ISNN 3030-3907

2026
MAY
ISSUE - 5
VOLUME - 5

DEVELOPMENT OF SCIENCE

scientific journal



Development of science

Ilmiy jurnal

MAY 2026
Issue - 5, VOLUME - 5

ISSN 3030 -3907

Ilmiy jurnal OAK rayosatining 2024 yil 27 sentabrdagi 361-son qaroriga asosan 02.00.00 kimyo fanlari hamda 2025 yil 12 fevral 367- son qaroriga asosan 05.00.00 texnika fanlari bo‘yicha falsafa doktori (PhD) va fan doktori (DSc) ilmiy darajasiga talabgorlarning dissertatsiya ishlari yuzasidan dissertatsiyalari asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxatiga kiritilgan.

BOSH MUHARRIR:
Temirov Alisher Hoshim o‘g‘li – texnika fanlari falsafa doktori (PhD),Dotsent.
TAHRIRIYAT KENGASH RAISI:
Fozilov Sadriddin Fayzullayevich – texnika fanlari doktori, professor
TAHRIRIYAT KENGASH A’ZOLARI

TEXNIKA FANLARI/ TECHNICAL SCIENCES/ ТЕХНИЧЕСКИЕ НАУКИ

Bozorov G‘ayrat Rashidovich
Buxoro Davlat Texnika Universiteti, professor
Abdurahmonov Olim Rustamovich
Buxoro Davlat Texnika Universiteti, professor
Adizov Bobur Zamirovich
O‘zbekiston Respublikasi Fanlar akademiyasi Umumiy va noorganik kimyo instituti, professor
Hayitov Ruslan Rustamjonovich
Buxoro Davlat Texnika Universiteti, professor
Jumayev Qayum Karimovich
Buxoro Davlat Texnika Universiteti, professor.
Berdiyev Dorob Murodovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor
Maxmudov Rafiq Amonovich
Buxoro Davlat Texnika Universiteti, professor.
Tilloyev Lochin Ismatilloyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Raxmonov Qahramon Sanakulovich
Buxoro Davlat Texnika Universiteti, dotsent.
Barakayev Nusratullo Rajabovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor.
Jo‘rayev Xayrullo Fayziyevich
Buxoro Davlat Texnika Universiteti, professor.
Panoyev Erali Rajabboyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Ataullayev Sherzod Nabiullyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Malik Negmurodovich
Buxoro Davlat Texnika Universiteti, dotsent.
Axmedova Ozoda Bahronovna
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti.
Safarov Bahri Jumayevich
Buxoro Davlat Texnika Universiteti, dotsent.
Xaydarov Axtam Amonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Safarov Jasur Alijon o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.

KIMYO FANLARI/ CHEMICAL SCIENCES/ ХИМИЧЕСКИЕ НАУКИ

Axmedov Voxid Nizomovich
Buxoro Davlat Texnika Universiteti, professor
Umarov Baqo Bafoyevich
Buxoro Davlat Universiteti, professor
Kodirov Abduaxad Abduraximovich
Qarshi davlat Universiteti, professor
Qurbonov Mingniqul Jumagulovich
Qarshi davlat Universiteti, dotsent
Turemuratov Sharibay Naurizbaevich
O‘zbekiston Respublikasi Fanlar akademiyasi Qoraqalpog‘iston bo‘limi Bosh ilmiy kotibi, professor
Tursunov Kaxor Shonazarovich
Qarshi davlat Universiteti, professor
Do‘stov Hamro
Buxoro Davlat Texnika Universiteti, professor
Panoyev Nodir Shavkatovich
Buxoro Davlat Texnika Universiteti, dotsent.
Olimov Bobur Bahodir o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.
Kasimov Sherzod Abduazimovich
Termiz Davlat Universiteti, professor.
Aliqulov Rustam Valiyevich
Termiz Davlat Universiteti, professor
Tropov Xamza Tursunovich
Samarqand Davlat Universiteti, professor

IQTISODIYOT FANLARI/ ECONOMICS/ ЭКОНОМИЧЕСКИЕ НАУКИ

Nizamov Aslitdin Badreddinovich
Buxoro Davlat Texnika Universiteti, professor.
Boboyev Akmal Choriyevich
Buxoro Davlat Texnika Universiteti, professor.
Ergashxojayeva Shaxnoza Djasurovna
Toshkent davlat iqtisodiyot universiteti, professor
Saidaxmedova Nodira Ilxomovna
Toshkent davlat iqtisodiyot universiteti, professor
Muxsinov Bekzod Toxirovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shakarov Qulmat Ashirovich
Renessans ta'lim universiteti,dotsent.
Jumaeva Zulfiya Qayumovna
Buxoro Davlat Texnika Universiteti, dotsent.
Norova Salomat Yusupovna
Buxoro Davlat Texnika Universiteti, dotsent.
Avezova Shaxnoza Maxmudjonovna
Buxoro Davlat Texnika Universiteti, dotsent.
Jalilov Jamshid G‘anijonovich
Toshkent davlat iqtisodiyot universiteti, dotsent
Xasanova Gulruh Djumanazarovna
Buxoro Davlat Texnika Universiteti, dotsent.

