etilgan, bu esa melatonin boshqaruvida jinsiy farq borligini va bu farq faslga qarab o‘zgarishi mumkinligini ko‘rsatadi.

Kortizol sirkadian fazaning muhim belgisi hisoblanadi, uning eng ma'lumotli ko‘rsatkichi esa uyg‘ongandan keyingi kortizol ko‘tarilishi (CAR) deb ataladi [3]. So‘lak, qon va siydikda melatonin hamda kortizolni aniqlash usullarini tahlil qilgan bir ishda ta'kidlanishicha, bu ikki gormon SCNning tashqi to‘qimalarga uzatiladigan signali sifatida ishlaydi. Ularning fazasi bir-biriga mos kelmasa, metabolizm, ruhiy holat va uyqu bilan bog‘liq muammolar ehtimoli oshadi. Kortizolning yillik o‘zgarishi melatoninnikiga qaraganda kamroq izchil bo‘lsa-da, yorug‘lik tanqis hududlarda qishda kortizol profili va sirkadian tizimlar orasidagi muvofiqlashuvning bo‘shashishi qayd etilgan. Kortizol va melatonin o‘rtasidagi bog‘liqlik alohida diqqatga sazovor ya’ni, melatonin miqdori ortganda odatda

ISSN 3030-3907

kortizol sekretsiyasi cheklanadi, shu tarzda ikki gormon bir-biriga qarama-qarshi, ammo bir-birini to‘ldiruvchi "tun-kun" signali sifatida markaziy va periferik soatlarni muvofiqlashtiradi [3].

Ma'lum faslda ko‘payadigan hayvonlar uchun kun uzunligi eng muhim tashqi signal hisoblanadi. G‘ozlar ustida o‘tkazilgan tajribada bahorgi va kuzgi tengkunlik hamda yozgi va qishki kunturish davrlarida epifiz bezining og‘irligi, hajmi va sekretor faolligi kun qisqarishi bilan ortgani, shu bilan birga melatonin retseptorlarining gipotalamus-gipofiz-gonad zanjirida fasl bo‘yicha tebranib turishi aniqlangan [4]. Bu ma'lumotlar melatonin sekretsiyasining o‘zi vaqt o‘lchash vositasi bo‘lib, reproduktiv tizimni to‘g‘ridan-to‘g‘ri boshqarishini ko‘rsatadi. Qo‘chqor va buqalarda o‘tkazilgan tadqiqotlarda ham shunga o‘xshash holat qayd etilganligi aniqlandi. Unga ko‘ra, melatonin qorong‘ulikda ancha ko‘p chiqadi va bu jinsiy bezlar faoliyatining yillik siklini belgilaydi [5]. Sutemizuvchilarda melatoninning mavsumiy ko‘payishga ta'siri gipotalamusning bir necha nuqtasi orqali amalga oshishi ko‘rsatilgan; fotoperiodga bog‘liq genlarning miya to‘qimasida ishga tushishi tana vazni va reproduktiv holatning mavsumiy o‘zgarishida ishtirok etadi [6]. Qushlarning ko‘chishga tayyorgarligi ham xuddi shu mexanizm bilan bog‘liqdir. Unga ko‘ra, kun uzunligining bahor va kuz oylaridagi o‘zgarishi gipofizning gonadotrop faolligini hamda energiya zaxirasini to‘plash uchun zarur bo‘lgan metabolik o‘zgarishlarni ishga tushiradi, natijada ko‘chishga tayyorgarlik kun uzunligi ma'lum chegaraga yetganda boshlanadi.

Melatonin va kortizolning fasl bo‘yicha o‘zgarishi harakat faolligi va uyqu-uyg‘onish tartibiga to‘g‘ridan-to‘g‘ri ta'sir qiladi. Qishda melatonin ko‘proq va uzoqroq chiqishi odamlarda uyquga moyillikni oshiradi, kunduzgi faollikni pasaytiradi va ba'zi kishilarda mavsumiy affektiv holat rivojlanishiga zamin yaratadi. Hayvonlarda esa fotoperiodning o‘zgarishi ko‘chish, qishki uyquga ketish va ko‘payish davrlarining aniq vaqtda boshlanishini ta'minlaydi, bu esa turning omon qolishi va soni barqarorligiga xizmat qiladi. Shuningdek biz ko‘rib chiqgan manbalarga ko‘ra, fasliy gormonal o‘zgarishning kuchi bir necha qo‘shimcha omilga bog‘liqligi qayd etilgan. Bundan tashqari, geografik kenglik muhim rol o‘ynar ekan. Bunda ekvatorga yaqin hududlarda kun uzunligi yil davomida deyarli o‘zgarmasligi sababli melatonin darajasidagi fasliy farq ham kichik bo‘ladi, shimoliy hududlarda esa qish va yoz orasidagi farq bir necha soatgacha yetib, gormonal tebranishni kuchaytiradi. Jins bo‘yicha ayollarda yorug‘likka yuqoriroq sezgirlik va shunga mos kuchliroq fasliy o‘zgarish qayd etilgan. Yosh omili bo‘yicha esa epifiz bezining ishlash qobiliyati yosh ulg‘aygan sari susayadi. Shu sababli keksa yoshda fasliy tebranishlar kamroq ifodalangan bo‘lishi mumkin, ammo bu masala hali yetarli o‘rganilmagan.

MUHOKAMA.

ISSN 3030-3907

Ko‘rib chiqilgan manbalar odam va hayvon organizmiga fasl almashinuvi fotoperiodik signalning epifiz bezi orqali melatoninga aylanishi orqali ta'sir qilishini ko‘rsatadi. Biroq bu ta'sirning oqibati ikki guruhda boshqacha namoyon bo‘ladi. Mavsumiy ko‘payuvchi hayvonlarda melatonin reproduktiv tizimni to‘g‘ridan-to‘g‘ri yoqadi yoki o‘chiradi. Bu qat'iy dasturlashtirilgan mexanizm hisoblanadi. Odamda esa zamonaviy turmush tarzi bu signalni ancha yumshatgan bo‘lsa-da, melatonin va kortizolning fasliy tebranishi hali ham ilmiy jihatdan qayd etilmoqda. Hamda, kortizol bilan melatonin orasidagi bog‘liqlik alohida muhokamaga loyiqdir. Ikkalasi ham SCN boshqaradigan markaziy soatning periferiyadagi ijrochisi bo‘lib, qarama-qarshi fazada ishlaydi ya’ni, melatonin tun kelganini, kortizol esa kun boshlanganini bildiradi. Fasl o‘zgarishi bu ikki signal nisbatini o‘zgartirsa, uzoq muddatda uyqu sifati, kayfiyat va modda almashinuviga salbiy ta'sir qilishi mumkinligi bir necha muallif tomonidan ta'kidlanadi.

Tadqiqot davomida olingan natijalarning amaliy ahamiyatini ikki yo‘nalishda ko‘rishimiz mumkin. Tibbiyotda mavsumiy affektiv holat, uyqu buzilishi va yorug‘lik yordamida davolashga oid protokollarni ishlab chiqishda fasliy melatonin-kortizol dinamikasini hisobga olish zarur. Chorvachilik va parrandachilikda esa mavsumdan tashqari ko‘payishni boshqarish masalan, melatonin implantlari yordamida allaqachon qo‘llanilib kelinmoqda. Bu O‘zbekiston kabi qishloq xo‘jaligi rivojlangan mamlakatlar uchun ham foydali yo‘nalish bo‘lib hizmat qila oladi. Shuningdek, ko‘rib chiqilgan tadqiqotlarning ko‘pchiligi shimoliy yoki mo‘tadil iqlim hududida o‘tkazilgan, shu sababli natijalarni quyoshli kunlari ko‘p bo‘lgan O‘rta Osiyo iqlimiga to‘g‘ridan-to‘g‘ri ko‘chirishda ehtiyot bo‘lishimiz lozim. Kelajakda O‘zbekiston sharoitida aholi va mahalliy chorva zotlarida gormonal fonning fasl bo‘yicha o‘zgarishini o‘rganish alohida qiziqish uyg‘otishi mumkin.

Odam va hayvonlardagi fotoperiodik-gormonal boshqaruvni solishtirsak, bir necha umumiy va farqli jihat ko‘zga tashlanadi. Umumiy jihatlarga quyidagilar kiradi:

1. Ikkala guruhda ham melatonin sintezi tun davomiyligiga mutanosib ravishda ortadi,
2. SCN barcha umurtqali hayvonlarda markaziy soat vazifasini bajaradi.

Melatonin retseptorlari miya va periferik to‘qimalarda keng tarqalgan bo‘lib, evolyutsiya davomida deyarli o‘zgarmagan holda saqlanib qolgan. Farq esa asosan yakuniy natijada ko‘rinadi. Bunda mavsumiy ko‘payuvchi hayvonlarda melatonin signali gonadotropin-relizing gormon neyronlari faolligini bevosita o‘zgartirib reproduktiv siklni qat'iy boshqarsa, odamda bunday qat'iy bog‘liqlik amalda yo‘qolgan, faqat kayfiyat, uyqu va energiya almashinuviga bo‘lgan bilvosita ta'sir saqlanib qolgan. Bu farqni evolyutsion nuqtai nazardan tushuntirish mumkin: inson

ISSN 3030-3907

turining keng hududlarda yashash va ijtimoiy moslashish qobiliyati fotoperiodik reproduktiv dasturning qat'iy shaklidan asta-sekin yumshoqroq shaklga o‘tishiga sabab bo‘lgan degan taxmin mavjud. Shunga qaramay, insonda ham tug‘ilish statistikasidagi fasliy farqlar va qish oylarida kayfiyat buzilishining ko‘payishi kabi hodisalar bu mexanizm to‘liq yo‘qolmaganini ko‘rsatadi.

Xususan, fasliy melatonin-kortizol dinamikasini bilish klinik amaliyotda bir necha yo‘nalishda foydali bo‘ladi. Mavsumiy affektiv holatni davolashda yorug‘lik terapiyasining ta'sirchanligi aynan shu fotoperiodik-melatonin mexanizmiga tayanadi, ertalab yorqin yorug‘lik bilan davolash melatonin fazasini siljitib kayfiyatni yaxshilaydi. Uyqu tibbiyotida ekzogen melatonin fasl va vaqt mintaqasi bilan bog‘liq uyqu muammolarini tuzatishda ishlatiladi. Endokrinologiyada esa kortizolning tongi ko‘tarilish ko‘rsatkichi stress holatini baholashda qo‘llaniladi. Buni o‘lchashda fasl omilini hisobga olish natijani aniqroq talqin qilishga yordam beradi.

Chorvachilik va parrandachilikda fotoperiodik-melatonin mexanizmidan keng foydalaniladi. Qo‘y va echkilarda mavsumdan tashqari qo‘chqorlash dasturlarini yaratishda melatonin implantlari qo‘llaniladi, bu fermer xo‘jaligiga yil davomida bir necha marta qo‘zilash olish imkonini beradi. Sut chorvachiligida yorug‘lik rejimini o‘zgartirish orqali sut mahsuldorligini oshirish mumkinligi ham ko‘rsatilgan. Chunki yorug‘lik rejimi melatonin orqali energiya almashinuvi va o‘sish gormoni sekretsiyasiga ta'sir qiladi. Parrandachilikda sun'iy fotoperiod boshqaruvi tovuqlarning tuxum berish faolligini yil davomida barqaror saqlash vositalaridan biri hisoblanadi.

O‘tkazilgan tahlil asosida bir necha amaliy tavsiyalar berib o‘tishimiz mumkin. Tibbiyot uchun:

1. Kayfiyat va uyqu shikoyatlari bilan murojaat qilgan bemorni tekshirishda fasl va joylashuvni hisobga olish tavsiya etiladi,
2. Qishda kunduzgi tabiiy yorug‘likka chiqish vaqtini oshirish (kamida yarim soat ertalab) sirkadian tizimni barqarorlashtirishi mumkin,
3. Kechqurun ekran nuridan cheklanish melatoninning o‘z vaqtida boshlanishiga yordam beradi.

Qishloq xo‘jaligi uchun:

1. Mavsumdan tashqari ko‘payishni rejalashtirishda fotoperiodik usullardan foydalanish mahsuldorlikni oshirishning samarali yo‘li bo‘lib qolmoqda,
2. O‘zbekistonning issiq iqlimi va uzun yozgi kuni sharoitida qishki fotoperiodik ta'sirni sun'iy kuchaytirish orqali chorva mahsuldorligini boshqarish istiqbolli yo‘nalish bo‘lishi mumkin.

Kelajakdagi ilmiy tadqiqot uchun esa O‘zbekistonning turli mintaqalarida yashovchi aholi va mahalliy chorva zotlarida melatonin-kortizol dinamikasini

ISSN 3030-3907

o‘rganuvchi mahalliy loyihalarni boshlash tavsiya etamiz. Yuqoridagi tahlilni yakunlash uchun quyidagi jadvalda odam va mavsumiy ko‘payuvchi hayvonlardagi fotoperiodik-gormonal boshqaruvning asosiy xususiyatlari qisqacha keltirilgan.

1-Jadval

Ko‘rsatkich	Odamda	Mavsumiy ko‘payuvchi hayvonlarda
Melatonin sekretsiyasi (qish)	Davomiyligi ortadi, cho‘qqisi yuqori	Davomiyligi ortadi, epifiz faolligi kuchayadi
Kortizol dinamikasi	Tongi ko‘tarilish fasl bo‘yicha o‘zgaradi	Kam o‘rganilgan, buyrak usti bezi o‘qi orqali boshqariladi
Reproduktiv ta'sir	Bilvosita, qat'iy emas	To‘g‘ridan-to‘g‘ri, jinsiy gormonlar orqali qat'iy boshqariladi
Asosiy fiziologik oqibat	Kayfiyat, uyqu, faollik o‘zgarishi	Ko‘payish, ko‘chish, qishki uyqu vaqti
Amaliy qo‘llanilishi	Yorug‘lik terapiyasi, ekzogen melatonin	Melatonin implantlari, sun'iy yorug‘lik rejimi

XULOSA.

Xulosa sifatida aytishimiz mumkinki, yil davomida kun uzunligi, yorug‘lik kuchi va haroratning davriy o‘zgarishi odam va hayvon organizmidagi asosiy gormonal tizimlarga ya’ni, melatonin va kortizol sekretsiyasiga ilmiy jihatdan ta’sir ko‘rsatishi tasdiqlangan. Ma’lum bo‘lishicha, melatonin qisqa kunli fasllarda uzoqroq chiqib, o‘ziga xos fotoperiodik belgi vazifasini bajaradi, kortizol esa unga qarama-qarshi, ammo bog‘liq tarzda o‘z tebranishini namoyon qiladi. Hayvonlarda bu mexanizm reproduktiv siklni qat'iy belgilasa, odamda u ko‘proq kayfiyat, uyqu va faollikka bilvosita ta'sir ko‘rsatuvchi omil sifatida ishlaydi. Olingan xulosalar tibbiyot, fiziologiya va zootexniya sohalarida amaliy ahamiyatga ega bo‘lib, fasliy gormonal o‘zgarishlarni hisobga olgan holda profilaktika, davolash va mahsuldorlikni boshqarish yondashuvlarini yaxshilashga xizmat qiladi.

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ISSN 3030-3907

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ISSN 3030-3907

SHOLI UNIDAN MAZALI VA SIFATLI PISHIRIQLAR TAYYORLASH

Shadiyeva Muxiba Shuxrat qizi
Buxoro davlat texnika universiteti 12-24 OOT guruh magistranti
Ergasheva Xusnirabo Bobonazarovna
Buxoro davlat texnika universiteti OOMT kafedrasi professori

Annotatsiya. Ushbu maqolada sholi unidan mazali, sifatli va iste'molchilar talabiga javob beradigan pishiriqlar tayyorlashning zamonaviy texnologik imkoniyatlari tahlil qilinadi. Sholi uni tarkibida kleykovina hosil qiluvchi oqsillar mavjud emasligi sababli uni non-bulka va qandolat mahsulotlari ishlab chiqarishda qo'llash bug'doy unidan texnologik jihatdan farq qiladi. Tadqiqotning asosiy maqsadi sholi unining fizik-kimyoviy xususiyatlarini hisobga olgan holda pishiriqlarning ta'mi, hidi, rangi, tuzilishi, g'ovakligi va umumiy iste'mol qiymatini yaxshilash imkoniyatlarini aniqlashdan iborat. Ilmiy manbalar tahlili shuni ko'rsatadiki, sholi unining zarracha o'lchami, suvni yutish qobiliyati, kraxmalning xususiyatlari va retsepturadagi qo'shimcha komponentlar tayyor mahsulot sifatiga sezilarli ta'sir ko'rsatadi. Ayniqsa, mayda zarrachali sholi unidan foydalanish pishiriqlarning yumshoqligi, g'ovakligi va iste'mol xususiyatlarini yaxshilashi mumkin. Shuningdek, suli uni, dukkakli ekinlar uni, oziqaviy tolalar va boshqa funksional komponentlardan foydalanish mahsulotning oziqaviy qiymatini oshirish imkonini beradi. Maqolada sholi unidan pechenye, keks, biskvit va boshqa pishiriqlar ishlab chiqarish istiqbollari ham yoritilgan.

Kalit so'zlar: sholi uni, pishiriq, pechenye, keks, biskvit, kleykovinasiz mahsulot, kraxmal, oziqaviy qiymat, organoleptik ko'rsatkichlar, texnologiya.

Аннотация. В статье рассматриваются современные технологические возможности производства вкусных и качественных мучных изделий на основе рисовой муки. В связи с отсутствием белков, образующих клейковину, использование рисовой муки при производстве хлебобулочных и кондитерских изделий имеет ряд технологических особенностей по сравнению с пшеничной мукой. Основной целью исследования является определение возможностей улучшения вкуса, аромата, цвета, структуры, пористости и общей потребительской ценности изделий с учетом физико-химических свойств рисовой муки. Анализ научных исследований показывает, что размер частиц рисовой муки, водопоглотительная способность, свойства крахмала и дополнительные компоненты рецептуры оказывают существенное влияние на качество готового продукта. Использование муки с мелким размером частиц может способствовать улучшению мягкости, пористости и органолептических свойств изделий. Кроме того, применение овсяной муки, муки бобовых

ISSN 3030-3907

культур, пищевых волокон и других функциональных компонентов позволяет повысить пищевую ценность изделий. В статье также рассматриваются перспективы производства печенья, кексов, бисквитов и других изделий на основе рисовой муки.

Ключевые слова: рисовая мука, выпечка, печенье, кекс, бисквит, безглютеновые продукты, крахмал, пищевая ценность, органолептические показатели, технология.

Abstract. This article examines modern technological approaches to the production of tasty and high-quality bakery products based on rice flour. Since rice flour does not contain gluten-forming proteins, its application in bakery and confectionery production differs technologically from the use of wheat flour. The main objective of this study is to identify approaches for improving the taste, aroma, color, texture, porosity, and overall consumer quality of rice-flour-based bakery products. A review of scientific studies shows that rice flour particle size, water absorption capacity, starch properties, and additional formulation ingredients significantly affect the quality of finished products. The use of fine rice flour can improve softness, porosity, and sensory characteristics of rice-based cakes. In addition, the incorporation of oat flour, legume flours, dietary fiber, and other functional ingredients may increase the nutritional value of the products. The article discusses the prospects of producing cookies, cakes, biscuits, and other bakery products using rice flour.

Keywords: rice flour, bakery products, cookies, cake, biscuit, gluten-free products, starch, nutritional value, sensory properties, food technology.

KIRISH.

Bugungi kunda oziq-ovqat sanoatida aholining turli xil oziqaviy ehtiyojlarini hisobga olgan holda yangi turdagi mahsulotlarni ishlab chiqarish muhim yo‘nalishlardan biri hisoblanadi. Ayniqsa, don mahsulotlarini chuqur qayta ishlash, mahalliy xomashyodan yuqori qo‘shilgan qiymatga ega mahsulotlar olish va an’anaviy bug‘doy uniga muqobil xomashyolardan foydalanish bo‘yicha ilmiy tadqiqotlar kengayib bormoqda. Sholi dunyodagi muhim don ekinlaridan biri bo‘lib, undan guruch bilan bir qatorda un ham olish mumkin. Sholi unining oziq-ovqat sanoatidagi qo‘llanilish sohasi keng bo‘lib, undan turli xil kleykovinasiz non mahsulotlari, pechenye, keks, biskvit va boshqa pishiriqlar tayyorlash mumkin. Ilmiy sharhlarda sholi uni kleykovinasiz pishiriqlar uchun eng ko‘p ishlatiladigan xomashyolardan biri ekanligi qayd etilgan.

Sholi unining asosiy texnologik xususiyati uning kleykovina hosil qilmasligidir. Bug‘doy unida mavjud gliadin va glutenin oqsillari xamirga

ISSN 3030-3907

elastiklik va strukturaviy mustahkamlik beradi. Sholi unida bunday tizim mavjud emasligi sababli undan tayyorlangan pishiriqlarning hajmi, g‘ovakligi, elastikligi va teksturasi alohida texnologik yondashuvni talab qiladi. Shu sababli sholi unidan mazali pishiriq ishlab chiqarishda faqat unning o‘zidan foydalanish bilan cheklanib qolmasdan, uning zarracha o‘lchami, namlik miqdori, suvni yutish qobiliyati, kraxmalning kleysterlanish xususiyatlari hamda retsepturadagi yog‘, tuxum, shakar, kraxmal, oziqaviy tolalar va boshqa komponentlarning nisbatlarini optimallashtirish zarur.

2025-yilda e’lon qilingan ilmiy sharhda sholi uni kleykovinasiz pechenye ishlab chiqarishda eng ko‘p qo‘llanadigan bug‘doy uni o‘rnini bosuvchi xomashyolardan biri sifatida ko‘rsatilgan. Shuningdek, sholi uni asosidagi mahsulotlarning rangi va yengil tuzilishi ijobiy xususiyat sifatida qayd etilgan, biroq teksturani optimal darajaga keltirish formulatsiyani to‘g‘ri tanlashni talab qiladi. Demak, sholi unidan mazali pishiriqlar tayyorlash texnologiyasini takomillashtirish nafaqat yangi mahsulot yaratish, balki mahalliy don xomashyosidan samarali foydalanish nuqtayi nazaridan ham dolzarbdir.

TADQIQOTNING MAQSADI VA VAZIFALARI

Tadqiqotning asosiy maqsadi **sholi unidan yuqori organoleptik va texnologik sifatga ega mazali pishiriqlar tayyorlash imkoniyatlarini ilmiy asoslash**dan iborat.

Ushbu maqsadga erishish uchun quyidagi vazifalar belgilandi:

- sholi unining asosiy texnologik xususiyatlarini o‘rganish;
- sholi unining pishiriqlar sifatiga ta’sirini tahlil qilish;
- un zarracha o‘lchamining tayyor mahsulot xususiyatlariga ta’sirini aniqlash;
- pishiriqlarning ta’mi, hidi, rangi va konsistensiyasini yaxshilash imkoniyatlarini baholash;
- turli qo‘shimcha komponentlarning mahsulot sifatiga ta’sirini o‘rganish;
- sholi unidan kleykovinasiz pishiriqlar ishlab chiqarishning texnologik sxemasini taklif etish;
- tayyor mahsulotning organoleptik ko‘rsatkichlarini baholash;
- sholi unidan foydalanishning oziq-ovqat sanoatidagi istiqbollarini aniqlash.

TADQIQOT OBYEKTI VA USULLARI.

Tadqiqot obyekti sifatida sholi uni va undan tayyorlanadigan pishiriqlar tanlandi. Tadqiqotda sholi unining fizik-kimyoviy va texnologik xususiyatlari, shuningdek, undan tayyorlangan mahsulotlarning organoleptik ko‘rsatkichlari tahlil qilindi.

Pishiriqlar sifatini baholashda quyidagi asosiy ko‘rsatkichlarga e’tibor qaratish mumkin:

1. tashqi ko‘rinishi;

ISSN 3030-3907

2. shakli;
3. rangi;
4. hidi;
5. ta’mi;
6. ichki tuzilishi;
7. g‘ovakligi;
8. yumshoqligi;
9. namligi;
10. mahsulotning umumiy iste’mol qiymati.

Sholi unining zarracha o‘lchami ham muhim texnologik omil hisoblanadi. 2024-yilda chop etilgan tadqiqotda sholi unini mikromaydalash natijasida uning suvni ushlab qolish qobiliyati oshgani, kleysterlanish harorati pasaygani va sholi unidan tayyorlangan kekslarning qattiqligi kamaygani ko‘rsatilgan. Tadqiqotda mayda zarrachali un mahsulotning g‘ovakligi va o‘ziga xos hajmini ham yaxshilagani qayd etilgan. Bu natijalar sholi unidan pishiriq tayyorlashda **maydalash darajasini texnologik parametr sifatida boshqarish** muhimligini ko‘rsatadi.

SHOLI UNINING PISHIRIQ ISHLAB CHIQARISHDAGI AHAMIYATI.

Sholi unining asosiy tarkibiy qismi kraxmal hisoblanadi. Kraxmalning miqdori va xususiyatlari pishirish vaqtida xamirning qizdirilish jarayoniga, namlikning taqsimlanishiga va tayyor mahsulot strukturasining shakllanishiga ta’sir qiladi. Bug‘doy unidan farqli ravishda sholi uni xamirda elastik kleykovina to‘rini hosil qilmaydi. Natijada sholi unidan tayyorlangan mahsulotlar ayrim hollarda tez uvalanuvchan yoki qattiqroq bo‘lishi mumkin. Shu sababli retsepturani shakllantirishda namlik, yog‘, tuxum va strukturani yaxshilovchi komponentlarning nisbatini optimallashtirish talab etiladi. Ilmiy tadqiqotlarda sholi uni asosidagi kleykovinasiz mahsulotlarda un tarkibini boshqa kraxmal, oqsil va oziqaviy tolalar bilan boyitish orqali texnologik xususiyatlarni yaxshilash mumkinligi ko‘rsatilgan. Sholi unining yana bir afzalligi uning nisbatan neytral ta’mga ega bo‘lishidir. Bu xususiyat turli xil ta’m beruvchi komponentlar bilan uyg‘unlashtirish imkonini beradi. Masalan, kakao, vanilin, meva pyuresi, quritilgan mevalar, yong‘oq mahsulotlari va boshqa tabiiy komponentlardan foydalanish orqali pishiriqlarning iste’mol xususiyatlarini yaxshilash mumkin.

SHOLI UNINING ZARRACHA O‘LCHAMI VA PISHIRIQ SIFATI

Sholi unining zarracha o‘lchami pishiriq sifatiga ta’sir qiluvchi muhim texnologik omillardan biridir. Un qanchalik mayda va bir xil zarracha tarkibiga ega bo‘lsa, uning suv bilan o‘zaro ta’siri va xamir tarkibida bir tekis taqsimlanishi shunchalik samarali bo‘lishi mumkin. 2024-yilgi tadqiqot natijalarida sholi uni zarrachalarining maydalash darajasi oshirilganda suvni ushlab qolish qobiliyati

ISSN 3030-3907

ortgani, mahsulotning qattiqligi va chaynashga qarshiligi kamaygani hamda g‘ovaklik ko‘rsatkichlari yaxshilangani aniqlangan. Eng mayda fraksiyalardan foydalanilganda sholi kekslarining sensor baholari ham yuqoriroq bo‘lgan.

Shundan kelib chiqib, sholi unidan pishiriq tayyorlashda unni elash va zarracha o‘lchamini nazorat qilish mahsulot sifatini boshqarishning muhim bosqichi sifatida qaralishi mumkin. Biroq unni haddan tashqari maydalash ham har doim ijobiy natija bermasligi mumkin. Chunki zarracha o‘lchami bilan kraxmalning shikastlanish darajasi o‘rtasida bog‘liqlik mavjud. Shuning uchun optimal maydalash darajasi tajriba asosida aniqlanishi kerak.

SHOLI UNIDAN MAZALI PISHIRIQ TAYYORLASH TEXNOLOGIYASI

Sholi unidan pishiriq tayyorlash jarayoni bir necha asosiy texnologik bosqichlardan tashkil topadi:

Sholi → tozalash → quritish → maydalash → elash → retsept komponentlarini tayyorlash → aralashtirish → xamir tayyorlash → shakllantirish → pishirish → sovitish → qadoqlash → saqlash.

Xomashyoni tayyorlash. Avvalo sholi doni begona aralashmalardan tozalanadi. Donning sifati tayyor un va undan olinadigan mahsulot sifatiga bevosita ta’sir qiladi.

Maydalash. Tozalangan sholi tegirmon yoki boshqa maydalash uskunalarida maydalanadi. Olingan un elakdan o‘tkazilib, yirik zarrachalar ajratiladi.

Retsepturani shakllantirish. Sholi unidan pishiriq tayyorlashda asosiy xomashyoga qo‘shimcha ravishda tuxum, shakar, yog‘, sut yoki boshqa suyuq komponentlar, pishirish kukuni va ta’m beruvchi moddalar qo‘shilishi mumkin.

Mahsulotning texnologik va oziqaviy xususiyatlarini yaxshilash maqsadida boshqa don yoki dukkakli ekinlar unidan ham ma’lum miqdorda foydalanish mumkin. Masalan, 2025-yilgi tadqiqotlarda sholi unidan tayyorlangan kleykovinasiz keksga brokkoli niholi kukunini qo‘shish mahsulotning oqsil, yog‘, kul va oziqaviy tola miqdorini oshirishi, shuningdek, ayrim tekstura va texnologik ko‘rsatkichlarni yaxshilashi aniqlangan.

Xamir tayyorlash

Komponentlar belgilangan ketma-ketlikda aralashtiriladi. Sholi unida kleykovina mavjud bo‘lmagani uchun xamirni haddan tashqari uzoq aralashtirish talab etilmaydi. Asosiy maqsad barcha komponentlarning bir xil taqsimlanishini ta’minlashdir.

Shakllantirish. Tayyor massa mahsulot turiga qarab qoliplarga joylashtiriladi yoki kerakli shaklga keltiriladi.

Pishirish jarayonida kraxmalning kleysterlanishi, namlikning bug‘lanishi, oqsillarning denaturatsiyasi va mahsulot yuzasida rang hamda xushbo‘y hidning

ISSN 3030-3907

shakllanishi sodir bo‘ladi. Pishirish harorati va davomiyligi mahsulot turiga, uning massasiga va namligiga bog‘liq bo‘lib, tajriba orqali optimallashtirilishi lozim.

SHOLI UNIDAN TAYYORLANGAN PISHIRIQLARNING SIFAT KO‘RSATKICHLARI.

Tayyor mahsulot sifatini aniqlashda organoleptik baholash muhim o‘rin tutadi. Bunda mahsulotning tashqi ko‘rinishi, rangi, hidi, ta’mi va konsistensiyasi baholanadi.

1-jadval.

Pishiriq sifatini organoleptik baholash mezonlari

Ko‘rsatkich	Yaxshi sifatli mahsulot tavsifi
Tashqi ko‘rinishi	Shakli bir tekis, yuzasi silliq
Rangi	Bir xil, mahsulot turiga xos
Hidi	Yoqimli, begona hidsiz
Ta’mi	Yoqimli, sholi uniga xos yengil ta’m
Ichki tuzilishi	Bir tekis va yetarli darajada g‘ovak
Konsistensiyasi	Yumshoq yoki mahsulot turiga mos
Namligi	Mahsulot turiga mos, ortiqcha nam emas
Umumiy baho	Iste’molchi uchun yoqimli

Sholi unidan tayyorlangan mahsulotlarning iste’mol xususiyatlariga un zarracha o‘lchami, formuladagi komponentlar va pishirish sharoitlari katta ta’sir ko‘rsatadi.

2026-yilgi tadqiqotda bug‘doy unining bir qismini tabiiy yoki issiqlik-namlik bilan ishlov berilgan sholi uni bilan almashtirish natijasida pechenyening ayrim tekstura ko‘rsatkichlari o‘zgargani va chidamli kraxmal miqdori oshgani aniqlangan. Tadqiqotchilar issiqlik-namlik bilan ishlov berilgan sholi unini funksional xususiyatlari yaxshilangan ingredient sifatida baholagan.

Bu esa sholi unini oddiy muqobil xomashyo sifatida emas, balki **oldindan texnologik ishlov berilgan funksional ingredient** sifatida ham o‘rganish mumkinligini ko‘rsatadi.

SHOLI UNINI BOSHQA XOMASHYOLAR BILAN KOMBINATSIYALASH

Sholi unidan tayyorlangan pishiriqlarning oziqaviy va texnologik xususiyatlarini yaxshilash uchun uni boshqa unlar bilan kombinatsiyalash mumkin. Masalan, suli uni sholi uni asosidagi fermentlangan kekslarning suvni bog‘lash xususiyatini va ayrim tekstura ko‘rsatkichlarini o‘zgartirishi aniqlangan. 2025-yilgi

ISSN 3030-3907

tadqiqotda suli uni qo‘shilishi mahsulotning o‘ziga xos hajmi va ayrim strukturaviy xususiyatlariga ta’sir ko‘rsatgani qayd etilgan. Bundan tashqari, amarant, grechka, quinoa, sorgo va boshqa o‘simlik xomashyolari sholi uni bilan kombinatsiyada qo‘llanishi mumkin. 2025-yilgi keng qamrovli sharhda sholi uni asosidagi kleykovinasiz pechenyelarni boshqa o‘simlik unlari bilan boyitish mahsulotning oqsil, oziqaviy tola va mineral tarkibini yaxshilashi mumkinligi ko‘rsatilgan. Bunday kombinatsiyalashda asosiy masala qo‘shimcha komponent miqdorini optimal darajada tanlashdir. Chunki qo‘shimcha un miqdorining ortib ketishi mahsulotning ta’mi, rangi, hidi yoki teksturasini salbiy o‘zgartirishi mumkin.

TADQIQOT NATIJALARI VA MUHOKAMA.

Adabiyotlar tahlili shuni ko‘rsatadiki, sholi unidan mazali pishiriqlar tayyorlashda bir nechta omillar birgalikda hisobga olinishi kerak. Birinchi navbatda, **sholi unining zarracha o‘lchami** muhim. Mayda va bir xil zarrachali un suvni yaxshiroq bog‘lab, mahsulotning strukturaviy xususiyatlarini yaxshilashi mumkin. Ikkinchidan, **retsepturadagi komponentlarning nisbati** tayyor mahsulot sifatini belgilaydi. Sholi unining o‘zi kleykovina hosil qilmagani sababli tuxum, kraxmal, oqsil komponentlari va oziqaviy tolalar mahsulot strukturasini shakllantirishda muhim rol o‘ynashi mumkin. Uchinchidan, **issiqlik bilan ishlov berish** sholi unining funksional xususiyatlarini o‘zgartirishi mumkin. Issiqlik-namlik bilan ishlov berish kraxmalning xususiyatlariga ta’sir etib, tayyor mahsulotning hazm bo‘lish xususiyatlarini ham o‘zgartirishi mumkin. To‘rtinchidan, **sensor baholash** mahsulot yaratish jarayonining ajralmas qismi bo‘lishi kerak. Chunki mahsulotning kimyoviy tarkibi yaxshi bo‘lishining o‘zi yetarli emas; uning ta’mi, hidi, ko‘rinishi va konsistensiyasi ham iste’molchi talabiga javob berishi zarur. Sholi unidan tayyorlangan pishiriqlarning asosiy afzalligi — kleykovinasiz xomashyo asosida mahsulot yaratish imkoniyatidir. Shu bilan birga, an’anaviy bug‘doyli mahsulotlarga o‘xshash hajm, yumshoqlik va teksturani ta’minlash texnologik jihatdan asosiy muammolardan biri bo‘lib qolmoqda. Ilmiy sharhlarda ham kleykovinasiz pishiriqlarda texnologik va sensor sifatni bir vaqtning o‘zida ta’minlash hali ham muhim tadqiqot masalasi ekanligi ko‘rsatilgan.

SHOLI UNIDAN PISHIRIQ TAYYORLASHNING AFZALLIKLARI

Sholi unidan pishiriqlar ishlab chiqarishning quyidagi afzalliklarini ko‘rsatish mumkin:

- mahalliy don xomashyosidan samarali foydalanish;
- mahsulot assortimentini kengaytirish;
- kleykovinasiz mahsulotlar ishlab chiqarish imkoniyati;
- sholi unining neytral ta’mi tufayli turli retsepturalarni yaratish;
- turli funksional komponentlar bilan boyitish imkoniyati;

ISSN 3030-3907

- yangi texnologik ishlov berish usullarini qo‘llash imkoniyati;
- iste’molchilar uchun yangi turdagi mahsulotlar yaratish.

Sholi unidan tayyorlangan mahsulotlar nafaqat pechenye, balki keks, biskvit, pirog asoslari, kraker va boshqa pishiriqlar ko‘rinishida ham ishlab chiqarilishi mumkin.

O‘ZBEKISTON SHAROITIDA TADQIQOTNING ISTIQBOLLARI

O‘zbekistonda oziq-ovqat sanoatida mahalliy xomashyodan foydalanish, don mahsulotlarini chuqur qayta ishlash va yangi turdagi oziq-ovqat mahsulotlarini ishlab chiqarish muhim ahamiyatga ega. Sholi yetishtiriladigan hududlarda uning donidan un olish va ushbu unni qandolat mahsulotlari ishlab chiqarishda qo‘llash mahalliy xomashyoni qayta ishlash darajasini oshirishi mumkin.

Kelajakdagi tadqiqotlarda mahalliy sholi navlaridan olingan unlarning:

- namligi;
- oqsil miqdori;
- kraxmal miqdori;
- kul miqdori;
- suvni yutish qobiliyati;
- zarracha o‘lchami;
- kleysterlanish xususiyatlari;
- yog‘ni yutish qobiliyati kabi ko‘rsatkichlarini aniqlash maqsadga muvofiq.

Shuningdek, turli navdagi sholi unlari asosida pishiriqlar tayyorlab, ularning organoleptik va fizik-kimyoviy ko‘rsatkichlarini o‘zaro taqqoslash ilmiy jihatdan qiziqarli natijalar berishi mumkin.

XULOSA.

O‘tkazilgan adabiyotlar tahlili va ilmiy tadqiqotlar natijalarini umumlashtirish asosida sholi unidan mazali va sifatli pishiriqlar tayyorlash istiqbolli yo‘nalish ekanligi aniqlandi. Sholi uni kleykovinasiz pishiriqlar ishlab chiqarish uchun muhim xomashyo hisoblanadi. Biroq uning texnologik xususiyatlari bug‘doy unidan farq qilishi sababli tayyor mahsulotning hajmi, yumshoqligi, g‘ovakligi va strukturasi maxsus texnologik yondashuvni talab qiladi. Mahsulot sifatiga sholi unining zarracha o‘lchami katta ta’sir ko‘rsatadi. Mayda zarrachali sholi unidan foydalanish ayrim hollarda pishiriqlarning yumshoqligi, g‘ovakligi va sensor xususiyatlarini yaxshilashi mumkin. Sholi unini boshqa don va dukkakli ekinlar unlari, kraxmal, oqsil, oziqaviy tolalar hamda funksional komponentlar bilan kombinatsiyalash orqali mahsulotning oziqaviy va texnologik qiymatini oshirish mumkin.

Kelgusida mahalliy sholi navlaridan olingan unlarni chuqur o‘rganish, optimal maydalash darajasini aniqlash, turli retsepturalarni ishlab chiqish va tayyor pishiriqlarning sensor bahosini o‘tkazish muhim ilmiy-amaliy ahamiyatga ega.

ISSN 3030-3907

Shunday qilib, **sholi unidan mazali pishiriqlar tayyorlash texnologiyasini takomillashtirish** oziq-ovqat texnologiyasi uchun istiqbolli tadqiqot yo‘nalishi bo‘lib, mahalliy xomashyodan foydalanish, mahsulot assortimentini kengaytirish va zamonaviy iste’mol talablariga mos yangi oziq-ovqat mahsulotlarini yaratish imkonini beradi.

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ПОЛУЧЕНИЕ АРОМАТИЧЕСКИХ УГЛЕВОДОРОДОВ ИЗ ПРОПАНА НА ВЫСОКОКРЕМНЕЗЕМНЫХ КАТАЛИЗАТОРАХ

Сайфитдинова Моҳинур Баходировна
Студентка 122-й группы педиатрического факультета
Яхшиликова Хумора Лочинбековна
Студентка 122-й группы педиатрического факультета
Шукуров Бахриддин Шадикулович
Ассистент кафедры медицинской химии Самаркандского государственного медицинского университета, PhD.

Аннотация. В данной работе изучены закономерности превращения пропана в ароматические углеводороды на цеолитном катализаторе структурного типа ZSM-5, модифицированном галлием. Актуальность исследования обусловлена необходимостью эффективной утилизации природного, попутного и отходящего газа нефтедобывающих и нефтеперерабатывающих предприятий с целью получения ценных нефтехимических продуктов. Рассмотрена роль высококремнеземных цеолитов в процессах ароматизации легких алканов, а также влияние модифицирования галлием на каталитическую активность и селективность катализатора. Особое внимание уделено получению ароматических углеводородов, в том числе фракции бензол–толуол–ксилол (БТК), имеющей важное значение в производстве моторных топлив, синтетических каучуков, пластмасс, лекарственных препаратов и лакокрасочных материалов. Полученные результаты представляют научный и практический интерес для разработки эффективных каталитических систем переработки легких углеводородов в высокоценные ароматические соединения.

Ключевые слова: пропан, ароматизация, цеолит ZSM-5, модификация галлием, катализатор, ароматические углеводороды, бензол-толуол-ксилол (БТК), легкие алканы, нефтехимические продукты, селективность.

Abstract. This study investigates the conversion of propane into aromatic hydrocarbons over a gallium-modified ZSM-5 zeolite catalyst. The relevance of the research is determined by the need for efficient utilization of natural, associated petroleum, and refinery off-gases to produce valuable petrochemical products. The role of high-silica zeolites in the aromatization of light alkanes and the effect of gallium modification on the catalytic activity and selectivity of ZSM-5 catalysts are discussed. Particular attention is paid to the formation of aromatic hydrocarbons, especially the benzene–toluene–xylene (BTX) fraction, which is widely used in the production of motor fuels, synthetic rubbers, plastics, pharmaceuticals, and coating materials. The obtained results provide scientific

ISSN 3030-3907

and practical insights into the development of efficient catalytic systems for the conversion of light hydrocarbons into high-value aromatic compounds.

Keywords: propane, aromatization, ZSM-5 zeolite, gallium modification, catalyst, aromatic hydrocarbons, benzene–toluene–xylene (BTX), light alkanes, petrochemical products, selectivity.

Annotatsiya. Mazkur maqolada propanni aromatik uglevodorodlarga aylantirish jarayonining qonuniyatlari galliy bilan modifikatsiyalangan ZSM-5 turidagi seolit katalizatori ishtirokida o‘rganilgan. Tabiiy, yo‘ldosh va neftni qayta ishlash korxonalaridan chiqadigan gazlarni samarali utilizatsiya qilish hamda ulardan yuqori qo‘shilgan qiymatga ega neft-kimyo mahsulotlarini olish bugungi kunda dolzarb masalalardan biri hisoblanadi. Tadqiqotda yengil alkanlarni aromatlashtirish jarayonida yuqori kremniyli seolitlarning, xususan ZSM-5 katalizatorining ahamiyati ko‘rib chiqilgan. Galliy bilan modifikatsiyalash katalizatorning faolligi va selektivligiga ta’sir etuvchi muhim omil sifatida baholangan. Aromatizatsiya natijasida olinadigan benzol–toluol–ksilol (BTK) fraksiyasining sanoatdagi ahamiyati va undan motor yoqilg‘ilari hamda turli organik sintez mahsulotlarini ishlab chiqarishda foydalanish imkoniyatlari yoritilgan. Olingan natijalar yengil uglevodorodlarni qimmatbaho aromatik birikmalarga aylantirish uchun samarali katalitik tizimlarni yaratishda muhim ilmiy-amaliy ahamiyatga ega.

Kalit so‘zlar: propan, aromatizatsiya, ZSM-5 seoliti, galliy modifikatsiyasi, katalizator, aromatik uglevodorodlar, benzol–toluol–ksilol (BTK), yengil alkanlar, neft-kimyo mahsulotlari, selektivlik.

ВВЕДЕНИЕ.

В настоящее время весьма актуальна проблема получения нефтехимических продуктов из природных, попутных и отходящих газов нефтедобывающих и нефтеперерабатывающих предприятий. Утилизация попутного нефтяного газа на нефтедобывающих странах проводится путем сжигания его в огромных количествах на факельных установках из-за невозможности или экономической нецелесообразности транспортирования на газоперерабатывающие комплексы. В результате этого не только теряется невосполнимый энергетический ресурс, являющийся к тому же и ценным химическим сырьем, но и наносится огромный ущерб окружающей среде. Основными компонентами этих природных углеводородных газов, наряду с метаном, считают пропан и бутан. Известны работы [1-4], где с использованием цеолитных катализаторов удавалось превращать низшие алканы в ароматические углеводороды. Эффективными катализаторами

ISSN 3030-3907

получения ароматических углеводородов в процессе превращения парафинов или олефинов C_2–C_{12} являются высококремнеземные цеолиты группы пентасилов ZSM-5, ZSM-11, ЦВМ, ЦВН и т.д., каталитическая активность которых большинством исследователей связывается с кислотно-основными свойствами их поверхности, и обусловлена наличием протонных (бренстедовских) и апротонных (льюисовских) кислотных центров. Особую ценность в составе ароматических углеводородов представляет фракция бензол-толуол-ксилол (БТК). БТК применяется как в качестве компонента моторных топлив, так и в качестве сырья для получения синтетических каучуков, пластмасс, лекарственных средств, лакокрасочных изделий и т.д. после разделения.

Вместе с тем, промышленная реализация каталитической конверсии алканов C_1-C_4 обусловлена рядом факторов, в том числе необходимостью разработки способов повышения селективности катализаторов образования ароматических углеводородов из легких алканов. Решение этой задачи связано, в первую очередь, с созданием активных и селективных катализаторов и изучением влияния способа их синтеза и дальнейшей модификации на свойства ароматизации легких алканов.

В последнее время в исследованиях цеолитных носителей для ароматизации метана большое внимание уделяется синтезу соединенных структур типа MFI/MEL (ZSM-5/11) [5-8]. Аналогичный цеолит ранее использовался в качестве носителя при синтезе олефинов из диметилового эфира. Такая структура позволяет улучшить показатели работы катализаторов ароматизации метана вследствие увеличенного диаметра выходов каналов микропор.

В данной работе изучены закономерности превращения пропана в ароматические углеводороды на цеолитном катализаторе структурного типа ZSM-5, модифицированным галлием.

ЭКСПЕРИМЕНТАЛЬНАЯ ЧАСТЬ

Получение цеолитных катализаторов

Высококремнеземные цеолиты (алюмосиликаты, АС) с силикатным модулем 40 получали гидротермальным синтезом из щелочных алюмокремнегелей в автоклавах из нержавеющей стали с тефлоновыми ставками при температуре170-175 ºС в течение 5 суток. Исходную реакционную смесь готовили путем добавления к жидкому стеклу (29% SiO_2, 9% Na_2O, 62% H_2O) водного раствора нитрата алюминия $Al(NO_3)_3 \cdot 9H_2O$, в качестве темплата использовали гексаметилендиамин (ГМДА), при интенсивном перемешивании, pH реакционной смеси регулировали добавлением 0,1 N раствора азотной кислоты.

ISSN 3030-3907

Галлоалюмосиликат (Ga-AC) был получен путем частичной замены алюминия на галлий в исходном алюмокремнегеле ($SiO_2/Al_2O_3+Ga_2O_3=40$). Концентрация оксида галлия в цеолите составляла [Ga_2O_3] = 1,85 масс. %.

После окончания кристаллизации твердую фазу отделяли от жидкой фильтрованием, промывали дистиллированной водой до pH промывных вод ≤ 9, сушили в атмосфере воздуха при 110 °C в течение 24 часов и прокаливали для удаления ГМДА при 550 °C в течение 8 часов.

Для перевода в активную H-форму полученные образцы обрабатывали 25%-ным водным раствором NH_4Cl при 90 °C в течение 2 часов при расходе 10 г цеолита. После удаления Na^+ цеолиты в NH_4-форме сушили при 110 °C и прокаливали в атмосфере воздуха при 540 °C в течение 6 часов для получения H-формы цеолита.

Данные о составе и степени кристалличности полученных катализаторов представлены в табл. 1. Введение в состав цеолитов галлия на стадии гидротермального синтеза приводит к небольшому снижению степени кристалличности цеолитного катализатора, которая для обоих образцов является высокой.

Таблица 1.

Состав и степень кристалличности цеолитного катализатора

Образец	Концентрация, масс. %		Мольное соотношение $SiO_2/Al_2O_3+Me_2O_3$	Степень кристалличности, %
	Me_2O_3	Al_2O_3		
AC	–	4,07	40	100
Ga-AC	1,85	3,01	40	97

Каталитические испытания цеолитных катализаторов

Для изучения процесса превращения пропана на исследуемых катализаторах использовалась стендовая установка проточного типа. Конверсию пропана (степень чистоты 99,95% об.) осуществляли при атмосферном давлении с варьированием температуры реакции от 400 до 600 °C, объемная скорость подачи сырья составляла 500 $час^{-1}$. Испытание катализатора при каждой температуре проводили в течение 60 мин. До и после каждого опыта реактор с образцом продували азотом. Продукты реакции анализировали методом ГЖХ на хроматографе Хроматэк-Кристалл 500.2. Для определения состава жидкой фазы использовали капиллярную колонку BP-1 PONA (100 м × 0,25 мм × 0,5 мкм), а для определения состава газовой фазы – капиллярную колонку GS-Gas-Pro (60 м × 0,32 мм) и набивную колонку Carbosieve S-II (4 м × 2 мм, 60/80 меш). При проведении экспериментов определяли степень превращения пропана, выход

ISSN 3030-3907

газообразных и жидких продуктов, а также рассчитывали селективность образования продуктов реакции.

РЕЗУЛЬТАТЫ И ИХ ОБСУЖДЕНИЕ.

Немодифицированный цеолит в Н-форме проявляет относительно невысокую активность в процессе превращения пропана в ароматические углеводороды. Результаты приведены в табл. 2. В образующихся продуктах реакции содержится большое количество метана и низших олефинов. Конверсия пропана и выход ароматических углеводородов, образующихся при 600 °С на алюмосиликатном катализаторе, составляет соответственно 94 и 34,4%.

Использование галлоалюмосиликата в процессе превращения пропана позволяет значительно повысить выход ароматических углеводородов и снизить образование метана и этана. На этом катализаторе заметное превращение пропана наблюдается при температуре реакции 450 °С. С повышением температуры реакции конверсия пропана резко возрастает и при 600 °С достигает 100%. При 500 °С наблюдается заметное образование ароматических углеводородов, а при 600 °С – достигает 52,5%.

Таблица 2.

Показатели процесса превращения пропана на цеолитных катализаторах

Катализатор	T, °C	X, %	S_1, %	S_2, %	S_3, %	S_4, %	S_5, %	A, %
AC	400	8	0,6	24,9	65,6	6,2	2,7	0,2
	450	20	1,2	43,5	40,9	9,5	4,9	0,9
	500	40	2,3	65,1	12,3	12,9	7,4	3,0
	550	78	2,5	50,0	1,0	9,6	36,9	28,6
	600	94	3,2	51,5	0,1	8,7	36,5	34,4
GA-AC	400	11	4,8	27,9	47,0	5,8	14,5	1,6
	450	26	7,8	51,9	16,1	7,7	16,5	4,3
	500	68	4,6	34,6	1,9	4,6	54,3	36,6
	550	92	4,4	34,7	0,3	4,0	56,6	51,8
	600	100	4,4	37,6	0,1	5,4	52,5	52,5

Примечание. T – температура реакции; X – конверсия; S_1 – селективность образования водорода; S_2 – селективность образования алканов C_1-C_2; S_3 – селективность образования алканов C_3-C_5; S_4 – селективность образования алкенов C_2-C_4; S_5 – селективность образования ароматических углеводородов; A – выход ароматических углеводородов.

ISSN 3030-3907

Из приведенных данных в таблице 3 видно, что основными продуктами превращения пропана на исследуемых катализаторах являются жидкие и газообразные углеводороды состава C_1-C_5. Катализат содержит смесь ароматических углеводородов, состоящую в основном из бензола, толуола и ксилолов (БТК), в небольших количествах также присутствуют алкилбензолы C_{9+}, нафталин и алкилнафталины. Газообразные продукты состоят преимущественно из метана и этана, а также в небольшом количестве присутствуют водород, алканы C_3-C_5 и олефины C_2-C_4.