PEDAGOGIKA FANLARI/ PEDAGOGICAL SCIENCES / ПЕДАГОГИЧЕСКИЕ НАУКИ

Siddiqova Sadoqat G‘afforovna
Buxoro Davlat Texnika Universiteti, dotsent.
Zoyirov Erkin Xalilovich
Buxoro Davlat Texnika Universiteti, DSc, professor
Gaffarov Feruz Hasanovich
Puchon Universiteti, *professor*
Ruziyev Davron Yuldashevich
Buxoro Davlat Universiteti, professor
Muradova Firuza Rashidovna
Buxoro Davlat Texnika Universiteti, professor.
Yunusova Gulandon Samiyevna
Buxoro Davlat Texnika Universiteti, professor.
To‘xtayeva Zebo Sharifovna
Buxoro Davlat Texnika Universiteti, professor.
Navro‘zova Gulchixra Nigmatovna
Buxoro Davlat Texnika Universiteti, dotsent.
Uzoqova Laylo Polvonovna
Buxoro muhandislik – texnologiya instituti, dotsent.
To‘raqulova Marjona Qiyom qizi
Buxoro Davlat Texnika Universiteti, dotsent.
Muradova Zarina Rashidovna
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Sanjar Aslonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shodiyev Jahongir Jo‘raqulovich
Buxoro Davlat Texnika Universiteti, dotsent
Gaffarov Laziz Hasanovich
Buxoro muhandislik – texnologiya instituti, dotsent.

Tahririyat a’zolarning to‘liq ro‘yxati jurnalning www.devos.uz saytida keltirilgan.

Tahririyat hay’ati a’zolarining tarkibini o‘zgartirish hamda qo‘shimcha kiritish yoki tahririyat a’zoligidan chiqarish bosh muharrir tomonidan amalga oshiriladi.

ISSN 3030-3907

Development of science ilmiy jurnali 2024 yil 15 aprel kuni №256445 sonli guvohnoma bilan Davlat ro‘yxatidan o‘tgan.

To‘plam elektron ko‘rinishda (pdf formatida) mualliflarga taqdim etiladi. To‘plamga kiritiladigan maqolalarning mazmuni, ulardagi statistik ma’lumotlar va me’yoriy hujjatlarning to‘g‘riligiga hamda har qanday fikr - mulohazalarga mualliflarning o‘zlari mas’ul hisoblanadilar. Talablarga javob bermaydigan maqolalar to‘plamga kiritilmaydi. Tashkiliy qo‘mita maqola matnini qisqartirish, qisman tuzatish kiritish, seksiyalarga joylashtirish huquqiga ega.

ISSN 3030-3907

THERMAL BEHAVIOR OF PHOSPHORUS-MODIFIED COPPER PHTHALOCYANINE PIGMENT (CuPc–P) INVESTIGATED BY COMBINED TGA–DTG–DSC ANALYSIS

Oybek Alisherov
Chemistry teacher at the specialized school of Mingbuloq district. Namangan City, Republic of Uzbekistan
E-mail: oybekalisherov@gmail.com
Firdavs Ormanov
Master's student, Department of Chemical Engineering, Namangan State Technical University, Namangan City, Republic of Uzbekistan
E-mail: Firdavs9555@mail.ru
Gulsevar Jurayeva
Student at Namangan State Technical University. Namangan City, Republic of Uzbekistan
E-mail: jorayevagulsevar41@gmail.com
Yusupov Muzafar
Associate Professor, Department of Chemical Engineering, Namangan State Technical University, Republic of Uzbekistan, Namangan region
E-mail: muz.yusupov90@gmail.com
Abdugani Oxundadayev
Head of the Department of Chemical Engineering, Namangan State Technical University, Namangan City, Republic of Uzbekistan
E-mail: aoxundada@gmail.com

Abstract. Phosphorus-modified copper phthalocyanine pigment (CuPc-P) represents a promising class of thermally stable functional materials widely used in advanced coatings and composite systems. In this study, the thermal stability and decomposition behavior of CuPc-P pigment were systematically investigated using simultaneous thermogravimetric (TGA), derivative thermogravimetric (DTG), and differential scanning calorimetric (DSC) techniques. The obtained results revealed a multistage thermal degradation mechanism involving moisture removal, ligand decomposition, macrocyclic fragmentation, and carbonization processes. The initial minor mass loss below 200 °C was associated with the elimination of physically adsorbed moisture and volatile impurities. A major decomposition stage observed within 200-450 °C corresponded to the gradual destruction of phosphorus-containing substituents and peripheral fragments. Further degradation at higher temperatures (450-700 °C) indicated the breakdown of the phthalocyanine macrocycle. The final stage above 700 °C resulted in the formation of thermally stable inorganic residues. The combined thermal analysis

ISSN 3030-3907

confirmed the enhanced thermal resistance of CuPc-P pigment, suggesting its suitability for high-temperature coatings and functional composite materials.