Таблица 3.

Состав жидких и газообразных продуктов превращения пропана на цеолитных катализаторах

Катализатор	Состав жидких продуктов, % масс.				
	БТК	Алкилбензолы C_{9+}	Нафталин	Алкилнафталины	
АС	85	5	7	3	
GA-AC	83	5	8	5	
Состав газообразных продуктов, % масс.					
Катализатор	H_2	CH_4	C_2H_6	Алкены C_2-C_4	Алканы C_3-C_5
АС	2,7	36,2	18,0	10,4	32,7
GA-AC	8,1	45,3	20,9	7,6	18,1

В составе газообразных продуктов превращения пропана на галлоалюмосиликате содержатся больше водорода, метана и меньше алкенов C_2-C_4 и алканов C_3-C_5 по сравнению с продуктами, полученными на алюмосиликате. Низкий выход алкенов в продуктах реакции указывает на то, что они являются промежуточными продуктами, которые активно вступают в дальнейшее взаимодействие, приводящие к образованию ароматических углеводородов.

ЗАКЛЮЧЕНИЕ.

Полученные экспериментальные данные свидетельствуют о высокой активности высококремнеземного цеолита в процессе превращения пропана и относительно невысокой селективности образования ароматических углеводородов.

Введение на стадии гидротермального синтеза в состав цеолита галлия существенно повышает его активность в отношении образовании целевого продукта.

ISSN 3030-3907

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NON-AUTOCLAVED AERATED CONCRETE D600 MODIFIED WITH MINERALIZED FIBROUS LICORICE ROOT WASTE

Soy Vladimir Mikhailovich
Doctor of technical sciences, professor, Tashkent State Transport University, Tashkent, Uzbekistan, Tashkent 100167
E-mail: volodya_tsoy@inbox.ru
Eshbekov Shukhrat Gadoymurotovich
Assistant, Tashkent State Transport University Tashkent, Uzbekistan, Tashkent 100167
E-mail: sh.eshbekov77@gmail.com
Jumageldiev Aziz Olimovich
Master's degree, Tashkent State Transport University Tashkent, Uzbekistan, Tashkent 100167
E-mail: jumageldiyevaziz@gmail.com
Turgayev Janbul Adilbaevich
Doctor PhD in technical science, professor, Karakalpak state university Karakalpakstan, Uzbekistan, 230100
E-mail: jambulturgaev46@gmail.com

Abstract. The paper presents a shortened English version of a study on non-autoclaved aerated concrete of density class D600 modified with processed fibrous waste from licorice root. The research is aimed at improving the crack resistance of pore walls, reducing drying shrinkage and involving local plant waste in the production of lightweight wall materials. The fiber was prepared by sorting, grinding, hot-water washing, lime treatment and mild silicate mineralization. Direct addition of untreated licorice root waste delayed setting, destabilized gas expansion and reduced strength. The best composition, NAC-3, contained 3.5 kg/m3 of cleaned and lime-silicate-mineralized fiber. At an average density of 606 kg/m3 it reached a 28-day compressive strength of 3.05 MPa, flexural strength of 0.72 MPa, water absorption of 36% and drying shrinkage of 0.52 mm/m.

Keywords: non-autoclaved aerated concrete, D600, licorice root, plant fiber, mineralization, lime-silicate treatment, compressive strength, flexural strength, shrinkage, water absorption.

Annotatsiya. Qizilmiya ildizidan qayta ishlangan tolali chiqindilar bilan o‘zgartirilgan, zichligi D600 sinfidagi avtoklavlanmagan gazbeton bo‘yicha tadqiqotning qisqartirilgan inglizcha versiyasi keltirilgan. Tadqiqot teshik devorlarining yorilishga chidamliligini oshirish, quritish qisqarishini kamaytirish va mahalliy o‘simlik chiqindilarini engil devor materiallarini ishlab chiqarishga jalb etishga qaratilgan. Elyaf saralash, maydalash, issiq suvda yuvish, ohak bilan ishlov berish va yumshoq silikat minerallashuvi orqali tayyorlangan. Qayta ishlanmagan qizilmiya ildizi chiqindilarini to‘g‘ridan-to‘g‘ri qo‘shish,

ISSN 3030-3907

sozlashning kechikishiga, gazning kengayishini beqarorlashtirishga va mustahkamlikni pasayishiga olib keladi. Eng yaxshi kompozitsion NAC-3 tarkibida 3,5 kg/m3 tozalangan va ohak-silikat-mineralizatsiyalangan tola mavjud edi. O‘rtacha zichligi 606 kg/m3 bo‘lgan 28 kunlik bosim kuchi 3,05 MPa, egilish kuchi 0,72 MPa, suvni singdirish 36% va quritish qisqarishi 0,52 mm/m ni tashkil etdi.

Kalit so‘zlar: avtoklavlanmagan gazbeton, D600, qizilmiya ildizi, o‘simlik tolasi, minerallashuv, ohak-silikat bilan ishlov berish, bosim kuchi, egilish kuchi, qisqarish, suvni singdirish.

Аннотация. В статье представлена сокращенная англоязычная версия исследования неавтоклавного газобетона класса плотности D600, модифицированного переработанными волокнистыми отходами из корня. Цель исследования — повысить трещиностойкость стенок пор, уменьшить усадку при высыхании и использовать местные растительные отходы в производстве легких стеновых материалов. Волокно было подготовлено путем сортировки, измельчения, промывки в горячей воде, обработки известью и слабой силикатной минерализацией. Непосредственное добавление необработанных отходов из корня солодки замедляло схватывание, приводило к дестабилизации газовыделения и снижению прочности. Наилучший состав, NAC-3, содержал 3,5 кг/м3 очищенного и обработанного известью и силикатами волокна. При средней плотности 606 кг/м3 прочность на сжатие через 28 дней составила 3,05 МПа, прочность на изгиб — 0,72 МПа, водопоглощение — 36 %, а усадка при высыхании — 0,52 мм/м.

Ключевые слова: неавтоклавный газобетон, D600, корень солодки, растительное волокно, минерализация, силикатно-известковая обработка, прочность на сжатие, прочность на изгиб, усадка, водопоглощение.

1. INTRODUCTION.

When concrete is subjected to shrinkage, a need for deformation will occur. If this deformation is restrained, restraint forces will appear. When a concrete member is cast against an existing concrete member restraint forces may occur due to different needs of movement, which may lead to cracking. Two specific cases are when edge beams on concrete bridges are replaced and when concrete retaining walls are cast against an existing concrete foundation slab. Even though cracks are natural in reinforced concrete during the service state, they can cause durability problems if they become too large. Increased reinforcement amount and addition of fibre reinforcement to the concrete are two possibilities to

ISSN 3030-3907

control the cracking. However, guidance of how to design restrained members with regards to crack widths is insufficient in codes used today. Therefore, non-linear finite element analyses were performed in order to increase the understanding of the cracking response in restraint situations and how to design in these situations.

Finite element analyses were compared with test results on tie-rod tests carried out on concrete specimens with ordinary and fibre reinforcement. When using uniform material properties determined from tests, good agreement was achieved for the case with ordinary reinforcement. For the fibre reinforced concrete it was necessary to take into account the heterogeneity of the combined material. A new model, showing good agreement with test results, was proposed to simulate the behaviour of fibre reinforced concrete. When the modelling technique had been verified, it was also used to investigate the cracking response in other applications.

Non-autoclaved aerated concrete is widely used as a wall and heat-insulating structural material because it can be produced without energy-intensive autoclave curing. However, normal-cured aerated concrete is sensitive to the stability of gas formation, early setting and drying conditions. A common problem is the formation of microcracks in thin pore walls, which leads to increased shrinkage and insufficient bending resistance.

Dispersed fibers are usually introduced into cellular concrete to improve crack resistance. Mineral, basalt, polymer and industrial fibers are effective, but they increase the cost of the mixture and do not always correspond to the principle of local resource use. In regions where licorice root is processed, a considerable amount of fibrous plant waste is generated. This waste can be considered as a functional additive, but it cannot be used directly in cement systems because water-soluble sugars, extractives and phenolic compounds inhibit cement hydration and disturb the formation of a stable porous matrix.

The objective of this work was to evaluate the influence of cleaned and lime-silicate-mineralized licorice root fiber on the physical and mechanical properties of non-autoclaved aerated concrete D600. The study compared a reference mix without fiber, a mix with untreated waste, a mix with hot-water-washed fiber and a mix with fully mineralized fiber.

2. MATERIALS AND METHODS.

For the most part, this report makes use of metric units despite the fact that the cement (and concrete) industry, at the time of writing, continues to use nonmetric units for commerce and a mix of units for internal accounting. Nonmetric units are also commonly encountered in the literature on cement. Conversion of units is provided below for the convenience of the reader. It is important to note that some of the conversion factors are given here to more significant figures than can generally be justified in reporting cement data.

ISSN 3030-3907

In the increasingly popular industrial ecology paradigm, it is desirable to have industries and industrial processes that are interconnected and interdependent, particularly in the context of having no, or greatly reduced, net wastes by the entire multi-industry complex. In other words, it is desirable to have industries that consume other industries' waste products (the CemStar process, mentioned earlier, is a good example of this). Given that cement and concrete are produced and consumed in huge quantities worldwide, the manufacture of cement to meet this demand insures that enormous quantities of raw materials and fuels will also be required. The manufacture of cement (actually clinker) has virtue in its inefficiencies of high requisite temperatures and long residence times for clinker formation.

The cement industry tends not to distinguish between units of weight and mass but almost invariably conducts its business in the sense of weight. Thus the metric ton, a unit of mass, is treated as if it were a unit of weight; strictly, the conversions to weight are applicable only at mean sea level. Barrel (bbl) as a unit of cement weight (not volume) is no longer used by the cement industry but is frequently encountered in the historical literature. Its weight conversion has varied over the years by type of cement, reporting source, and by reporting region. For original (not re-converted) data reported by the Government, equivalences are as follows:

Portland cement M500 was used as the main binder. Hydrated lime Ca(OH)2 was introduced to provide an alkaline medium, stabilize gas formation and participate in the formation of the cement-silicate matrix. Finely ground quartz sand was used as the siliceous component. Fly ash or finely ground blast-furnace slag, silica fume, gypsum, a polycarboxylate superplasticizer, aluminium powder and water were also included in the compositions.

The fibrous licorice root waste was prepared in several stages: sorting, grinding to a fraction of 3-12 mm, hot-water washing, treatment with a calcium hydroxide suspension, mild silicate mineralization with diluted liquid glass, pressing and drying to working moisture. Hot washing removed soluble extractives, sugars, saponins and phenolic compounds. Lime-silicate mineralization formed a thin mineral layer on the fiber surface, improving its compatibility with the cement-lime matrix.

Table 1

Experimental variants of non-autoclaved aerated concrete D600

Mix	Fiber condition	Fiber dosage, kg/m3	Technological feature

ISSN 3030-3907

NAC-0	No fiber	-	Reference aerated concrete
NAC-1	Untreated licorice root waste	3.5	Direct addition of organic waste
NAC-2	Hot-water-washed fiber	3.5	Removal of soluble inhibitors
NAC-3	Cleaned and lime-silicate-mineralized fiber	3.5	Improved fiber-matrix compatibility

The mixture was prepared by dry mixing the mineral components, dispersing the prepared fiber in part of the mixing water with superplasticizer, adding this suspension to the dry mixture and finally introducing aluminium powder. The gas-forming additive was added at the last stage to avoid premature disruption of expansion. Specimens were kept in molds under film for 24 h and then cured under moist and normal laboratory conditions up to 28 days. Average density, settlement of the gas-concrete mass after maximum rise, setting delay, compressive strength at 7 and 28 days, flexural strength, water absorption, drying shrinkage and dry-state thermal conductivity were measured.

3. RESULTS AND DISCUSSION

Chemical control confirmed that the initial plant waste contained a high amount of soluble extractives and reducing sugars. Hot-water washing reduced the content of extractives from 14.6% to 2.6% and reducing sugars from 2.15% to 0.42%. After mineralization, these values decreased further to 1.9% and 0.31%, while the pH of the aqueous extract increased from 5.7 to 9.1. This means that the treated fiber became more suitable for a cement-lime environment.

Table 2

Main physical and mechanical properties of the experimental mixes

Mix	Density, kg/m3	Settlement, mm	Setting delay, min	Compressive strength 28 d, MPa	Flexural strength 28 d, MPa	Water absorption, %	Drying shrinkage, mm/m
NAC-0	604	5	0	2.08	0.44	44	0.78
NAC-1	598	17	110-125	1.18	0.28	53	0.94

ISSN 3030-3907

NAC-2	601	8	35-45	2.05	0.49	43	0.68
NAC-3	606	4	0-10	3.05	0.72	36	0.52

The results show that untreated licorice root waste had a negative effect on early structure formation. In NAC-1, the beginning of setting was delayed by 110-125 min compared with the control mix, and settlement after maximum rise increased to 17 mm. The 28-day compressive strength decreased from 2.08 MPa in the control composition to 1.18 MPa. Flexural strength also decreased from 0.44 MPa to 0.28 MPa. These results indicate that untreated organic matter acts as an inhibitor and destabilizes the porous structure.

Hot-water washing partly eliminated the harmful effect of soluble organic compounds. NAC-2 showed a 28-day compressive strength of 2.05 MPa, which was close to the reference mix. Flexural strength increased to 0.49 MPa and drying shrinkage decreased to 0.68 mm/m. Thus, washing is a necessary but not sufficient condition for the efficient use of plant fiber in aerated concrete.

The best performance was achieved for NAC-3 with cleaned and lime-silicate-mineralized fiber. The 28-day compressive strength reached 3.05 MPa, which is 46.6% higher than the control value. Flexural strength increased to 0.72 MPa, or 63.6% above the control value. At the same time, water absorption decreased from 44% to 36%, and drying shrinkage decreased from 0.78 to 0.52 mm/m. The average density remained within the D600 class and amounted to 606 kg/m3.

The improvement can be explained by the combined action of several mechanisms. First, hot washing removes organic inhibitors that delay hydration. Second, calcium hydroxide neutralizes acidic groups on the plant surface and saturates it with calcium ions. Third, silicate mineralization forms a thin calcium-silicate shell, which improves adhesion between the fiber and the cement-lime matrix. Finally, dispersed mineralized fibers reinforce pore walls and limit shrinkage microcracking without disturbing gas formation, because the fiber dosage is relatively low.

Table 3

Comparison of the proposed composition with the closest prototype

Indicator	Prototype RU2616303C1 D600	Proposed NAC-3	Change
7-day compressive strength, MPa	1.40	1.78	+0.38 MPa / +27.1%

ISSN 3030-3907

28-day compressive strength, MPa	1.60	3.05	+1.45 MPa / +90.6%
Average density, kg/m3	about 600	606	Comparable D600 density
Reinforcing component	Basalt fibrous waste	Mineralized licorice root fiber	Different nature and preparation of fiber

Compared with the nearest prototype in the same density class, the proposed composition is aimed at a substantial increase in 28-day compressive strength. This result is achieved not by the simple replacement of mineral fibers with plant raw material, but by controlled preparation of the licorice root fiber, including fractionation, hot washing, chemical control, lime neutralization and mild silicate mineralization. From a practical point of view, the composition may be used for wall blocks, partition slabs and heat-insulating structural elements of density class D600. It also allows local licorice root processing waste to be utilized in building materials.

When the concrete shrinks, there is a need for deformation. About this deformation prevention of the emergence of forced forces. When pouring concrete element against the existing element concrete construction, forcing forces can occur due to different movement needs, which can cause cracking. Two typical examples are edge beams on concrete bridges if the replacement and retaining walls are thrown against the existing foundation plate. Although it is natural during the service life, cracks may appear in the reinforced concrete structure if they are too large, cause durability problems. Increasing the amount of reinforcement or using fiber reinforcement in concrete are different ways to limit and control cracking. Guidance on how to measure the structures to be affected The current rules are insufficient in terms of the width of the cracks. Therefore non-linear finite elemental analysis was performed for for to increase to understand for the process of cracking in forced situations, as well as what volume to be such situations.

4. CONCLUSIONS.

1. A composition of non-autoclaved aerated concrete D600 with 3.5 kg/m3 of cleaned and lime-silicate-mineralized fibrous licorice root waste was developed.

2. Untreated licorice root waste worsened the properties of aerated concrete: 28-day compressive strength decreased to 1.18 MPa, water absorption increased to 53%, and drying shrinkage increased to 0.94 mm/m.

ISSN 3030-3907

3. Hot-water washing reduced soluble organic inhibitors and partly restored strength, but the maximum effect was achieved only after lime-silicate mineralization.

4. The rational composition NAC-3 had an average density of 606 kg/m3, compressive strength of 3.05 MPa, flexural strength of 0.72 MPa, water absorption of 36% and drying shrinkage of 0.52 mm/m.

5. The improvement is related to better adhesion between mineralized plant fiber and the cement-lime matrix, as well as dispersed reinforcement of pore walls.

6. The proposed approach expands the raw-material base for non-autoclaved aerated concrete and supports the resource-saving use of licorice root processing waste.

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YUZ, HARAKAT VA VAQTGA BOG‘LIQ MODELLAR ASOSIDA KO‘P MODALLI BIOMETRIK UZLUKSIZ AUTENTIFIKATSIYA TIZIMI: MUAMMOLAR VA YECHIMLAR

Alayev Ruhillo Habibovich
Mirzo Ulug‘bek nomidagi O‘zbekiston Milliy universiteti dotsenti, PhD.
E-mail: alayev_r@nuu.uz
Nurmatov Abduraxim Shaxriyor o‘g‘li
Mirzo Ulug‘bek nomidagi O‘zbekiston Milliy universiteti magistr talabasi
E-mail: codergq@gmail.com

Annotatsiya. Ushbu tezisda web-kamera video oqimi asosida foydalanuvchini sessiya davomida uzluksiz autentifikatsiya qilish masalasi bo‘yicha olib borilgan so‘nggi ilmiy ishlar tahlil qilinadi. Uzluksiz autentifikatsiya odatiy bir martalik autentifikatsiyadan farqli ravishda, foydalanuvchini seans davomida haqiqiy yoki haqiqiy emasligini passiv va uzluksiz tekshiruvchi yondashuv bo‘lib, u biometrik, xulqiy va kontekstga oid sensor belgilariga tayangani sababli xavfsizlik bilan birga maxfiylik muammolarini ham keltirib chiqaradi [1]. Tahlil doirasida yuz biometrikasi (CNN/embedding), harakat signallari (bosh holati, kichik harakatlar kabi) hamda vaqtga bog‘liq modellar (LSTM/GRU va Transformer) asosida ko‘p modalli (multimodal) autentifikatsiya arxitekturasi qanday shakllanishi, qaysi bosqichlarda xatoliklar yuzaga kelishi va ularni kamaytirish yechimlari yoritiladi. Ko‘p modalli yondashuvning motivatsiyasi — yakka modal tizimlardagi samaradorlik pastligi va taqdimot hujumlari (presentation attacks) xavfi — ham nazariy, ham amaliy manbalar orqali asoslanadi [2]. Shuningdek, spoofing/replay va deepfake tahdidlariga qarshi PAD/tiriklikni aniqlash standart metrikalari, real vaqt sharoitida resurs cheklovlari [3] va tasvir sifati masalalari bo‘yicha xulosalar beriladi.

Kalit so‘zlar: uzluksiz autentifikatsiya, ko‘p modalli biometrika, yuzni tanish, vaqtga bog‘liq modellar, Transformer, LSTM/GRU, tiriklikni aniqlash, taqdimot hujumlarini aniqlash.

Аннотация. В данной тезисной работе представлен анализ последних научных исследований в области непрерывной аутентификации пользователя на основе видеопотока веб-камеры в течение сессии. В отличие от традиционной одноразовой аутентификации, непрерывная аутентификация представляет собой пассивный и непрерывный подход к проверке подлинности пользователя на протяжении всей сессии. Поскольку данный подход основывается на биометрических, поведенческих и контекстных сенсорных признаках, наряду с повышением уровня безопасности он также приводит к возникновению проблем конфиденциальности [1]. В рамках анализа рассматривается формирование

ISSN 3030-3907

мультимодальной архитектуры аутентификации на основе лицевой биометрии (CNN/embedding), сигналов движения (положение головы и небольшие движения), а также временных моделей (LSTM/GRU и Transformer). Освещаются этапы возникновения ошибок и подходы к их снижению. Мотивация использования мультимодального подхода, обусловленная более низкой эффективностью одномодальных систем и риском атак представления (presentation attacks), обосновывается на основе теоретических и практических источников [2]. Также представлены выводы относительно стандартных метрик PAD/обнаружения живости для противодействия угрозам spoofing/replay и deepfake, ограничений вычислительных ресурсов в условиях реального времени [3], а также проблем качества изображений.

Ключевые слова: непрерывная аутентификация, мультимодальная биометрия, распознавание лица, временные модели, Transformer, LSTM/GRU, обнаружение живости, обнаружение атак представления.

Abstract. This thesis presents an analysis of recent scientific research on continuous user authentication based on webcam video streams throughout a session. Unlike conventional one-time authentication, continuous authentication is a passive and ongoing approach to verifying the authenticity of a user throughout the session. Since this approach relies on biometric, behavioral, and contextual sensor features, it not only enhances security but also introduces privacy concerns [1]. The analysis focuses on the development of multimodal authentication architectures based on facial biometrics (CNN/embedding), motion-related signals (head pose and subtle movements), and temporal models (LSTM/GRU and Transformer). The stages at which errors may occur and approaches to reducing such errors are also discussed. The motivation for adopting a multimodal approach, driven by the lower effectiveness of unimodal systems and the risk of presentation attacks, is substantiated through both theoretical and practical sources [2]. The thesis also provides conclusions regarding standard PAD/liveness detection metrics for countering spoofing/replay and deepfake threats, computational resource constraints in real-time environments [3], and image quality issues.

Keywords: continuous authentication, multimodal biometrics, face recognition, temporal models, Transformer, LSTM/GRU, liveness detection, presentation attack detection.

KIRISH.

ISSN 3030-3907

Ko‘plab amaliy tizimlarda autentifikatsiya kirishda tekshirish (parol/2FA/biometrika) bilan cheklanadi; ammo sessiya davomida qurilma yoki xizmatdan foydalanayotgan shaxs almashib qolishi (masalan, ish joyida kompyuterni tark etish, masofaviy imtihonda o‘rin almashish, uy sharoitida umumiy qurilmadan foydalanish) ehtimoli doimo mavjud. Shu ehtiyoj fonida uzluksiz autentifikatsiya (continuous authentication) konsepsiyasi taklif qilinadi: u foydalanuvchini seans davomida passiv va uzluksiz tarzda tekshiradi, biometrik, xulq hamda kontekstga oid belgilarni birlashtirishi mumkin [1].

Biroq uzluksiz autentifikatsiyaning amaliy joriy etilishi bir vaqtning o‘zida bir nechta sinf muammolarni keltirib chiqaradi. Birinchidan, uzluksiz autentifikatsiya ko‘pincha shaxsga oid ma’lumotlar bilan ishlaydi va bu maxfiylik xavotirlarini kuchaytiradi [1]. Ikkinchidan, uzluksiz tekshiruv real-vaqt hisoblashini, past kechikishni va resurs tejamkorligini talab qiladi; buning ustiga tadqiqotlarda uzluksiz autentifikatsiya usullari qalbakilashtirish orqali aldash (spoofing) va qayta foydalanish (replay) hujumlari kabi amaliy xavflar qayd etiladi [3]. Uchinchidan, yuzga asoslangan autentifikatsiya web-kamera real hayotda maska, yorug‘lik, kamera sifati, rakurs, qisman to‘silish kabi omillarga sezgir bo‘lib, xato qabul/xato inkor (false accept/false reject) balansini buzishi mumkin; shu bois real tizimlar ko‘pincha sifat nazorati va namunani tanlash kabi yordamchi bosqichlarni talab qiladi [4].

Shu maqsadda *ko‘p modalli biometrika* muhim yozndashuv sifatida foydalaniladi: *yagona modal* identifikatsiya cheklovlarini yumshatish va ishonchlilikni oshirish uchun bir nechta signal manbalarini (masalan, yuz + harakat + vaqt bo‘yicha o‘zgarish) birlashtirish tavsiya etiladi. Ko‘p modalli yondashuv yagona modal tizimlarning cheklovlarini bartaraf etish zarurati, uning qo‘llanish motivatsiyasi va ustunliklari, shuningdek xususiyatlar, ballar, qaror va reyting darajasidagi birlashtirish strategiyalarini batafsil tahlil qiluvchi ilmiy maqolalar bilan asoslanadi [4]. Mazkur tezisda aynan web-kamera video oqimi kontekstida “yuz + harakat + vaqtga bog‘liq model” kombinatsiyasining ilmiy-texnik muammolari va ularni bartaraf etish yechimlari umumlashtiriladi.

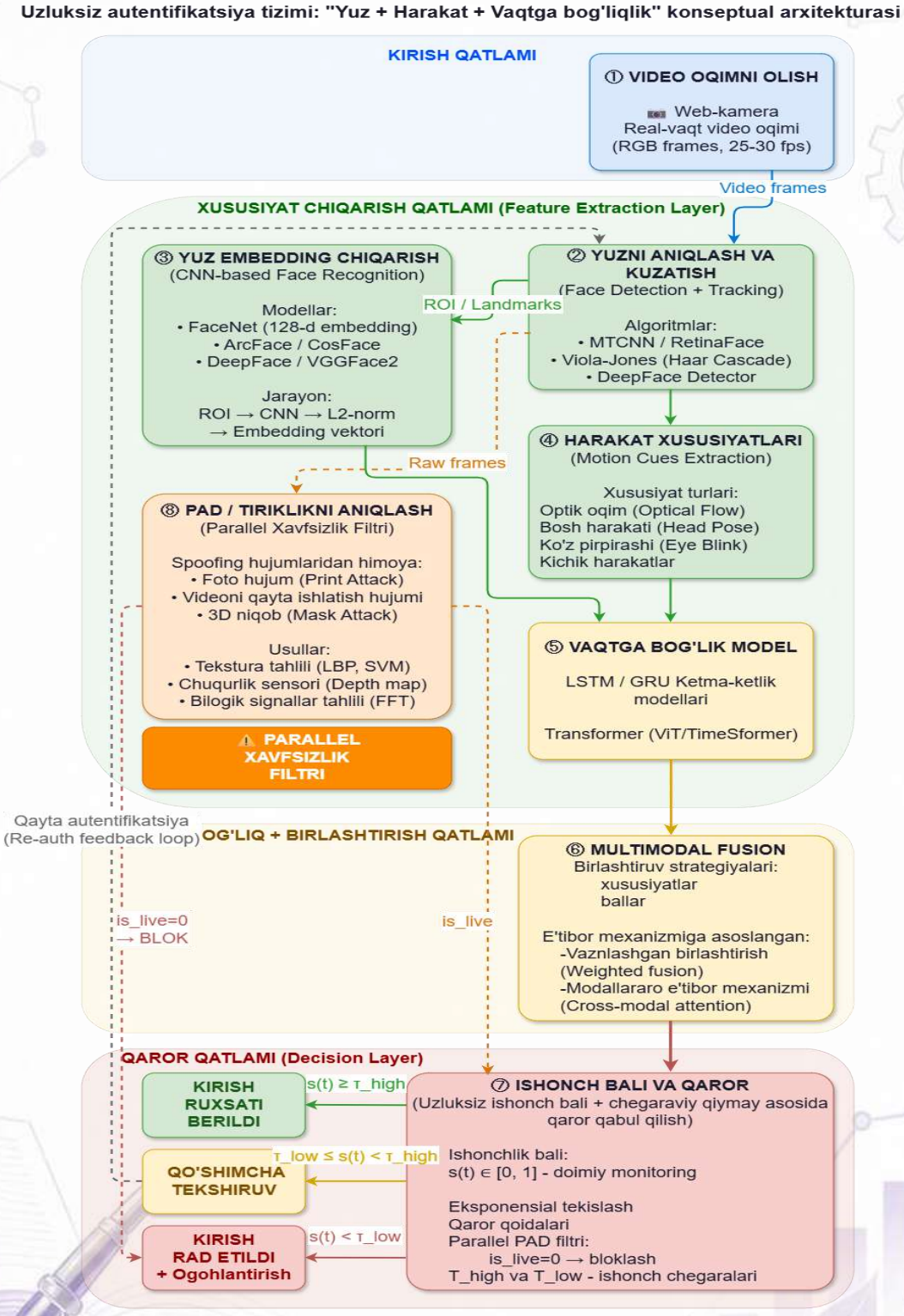
METODOLOGIYA

Ushbu ish mavjud ilmiy manbalardagi yondashuvlarni tizimlashtirish, muammolarni sinflarga ajratish va real vaqt web-kamera uzluksiz autentifikatsiya uchun amaliy tavsiyalarni berishni maqsad qilgan. Manbalar tanlashda uch mezon asos bo‘ldi: (1) uzluksiz autentifikatsiya konsepti va amaliy muammolar (xavfsizlik/maxfiylik/resurs), (2) multimodal fusion strategiyalari va vaqtga bog‘liq modellar, (3) taqdimot hujumlari (spoofing/replay/deepfake) va taqdimot

ISSN 3030-3907

hujumlarini aniqlash (Presentation Attack Detection, PAD)/tiriklikni aniqlashning standart metrikalari [4].

Tahlil natijasida “yuz + harakat + vaqtga bog‘liqlik” asosidagi uzluksiz autentifikatsiya tizimini quyidagi konseptual pipeline sifatida ifodalash mumkin (1-rasm).



1-rasm. Uzluksiz autentifikatsiya tizimi konseptual arxitekturasi. Ma’lumot oqimi va asosiy qatlamlar

ISSN 3030-3907

Yuz embedding (CNN/Face Recognition). Amaliy tizimlar odatda yuzni to‘g‘ridan-to‘g‘ri identifikatsiya qilishdan ko‘ra, avval yuzni kompakt fazoda vektorga aylantirib, keyin masofa/yaqinlik orqali tekshiradi. Masalan, FaceNet yondashuvi yuz tasvirlarini kompakt Evklid fazosiga o‘tkazib, masofani “o‘xshashlik” o‘lchoviga aylantiradi; o‘qitish jarayonida *triplet loss* ishlatilib, bir shaxs ichidagi masofa kichraytiriladi va turli shaxslar orasidagi masofa oshiriladi [5]. FaceNet’da 128 o‘lchamli embedding (kvantlash orqali ixcham saqlash) yondashuvi ham amalda ko‘p uchraydi [5]. Yangi avlod *yuzni chuqur tanish (deep face recognition)* tadqiqotlarida esa diskriminativlikni oshirish uchun *chegaraviy farqqa asoslangan yo‘qotish funksiyalari (margin-based loss)* qo‘llaniladi; *ArcFace additive angular margin* orqali *Gipersfera* geometriyasida sinflar ajraluvchanligini kuchaytirishni taklif qiladi [6].

Harakat modali. Web-kamera oqimida harakat signallari yuzning statik ko‘rinishidagi o‘zgaruvchanlikni qisman kompensatsiya qiladi: boshning burilishi / boshni oldinga-orqaga egilish(pitch) / chapga–o‘ngga burilish(yaw), mikromimika, ko‘z qimirlashi va boshqa kichik harakatlar tiriklik belgilariga ham, shaxsga xos xulq belgilarga ham ishora qilishi mumkin. Bunday signallar ko‘pincha ketma-ket freymlarda barqarorroq ko‘rinadi; shu bois ularni vaqtga bog‘liq model bilan bog‘lash mantiqan asosli [4].

Vaqtga bog‘liq modellar (LSTM/GRU va Transformer). Uzluksiz autentifikatsiyada qaror bitta kadr asosida emas, balki “*sliding window*” ketma-ketligi asosida qabul qilinadi. Bu yondashuv shovqin, qisqa muddatli qisman yopilish holati yoki yoritish o‘zgarishini yumshatadi va “ishtirokchi bir zumga kameraga qaramadi” kabi holatlarni “*yolg‘on bekor*”-ga aylantirib yubormaslikka yordam beradi [3]. Adabiyotlarda vaqt bog‘liq modellashtirish uchun RNN oilasidagi LSTM/GRU chuqur neyron tarmoqlari hamda uzun bog‘liqliklarni ushlashda *o‘zaro e’tibor (self-attention)* mexanizmiga tayanuvchi Transformer arxitekturalari qo‘llanishi haqida bayon qilingan.

Multimodal birlashtirish strategiyalari. Multimodal identifikatsiyada eng kritik arxitektura qarori – qaysi bosqichda birlashtirish. Ilmiy taqdqiqotlar sharhida multimodal identifikatsiyada xususiyatlar, moslik ballari, qaror va reyting darajalarida birlashtirish kabi bir necha birlashtirish strategiyalarini tizimlashtiradi. Bu ish doirasida web-kamera uzluksiz autentifikatsiya uchun ikki amaliy yo‘l ajratildi:

- Xususiyatlar darajasida birlashtirish: yuz embedding + harakat vektorlari vaqtga bog‘liq blokka kirishdan oldin birlashtiriladi; afzalligi – model o‘rganishda boyroq signal ko‘radi, kamchiligi – normalizatsiya, o‘lcham moslash va domen siljishi (domain shift)ga sezgirlik.

ISSN 3030-3907

•Moslik ballar darajasida birlashtirish: har bir modal alohida ballga aylantirilib (masalan, yuz o‘xshashligi + harakat mosligi + tiriklik bali), yakuniy “ishonch bali”ga yig‘iladi; afzalligi – modul/komponentlarni mustaqil sozlash, kamchiligi – optimal og‘irliklarni tanlash va kalibrlash muammosi.

PAD / tiriklikni aniqlash va metrikalar. Spoofing/replay/deepfake kabi hujumlar web-kamera biometrikasining eng kuchsiz nuqtalaridan biri bo‘lib, ularni alohida filtrlash kerak [1]. PAD bo‘yicha ISO standartlari sinash va hisobot tayyorlash tamoyillarini belgilaydi: ISO/IEC 30107-3:2017 PAD mexanizmlarining samaradorlikni baholash prinsiplari, test natijalari hisobotini tayyorlash va ma’lum hujum turlarini tasniflashni ko‘zda tutadi; shu bilan birga, u aniq anti-spoofing algoritmlarini standartlashtirishni o‘z ichiga olmaydi [10]. Standart metrikalar amaliy muhokamada juda muhim: masalan, APCER (attack presentation classification error rate) – hujum namunalarining haqiqiy (bona fide) sifatida noto‘g‘ri tasniflanish ulushi; BPCER (bona fide presentation classification error rate) – haqiqiy (bona fide) namunalarning hujum sifatida noto‘g‘ri rad etilish ulushi [11].

NATIJALAR VA MUHOKAMA.

Ilmiy ishlar sharhi natijalari web-kamera asosidagi “yuz + harakat + vaqtga bog‘liq” uzluksiz autentifikatsiya tizimida muammolarni 5 ta asosiy blokka ajratish mumkinligini ko‘rsatadi: (1) tasvir sifati va real muhitning beqarorligi, (2) spoofing/replay/deepfake, (3) vaqt bo‘yicha barqarorlik va chegaraviy qiymat asosida qaror qabul qilish, (4) real vaqt resurs cheklovlari, (5) maxfiylik.

Tasvir sifati va real muhit beqarorligi. Web-kamera oqimida yuzni aniqlash va embedding chiqarish sifati tasvir sifatiga kuchli bog‘liq. NIST-ning FRVT Quality Assessment konseptual hujjatlarida qayd etilishicha, yuz tasvirlarini almashinuvi va tasvirga olish talablariga oid standartlar mavjud bo‘lishiga qaramay, yuz tasviri sifatini avtomatik baholash hamda ushbu algoritmlarning samaradorligini obyektiv mezonlar asosida baholash bo‘yicha yetuk standartlar yetarli darajada ishlab chiqilmagan. Mazkur muammoni hal etish maqsadida NIST tasvir sifatini skalyar ko‘rsatkich (scalar quality score) ko‘rinishida qaytaruvchi yondashuvlarni ishlab chiqish va ularni standartlashtirilgan baholash metodologiyalari asosida tahlil qilishni ilgari suradi [4].

Amaliy usullar. Tadqiqotlar tahlili shuni ko‘rsatadiki, web-kamera uzluksiz autentifikatsiyada quyidagi amaliy usullar yuqori baholanadi:

•*Quality-aware sample selection*: har bir kadrni tekshirish o‘rniga, sifat bahosi yuqori bo‘lgan freymlarni (yaxshi fokus, mos yaw/pitch, yetarli rezolyutsiya) tanlab olish; bu *yolg‘on bekor qilishni* kamaytirishi va resurs sarfini tushirishi mumkin.

ISSN 3030-3907

•*Face tracking + "best-shot" tanlash*: qisqa vaqt oynasida (masalan 1–3 soniya) bir nechta kadrdan eng yaxshi/eng barqarorini olish – embedding shovqinini kamaytiradi, vaqtga bog‘liq modelga kiruvchi signalni silliqlashtiradi.

•*Margin-based embeddinglar*: FaceNet (triplet-loss asosida) va ArcFace (margin-based loss asosida) kabi embedding yondashuvlari amaliyotda yuqori darajadagi diskriminativ xususiyatlarni shakllantirishga xizmat qiladi. Bu esa uzluksiz autentifikatsiya tizimlarida yuz signali sifatini oshirish va identifikatsiya aniqligini yaxshilash uchun muhim omil hisoblanadi.

Spoofing, replay va deepfake. Uzluksiz autentifikatsiyada tahdid modeli odatda tasodifiy emas: hujumchi foto ko‘rsatishi, ekran orqali videoni qayta qo‘yishi yoki deepfake orqali real vaqtga yaqin manipulyatsiya qilishi mumkin; shuning uchun tiriklik/PAD blokini alohida qatlam sifatida qo‘shish talab etiladi.

Standart metrikalar va hisobot tayyorlash. PAD baholashda APCER/BPCER kabi metrikalar tizimning xavfsizlik-qulaylik kompromissini aniq ko‘rsatadi: APCER past bo‘lsa – hujumni o‘tkazib yuborish kamayadi, BPCER past bo‘lsa – real foydalanuvchini noto‘g‘ri rad etish kamayadi [11]. ISO/IEC 30107-3 esa PAD mexanizmlarini baholash va hisobot tayyorlash uchun metodik qo‘llanma beradi [10].

Deepfake texnologiyalarining umumlashtirish muammosi. Zamonaviy multimedia forensika tadqiqotlarida deepfake aniqlash usullari uchun cross-dataset baholash muhim metodologik bosqich sifatida qaraladi. Bunga sabab, real sharoitda o‘qitish ma’lumotlaridan farq qiluvchi yangi hujum turlarining doimiy ravishda yuzaga kelishi va "statik distribusiya" farazining buzilishidir. Ushbu holat modelning ilgari ko‘rilmagan hujumlarga nisbatan umumlashtirish qobiliyatining pasayishiga olib keladi. Eng xavfli ssenariya – uzluksiz autentifikatsiya tizimida yuz signali "ishonchli" ko‘ringani holda, hujumchi deepfake/replay bilan tizimni aldashi. Shu bois PAD nafaqat bir martalik kirish bosqichida, balki sessiya davomida ham (masalan, davriy yoki trigger asosida) ishlashi maqsadga muvofiq [12].

Vaqt bo‘yicha barqarorlik va chegaraviy qiymat asosida qaror qabul qilish. Uzluksiz autentifikatsiya qarori odatda bitta embedding mosligiga emas, vaqt bo‘yicha yig‘ilgan dalillarga tayanadi. Bu yondashuvning kuchli tomoni – "bir kadrdagi shovqin"ni kamaytirish, lekin zaif tomoni – *chegaraviy qiymat* va *oynaning uzunligini* noto‘g‘ri tanlashda tizim kechikishi yoki *yolg‘on ogohlantirish* ko‘payishi.

Tadqiqotlar tahlili asosida tavsiyalar:

•*Sliding window + silliqlashtirish*: ballarni (yuz o‘xshashligi darajasi, harakatning izchilligi, tiriklik ko‘rsatkichi) vaqt bo‘yicha silliqlashtirish va qarorni

ISSN 3030-3907

bir nechta ketma-ket *oynalarda* mustahkamlash – uzluksiz autentifikatsiyada keng qo‘llaniladigan holat sifatida qaraladi.

•*Moslashuvchan chegaraviy qiymat asosida qaror qabul qilish*: yorug‘lik sharoitlarining o‘zgarishi, kameraga masofaning ortishi yoki yuzning qisman yopilishi kabi omillar ta’sirida qaror chegarasini dinamik tarzda moslashtirish, shuningdek past sifatli tasvirlar uchun qayta namuna olish mexanizmlarini qo‘llash yolg‘on rad etish darajasini kamaytirishga xizmat qiladi. Mazkur yondashuvni samarali tashkil etishda tasvir sifati bahosi konseptlari asosiy metodologik omil hisoblanadi [4].

Real vaqt hisoblash va resurs cheklovlari

Web-kamera asosidagi uzluksiz autentifikatsiya tizimlarining amaliy qo‘llanishi hisoblash resurslari cheklovlari bilan chambarchas bog‘liq. Uzluksiz video oqimini qayta ishlash yuqori darajadagi CPU/GPU yuklanishini keltirib chiqaradi, energiya sarfini oshiradi va natijada tizimning foydalanuvchi tajribasiga (user experience) salbiy ta’sir ko‘rsatishi mumkin [4]. Resurs cheklangan qurilmalarda uzluksiz autentifikatsiya yondashuvlari “kam tekshiruv bilan yetarli ishonch” tamoyiliga intiladi: masalan, ayrim ishlar yuzni embeddingga aylantirib, atrof-muhit triggerlari (yorug‘lik yoki shovqin o‘zgarishi) bo‘lganda qayta tekshiruvni amalga oshirish orqali ortiqcha tekshiruvlarni kamaytirishni ko‘rsatadi [3]. Ushbu konsepsiya web-kamera asosidagi uzluksiz autentifikatsiya tizimlariga tatbiq etilishi mumkin. Doimiy ravishda har bir kadr uchun *inference* bajarish o‘rniga, adaptiv monitoring strategiyasini qo‘llash tavsiya etiladi: (a) bosh holati, fokus yoki tasvir sifati o‘zgarishida, (b) foydalanuvchining ekran bilan o‘zaro masofasi o‘zgarganda, (c) liveness bo‘yicha shubhali signallar aniqlanganda tekshiruv jarayoni kuchaytiriladi.

1-jadval ilmiy ishlar tahlili asosida “yuz, harakat, vaqtga bog‘liq model va PAD” komponentlaridan tashkil topgan tizimda uchraydigan muammolar hamda ularga mos yechim yo‘nalishlarini tizimli ravishda umumlashtiradi.

1-jadval.

Multimodal uzluksiz autentifikatsiya tizimining (yuz, harakat, temporal model va PAD) komponentlari bo‘yicha muammo va yechimlar tahlili

Komponent	Tipik signal yoki algoritm	Tipik muammo	Review asosidagi yechim yo‘nalishi (misollar)
Yuz embedding (CNN)	Yuz embedding, kosinius yoki Evklid masofasi	Rakurs, yorug‘lik va qisman yopilish sabab	Sifatga asoslangan kadr tanlash; kuzatish; diskriminativ yo‘qotish

ISSN 3030-3907

		o‘xshashlik pasayishi	funksiyalari (FaceNet, ArcFace oilasi) [5,6]
Harakat	Bosh holati (pitch/yaw), kichik harakatlar, vaqt bo‘yicha izchillik	Statik rasm yoki replay hujumlarini ajratish qiyinligi	Harakatni tiriklik signali sifatida qo‘shish; Vaqt bo‘yicha izchillikni tekshirish [4]
Vaqtga bog‘liq model	LSTM/GRU, Transformer	Vaqt oynasi parametrlari va chegaraviy qiymat noto‘g‘ri tanlanganda kechikish yoki yolg‘on ogohlantirish	*Sliding window* asosida silliqlashtirish; moslashuvchan chegaraviy qiymat; sifat bahosi asosida tanlab olish [3]
Birlashtirish	Xususiyatlar darajasi yoki moslik ballari darajasida birlashtirish	Kalibrlash muammolari, modal signallar siljishi, domen siljishi	Birlashtirish strategiyalarini tizimli tanlash (feature/score/decision); modullarni kalibrlash [4]
PAD / tiriklikni aniqlash	APCER/BPCER metrikalari asosida baholash	Deepfake va yangi turdagi hujumlarda umumlashtirish muammosi	ISO/IEC 30107-3 asosida testlash; cross-dataset baholash; davriy PAD [10-11]

XULOSA.

Ilmiy tadqiqotlar tahlili shuni ko‘rsatadiki, web-kamera asosida uzluksiz autentifikatsiya qilishda faqat *yuzni tanishga* tayanish ko‘pincha yetarli emas: real muhitdagi tasvir sifati, qisman yopilish va yoritish o‘zgarishi, shuningdek spoofing/replay/deepfake tahdidlari bitta modalni zaiflashtiradi. Shu bois multimodal yonfashuv – yuz embedding + harakat signallari + vaqtga bog‘liq modellashtirish + PAD/tiriklikni aniqlash – amaliy barqarorlikni oshiruvchi asosiy yo‘nalish sifatida ajralib chiqadi. Multimodal birlashtirish strategiyalari (feature/score/decision) bo‘yicha ilmiy tadqiqotlar bunday tizimlarni konseptual asoslash va arxitektura tanlovlarini tartibga solish uchun nazariy asos beradi.

Multimodal yondashuvlar barcha muammolarni avtomatik ravishda hal etmaydi. Birinchidan, real vaqtli hisoblash resurslari cheklovlari sharoitida *inference* chastotasini optimallashtirish, xususan trigger asosida va sifat

ISSN 3030-3907

ko‘rsatkichiga asosida tanlab olish mexanizmlarini joriy etish zarur. Ikkinchidan, PAD tizimlarini ISO/IEC 30107-3 standartiga muvofiq APCER va BPCER metrikalari asosida baholash hamda natijalarni standartlashtirilgan shaklda hisobot ko‘rinishida taqdim etish talab etiladi. Uchinchidan, deepfake texnologiyalarining jadal rivojlanishi fonida cross-dataset umumlashtirish muammosi dolzarbligicha qolmoqda. To‘rtinchidan, maxfiylik masalalari tizim arxitekturasining markazida turishi zarur, chunki demografik farqlar va ma’lumotlar maxfiyligi bilan bog‘liq xavflar uzluksiz autentifikatsiya tizimlarining amaliy qo‘llanishiga bevosita ta’sir ko‘rsatadi.

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NIKEL(II) IONINI 6-XLOR-4-GIDROKSI-3-NITROZONAFTALIN-2,7-DISULFOKISLOTA BILAN YANGI SPEKTROFOTOMETRIK ANIQLASH USULI

Nazirov Shohjohon Sobirovich
Ilg‘or texnologiyalar markazi.
Ixtisoslashtirilgan Atmosfera laboratoriyasi markazi, Markaziy Osiyo atrof-muhit va iqlim o‘zgarishlarini o‘rganish universiteti (Green University).
E-mail: shohjohonnazirov@gmail.com
To‘rayev Xayit Xudoynazarovich
Termiz davlat universiteti.
Turabov Nurmuhammat
Mirzo Ulug‘bek nomidagi O‘zbekiston Milliy universiteti.
Xojiyev Shokir G‘ofurovich
Ilg‘or texnologiyalar markazi.

Annatatsiya. Ushbu maqolada nikel(II) ionini 6-xlor-4-gidroksi-3-nitrozonaftalin-2,7-disulfokislota (XGNDS-2,7) reagenti yordamida spektrofotometrik aniqlashning yangi usuli ishlab chiqildi. Aniqlanishicha, Ni(II) ioni XGNDS-2,7 reagenti bilan intensiv ko‘k-yashil rangli, suvda eruvchan kompleks hosil qiladi. Kompleks hosil bo‘lishining optimal sharoitlari aniqlandi: λ_{max} = 550 nm, pH = 5,5 (universal bufer), 10 μg/25 ml Ni(II) uchun 0,05 % li XGNDS-2,7 reagentining 1,2 ml hajmi yetarli ekanligi ko‘rsatildi. Buger-Lambert-Ber qonuniga bo‘ysunish sohasi 1,0-20,0 μg/25 ml ni tashkil etdi. Kompleksning Sendel bo‘yicha sezgirligi 0,0019 μg/sm^2, kontrastligi $\Delta\lambda$ = 100 nm va haqiqiy molyar so‘ndirish koeffitsiyenti $\varepsilon = 52632\ L\cdot mol^{-1}\cdot sm^{-1}$ ga tengligi aniqlandi. Spektrofotometrik titrlash, izomolyar seriyalar va Asmus metodlari yordamida kompleksning tarkibi 1:2 ekanligi isbotlandi. Hosil bo‘lish muvozanat konstantasi (K_{muv}=0,217), barqarorlik konstantasi (lgβ=19,07) hisoblandi.

Kalit so‘zlar: nikel(II) ioni, 6-xlor-4-gidroksi-3-nitrozonaftalin-2,7-disulfokislota, spektrofotometriya, xromogen reagent, kompleks birikma, Buger–Lambert–Ber qonuni, molyar so‘ndirish koeffitsiyenti**.**

Abstract. A new spectrophotometric method for the determination of nickel(II) ions using 6-chloro-4-hydroxy-3-nitrosonaphthalene-2,7-disulfonic acid (CHNDS-2,7) as a reagent was developed. It was established that Ni(II) ions form an intensely colored, water-soluble blue-green complex with the CHNDS-2,7 reagent. The optimum conditions for complex formation were determined: λ_{max}=550 nm and pH=5.5 (universal buffer). It was shown that 1.2 mL of 0.05 % CHNDS-2,7 reagent is sufficient for 10 μg/25 mL of Ni(II). The concentration range obeying the Beer–Lambert law was 1.0–20.0 μg/25 mL. The Sandell

ISSN 3030-3907

sensitivity was 0.0019 μg/cm^2, the contrast Δλ=100 nm, and the true molar absorptivity coefficient ε=52,632 L·mol^{-1}·cm^{-1}. The 1:2 composition of the complex was established using spectrophotometric titration, the method of continuous variations, and the Asmus method. The complex formation equilibrium constant (K_{eq}=0.217) and stability constant (lgβ=19.07) were calculated.

Keywords: nickel(II) ion, 6-chloro-4-hydroxy-3-nitrosonaphthalene-2,7-disulfonic acid, spectrophotometry, chromogenic reagent, complex compound, Beer–Lambert law, molar absorptivity.

Аннотация. В статье разработан новый спектрофотометрический метод определения ионов никеля(II) с использованием реагента 6-хлор-4-гидрокси-3-нитрозонафталин-2,7-дисульфокислоты (ХГНДС-2,7). Установлено, что ионы Ni(II) образуют с реагентом интенсивно окрашенный сине-зелёный водорастворимый комплекс. Определены оптимальные условия комплексообразования: λ_{max}=550 нм, pH=5,5 (универсальный буфер); показано, что для 10 мкг/25 мл Ni(II) достаточно 1,2 мл 0,05 %-ного раствора реагента ХГНДС-2,7. Интервал подчинения закону Бугера–Ламберта–Бера составляет 1,0–20,0 мкг/25 мл. Чувствительность по Санделлу составляет 0,0019 мкг/см², контрастность Δλ=100 нм, а истинный молярный коэффициент поглощения ε=52632 л·моль$^{-1}$·см$^{-1}$. С использованием спектрофотометрического титрования, метода изомолярных серий и метода Асмуса доказано, что состав образующегося комплекса составляет 1:2. Рассчитаны константа равновесия комплексообразования ($K_{равн}$=0,217) и константа устойчивости (lgβ=19,07).

Ключевые слова: ион никеля(II), 6-хлор-4-гидрокси-3-нитрозонафталин-2,7-дисульфокислота, спектрофотометрия, хромогенный реагент, комплексное соединение, закон Бугера–Ламберта–Бера, молярный коэффициент поглощения.

KIRISH.

Nikel o‘tish metallari guruhiga mansub elementlardan biri bo‘lib, korroziyaga chidamli qotishmalar, galvanik qoplamalar, katalizatorlar, qayta zaryadlanuvchi batareyalar hamda boshqa funksional materiallar ishlab chiqarishda keng qo‘llaniladi[1]. Shu bilan birga, nikel ionlarining atrof-muhit obyektlari va texnologik mahsulotlar tarkibidagi miqdorini nazorat qilish ekologik xavfsizlik hamda mahsulot sifatini baholash nuqtai nazaridan muhim ahamiyat kasb etadi[2]. Shu sababli Ni(II) ionini sodda, tezkor, yuqori sezgir va selektiv

ISSN 3030-3907

usullar yordamida aniqlash analitik kimyoning dolzarb yo‘nalishlaridan biri hisoblanadi[3].

Ni(II) ionini aniqlashda atom-absorbsiya spektrometriyasi, induktiv bog‘langan plazmali optik emissiya spektrometriyasi, induktiv bog‘langan plazmali massa-spektrometriyasi, voltamperometriya hamda spektrofotometriya usullaridan keng foydalaniladi. Ushbu usullar orasida spektrofotometriya sodda bajarilishi, iqtisodiy jihatdan qulayligi, yuqori sezgirligi va murakkab asbob-uskunalarni talab qilmasligi bilan ajralib turadi. Biroq usulning selektivligi va analitik imkoniyatlari, asosan, qo‘llaniladigan xromogen reagentning kompleks hosil qilish xususiyatlariga bog‘liq[4–8].

So‘nggi yillarda Ni(II) ionini spektrofotometrik aniqlash uchun turli xromogen reagentlardan foydalanishga alohida e'tibor qaratilmoqda. Jumladan, mualliflar HPEDN (1-((4-(1-(2-gidroksifenilimino)etil)fenil)diazenil)naftalen-2-ol) azo-Shiff ligandi yordamida Ni(II) ionini spektrofotometrik aniqlash usulini ishlab chiqqanlar. Tadqiqot natijalariga ko‘ra, Ni(II)-HPEDN kompleksi λ_{max}=516 nm da maksimal yutilishga ega bo‘lib, optimal kompleks hosil bo‘lish sharoiti pH = 9,0, harorat 25 °C va reaksiya vaqti 15 min etib aniqlangan. Kompleksning stexiometrik tarkibi Me:R = 1:2 bo‘lib, Buger-Lambert-Ber qonuniga bo‘ysunish sohasi 1,1-7,1 μg/ml ni tashkil etgan. Usulning molyar yutish koeffitsiyenti ε = 2648 $L \cdot mol^{-1} \cdot sm^{-1}$, aniqlash va miqdoriy aniqlash chegaralari mos ravishda LOD = 0,3928 μg/ml va LOQ = 1,3082 μg/ml ga teng bo‘lgan. Ishlab chiqilgan usulning natijalari alanga atom-absorbsiya spektrometriyasi natijalari bilan yaxshi mos kelgan[9].

Shuningdek, Ni(II) ionini aniqlashda 1-(2-piridilazo)-2-gidroksi-4-merkaptophenol (PAGMP) va aminofenollar asosidagi turlicha ligandli komplekslardan ham samarali foydalanilgan. Mazkur komplekslar kuchsiz kislotali muhitda (pH 3,5-6,5) hosil bo‘lib, λ_{max} = 620-650 nm da maksimal yutilishni namoyon etgan. Kompleks hosil bo‘lishi uchun PAGMP va aminofenollarning optimal konsentratsiyalari mos ravishda $(1,2\text{-}1,5)\cdot10^{-3}$ M va $(2,4\text{-}2,6)\cdot10^{-3}$ M etib aniqlangan. Kompleksning molyar yutish koeffitsiyenti ε = $(2,3\text{-}2,5)\cdot10^{4}$ $L \cdot mol^{-1} \cdot sm^{-1}$ ni tashkil etib, Buger-Lambert-Ber qonuniga bo‘ysunish sohasi 0,5-18 μg/ml oralig‘ida kuzatilgan. Ishlab chiqilgan usul suv va tuproq namunalarida Ni(II) ionini aniqlashda muvaffaqiyatli qo‘llanilgan[10].

Bundan tashqari, 4-((imidazol-2-il)diazenil)-N-(pirimidin-2-il)benzolsulfonamid asosidagi yangi azo reagent yordamida ham Ni(II) ionini yuqori sezgirlikda spektrofotometrik aniqlash usuli taklif etilgan. Aniqlanishicha, Ni(II) ioni reagent bilan pH = 7 muhitda to‘q jigarrang rangli Me:R=1:2 tarkibli kompleks hosil qilib, λ_{max}=486 nm da maksimal yutilishni namoyon etgan. Usul uchun molyar yutish koeffitsiyenti ε = 3299 $L \cdot mol^{-1} \cdot sm^{-1}$, Sendel sezgirligi 0,0177

ISSN 3030-3907

μg/sm^2, Buger-Lambert-Ber qonuniga bo‘ysunish sohasi 0,5-7,6 μg/ml hamda aniqlash chegarasi LOD = 0,1927 μg/ml ni tashkil etgan. Ishlab chiqilgan usul yuqori aniqlik (RSD = 0,392 %) va qayta tiklanish (Recovery = 98,7 %) ko‘rsatkichlariga ega bo‘lib, qotishma namunalarida Ni(II) ionini aniqlashda muvaffaqiyatli qo‘llanilgan[11].

Nitrozonaftalin hosilalari orasida 7-brom-2-nitrozo-1-oksonaftalin-3,6-disulfokislota (BNOKS-S-3,6) ham Ni(II) ionini aniqlash uchun samarali xromogen reagent sifatida tavsiya etilgan. Aniqlanishicha, Ni(II)-BNOKS-S-3,6 kompleksi λ_{max}=640 nm va pH = 6,5 da maksimal yutilishni namoyon etib, Buger-Lambert-Ber qonuniga 1,0-17,5 μg/25 ml konsentratsiyalar oralig‘ida bo‘ysunadi. Kompleksning stexiometrik tarkibi Me:R = 1:2 bo‘lib, Sendel bo‘yicha sezgirligi 0,0011 μg/sm^2, kontrastligi $\Delta\lambda$ = 100 nm, molyar yutish koeffitsiyenti $\varepsilon = 5{,}0\cdot10^4$ $L\cdot mol^{-1}\cdot sm^{-1}$, barqarorlik konstantasi lgβ = 18,87 va aniqlashning quyi chegarasi Q_{min} = 0,203 μg/25 ml ga tengligi aniqlangan. Ishlab chiqilgan usul yuqori aniqlik (Sr ≤ 0,021) bilan tavsiflanib, sun'iy aralashmalar tarkibidagi Ni(II) ionini aniqlashda muvaffaqiyatli qo‘llanilgan[12].

Tahlil qilingan adabiyotlar natijalari shuni ko‘rsatadiki, Ni(II) ionini spektrofotometrik aniqlash uchun turli xromogen reagentlar asosida sezgir va ishonchli usullar ishlab chiqilgan. Biroq ularning analitik ko‘rsatkichlari, jumladan, optimal pH qiymati, maksimal yutilish to‘lqin uzunligi, molyar yutish koeffitsiyenti, aniqlash diapazoni hamda aniqlash chegarasi reagentning kimyoviy tabiatiga bog‘liq ravishda sezilarli darajada farqlanadi. Ayniqsa, nitrozonaftalin hosilalari yuqori analitik tavsiflari bilan ajralib turishi ularning yangi hosilalarini analitik amaliyotga joriy etish istiqbolli yo‘nalish ekanligini ko‘rsatadi. Shu bilan birga, 6-xlor-4-gidroksi-3-nitrozonaftalin-2,7-disulfokislota (XGNDS-2,7) reagenti yordamida Ni(II) ionini spektrofotometrik aniqlashning analitik imkoniyatlari yetarli darajada o‘rganilmagan.

Shu munosabat bilan ushbu tadqiqotning maqsadi 6-xlor-4-gidroksi-3-nitrozonaftalin-2,7-disulfokislota (XGNDS-2,7) reagenti yordamida Ni(II) ionini spektrofotometrik aniqlashning yangi usulini ishlab chiqish, kompleks hosil bo‘lishining optimal sharoitlarini aniqlash, usulning analitik ko‘rsatkichlarini baholash hamda ishlab chiqilgan usulni sun'iy aralashmalar tarkibidagi Ni(II) ionini aniqlashda qo‘llashdan iborat.

MATERIALLAR VA METODIKALAR.

Eritmalarning spektrofotometrik tadqiqotlari Germaniyaning „EMCLAB Instruments GmbH‘‘ zavodida ishlab chiqarilgan EMC-31PC-UV spektrofotometrida o‘tkazildi. Eritmalarning pH darajasi ±0,05 pH birliklari aniqligi bilan pH metr (pH-150M OAO „ Гомельский завод измерительных приборов“) yordamida aniqlandi.

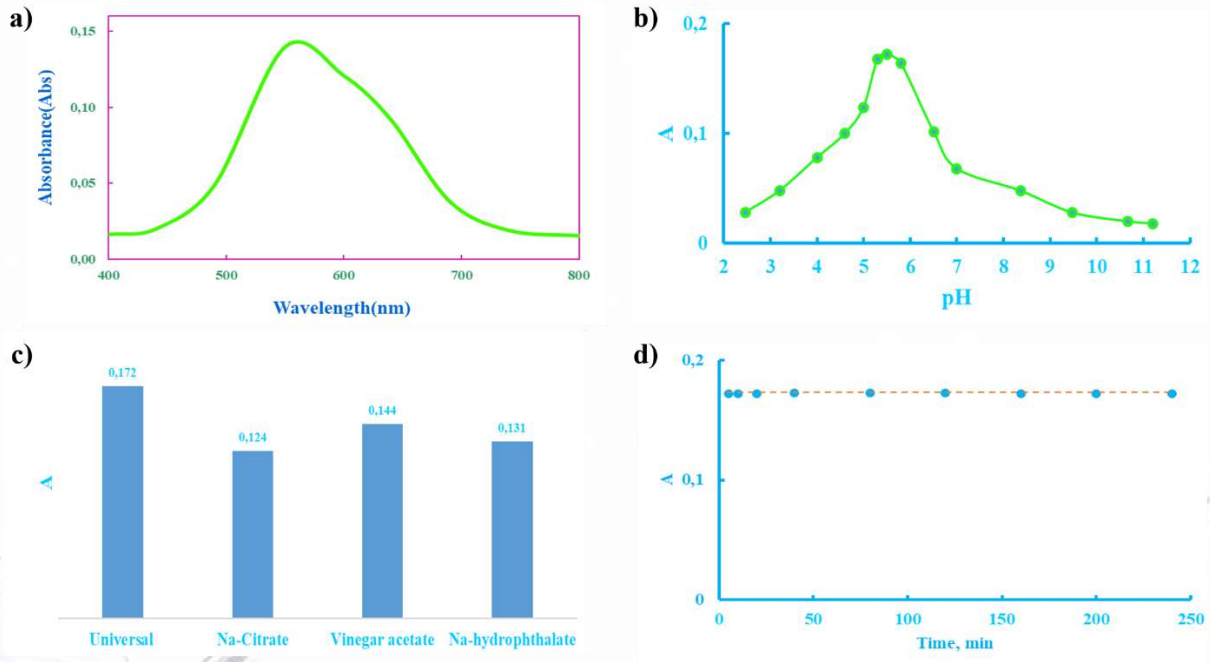
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Tajribaviy qism. Reaktivlar va eritmalar. T_{Cu}^{2+} = 1000 mg/ml titri bo‘lgan $CuSO_4 \cdot 5H_2O$ „kimyoviy toza‘‘ markali suvda eruvchan tuzini analitik tarozida aniq tortilgan miqdorini, 1000 ml hajmli o‘lchov kolbasiga solindi ustuga 1-2 tomchi sulfat kislota eritmasidan hamda o‘lchov chizig‘igacha bidistillangan suv qo‘shildi. Ni(II) ni kichik konsentratsiyali ishchi eritmalar standart eritmani suyultirish orqali tayyorlandi. Reagent eritmalari 0,0500 g reagentni 100 ml hajmli o‘lchov kolbasiga solindi hamda o‘lchov chizig‘igacha bidistillangan suv qo‘shildi. Turli xil pH qiymatlari bo‘lgan bufer eritmalarini tayyorlash uchun analitik kimyo bo‘yicha ma'lumotnomalardan foydalanildi.

NATIJALAR VA MUHOKAMALAR.

Ma’lumki har bir kimyoviy modda, tabiatiga ko‘ra ma’lum bir to‘lqin uzunligidagi nurlarni yutadi. Ni(II) ni 6-xlor-4-gidroksi-3-nitrozonaftalin-2,7-disulfokislota(XGNDS-2,7) reagenti bilan kompleksining eng yuqori nur yutish sohasi quyidagicha aniqlandi.

Aniqlash uslubi: 25 ml li o‘lchov kolbasiga universial bufer eritmadan 5.0 ml , 0.05 %li XGNDS-2,7 eritmasidan 1.0 ml, 15 μg/ml li Ni(II) eritmasidan 1,0 ml solib, so‘ngra kolbaning belgisigacha bidistillangan suv bilan to‘ldirildi. Hosil bo‘lgan rangli kompleks birikmaning optik zichligi EMC-31PC-UV spektrofotometrida o‘lchandi. Solishtirma eritma sifatida erkin eritma (Ni(II) dan boshqa hamma komponentlar mavjud eritma) dan foydalanildi.



1-rasm. a) Optik zichlikning to‘lqin uzuligiga bog‘liqlik grafigi; b) pH ning kompleks hosil bo‘lishiga ta'siri; c) Bufer tarkibining kompleks hosil bo‘lishiga ta'siri; d) Kompleksning vaqt bo‘yicha barqarorligi.

1a-rasmda keltirilgan natijalarga ko‘ra, hosil bo‘lgan kompleks birikma λ_{max}=550 nm to‘lqin uzunligida eng yuqori optik zichlik namoyon qildi.

ISSN 3030-3907

Ni(II) ning XGNDS-2,7 bilan rangli kompleks hosil bo‘lishining optimal sharoitlari: eritma muhitiga bog‘liqligi, bufer eritma tarkibiga bog‘liqligi, vaqtga bog‘liqligi, komponetlaring quyilish tartibiga bog‘liqligi, qo‘shilgan reagent miqdoriga bog‘liqligi o‘rganildi.

1-jadval

Kompleksning hosil bo‘lishining komponetlarning quyilish tartibiga bog‘liqligi.

(λ_{max}=550 nm, pH=5.5, n=5)

№	**Komponetlarning quyilish tartibi**	A
1	**Bufer-reagent-Ni(II)-dist.suv**	0,192
2	Reagent- bufer - Ni(II) - dist.suv	0,172
3	Ni(II) -bufer-reagent- dist.suv	0,168
4	Bufer - Ni(II) –reagent-dist.suv	0,164
5	Reagent- Ni(II) -bufer- dist.suv	0,159
6	Ni(II)-reagent- bufer- dist.suv	0,163
7	Ni(II) -dist.suv- bufer – reagent	0,148
8	Dist.suv-reagent-Ni(II)-bufer	0,124
9	Dist.suv-Ni(II)-bufer-reagent	0,121
10	Dist.suv-bufer-Ni(II)-reagent	0,118

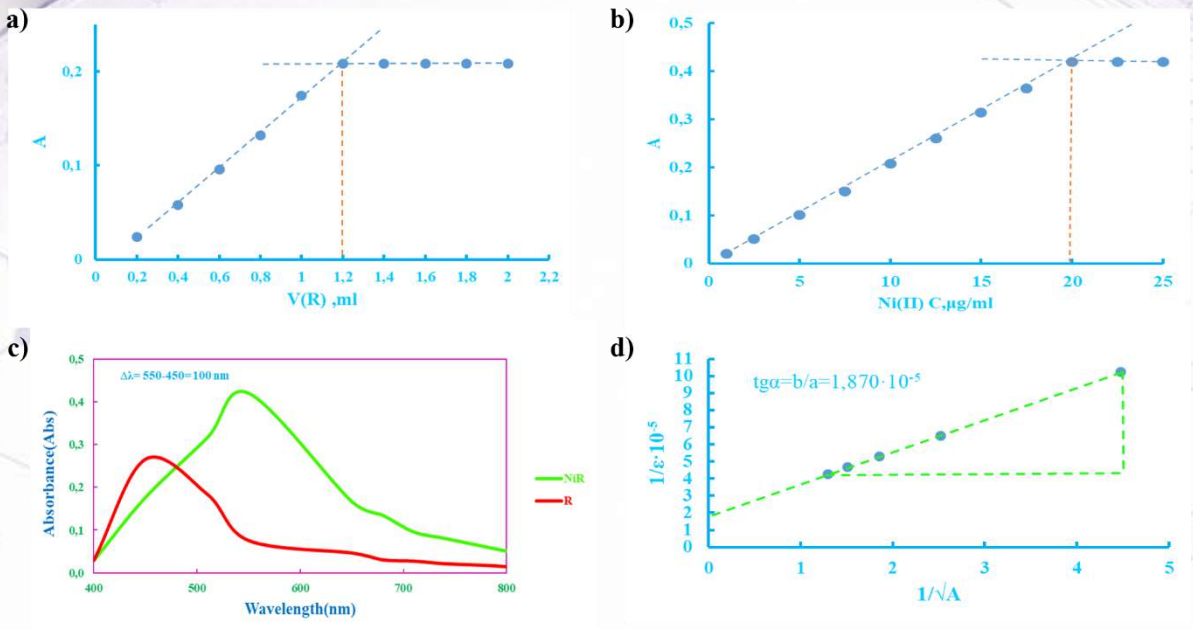
Olingan natijalar shuni ko‘rsatadiki, Ni(II) ning XGNDS-2,7 bilan rangli kompleks hosil bo‘lishining optimal sharoitlari: pH=5.5 (1b-rasm), universial buffer(1c-rasm), 240 min(1d-rasm), Bufer-reagent-Ni(II)-dist.suv(1-jadval),V_R= 1.2 ml(2a-rasm) ekanligi aniqlandi.

Buger-Lambert-Ber qonuniga bo‘ysunishi. Ni(II)ning XGNDS-2,7 bilan hosil qilgan rangli kompleks eritmasining Ber qonuniga bo‘ysunishi tanlangan optimal sharoitlarda o‘rganildi.

Aniqlash uslubi: 25 ml li o‘lchov kolbalariga 5,0 ml pH=5.5 bo‘lgan universal bufer eritma, 1.2 ml 0,05 % li XGNDS-2,7 suvli eritmasi, o‘zgaruvchan miqdorda 5 μg/ml li Ni(II)ning standart eritmasidan kolbaning belgisigacha bidistillangan suv qo‘shiladi. Eritmalarni aralashtirib optik zichliklari solishtirma eritmaga nisbatan o‘lchandi(2b-rasm).

Olingan natijalardan ko‘rinib turibdiki, Buger-Lambert-Ber qonuniga bo‘ysunish sohasi 25 ml eritmada 1,0-20 μg/25ml gacha bo‘lgan oraliqda kuzatildi. Undan yuqori konsentratsiyalarda esa to‘g‘ri chiziqli bog‘lanishdan chetlanish ro‘y berdi.

ISSN 3030-3907



2-rasm. a) Reagent miqdorining ta'siri; b) Buger–Lambert–Ber qonuni grafigi; c) XGNDS-2,7 va Ni(II)–XGNDS-2,7 kompleksining yutilish spektrlari; d) Molyar so‘ndirish koeffitsiyentini aniqlash grafigi.

Yutilish spektrlari. XGNDS-2,7 reagenti va Ni(II) bilan hosil qilgan kompleksini tanlangan optimal sharoitda yutilish spektrlari olindi. (2-jadval, 3c-rasm). Metodning Sendel bo‘yicha sezgirligi µg/sm^2 0,001 birlik uchun nur yutilishi quyidagi formula bilan hisoblandi[13]:

$$S.s = \frac{Q \cdot \ell \cdot 0{,}001}{A \cdot 25} = \frac{20 \cdot 1 \cdot 0{,}001}{0{,}42 \cdot 25} = 0.0019\ \mu g/cm^2 \qquad (1)$$

Bu yerda: S.s-Sendel bo‘yicha segirlik, Q-olingan metall ioni miqdori, ℓ - kyuveta qalingili, A-optik zichlik.

2-jadval.

XGNDS-2,7 (HR) va uning Ni(II) bilan kompleksining(MeR) spektral tavsifi (C_{Cu2+}= 20 µg, λ_{max}=550nm, ℓ=1,0 sm, pH=5.5, n=5)

Kompleks rangi	pH	Maksimum l, nm		Δλ	C_{Me}^{2+}, µg/25 ml	C_{Me}^{2+}, mol/l	Ā	Sendel bo‘yicha sezgirlik µg/sm^2
		Me R	HR					
Kompleks Ni(II) bilan R (ℓ=1,0 sm, n=5)								
Ko‘k-yashil	5,5	550	450	100	20	$1.363 \cdot 10^{-5}$	0,420	0,0019

Tadqiqot davomida olingan natijalardan ko‘rinib turibdiki, reaksiya birmuncha kontrastlikka (Δλ=100 nm) va yuqori sezgirlikka (S.b.s=0,0019 µg/sm^2) ega ekan.

Ni(II) ning XGNDS-2,7 reagenti bilan rangli kompleks hosil qilish reaksiyasini to‘laroq o‘rganish maqsadida, asosiy tavsiflaridan kompleksning

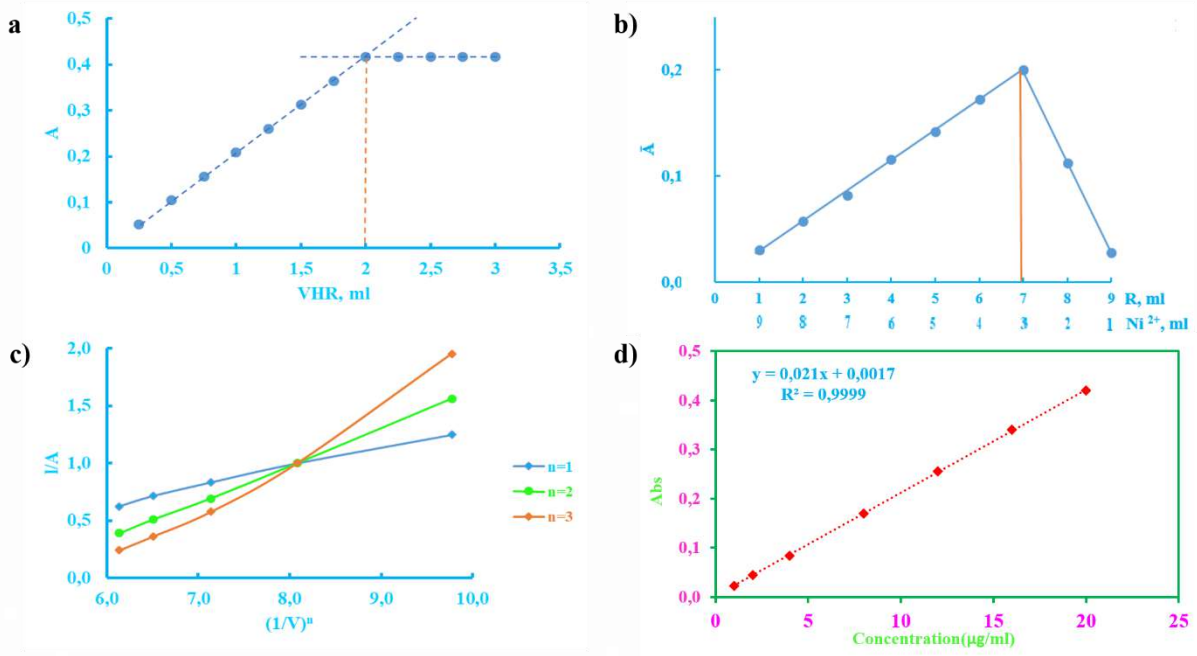
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haqiqiy molyar so‘ndirish koeffitsienti hamda hosil bo‘lish muvozanat konstantasi Tolmachyovning grafik metodi yordamida aniqlandi(3d-rasm).

$$\varepsilon_{haq} = \frac{1}{1/\varepsilon \cdot 10^{n}} = \frac{1}{1{,}9 \cdot 10^{-5}} = 52632 \qquad (2)$$

$$K_{muv} = \frac{C_H^n \cdot l^n}{n^n \cdot \varepsilon_x \cdot в^{n+1}} = \frac{0{,}0000173^2 \cdot 1^2}{2^2 \cdot 52632 \cdot (1{,}870 \cdot 10^{-5})^3} = 0{,}217 \qquad (3)$$

Kompleksning tarkibi va kompleks hosil bo‘lish mexanizimi. Nazarenko metodidan foydalangan holda, Ni(II) ning kompleks hosil qiluvchi shakli Cu^{2+} holatda ekanligi aniqlandi. Ni(II)ning XGNDS-2,7 bilan hosil qilgan rangli kompleksning steoxiometriyasi, spektrofotometrik titrlash metod(3a-rasm.), Izomolyar seriyalar metodi(3b-rasm.) va Asmusning to‘g‘ri chiziqli metodi(3c-rasm.) lari yordamida o‘rganildi. Olingan natijalar barcha metodlar kompleksdagi Ni:R=1:2 nisbatda ekanligini tasdiqladi.



3-rasm. a) Spektrofotometrik titrlash; b) Izomolyar seriyalar usuli; c) Asmusning to‘g‘ri chiziq usuli; d) Cu(II) ni aniqlashning kalibrlash grafigi.

Hosil bo‘lgan kompleksning barqarorlik konstantasi Babko usuli yordamida aniqlandi(3-jadval).

Bu yerda: C_H - H^+ ionlari konsentratsiyasi, l-kyuveta qalinligi, $\varepsilon_{haq.}$-kompleksning haqiqiy molyar so‘ndirish koeffitsenti, n-stexiometrik koeffitsient.

$$K_{beqaror.(MeR)} = \frac{[H^+] \cdot (A_1 \cdot C_2 - A_2 \cdot C_1)^{q+1}}{(C_1 \cdot \sqrt[3]{A_2} - C_2 \cdot \sqrt[3]{A_1}) \cdot (A_1 \cdot \sqrt[3]{A_2} - A_2 \cdot \sqrt[3]{A_1})^{q}} \qquad (4)$$

$$K_{barqaror.(MeR)} = \frac{1}{K_{beqaror.(MeR)}} \qquad (5)$$

ISSN 3030-3907

Bu yerda: $[H^+]$-vodorod ionlari konsentratsiyasi, A_1, A_2-optik zichliklar, C_1, C_2-metall ioni konsentratsiyalari.

Olingan natijalar shuni ko‘rsatdiki, Ni(II) ning XGNDS-2,7 reagenti bilan hosil qilgan rangli kompleksning ε_{haq}=52632, K_{muv}=0.217 va lgβ=19.07 qiymatlariga ega ekanligi aniqlandi. Olingan natijalardan shunday xulosa qilish mumkinki, ishlab chiqilgan usul yuqori sezgirlikka, kompleks birikma esa o‘rtacha barqarorlikka ega ekanligi aniqlandi.

3-jadval.

Babko usuli yordamida kompleksning barqarorlik konstantasini aniqlash natijalari

№	$V_{Cu^{2+}}$, ml	V_{R1}, ml	$C_1 \cdot 10^{-6}$	A_1	$C_2 \cdot 10^{-6}$	A_2	$K_{beqaror}$ (MeR)	$K_{barqaror}$ (MeR) (β_k)	$lgK_{barqaror.}$ (MeR) ($lg\beta_k$)
1	0,5	1	3,41	0,050	1,71	0,024	$1,04 \cdot 10^{-19}$	$2,17 \cdot 10^{18}$	18.98
2	1	2	6,82	0,154	3,41	0,075	$2.95 \cdot 10^{-20}$	$7,75 \cdot 10^{19}$	19.53
3	1,5	3	10,23	0,291	5,12	0,143	$6.65 \cdot 10^{-20}$	$3,42 \cdot 10^{19}$	19.18
4	2	4	13,64	0,463	6,82	0,227	$1.18 \cdot 10^{-19}$	$7,14 \cdot 10^{18}$	18.93
5	2,5	5	17,05	0,633	8,53	0,310	$1.85 \cdot 10^{-19}$	$3,20 \cdot 10^{18}$	18.73
Σ							$1,01 \cdot 10^{-19}$	$8,09 \cdot 10^{19}$	19.07

Graduirovkali grafik natijalarini kichik kvadratlar usuli bilan matematik qayta ishlandi shu bilan bergalikda to‘g‘iri chiziqli matematik tenglamasi tuzildi(3d-rasm).

Olingan natijalardan kelib chiqib graduirovkali grafik (darajalangan grafik) to‘g‘ri chiziq tenglamasi $Y_i = aX_i + b$ ya’ni $Y_i = 2.1 \cdot 10^{-2} X_i + 1.3 \cdot 10^{-3}$ ishlab chiqildi.

XULOSA. Ni(II) ionini XGNDS-2,7 reagent bilan kompleks hosil bo‘lishining optimal sharoitlari o‘rganildi: pH=5.5, universial buffer, 240 min, Bufer-reagent-Ni(II)-dist.suv,V_R=1.2 ml. Buger-Lambert-Ber qonuniga bo‘ysunish sohasi 1-20 μg/25ml, S.b.s= 0,0019 μg/sm^2, Δλ=100 nm. Spektrofotometrik titrlash metodi, Izomolyar seryalar metodi va Asmusning to‘g‘ri chiziq metodi yordamida tarkib Me:R=1:2 ekanligini tasdiqladi. Tolmachyovning grafik metodi yordamida hosil bo‘lgan kompleksning haqiqiy molyar so‘ndirish koeffitsienti(ε_{haq}=52632) va hosil bo‘lish muvozanat konstantasi (K_{muv}=0.217),

ISSN 3030-3907

Babko usuli yordamida rangli kompleksning barqarorlik konstantasi(lgβ=19.07) aniqlandi. Graduirovkali grafik (darajalangan grafik) to‘g‘ri chiziq tenglamasi $Y_i = 2{,}1 \cdot 10^{-2} X_i + 1{,}3 \cdot 10^{-3}$ ishlab chiqildi.

Minnatdorchilik

Mazkur tadqiqot Ilg‘or texnologiyalar Markazi va *Markaziy Osiyo atrof-muhit va iqlim o‘zgarishlarini o‘rganish universiteti (Green University) lari*ning byudjet mablag‘lari hisobidan moliyalashtirildi.

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SUN’IY INTELLEKT VA KOMPYUTER KO‘RISH TEXNOLOGIYALARIGA ASOSLANGAN MIYA O‘SMALARINI AVTOMATIK DIAGNOSTIKA QILISH ALGORITMLARINI ISHLAB CHIQISH

Jumaniyazova Mashxura Azamatovna
Urganch RANCH texnologiylari Universiteti Kompyuter injineringi magistranti
E-mail: mashhurajumaniyazova2308@gmail.com
Urazmatov Tohir Quranboyevich
Urganch RANCH texnologiyalari universiteti

Annotatsiya. Mazkur maqolada miya o‘smalarini magnit-rezonans tomografiya (MRT) tasvirlari asosida avtomatik aniqlash, segmentatsiya qilish va tasniflash uchun sun’iy intellekt hamda kompyuter ko‘rish texnologiyalaridan foydalanish masalalari yoritilgan. Tasvirlarni dastlabki qayta ishlash, patologik hududlarni ajratish, chuqur o‘rganish asosida xususiyatlarni aniqlash va yakuniy diagnostik qarorni shakllantirish bosqichlari yagona algoritmik tizim sifatida ko‘rib chiqilgan. Konvolyutsion neyron tarmoqlar, U-Net oilasidagi segmentatsiya arxitekturalari va transfer learning yondashuvlarining imkoniyatlari tahlil qilingan. Model samaradorligini baholashda Dice, IoU, sezgirlik, spetsifiklik va F1-mezon kabi ko‘rsatkichlardan foydalanish zarurligi asoslangan. Taklif etilayotgan tizim shifokorni almashtirish emas, balki MRT tasvirlarini saralash, shubhali o‘choqlarni aniqlash va klinik qaror qabul qilishni qo‘llab-quvvatlashga mo‘ljallangan.

Kalit so‘zlar: sun’iy intellekt, kompyuter ko‘rish, miya o‘smasi, MRT, segmentatsiya, chuqur o‘rganish, konvolyutsion neyron tarmoq, avtomatik diagnostika.

Аннотация. В статье рассматриваются вопросы разработки алгоритмов автоматической диагностики опухолей головного мозга на основе изображений магнитно-резонансной томографии (МРТ) с применением искусственного интеллекта и технологий компьютерного зрения. Рассмотрены этапы предварительной обработки изображений, сегментации патологических областей, автоматического выделения признаков с использованием глубокого обучения и формирования итогового диагностического решения. Проанализированы возможности сверточных нейронных сетей, архитектур семейства U-Net и подходов transfer learning. Обоснована необходимость оценки качества моделей по показателям Dice, IoU, чувствительности, специфичности и F1-мере. Предлагаемая система рассматривается как инструмент поддержки принятия клинических решений, а не как замена врача.

ISSN 3030-3907

Ключевые слова: искусственный интеллект, компьютерное зрение, опухоль головного мозга, МРТ, сегментация, глубокое обучение, сверточная нейронная сеть, автоматическая диагностика.

Abstract. This paper examines the development of artificial intelligence and computer vision algorithms for the automatic diagnosis of brain tumors using magnetic resonance imaging (MRI). The study considers image preprocessing, pathological-region segmentation, automatic feature extraction through deep learning, and final diagnostic classification as an integrated algorithmic workflow. The practical potential of convolutional neural networks, U-Net-based segmentation architectures, and transfer learning is discussed. The importance of evaluating model performance using Dice, IoU, sensitivity, specificity, and F1-score is emphasized. The proposed system is intended to support clinical decision-making by assisting specialists in image screening, tumor localization, and quantitative assessment rather than replacing medical expertise.

Keywords: artificial intelligence, computer vision, brain tumor, MRI, segmentation, deep learning, convolutional neural network, automatic diagnosis.

KIRISH.

Miya o‘smalari markaziy asab tizimining murakkab va klinik jihatdan muhim patologiyalaridan biri hisoblanadi. Ularning joylashuvi, hajmi, infiltratsiya darajasi va to‘qimalar bilan o‘zaro munosabati bemorning hayot sifati hamda davolash taktikasiga bevosita ta’sir ko‘rsatadi. Shu sababli kasallikni imkon qadar erta aniqlash, o‘sma chegaralarini aniq belgilash va uning turini to‘g‘ri baholash zamonaviy neyrodiagnostikaning muhim vazifalaridan biridir. Amaliyotda bu jarayon ko‘pincha MRT tasvirlarini tahlil qilishga asoslanadi. Biroq tasvirlar sonining ko‘pligi, o‘sma shaklining xilma-xilligi va sog‘lom hamda patologik to‘qimalar orasidagi farqning ayrim hollarda juda kichik bo‘lishi mutaxassis uchun qo‘shimcha yuklama hosil qiladi.

So‘nggi yillarda sun’iy intellektning tibbiy tasvirlarni qayta ishlash sohasiga jadal kirib kelishi ushbu muammoni yangi nuqtayi nazardan ko‘rib chiqish imkonini berdi. Ayniqsa, kompyuter ko‘rish va chuqur o‘rganish algoritmlari tasvirdagi murakkab naqshlarni inson tomonidan qo‘lda berilgan qoidalarga kamroq bog‘liq holda o‘rganishi bilan ajralib turadi. Bunday tizimlar o‘sma mavjudligini aniqlash, uning konturini belgilash, patologik hudud hajmini baholash va ayrim hollarda o‘sma turini tasniflash vazifalarida qo‘llanmoqda.

Ushbu maqolaning maqsadi miya o‘smalarini MRT tasvirlari asosida avtomatik diagnostika qilishga mo‘ljallangan algoritmik yondashuvni ishlab chiqishning nazariy va amaliy asoslarini bayon etishdan iborat. Bunda

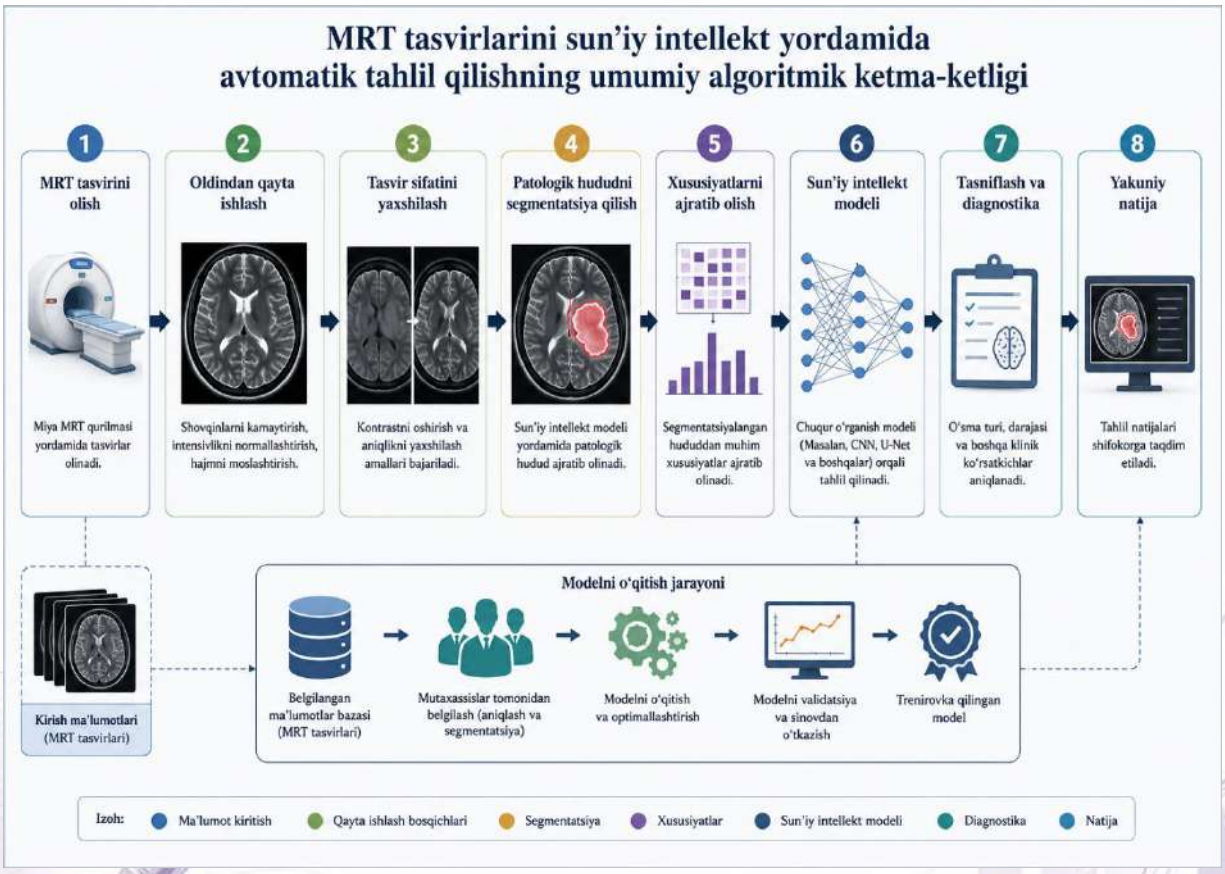
ISSN 3030-3907

ma’lumotlarni tayyorlashdan tortib modelni o‘qitish, baholash va klinik qo‘llashgacha bo‘lgan bosqichlar yagona tizim sifatida ko‘rib chiqiladi.

1. Miya o‘smalarini diagnostika qilishda MRT tasvirlarining o‘rni

MRT markaziy asab tizimi tuzilmalarini yuqori kontrast bilan tasvirlash imkonini beradigan noinvaziv diagnostika usulidir. T1, T2, FLAIR va kontrast bilan kuchaytirilgan T1 kabi ketma-ketliklar o‘smaning turli morfologik xususiyatlarini aks ettiradi. Bir tasvir turida yaxshi ko‘rinadigan patologik o‘zgarish boshqa ketma-ketlikda boshqacha ko‘rinishga ega bo‘lishi mumkin. Shuning uchun avtomatik tahlil tizimida multimodal tasvirlardan foydalanish modelga o‘sma va sog‘lom to‘qima o‘rtasidagi farqlarni yanada to‘liq o‘rganish imkonini beradi.

MRT tasvirlarining muhim xususiyati shundaki, ular turli qurilmalar, protokollar va parametrlar yordamida olinadi. Natijada bir xil kasallikka ega bemorlarda tasvirlarning intensivligi, o‘lchami va shovqin darajasi sezilarli farq qilishi mumkin. Algoritm faqat bitta markaz ma’lumotlariga moslashib qolsa, boshqa klinik muhitdagi tasvirlarda natijaning aniqligi pasayishi ehtimoli mavjud. Shu sababli avtomatik diagnostika tizimini ishlab chiqishda ma’lumotlarning xilma-xilligi va standartlashtirilishi alohida ahamiyat kasb etadi.



1-rasm. MRT tasvirlarini sun’iy intellekt yordamida avtomatik tahlil qilishning umumiy algoritmik ketma-ketligi.

ISSN 3030-3907

MRT tasvirlarini kompyuter orqali tahlil qilish odatda uchta asosiy vazifani qamrab oladi: patologik o‘choqni aniqlash, o‘sma hududini segmentatsiya qilish va o‘sma turini yoki darajasini tasniflash. Ushbu vazifalar bir-biridan mustaqil bo‘lishi mumkin, biroq amaliy tizimda ular ketma-ket yoki yagona ko‘p vazifali model tarkibida bajarilishi mumkin.

2. Ma’lumotlarni tayyorlash va dastlabki qayta ishlash

Har qanday mashinali o‘rganish tizimining sifati, avvalo, undan foydalaniladigan ma’lumotlar to‘plamining sifati bilan belgilanadi. Miya o‘smalarini aniqlash uchun MRT ma’lumotlari bemorning klinik holati, tasvir ketma-ketligi va ekspert tomonidan belgilangan haqiqiy javob bilan bog‘langan bo‘lishi lozim. Segmentatsiya masalasida esa har bir tasvir uchun o‘sma hududining konturi yoki piksel darajasidagi niqobi talab qilinadi. Bunday belgilashlar tajribali radiolog yoki neyroxirurg tomonidan tasdiqlanishi model uchun ishonchli o‘quv namunalarini shakllantiradi.

Dastlabki qayta ishlash bosqichida tasvir o‘lchamini standartlashtirish, intensivlikni normallashtirish, keraksiz fonni olib tashlash va shovqinni kamaytirish kabi amallar bajariladi. Intensivlikni normallashtirish turli skanerlardan olingan tasvirlar o‘rtasidagi texnik tafovutlarni kamaytiradi. Biroq ortiqcha filtrlash o‘smaning mayda chegaralarini yo‘qotishi mumkinligi sababli parametrlarni ehtiyotkorlik bilan tanlash talab etiladi.

1-jadval.

MRT tasvirlarini dastlabki qayta ishlash bosqichlari.

Bosqich	Asosiy amal	Maqsad	Natija
Formatlash	O‘lcham va voxel oralig‘ini standartlashtirish	Tasvirlarni bir xil ko‘rinishga keltirish	Barqaror kirish
Normalizatsiya	Intensivlikni me’yorlash	Skaner farqlarini kamaytirish	Umumlashtirish
Shovqinni kamaytirish	Yengil filtrlash	Keraksiz tebranishlarni kamaytirish	Sifat oshadi
Augmentation	Burish, masshtablash, intensivlik o‘zgarishi	Namuna xilma-xilligini oshirish	Overfitting kamayadi

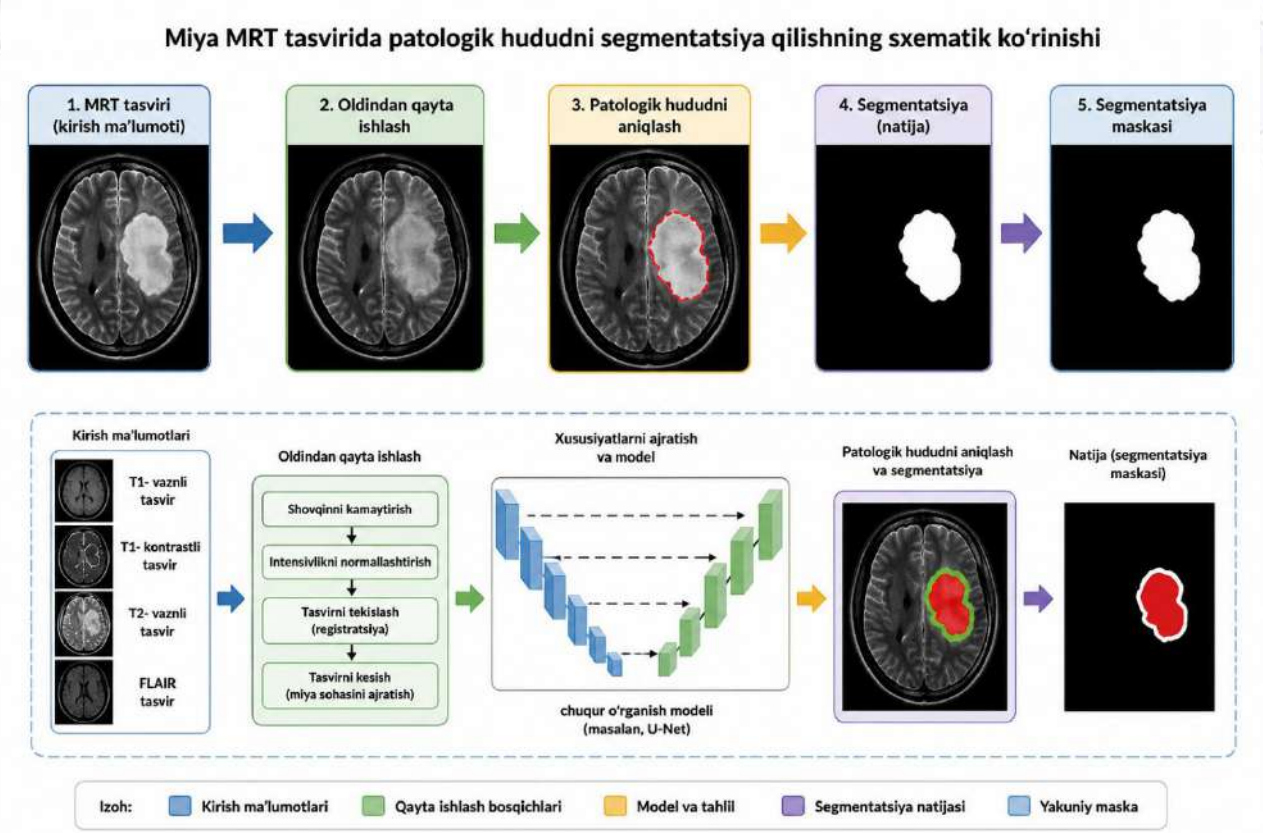
Ma’lumotlarni kengaytirish, ya’ni augmentation ham muhim bosqichdir. Tasvirni kichik burchakka burish, masshtabini o‘zgartirish, gorizontal yoki vertikal o‘zgartirish, yorqinlikni biroz almashtirish kabi usullar modelni turli tasvir

ISSN 3030-3907

sharoitlariga moslashishga yordam beradi. Biroq anatomik jihatdan mantiqsiz transformatsiyalar qo‘llansa, model real klinik holatga mos kelmaydigan belgilarni o‘rganib qolishi mumkin. Shu sababli augmentation tibbiy mazmunni saqlab qoladigan chegaralarda amalga oshirilishi kerak.

3. Kompyuter ko‘rish asosida o‘sma hududini aniqlash

Kompyuter ko‘rish tizimining birinchi vazifasi tasvirdagi shubhali hududni aniqlashdir. Klassik yondashuvlarda chegaraviy qiymatga asoslangan segmentatsiya, morfologik amallar, kontur aniqlash va tekstura belgilaridan foydalanilgan. Bunday usullar ayrim nazorat qilinadigan sharoitlarda samarali bo‘lsa-da, o‘smaning shakli va intensivligi turlicha bo‘lgan murakkab MRT tasvirlarida universal natija berishi qiyin.



2-rasm. Miya MRT tasvirida patologik hududni segmentatsiya qilishning sxematik ko‘rinishi.

Chuqur o‘rganish usullari bu muammoni tasvirdan belgilarni avtomatik ajratib olish orqali hal qilishga intiladi. Konvolyutsion neyron tarmoqlar tasvirning dastlabki qatlamlarida chegaralar va oddiy teksturalarni, keyingi qatlamlarda esa murakkab shakl va strukturaviy bog‘lanishlarni o‘rganadi. Natijada model o‘smani faqat bitta piksel intensivligi bilan emas, balki uning atrofidagi anatomik kontekst bilan birgalikda baholaydi.

Segmentatsiya uchun U-Net arxitekturasi amaliy jihatdan qulay yechimlardan biridir. Uning kodlovchi qismi tasvirdan yuqori darajadagi

ISSN 3030-3907

xususiyatlarni ajratadi, dekodlovchi qismi esa ushbu ma’lumotlarni fazoviy aniqlikni saqlagan holda tasvir o‘lchamiga qaytaradi. Skip-connection mexanizmi pastki qatlamlardagi mayda detallarni yuqori qatlamlardagi semantik ma’lumot bilan birlashtirish imkonini beradi. Shu sababli U-Net va uning modifikatsiyalari tibbiy tasvir segmentatsiyasida keng qo‘llanadi.

4. Taklif etilayotgan avtomatik diagnostika algoritmi

Miya o‘smalarini avtomatik diagnostika qilish uchun taklif etilayotgan algoritmni shartli ravishda besh bosqichga ajratish mumkin: ma’lumotni qabul qilish, oldindan qayta ishlash, o‘smani segmentatsiya qilish, xususiyatlarni aniqlash va yakuniy tasniflash. Tizimga MRT tasviri kiritilgandan so‘ng u yagona formatga keltiriladi va normalizatsiya qilinadi. Keyingi bosqichda segmentatsiya modeli o‘sma mavjud bo‘lgan hududni ajratadi. Ajratilgan hududdan geometrik, teksturaviy va chuqur o‘rganilgan xususiyatlar olinadi.

Algoritmning umumiy mantiqiy ketma-ketligi quyidagicha ifodalanadi: MRT → oldindan qayta ishlash → segmentatsiya → xususiyatlarni ajratish → tasniflash → diagnostik hisobot. Segmentatsiya natijasida o‘smaning taxminiy hajmi, yuzasi, shakli va joylashuvi aniqlanishi mumkin. Tasniflash bosqichida esa model o‘qitish ma’lumotlarida mavjud bo‘lgan sinflar bo‘yicha ehtimollik qiymatlarini shakllantiradi.

Modelni o‘qitishda ma’lumotlar odatda o‘quv, validatsiya va test qismlariga ajratiladi. Bunda bir bemorga tegishli tasvirlarning turli qismlarga aralashib ketishiga yo‘l qo‘ymaslik zarur. Aks holda model bir bemorning o‘ziga xos tasvir xususiyatlarini yodlab olishi va test natijalari sun’iy ravishda yuqori ko‘rinishi mumkin. Shu bois bo‘linish bemor darajasida amalga oshirilishi maqsadga muvofiq.

2-jadval.

Ma’lumotlar to‘plamini o‘qitish, validatsiya va test guruhlariga taqsimlash.

To‘plam	Vazifasi	Tavsiya etiladigan ulush
O‘quv	Model parametrlarini o‘rganish	70–80 %
Validatsiya	Giperparametrlarni tanlash	10–15 %
Test	Yakuniy mustaqil baholash	10–15 %

5. Chuqur o‘rganish va model arxitekturasini tanlash

Diagnostik modelni tanlashda aniqlik bilan bir qatorda hisoblash murakkabligi, o‘qitish uchun zarur ma’lumot hajmi va modelning klinik sharoitda

ISSN 3030-3907

ishlash tezligi ham hisobga olinadi. ResNet, DenseNet, EfficientNet kabi konvolyutsion arxitekturalar tasniflash vazifalarida qo‘llanishi mumkin. Segmentatsiya uchun U-Net, Attention U-Net yoki 3D U-Net kabi arxitekturalar mos keladi. Agar uch o‘lchamli hajmiy MRT ma’lumotlari mavjud bo‘lsa, 3D konvolyutsiyalar anatomik bog‘lanishlarni to‘liqroq ifodalashi mumkin.

Transfer learning ma’lumotlar hajmi cheklangan vaziyatlarda foydali bo‘lishi mumkin. Bunda avval katta hajmdagi tasvirlar ustida o‘qitilgan modelning dastlabki qatlamlari yangi vazifaga moslashtiriladi. Biroq tabiiy tasvirlar bilan tibbiy MRT tasvirlari o‘rtasidagi farqni hisobga olish kerak. Modelning barcha qatlamlarini o‘zgartirmasdan qo‘llash har doim ham optimal natija bermaydi; shu sababli fine-tuning bosqichi zarur bo‘lishi mumkin.

Segmentatsiya modelining yo‘qotish funksiyasi ham muhim. O‘sma hududi butun miya tasviriga nisbatan kichik bo‘lishi mumkinligi sababli oddiy piksel aniqligiga asoslangan yo‘qotish funksiyasi yetarli bo‘lmasligi mumkin. Dice loss, focal loss yoki ularning kombinatsiyasi kichik va nomutanosib hududlarni o‘rganishda ma’qul natija berishi mumkin. Tasniflashda esa cross-entropy asosidagi yo‘qotish funksiyasi keng tarqalgan.

3-jadval.

Avtomatik diagnostika modelini baholashning asosiy mezonlari.

Ko‘rsatkich	**Mazmuni**	**Qo‘llanish sohasi**
Dice	Prediksiya va haqiqiy niqob ustma-ust tushishi	Segmentatsiya
IoU	Kesishmaning birlashmaga nisbati	Segmentatsiya
Sezgirlik	Kasallikni to‘g‘ri aniqlash darajasi	Tasniflash
Spetsifiklik	Sog‘lom holatni to‘g‘ri ajratish	Tasniflash
F1-mezon	Precision va recall muvozanati	Tasniflash

6. Modelni baholash mezonlari

Avtomatik diagnostika tizimini baholashda faqat umumiy aniqlik ko‘rsatkichiga tayanish noto‘g‘ri xulosalarga olib kelishi mumkin. Tasniflash uchun aniqlik, sezgirlik, spetsifiklik, precision, F1-mezon va ROC-AUC kabi ko‘rsatkichlardan foydalaniladi. Sezgirlik kasallikka ega bemorlarni to‘g‘ri aniqlash qobiliyatini, spetsifiklik esa sog‘lom holatlarni noto‘g‘ri patologik deb belgilamaslik qobiliyatini tavsiflaydi.

ISSN 3030-3907

Segmentatsiya sifatini baholashda Dice Similarity Coefficient va Intersection over Union ko‘rsatkichlari keng qo‘llanadi. Dice ko‘rsatkichi model ajratgan hudud bilan ekspert belgilagan hudud o‘rtasidagi ustma-ust tushish darajasini ifodalaydi. Shu bilan birga, klinik nuqtayi nazardan o‘sma chegarasidagi kichik xatolar ham ahamiyatli bo‘lishi mumkin. Shuning uchun statistik ko‘rsatkichlardan tashqari chegaraviy xatolik, hajmni baholash xatosi va klinik ekspert xulosasi bilan moslik ham o‘rganilishi kerak.

Modelning ishonchliligini tekshirish uchun mustaqil test to‘plamidan foydalanish va imkon qadar boshqa tibbiy markazdan olingan tashqi ma’lumotlarda sinov o‘tkazish muhimdir. Tashqi validatsiya modelning real klinik muhitga qanchalik yaxshi ko‘chishini baholash imkonini beradi.

7. Algoritmning ishonchliligi va interpretatsiyasi

Tibbiy sun’iy intellekt tizimining asosiy talablaridan biri uning qarorini tushuntirish imkoniyatidir. Shifokor faqat yakuniy ehtimollik qiymatini emas, balki model qaysi hududga asoslanib qaror chiqarganini ham ko‘rishi maqsadga muvofiq. Shu nuqtayi nazardan Grad-CAM kabi vizualizatsiya usullari tasniflash modelining e’tibor qaratgan hududlarini ko‘rsatishga yordam beradi. Segmentatsiya modelida esa o‘sma niqobi bevosita MRT tasviri ustiga qo‘yilib, natija shifokor tomonidan tekshirilishi mumkin.

Interpretatsiya mexanizmi modelning xatolarini aniqlashda ham muhim. Agar tizim o‘sma mavjudligini anatomik jihatdan noto‘g‘ri hududga asoslanib bashorat qilsa, bunday natija klinik foydalanish uchun xavfli bo‘lishi mumkin. Shu sababli model ishlab chiqish jarayonida faqat yuqori metrikaga erishish emas, balki qaror qabul qilish mexanizmining mantiqiyligini tekshirish ham talab etiladi.

Bundan tashqari, ma’lumotlar to‘plamidagi yashirin og‘ishlar model natijasiga ta’sir qilishi mumkin. Skaner ishlab chiqaruvchisi, tasvir protokoli, bemorning yoshi yoki tasvirni olish markazi kabi omillar model tomonidan kasallik belgisi sifatida noto‘g‘ri o‘zlashtirilishi ehtimoldan xoli emas. Bunday holatlarni aniqlash uchun modelni turli guruhlar va turli sharoitlarda sinash zarur.

8. Amaliy tizimning dasturiy arxitekturasi

Amaliy avtomatik diagnostika tizimi bir nechta funksional modullardan tashkil topishi mumkin. Birinchi modul MRT ma’lumotlarini qabul qiladi va DICOM yoki boshqa standart formatdagi tasvirlarni qayta ishlashga tayyorlaydi. Ikkinchi modul oldindan qayta ishlash va normalizatsiyani amalga oshiradi. Uchinchi modul segmentatsiya neyron tarmog‘i yordamida patologik hududni aniqlaydi. To‘rtinchi modul tasniflash modelini ishga tushiradi va ehtimollik natijalarini shakllantiradi. Yakuniy modul natijalarni shifokor uchun tushunarli ko‘rinishda taqdim etadi.

ISSN 3030-3907

Dasturiy jihatdan Python ekotizimi, PyTorch yoki TensorFlow kabi chuqur o‘rganish kutubxonalari, OpenCV va tibbiy tasvirlarni qayta ishlash vositalari bilan integratsiya qilinishi mumkin. Modelni ishlab chiqish bosqichida GPU hisoblash resurslaridan foydalanish o‘qitish vaqtini sezilarli qisqartiradi. Klinik tizimga joriy etishda esa modelning inferensiya tezligi, xotira talabi va server infratuzilmasi bilan mosligi hisobga olinadi.

Tizim interfeysida original MRT tasviri, segmentatsiya niqobi, tasniflash natijasi va model ishonchlilik ko‘rsatkichlarini bir oynada ko‘rsatish qulaydir. Bunday yondashuv shifokorga avtomatik natijani mustaqil tasvir bilan taqqoslash imkonini beradi. Tizim yakuniy tashxisni mustaqil qo‘yuvchi vosita emas, balki klinik qarorni qo‘llab-quvvatlovchi axborot tizimi sifatida loyihalanishi lozim.

9. Tajriba metodologiyasi va kutilayotgan natijalar

Tadqiqotning tajriba qismida MRT ma’lumotlar to‘plami tanlanib, dastlab tasvirlarning texnik sifati va belgilashlar izchilligi tekshiriladi. Keyin ma’lumotlar bemorlar bo‘yicha o‘quv, validatsiya va test guruhlariga ajratiladi. Segmentatsiya modeli o‘qitilib, Dice va IoU ko‘rsatkichlari bo‘yicha baholanadi. Segmentatsiyadan olingan hududlar keyingi tasniflash bosqichiga uzatiladi.

Kutilayotgan natija sifatida avtomatik tizim MRT tasvirida miya o‘smasi mavjudligini yuqori sezgirlik bilan aniqlashi, o‘sma hududining chegaralarini ekspert belgilashlariga yaqin tarzda ajratishi va mavjud sinflar bo‘yicha barqaror tasniflash natijalarini berishi ko‘zda tutiladi. Bunda aniq sonli natijalar ma’lumotlar to‘plami, tasvir sifati, model arxitekturasi va o‘qitish parametrlariga bog‘liq bo‘ladi. Shu sababli tajriba o‘tkazmasdan turib ma’lum bir aniqlik foizini kafolatlash ilmiy jihatdan asosli emas.

Modelni takomillashtirishning istiqbolli yo‘nalishlaridan biri multimodal MRT ma’lumotlarini birgalikda tahlil qilishdir. T1, T2 va FLAIR kabi ketma-ketliklar bir-birini to‘ldiradi. Yana bir yo‘nalish — 3D modellar yordamida butun hajmiy tasvirni tahlil qilish. Bunday model ko‘proq hisoblash resurslarini talab qilsa-da, o‘smaning fazoviy tuzilishini yaxshiroq ifodalashi mumkin.

10. Klinik qo‘llash, cheklovlar va xavfsizlik masalalari

Sun’iy intellekt asosidagi diagnostika tizimini klinik amaliyotga joriy qilish faqat texnik jihatdan yaxshi ishlaydigan model yaratish bilan tugamaydi. Tizim mustaqil klinik validatsiyadan o‘tishi, turli bemor guruhlarida tekshirilishi va shifokor ish jarayoniga qanday ta’sir ko‘rsatishi baholanishi kerak. Ayniqsa, noto‘g‘ri manfiy natija o‘smani aniqlamay qolishga, noto‘g‘ri musbat natija esa keraksiz qo‘shimcha tekshiruvlarga olib kelishi mumkin.

Modelning asosiy cheklovlaridan biri ma’lumotlar hajmi va sifatiga bog‘liqligidir. Kam sonli yoki bir xil markazdan olingan tasvirlarda o‘qitilgan model boshqa klinik sharoitlarda kutilgan darajada ishlamasligi mumkin.

ISSN 3030-3907

Shuningdek, ayrim o‘sma turlari uchun yetarli miqdorda belgilangan ma’lumot mavjud emasligi sinflar nomutanosibligini yuzaga keltiradi. Bu muammoni qayta namunalash, og‘irliklarni moslashtirish yoki maxsus yo‘qotish funksiyalari orqali kamaytirish mumkin.

Bemor ma’lumotlarining maxfiyligi ham alohida ahamiyatga ega. MRT tasvirlari bilan ishlashda shaxsni aniqlovchi ma’lumotlarni himoyalash, ma’lumotlarni xavfsiz saqlash va ulardan foydalanish huquqini nazorat qilish talab etiladi. Klinik tizimga integratsiya qilinadigan modelning har bir qarori audit qilinishi va zarur holatda inson tomonidan tekshirilishi lozim.

11. Natijalarni muhokama qilish

Tahlil shuni ko‘rsatadiki, miya o‘smalarini avtomatik diagnostika qilishda eng maqbul strategiya tasvirni oddiy klassifikatsiya qilish bilan cheklanib qolmasdan, o‘sma hududini segmentatsiya qilish va keyin tasniflashni birlashtirishdan iborat. Segmentatsiya natijasi diagnostik model uchun qo‘shimcha fazoviy axborot beradi. Shu bilan birga, noto‘g‘ri segmentatsiya keyingi bosqichga xatoni uzatishi mumkin. Demak, butun tizimning ishlash sifati uning alohida modullaridan eng zaif bo‘lgan qismiga sezilarli darajada bog‘liq.

An’anaviy kompyuter ko‘rish usullari tushunarli va hisoblash jihatidan nisbatan sodda bo‘lsa-da, ular patologik o‘zgarishlarning xilma-xilligini to‘liq ifodalashda cheklanishi mumkin. Chuqur o‘rganish esa murakkab belgilarni avtomatik o‘zlashtirish imkonini beradi, biroq ko‘proq ma’lumot, hisoblash resurslari va ehtiyotkor validatsiyani talab qiladi. Shu sababli amaliy tizimda klassik tasvir qayta ishlash bosqichlari va chuqur neyron tarmoqlarni bir-birini to‘ldiruvchi usul sifatida qo‘llash maqsadga muvofiq.

Yana bir muhim masala — model natijasini klinik qaror bilan aralashtirib yubormaslikdir. Sun’iy intellekt tasvir asosida ehtimoliy natija beradi, yakuniy tashxis esa bemorning klinik holati, boshqa tekshiruvlar va mutaxassis xulosasi bilan birgalikda belgilanadi. Shu nuqtayi nazardan AI tizimining eng katta amaliy qiymati radiologga takroriy ishlarni kamaytirish, shubhali tasvirlarni ustuvorlashtirish va o‘sma chegaralarini baholashda yordam berishdan iborat.

XULOSA.

Miya o‘smalarini avtomatik diagnostika qilishda sun’iy intellekt va kompyuter ko‘rish texnologiyalaridan foydalanish tibbiy tasvirlarni tahlil qilish samaradorligini oshirish uchun istiqbolli yo‘nalish hisoblanadi. MRT tasvirlarini oldindan qayta ishlash, o‘sma hududini segmentatsiya qilish, chuqur xususiyatlarni ajratish va yakuniy tasniflashni yagona algoritmik zanjirga birlashtirish orqali shifokor ishini qo‘llab-quvvatlovchi tizim yaratish mumkin.

Tadqiqotda ko‘rib chiqilgan yondashuvning asosiy ustunligi o‘sma shakli va tuzilishidagi murakkab farqlarni avtomatik o‘rganish imkoniyatidir. Shu bilan

ISSN 3030-3907

birga, modelning haqiqiy klinik qiymatini aniqlash uchun mustaqil va tashqi validatsiya, ma’lumotlar sifati, interpretatsiya, maxfiylik va xavfsizlik masalalariga alohida e’tibor berish zarur. Kelgusida multimodal va 3D MRT ma’lumotlaridan foydalanish, ko‘p vazifali modellarni ishlab chiqish, model izohlanishini kuchaytirish hamda turli klinik markazlarda sinovdan o‘tkazish ushbu yo‘nalishning samaradorligini yanada oshirishi mumkin.

Shunday qilib, sun’iy intellekt asosidagi avtomatik diagnostika tizimi shifokorni almashtirish vositasi sifatida emas, balki klinik qaror qabul qilishni qo‘llab-quvvatlovchi texnologik vosita sifatida qaralishi kerak. To‘g‘ri tashkil etilgan ma’lumotlar bazasi, ilmiy asoslangan model tanlovi va qat’iy validatsiya bilan bunday tizimlar miya o‘smalarini aniqlash va baholash jarayonida amaliy ahamiyatga ega bo‘lishi mumkin.

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TALABALARDA FAZOVIY TAFAKKURNI ANIMATSIYALAR ORQALI RIVOJLANTIRISH METODLARI

Xo‘janiyozov Shokir Rustamovich
Abu Rayhon Beruniy nomidagi Urganch davlat universiteti o‘qituvchisi

Annotatsiya. Ushbu maqolada talabalarda fazoviy tafakkurni rivojlantirishda animatsion texnologiyalardan foydalanishning metodik asoslari yoritilgan. Fazoviy tafakkurning muhandislik, texnologiya, arxitektura, dizayn va texnik fanlarni o‘zlashtirishdagi ahamiyati tahlil qilinib, animatsiyalar yordamida murakkab geometrik shakllar, uch o‘lchovli obyektlar hamda ularning fazodagi o‘zaro joylashuvi va harakatini vizual namoyish etish imkoniyatlari ko‘rib chiqilgan. Shuningdek, interaktiv animatsiyalar, 3D modellar va raqamli ta’lim vositalari asosida o‘qitishni tashkil etishning samarali metodlari tavsiflangan. Animatsion ta’lim vositalaridan foydalanish talabalarning vizual idrokini, mantiqiy va fazoviy fikrlashini, tahlil qilish hamda muammolarni yechish ko‘nikmalarini rivojlantirishga xizmat qilishi asoslab berilgan.

Kalit so‘zlar: fazoviy tafakkur, animatsiya, 3D model, vizualizatsiya, raqamli ta’lim, interaktiv ta’lim, fazoviy tasavvur, grafik savodxonlik, multimedia texnologiyalari, pedagogik metodlar.

Аннотация. В данной статье рассмотрены методические основы развития пространственного мышления студентов с использованием анимационных технологий. Проанализировано значение пространственного мышления при изучении инженерных, технологических, архитектурных, дизайнерских и технических дисциплин. Особое внимание уделено возможностям анимации для визуализации сложных геометрических объектов, трёхмерных моделей, их пространственного расположения и динамических изменений. Описаны эффективные методы организации учебного процесса с применением интерактивной анимации, 3D-моделирования и цифровых образовательных ресурсов. Обосновано, что использование анимационных средств способствует развитию визуального восприятия, логического и пространственного мышления, аналитических способностей и навыков решения практических задач.

Ключевые слова: пространственное мышление, анимация, трёхмерное моделирование, визуализация, цифровое образование, интерактивное обучение, пространственное воображение, графическая грамотность, мультимедийные технологии, педагогические методы.

Abstract. This article examines methodological approaches to developing students’ spatial thinking through animation technologies. The importance of spatial thinking in engineering, technology, architecture, design, and technical education is analyzed. Particular attention is given to the use of animations for

ISSN 3030-3907

visualizing complex geometric structures, three-dimensional objects, their spatial relationships, and dynamic transformations. The paper describes effective instructional methods based on interactive animations, 3D modeling, and digital learning technologies. It is argued that the integration of animation into the educational process enhances students' visual perception, spatial reasoning, logical thinking, analytical abilities, and problem-solving skills while improving the quality and effectiveness of learning.

Keywords: spatial thinking, animation, 3D modeling, visualization, digital education, interactive learning, spatial reasoning, graphic literacy, multimedia technologies, teaching methods.

KIRISH.

Raqamli transformatsiya jarayonlari ta'lim tizimining barcha bo'g'inlarida o'qitish mazmuni, metodlari va didaktik vositalarini tubdan yangilashni talab qilmoqda. Ayniqsa, texnik, muhandislik, arxitektura, dizayn va axborot texnologiyalari yo'nalishlarida tahsil olayotgan talabalarda fazoviy tafakkurni rivojlantirish bugungi kunda dolzarb pedagogik vazifalardan biri hisoblanadi. Fazoviy tafakkur insonning uch o'lchovli obyektlarni idrok etishi, ularning shakli, o'lchami, joylashuvi va fazodagi o'zaro munosabatlarini tasavvur qilishi hamda ushbu tasavvurlar asosida tahlil, modellashtirish va amaliy qarorlar qabul qilish qobiliyatini ifodalaydi. Mazkur kompetensiya zamonaviy mutaxassisning kasbiy faoliyatida muhim o'rin egallaydi, chunki ko'plab muhandislik va texnologik masalalar aynan fazoviy tasavvurga tayangan holda hal etiladi.

An'anaviy ta'lim jarayonida fazoviy tafakkurni rivojlantirish ko'pincha statik chizmalar, rasmlar va maketlar orqali amalga oshiriladi. Biroq bunday vositalar murakkab uch o'lchovli obyektlarning ichki tuzilishi, harakat jarayoni yoki elementlarining fazodagi o'zaro bog'liqligini to'liq ifodalash imkoniyatiga ega emas. Natijada talabalarda geometrik shakllarni tasavvur qilish, murakkab konstruksiyalarni tahlil etish, detallarni turli rakurslarda idrok etish va ularni amaliy vazifalarda qo'llash jarayonida qiyinchiliklar yuzaga keladi. Ayniqsa, texnik chizmachilik, muhandislik grafikasi, mashinasozlik, qurilish va kompyuter grafikasi fanlarini o'zlashtirishda fazoviy tasavvurning yetarli darajada shakllanmaganligi o'quv natijalariga salbiy ta'sir ko'rsatadi. So'nggi yillarda ta'lim jarayoniga multimedia texnologiyalari, uch o'lchovli modellashtirish, virtual muhitlar va animatsion dasturlarni joriy etish fazoviy tafakkurni rivojlantirishning samarali yo'nalishlaridan biri sifatida e'tirof etilmoqda. Animatsiyalar yordamida murakkab obyektlarning hosil bo'lish jarayoni, geometrik o'zgarishlari, kesimlari, aylanishi, deformatsiyasi va fazodagi harakati bosqichma-bosqich vizual tarzda

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namoyish etiladi. Bu esa talabalarning vizual idroki va abstrakt fikrlashini faollashtirib, nazariy bilimlarni amaliy tasavvurlar bilan uyg‘unlashtirish imkonini yaratadi. Dinamik vizualizatsiya orqali o‘quv materiali yanada tushunarli bo‘lib, murakkab tushunchalarni o‘zlashtirish tezligi va sifati oshadi.

Animatsion ta’lim vositalari nafaqat axborotni ko‘rgazmali shaklda taqdim etadi, balki talabaning faol ishtirokini ta’minlaydigan interaktiv o‘quv muhitini ham yaratadi. Bunday muhitda talaba obyektlarni turli yo‘nalishlarda aylantirishi, masshtabini o‘zgartirishi, ichki tuzilishini tahlil qilishi, alohida qismlarini ajratib ko‘rishi va ularning o‘zaro bog‘liqligini kuzatishi mumkin. Natijada fazoviy fikrlash bilan bir qatorda mantiqiy tahlil qilish, muammoli vaziyatlarni hal etish, vizual xotira va ijodiy yondashuv kabi kompetensiyalar ham rivojlanadi.

Bugungi kunda Blender, Autodesk 3ds Max, SolidWorks, Autodesk Inventor, Fusion 360, SketchUp, Unity va boshqa zamonaviy animatsion hamda uch o‘lchovli modellashtirish platformalarining ta’lim jarayoniga integratsiyalashuvi fazoviy tafakkurni rivojlantirish uchun yangi imkoniyatlarni yaratmoqda. Ushbu dasturlar yordamida tayyorlangan animatsiyalar talabalarga obyektlarning geometrik tuzilishi, texnologik ishlov berish bosqichlari, mexanizmlarning ishlash prinsipi hamda konstruktiv elementlarning o‘zaro harakatini real vaqt rejimida kuzatish imkonini beradi. Shu sababli animatsion ta’lim vositalaridan foydalanish ta’limning ko‘rgazmalilik, tizimlilik, interfaollik va kompetensiyaviy yondashuv tamoyillarini samarali amalga oshirishga xizmat qiladi.

Shu nuqtai nazardan, talabalarda fazoviy tafakkurni animatsiyalar orqali rivojlantirish metodlarini ilmiy-pedagogik jihatdan asoslash, animatsion texnologiyalarni o‘quv jarayoniga integratsiyalashning samarali usullarini ishlab chiqish hamda ularning ta’lim sifati va kasbiy kompetensiyalarni rivojlantirishdagi imkoniyatlarini aniqlash zamonaviy pedagogikaning muhim ilmiy-amaliy yo‘nalishlaridan biri hisoblanadi. Mazkur yondashuv bo‘lajak mutaxassislarning kasbiy tayyorgarligini takomillashtirish, ularning innovatsion fikrlashi va fazoviy tasavvurini rivojlantirish, shuningdek, raqamli ta’lim muhitida samarali faoliyat yurita oladigan raqobatbardosh kadrlarni tayyorlashga xizmat qiladi.

ADABIYOTLAR TAHLILI VA TADQIQOT METODOLOGIAYSI.

Talabalarda fazoviy tafakkurni rivojlantirish, uni shakllantirishning pedagogik va psixologik asoslari hamda animatsion texnologiyalarning ta’lim jarayonidagi imkoniyatlari bo‘yicha olib borilgan ilmiy izlanishlar mazkur yo‘nalishning dolzarbligini ko‘rsatadi. Xorijiy va mahalliy olimlarning tadqiqotlarida fazoviy fikrlash insonning kognitiv faoliyatining muhim tarkibiy qismi sifatida baholanib, uni rivojlantirishda vizual vositalar, raqamli modellashtirish va interaktiv texnologiyalarning o‘rni alohida ta’kidlangan.

ISSN 3030-3907

R. E. Mayer (2001) o‘zining “Multimedia Learning” nomli ilmiy ishida multimedia vositalari orqali bilimlarni o‘zlashtirish jarayonining psixologik va pedagogik asoslarini tadqiq qilgan. Muallif multimedia taqdimotlarida matn, grafik tasvir va animatsiyalarning uyg‘un qo‘llanilishi talabalarning vizual idrokini kuchaytirishi hamda murakkab tushunchalarni chuqurroq anglashiga yordam berishini asoslagan. Mazkur nazariya animatsion texnologiyalardan foydalanishning ilmiy-pedagogik asoslarini belgilaydi.

R. E. Mayer va R. Moreno (2003) tomonidan chop etilgan “Nine Ways to Reduce Cognitive Load in Multimedia Learning” maqolasida multimedia ta’limida ortiqcha kognitiv yuklamani kamaytirish usullari tahlil qilingan. Tadqiqotchilar animatsiyalarni to‘g‘ri loyihalash orqali talabalarning axborotni qayta ishlash samaradorligini oshirish mumkinligini ko‘rsatganlar. Ushbu yondashuv fazoviy obyektlarni bosqichma-bosqich namoyish etishda muhim metodik asos bo‘lib xizmat qiladi.

G. Burdea va P. Coiffet (2003) “Virtual Reality Technology” nomli asarida virtual reallik va uch o‘lchovli modellashtirish texnologiyalarining imkoniyatlarini yoritgan. Mualliflar virtual muhitlar yordamida foydalanuvchilarda fazoviy tajriba shakllanishi, real obyektlarning raqamli modellarini o‘rganish va murakkab jarayonlarni vizual tahlil qilish imkoniyatlarini ko‘rsatgan. Ushbu qarashlar animatsion texnologiyalarni ta’lim jarayonida qo‘llash uchun nazariy asos yaratadi.

M. C. Linn va A. C. Petersen (2005) fazoviy qobiliyatlarni rivojlantirishda vizual ta’lim vositalarining ahamiyatini tahlil qilib, fazoviy fikrlashning muhim komponentlari sifatida fazoviy tasavvur, mental aylantirish va grafik tahlil qilish qobiliyatlarini ajratganlar. Ushbu tasnif bugungi kunda muhandislik va texnik ta’lim yo‘nalishlarida talabalarning fazoviy kompetensiyalarini baholashda qo‘llanilmoqda.

T. N. Höffler (2010) “Spatial Ability: Its Influence on Learning with Visualizations” nomli tadqiqotida vizual vositalarning ta’lim samaradorligiga ta’sirini o‘rgangan. Muallif statik tasvirlarga nisbatan dinamik vizualizatsiyalar va animatsiyalar murakkab fazoviy tushunchalarni tushuntirishda yuqori samaradorlikka ega ekanligini aniqlagan. Ushbu tadqiqot animatsiyalarning fazoviy tafakkurni rivojlantirishdagi pedagogik imkoniyatlarini ilmiy jihatdan asoslaydi.

C. A. Cohen va M. Hegarty (2014) “Visualizing Cross Sections: Training Spatial Thinking Using Interactive Animations” nomli tadqiqotida interaktiv animatsiyalar yordamida fazoviy fikrlashni rivojlantirish masalasini o‘rgangan. Tadqiqot natijalari shuni ko‘rsatganki, interaktiv 3D modellar va animatsiyalar yordamida talabalar murakkab geometrik obyektlarning ichki tuzilishini yaxshiroq tushunadi va mental rotatsiya qobiliyati rivojlanadi.

ISSN 3030-3907

S. H. Kim, J. Y. Kim va K. Park (2016) raqamli modellashtirish vositalarining muhandislik ta’limidagi ahamiyatini o‘rganib, CAD va 3D modellashtirish dasturlaridan foydalanish talabalarining konstruktiv fikrlash va fazoviy tasavvur qobiliyatlarini oshirishini aniqlaganlar.

T. N. Höffler va M. Leutner (2011) tomonidan olib borilgan tadqiqotlarda animatsiyalardan foydalanish samaradorligi tahlil qilingan. Mualliflar animatsiya ayniqsa jarayon va harakatni tushuntirishda statik tasvirlarga qaraganda yuqori didaktik imkoniyatlarga ega ekanligini ta’kidlaganlar.

G. Korakakis, E. A. Pavlatou, J. A. Palyvos va N. Spyrellis (2009) “3D Visualization Types in Multimedia Applications for Science Learning” nomli tadqiqotida uch o‘lchovli vizualizatsiya vositalarining ta’lim jarayonidagi samaradorligini tahlil qilgan. Mualliflar 3D modellar va animatsiyalar o‘quvchilarning murakkab ilmiy tushunchalarni o‘zlashtirish darajasini oshirishini ilmiy asoslagan.

A. A. Alavi va R. Leidner (2001) axborot texnologiyalarining ta’lim jarayonidagi o‘rnini o‘rganib, interaktiv raqamli vositalar talabaning mustaqil fikrlashi va bilimlarni faol o‘zlashtirishiga yordam berishini ko‘rsatgan.

H. A. Taylor, H. Burte va K. T. Renshaw (2023) “Connecting Spatial Thinking to STEM Learning through Visualizations” nomli tadqiqotida STEM ta’limida fazoviy fikrlashning ahamiyatini tahlil qilgan. Mualliflar zamonaviy vizualizatsiya texnologiyalari, jumladan 3D modellashtirish va animatsiyalar fazoviy kompetensiyalarni shakllantirishning samarali vositalari ekanligini ta’kidlagan.

A. M. Y. Yi, M. K. Ramlie va S. Subri (2024) “A Conceptual Framework for Integrating Mental Rotation and 3D Animation Pedagogy” nomli ishida mental rotatsiya va 3D animatsiya pedagogikasini integratsiyalash konsepsiyasini ishlab chiqqan. Tadqiqotchilar 3D animatsiyalar fazoviy tafakkurning asosiy komponentlarini rivojlantirishda samarali metodik vosita ekanligini asoslagan.

D. H. Saputra va K. Dwiningsih (2025) tomonidan olib borilgan tadqiqotda 3D animatsion vositalarning fazoviy vizualizatsiyani rivojlantirishdagi roli o‘rganilgan. Mualliflar raqamli animatsiyalar talabalarning murakkab obyektlarni tasavvur qilish qobiliyatini oshirishini aniqlagan.

MUHOKAMA.

Fazoviy tafakkur insonning uch o‘lchovli fazoda joylashgan obyektlarni idrok etish, ularning shakli, o‘lchami, o‘zaro joylashuvi va fazodagi harakatini tasavvur qilish hamda mazkur tasavvurlar asosida amaliy faoliyatni tashkil etish qobiliyatidir. Ushbu qobiliyat muhandislik, texnologiya, arxitektura, dizayn, robototexnika, qurilish va axborot texnologiyalari kabi ko‘plab sohalarda kasbiy kompetensiyaning asosiy tarkibiy qismlaridan biri hisoblanadi. Pedagogik va

ISSN 3030-3907

psixologik tadqiqotlarda fazoviy tafakkur insonning bilish faoliyatini rivojlantiruvchi muhim intellektual omillardan biri sifatida baholanadi. Fazoviy tafakkuri yuqori darajada rivojlangan talabalar murakkab grafik axborotni tezroq qabul qiladi, uch o‘lchovli modellarni oson tasavvur etadi hamda texnik masalalarni samarali yecha oladi. Shuningdek, ular geometrik modellashtirish, konstruktorlik loyihalari va grafik chizmalarni o‘qishda yuqori natijalarga erishadi.

Bugungi kunda oliy ta’lim muassasalarida muhandislik grafikasi, chizmachilik, mashina detallari, kompyuter grafikasi va 3D modellashtirish fanlarini o‘qitishda fazoviy tafakkurni rivojlantirish ustuvor vazifalardan biri sifatida qaralmoqda. Mazkur fanlarda talabalar nafaqat nazariy bilimlarni egallashi, balki ularni amaliy faoliyatda qo‘llay olishi ham zarur. Buning uchun esa fazodagi jismlarning tuzilishi, ularning geometrik xususiyatlari va o‘zaro bog‘liqligini chuqur anglash talab etiladi.

An’anaviy o‘qitish jarayonida fazoviy tafakkur asosan doskada chizilgan rasmlar, ikki o‘lchovli chizmalar, plakatlar va bosma darsliklar yordamida rivojlantiriladi. Mazkur vositalar nazariy tushunchalarni yoritishda muayyan samaradorlikka ega bo‘lsa-da, murakkab fazoviy jarayonlarni dinamik holatda ifodalash imkoniyatini bermaydi. Natijada talabalar uch o‘lchovli obyektlarni tasavvur qilishda, ularning kesimlarini, aylanishini yoki fazodagi o‘zgarishlarini anglashda qiyinchiliklarga duch keladi.

Raqamli texnologiyalarning rivojlanishi ushbu muammoni bartaraf etishda yangi imkoniyatlarni yaratdi. Xususan, animatsiyalar, virtual laboratoriyalar, uch o‘lchovli modellar, kengaytirilgan (AR) va virtual reallik (VR) texnologiyalari fazoviy tafakkurni rivojlantirishning samarali vositalariga aylandi. Bunday texnologiyalar yordamida talaba obyektlarni har xil burchak ostida kuzatishi, ularni aylantirishi, kesimlarini ko‘rishi va ichki tuzilishini tahlil qilishi mumkin. Natijada nazariy bilimlar vizual tasvirlar orqali mustahkamlanadi.

Fazoviy tafakkur quyidagi asosiy komponentlardan tashkil topadi:

- Fazoviy idrok – obyektlarning shakli, hajmi va joylashuvini to‘g‘ri qabul qilish;
- Mental rotatsiya – obyektni ongda turli yo‘nalishlarda aylantirish qobiliyati;
- Fazoviy vizualizatsiya – murakkab geometrik shakllarning o‘zgarishini tasavvur qilish;
- Fazoviy orientatsiya – fazoda yo‘nalishni aniqlash va obyektlarning o‘zaro joylashuvini anglash;
- Grafik tafakkur – chizmalar va sxemalarni tahlil qilish hamda ulardan amaliy xulosalar chiqarish.

ISSN 3030-3907

Ushbu komponentlarning har biri talabaning kasbiy tayyorgarligida alohida ahamiyatga ega bo‘lib, ular bir-biri bilan uzviy bog‘langan holda rivojlanadi. Shu sababli ta’lim jarayonida fazoviy tafakkurni kompleks rivojlantirishga qaratilgan metodlardan foydalanish zarur. Animatsion texnologiyalar aynan ushbu komponentlarning barchasini bir vaqtning o‘zida rivojlantirish imkonini beradi. Masalan, uch o‘lchovli modelning bosqichma-bosqich aylanishi mental rotatsiyani rivojlantirsa, uning ichki qismlarining ketma-ket ochilishi fazoviy vizualizatsiyani shakllantiradi. Interaktiv animatsiyalar esa talabaning mustaqil kuzatish, tahlil qilish va xulosa chiqarish ko‘nikmalarini rivojlantiradi.

1-jadval.

Fazoviy tafakkurning tarkibiy komponentlari va ularning pedagogik ahamiyati

Komponent	**Mazmuni**	**Ta’limdagi ahamiyati**
Fazoviy idrok	Obyektlarning shakli va joylashuvini anglash	Grafik materiallarni to‘g‘ri tushunish
Mental rotatsiya	Obyektni ongda aylantirish	Chizmalarni o‘qish va modellashtirish
Fazoviy vizualizatsiya	Murakkab shakllarni tasavvur qilish	Muhandislik masalalarini yechish
Fazoviy orientatsiya	Fazoda yo‘nalishni aniqlash	Konstruktorlik faoliyati
Grafik tafakkur	Grafik axborotni tahlil qilish	Texnik hujjatlar bilan ishlash

Zamonaviy ta’lim jarayonida raqamli texnologiyalardan samarali foydalanish talabalarning bilish faoliyatini faollashtirish, murakkab ilmiy tushunchalarni oson o‘zlashtirish va amaliy kompetensiyalarni shakllantirishning muhim omillaridan biri hisoblanadi. Ayniqsa, animatsion texnologiyalar fazoviy tafakkurni rivojlantirishda yuqori pedagogik imkoniyatlarga ega bo‘lib, an’anaviy o‘qitish vositalarida mavjud bo‘lmagan dinamik vizual taqdimot imkoniyatlarini yaratadi.

Animatsiya — bu obyekt, jarayon yoki hodisaning vaqt davomida ketma-ket o‘zgarishini vizual tasvirlar orqali ifodalash texnologiyasi bo‘lib, ta’lim jarayonida murakkab tushunchalarni modellashtirish, namoyish etish va tushuntirish vositasi sifatida qo‘llaniladi. Oddiy grafik tasvirlardan farqli ravishda animatsiyalar obyektlarning nafaqat tashqi ko‘rinishini, balki ularning harakati, shakliy o‘zgarishi, tarkibiy qismlari o‘rtasidagi bog‘lanish va rivojlanish jarayonlarini ham aks ettirish imkonini beradi.

ISSN 3030-3907

Fazoviy tafakkurni rivojlantirish jarayonida animatsiyalarning asosiy afzalligi shundaki, ular talabalarga abstrakt fazoviy tushunchalarni aniq vizual obrazlar orqali idrok etish imkoniyatini beradi. Masalan, murakkab mexanizmning ishlash prinsipi, geometrik jismning aylanish jarayoni yoki konstruktiv elementlarning o‘zaro joylashuvi animatsiya yordamida bosqichma-bosqich ko‘rsatilishi mumkin. Bunday yondashuv talabaning obyektni faqat kuzatibgina qolmasdan, uning tuzilishi va ishlash mantig‘ini tushunishiga yordam beradi. Animatsion texnologiyalar asosida tashkil etilgan ta’lim jarayoni konstruktivistik pedagogik yondashuvga mos keladi. Chunki bunda talaba tayyor bilimni qabul qiluvchi emas, balki vizual axborotni mustaqil tahlil qiluvchi, obyektlar o‘rtasidagi bog‘lanishlarni aniqlovchi va xulosa chiqaruvchi faol subyekt sifatida ishtirok etadi. Bu esa fazoviy fikrlashning rivojlanishiga bevosita ta’sir ko‘rsatadi.

Ta’lim jarayonida foydalaniladigan animatsiyalarni bir necha turlarga ajratish mumkin:

1. Namoyish qiluvchi animatsiyalar. Ushbu turdagi animatsiyalar tayyor o‘quv materialini tushuntirishga xizmat qiladi. Masalan, detalning yig‘ilish jarayoni, mexanizm qismlarining harakati yoki geometrik shaklning hosil bo‘lish bosqichlari ko‘rsatiladi.

2. Interaktiv animatsiyalar. Talabaga obyekt bilan faol ishlash imkonini beradi. Talaba modelni aylantirishi, uning alohida qismlarini ajratishi, o‘lchamlarini o‘zgartirishi yoki turli ko‘rinishlarda kuzatishi mumkin.

3. Modellashtiruvchi animatsiyalar. Real jarayonlarni virtual muhitda aks ettirishga mo‘ljallangan. Bunday animatsiyalar texnik jarayonlar, ishlab chiqarish mexanizmlari va muhandislik obyektlarini o‘rganishda samarali hisoblanadi.

4. Simulyatsion animatsiyalar. Haqiqiy sharoitda kuzatish murakkab yoki imkonsiz bo‘lgan jarayonlarni modellashtiradi. Masalan, mashina mexanizmlarining ichki harakati yoki murakkab konstruksiyalarning deformatsiyasi.

Animatsion texnologiyalardan foydalanish talabalarning fazoviy tafakkurini rivojlantirishda quyidagi didaktik imkoniyatlarni yaratadi:

- **Ko‘rgazmalilik tamoyilini kuchaytiradi.** Murakkab obyektlar vizual shaklda namoyish etilib, tushunchalarning aniq shakllanishiga yordam beradi.
- **Abstrakt fikrlashni rivojlantiradi.** Talaba ko‘rinmaydigan jarayonlarni tasavvur qilish va mantiqiy bog‘lash imkoniyatiga ega bo‘ladi.
- **Mustaqil ta’lim imkoniyatlarini kengaytiradi.** Elektron platformalar orqali talabalar animatsion materiallarni mustaqil o‘rganishi mumkin.
- **Kasbiy kompetensiyalarni shakllantiradi.** Texnik loyihalash, modellashtirish va konstruktorlik faoliyatiga tayyorlaydi.

ISSN 3030-3907

• **O‘quv motivatsiyasini oshiradi.** Interaktiv va vizual materiallar talabaning fanga qiziqishini kuchaytiradi.]

2-jadval.

Animatsion texnologiyalarning fazoviy tafakkur komponentlariga ta’siri

Animatsion vosita	**Ta’sir qiluvchi fazoviy ko‘nikma**	**Pedagogik natija**
3D animatsiyalar	Fazoviy tasavvur	Uch o‘lchovli obyektlarni anglash yaxshilanadi
Interaktiv modellar	Mental rotatsiya	Obyektlarni turli holatda tasavvur qilish rivojlanadi
Virtual modellashtirish	Fazoviy tahlil	Murakkab konstruksiyalarni tushunish osonlashadi
Jarayon animatsiyasi	Dinamik fikrlash	Harakat va o‘zgarishlarni anglash shakllanadi
Simulyatsiyalar	Muammoli fikrlash	Amaliy masalalarni yechish qobiliyati rivojlanadi

Animatsion texnologiyalarni ta’lim jarayoniga joriy etishda pedagogdan nafaqat texnik vositalardan foydalanish, balki ularni didaktik maqsadlarga mos tanlash ham talab etiladi. Har qanday animatsiya o‘quv samaradorligini avtomatik ravishda oshirmaydi. Uning mazmuni, murakkablik darajasi, talabaning tayyorgarligi va fan xususiyatlariga mosligi muhim ahamiyatga ega. Shuningdek, animatsiyalardan foydalanishda bosqichlilik tamoyiliga amal qilish zarur. Dastlab oddiy geometrik obyektlar va sodda harakatlar asosida tushunchalar shakllantiriladi, keyinchalik murakkab konstruksiyalar, texnologik jarayonlar va real modellar bilan ishlashga o‘tiladi. Bunday metodik ketma-ketlik talabalarning fazoviy tafakkurini izchil va samarali rivojlantirish imkonini beradi.

Umuman olganda, animatsion texnologiyalar fazoviy tafakkurni rivojlantirishda nafaqat axborotni yetkazuvchi vosita, balki talabaning fikrlash faoliyatini tashkil etuvchi pedagogik mexanizm sifatida namoyon bo‘ladi. Ularning ta’lim jarayoniga maqsadli integratsiyasi talabalarni zamonaviy kasbiy faoliyatga tayyorlash, raqamli kompetensiyalarini shakllantirish va ijodiy fikrlash imkoniyatlarini kengaytirishga xizmat qiladi. Zamonaviy ta’lim jarayonida talabalarning fazoviy tafakkurini rivojlantirish faqatgina nazariy bilimlarni berish bilan cheklanib qolmasdan, ularning mustaqil fikrlashi, modellashtirish qobiliyati va amaliy muammolarni hal etish ko‘nikmalarini shakllantirishga yo‘naltirilgan tizimli metodik yondashuvni talab qiladi. Ayniqsa, animatsion texnologiyalar asosida tashkil etilgan ta’lim jarayoni talabaga fazoviy obyektlarni dinamik holatda

ISSN 3030-3907

kuzatish, ularning tuzilishini tahlil qilish va o‘zlashtirilgan bilimlarni amaliy vaziyatlarda qo‘llash imkonini beradi.

Talabalarda fazoviy tafakkurni animatsiyalar orqali rivojlantirish jarayonida pedagogik metodlarni to‘g‘ri tanlash muhim ahamiyatga ega. Chunki animatsiya faqat vizual axborotni taqdim etuvchi vosita emas, balki talabaning kognitiv faoliyatini boshqaruvchi didaktik instrument sifatida qaraladi. Shu sababli animatsion vositalardan foydalanish jarayonida muammoli ta’lim, loyihaviy yondashuv, interaktiv modellashtirish, vizual tahlil va amaliy mashg‘ulot metodlarining uyg‘unlashuvi yuqori samaradorlik beradi.

Vizualizatsiya metodi animatsion texnologiyalar orqali murakkab fazoviy obyektlarni ko‘rgazmali shaklda namoyish etishga asoslanadi. Ushbu metod yordamida talabalar ikki o‘lchovli chizma va tasvirlardan farqli ravishda obyektning uch o‘lchovli tuzilishini to‘liq idrok etish imkoniyatiga ega bo‘ladilar.

Masalan, muhandislik grafikasi mashg‘ulotlarida detalning old, yuqori va yon ko‘rinishlari alohida tushuntirilgandan so‘ng, uning 3D animatsion modeli namoyish qilinishi talabaning fazoviy tasavvurini sezilarli darajada oshiradi. Bunda obyektni turli yo‘nalishlarda aylantirish, kattalashtirish yoki qismlarga ajratish imkoniyati bilimlarni mustahkamlashga xizmat qiladi.

Interaktiv modellashtirish talabaning o‘quv jarayonidagi faol ishtirokini ta’minlovchi samarali metodlardan biridir. Ushbu metodda talabalar tayyor animatsiyani kuzatuvchi emas, balki virtual obyekt bilan faol ishlovchi subyekt sifatida qatnashadilar. Natijada talabalarda fazoviy manipulyatsiya, tahliliy fikrlash va texnik loyihalash ko‘nikmalari shakllanadi.

Muammoli ta’lim animatsiyalar asosida fazoviy tafakkurni rivojlantirishning samarali usullaridan biri hisoblanadi. Ushbu metodda talabalar oldiga ma’lum bir texnik yoki konstruktiv muammo qo‘yiladi va ular animatsion modellar yordamida muammoning yechimini izlaydilar. Loyihaviy metod talabalarning mustaqil ijodiy faoliyatini tashkil etishga qaratilgan bo‘lib, animatsion texnologiyalar yordamida real obyektlarning virtual modellarini yaratishni nazarda tutadi. Bu jarayon ularda nafaqat fazoviy tafakkur, balki kommunikativ, raqamli va kasbiy kompetensiyalarni ham rivojlantiradi.

3-jadval.

Animatsiyalar asosida fazoviy tafakkurni rivojlantirish metodlari

Metod	Qo‘llash vositalari	Rivojlantiriladigan ko‘nikmalar
Vizualizatsiya	3D animatsiya, videomodellar	Fazoviy idrok

ISSN 3030-3907

Interaktiv modellashtirish	CAD dasturlar, virtual modellar	Mental rotatsiya, konstruktiv fikrlash
Muammoli ta’lim	Simulyatsiya va virtual topshiriqlar	Tahliliy fikrlash
Loyihaviy metod	3D loyiha va animatsion taqdimotlar	Ijodiy yondashuv
Virtual tajriba	VR/AR texnologiyalar	Amaliy fazoviy faoliyat

Ta’lim jarayonida animatsion texnologiyalardan foydalanishning samaradorligi nafaqat nazariy jihatdan, balki amaliy mashg‘ulotlar jarayonida ham o‘z tasdig‘ini topadi. Fazoviy tafakkurni rivojlantirishga yo‘naltirilgan animatsion metodlardan foydalanish talabalarning geometrik obyektlarni tasavvur qilish, grafik axborotlarni tahlil qilish, modellashtirish va konstruktiv yechimlarni ishlab chiqish qobiliyatlariga ijobiy ta’sir ko‘rsatadi. Animatsion texnologiyalar asosida tashkil etilgan mashg‘ulotlarda talabalar an’anaviy ta’lim vositalari orqali o‘zlashtirish qiyin bo‘lgan murakkab fazoviy tushunchalarni vizual va interaktiv shaklda o‘rganish imkoniyatiga ega bo‘ladilar. Ayniqsa, uch o‘lchovli modellar, harakatlanuvchi grafik tasvirlar va virtual obyektlar bilan ishlash jarayonida talabalarning fazoviy idrok qilish tezligi hamda aniqligi oshadi.

Mazkur metodik yondashuv samaradorligini baholashda quyidagi mezonlardan foydalanish mumkin:

fazoviy tasavvur darajasi – obyektlarning shakli, hajmi va joylashuvini to‘g‘ri anglash qobiliyati;

grafik tafakkur darajasi – chizmalar, sxemalar va modellarni tahlil qilish ko‘nikmasi;

modellashtirish qobiliyati – real obyektlarning virtual modellarini yaratish va o‘zgartirish imkoniyati;

ijodiy va muammoli fikrlash – yangi konstruktiv yechimlarni ishlab chiqish qobiliyati.

Fazoviy tafakkurni rivojlantirish jarayoni bir necha ketma-ket bosqichlarda amalga oshiriladi:

1-bosqich. Motivatsion-tayyorlov bosqichi. Mazkur bosqichda talabalarda animatsion vositalarga qiziqish shakllantiriladi, fazoviy tafakkurning kasbiy faoliyatdagi ahamiyati tushuntiriladi. O‘qituvchi tomonidan oddiy 3D modellar, animatsion namoyishlar va vizual materiallar taqdim etilib, talabalar yangi texnologik muhitga moslashtiriladi.

2-bosqich. Vizual idrokni rivojlantirish bosqichi. Ushbu bosqichda talabalar animatsiyalar yordamida obyektlarning shakli, tuzilishi va fazodagi

ISSN 3030-3907

holatini o‘rganadilar. Turli rakurslardan kuzatish, obyektni aylantirish va qismlarga ajratish orqali fazoviy tasavvur shakllantiriladi.

3-bosqich. Modellashtirish va amaliy faoliyat bosqichi. Talabalar maxsus dasturlar yordamida mustaqil ravishda uch o‘lchovli modellar yaratadilar. Bu jarayon ularning fazoviy tahlil qilish, loyihalash va texnik fikrlash qobiliyatlarini rivojlantiradi.

4-bosqich. Baholash va refleksiya bosqichi. Talabalarning o‘zlashtirish darajasi amaliy topshiriqlar, grafik loyihalar, testlar va yaratilgan modellar asosida baholanadi. Ushbu bosqich natijalarga tahliliy baho berish va keyingi rivojlanish yo‘nalishlarini belgilash imkonini beradi.

4-jadval.

Animatsion texnologiyalar asosida fazoviy tafakkur rivojlanish ko‘rsatkichlari

Baholash mezonlari	**An’anaviy ta’lim**	**Animatsion texnologiyalar asosidagi ta’lim**
Fazoviy obyektlarni tasavvur qilish	Statik tasvirlar asosida	Dinamik 3D modellar asosida
Murakkab shakllarni tushunish	Qisman shakllanadi	Yuqori darajada rivojlanadi
Obyektlarni aylantirib tasavvur qilish	Cheklangan	Interaktiv imkoniyat mavjud
Mustaqil modellashtirish	Sekin rivojlanadi	Faol shakllanadi
Amaliy muammolarni hal qilish	Nazariy bilimlarga asoslanadi	Vizual va amaliy tajribaga asoslanadi

NATIJALAR.

Olingan natijalar shuni ko‘rsatadiki, animatsion texnologiyalardan foydalanish talabalar faoliyatida sezilarli pedagogik samaradorlikni ta’minlaydi. Birinchidan, animatsiyalar fazoviy obyektlarni real harakatda ko‘rsatish orqali talabaning vizual xotirasini mustahkamlaydi. Ikkinchidan, interaktiv modellar bilan ishlash talabalarni faol fikrlashga undaydi va ularning mustaqil qaror qabul qilish qobiliyatini rivojlantiradi.

An’anaviy o‘qitish usullarida talaba ko‘pincha tayyor grafik tasvirni qabul qiluvchi rolida bo‘lsa, animatsion ta’lim muhitida u obyektni tahlil qiluvchi,

ISSN 3030-3907

o‘zgartiruvchi va yangi model yaratuvchi faol ishtirokchiga aylanadi. Bu esa kompetensiyaviy yondashuv talablariga mos keladi.

Animatsion texnologiyalar quyidagi pedagogik samaralarni beradi:

✓ o‘quv materialining tushunarlilik darajasini oshiradi;
✓ murakkab fazoviy jarayonlarni soddalashtiradi;
✓ talabalar qiziqishi va motivatsiyasini kuchaytiradi;
✓ nazariya va amaliyot o‘rtasidagi bog‘liqlikni ta’minlaydi;
✓ raqamli kompetensiyalarni shakllantiradi.

XULOSA.

Animatsion texnologiyalar asosida tashkil etilgan ta’lim jarayoni talabalarda fazoviy tafakkurni rivojlantirishning samarali vositalaridan biri hisoblanadi. Tadqiq etilgan metodik yondashuvlar shuni ko‘rsatadiki, animatsiyalar yordamida tashkil etilgan mashg‘ulotlar talabalarning fazoviy tasavvuri, grafik tafakkuri, modellashtirish qobiliyati va ijodiy fikrlashini sezilarli darajada rivojlantiradi. Uch o‘lchovli modellar, interaktiv animatsiyalar va virtual vositalardan foydalanish murakkab obyektlarni o‘rganishni yengillashtirib, ta’lim jarayonining samaradorligini oshiradi. Shu sababli oliy ta’lim muassasalarida texnik va muhandislik yo‘nalishlari fanlarini o‘qitishda animatsion texnologiyalarni tizimli ravishda joriy etish talabalarning kasbiy kompetensiyalarini shakllantirish, ularni zamonaviy raqamli muhitda faoliyat yuritishga tayyorlash hamda innovatsion fikrlash qobiliyatlarini rivojlantirish uchun muhim pedagogik shartlardan biri hisoblanadi.

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ISSN 3030-3907

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ISSN 3030-3907