Keywords: copper phthalocyanine, phosphorus modification, thermal analysis, TGA-DTG-DSC, thermal stability, functional pigments.

Аннотация. Фосфор-модифицированный пигмент медного фталоцианина (CuPc-P) представляет собой перспективный класс термостойких функциональных материалов, широко применяемых в современных покрытиях и композиционных системах. В данной работе термическая стабильность и поведение при разложении пигмента CuPc-P были систематически исследованы с использованием методов синхронного термогравиметрического анализа (TGA), дифференциального термогравиметрического анализа (DTG) и дифференциальной сканирующей калориметрии (DSC).Полученные результаты показали многостадийный механизм термического разложения, включающий удаление влаги, разложение лигандов, разрушение макроциклической структуры и процессы карбонизации. Начальная незначительная потеря массы при температурах ниже 200 °C связана с удалением физически адсорбированной влаги и летучих примесей. Основная стадия разложения, наблюдаемая в диапазоне 200–450 °C, соответствует постепенному разрушению фосфорсодержащих заместителей и периферийных фрагментов. Дальнейшее разложение при 450–700 °C указывает на разрушение макроцикла фталоцианина. Заключительная стадия при температурах выше 700 °C сопровождается образованием термически стабильных неорганических остатков.Комплексный термический анализ подтвердил повышенную термостойкость пигмента CuPc-P, что свидетельствует о его пригодности для использования в высокотемпературных покрытиях и функциональных композиционных материалах.

Ключевые слова: медный фталоцианин, фосфорная модификация, термический анализ, TGA-DTG-DSC, термостойкость, функциональные пигменты.

Annotatsiya. Fosfor bilan modifikatsiyalangan mis ftalosiyanin pigmenti (CuPc-P) yuqori issiqlikka chidamli funksional materiallarning istiqbolli sinfi bo‘lib, ilg‘or qoplamalar va kompozit tizimlarda keng qo‘llaniladi. Ushbu tadqiqotda CuPc-P pigmentining issiqlikka chidamliligi va parchalanish xususiyatlari bir vaqtning o‘zida olib boriladigan termogravimetrik (TGA), hosilaviy termogravimetrik (DTG) va differensial skanerlovchi kalorimetriya (DSC) usullari yordamida tizimli ravishda o‘rganildi. Olingan natijalar namlikning yo‘qolishi, ligandlarning parchalanishi, makrotsiklik tuzilmaning buzilishi hamda

ISSN 3030-3907

karbonizatsiya jarayonlarini o‘z ichiga olgan ko‘p bosqichli issiqlik parchalanish mexanizmini ko‘rsatdi.200 °C dan past haroratlarda kuzatilgan dastlabki kichik massa yo‘qotilishi fizik adsorbsiyalangan namlik va uchuvchan aralashmalarning ajralishi bilan bog‘liq. 200–450 °C oralig‘ida kuzatilgan asosiy parchalanish bosqichi fosfor tutuvchi substituentlar va periferik fragmentlarning asta-sekin yemirilishiga to‘g‘ri keladi. 450–700 °C diapazondagi keyingi parchalanish ftalosiyanin makrotsikl tuzilmasining buzilishini ko‘rsatadi. 700 °C dan yuqori haroratlarda esa termal jihatdan barqaror noorganik qoldiqlar hosil bo‘lishi bilan yakuniy bosqich kuzatildi.Kompleks termik tahlil natijalari CuPc-P pigmentining yuqori issiqlikka chidamliligini tasdiqlab, uni yuqori haroratli qoplamalar va funksional kompozit materiallarda qo‘llash uchun mos ekanligini ko‘rsatdi.

Kalit so‘zlar: mis ftalosiyanin, fosfor modifikatsiyasi, termik tahlil, TGA-DTG-DSC, issiqlikka chidamlilik, funksional pigmentlar.

INTRODUCTION.

Metal phthalocyanine pigments occupy an important position in modern pigment chemistry and functional materials science due to their high thermal stability, chemical inertness, light resistance, and strong optical properties [1-3]. The phthalocyanine macrocycle consists of an 18 π-electron conjugated aromatic system coordinated with a central metal ion, which provides high resonance stability. These structural features determine the resistance of metal phthalocyanines to heat, oxidative environments, solvents, and light exposure [4,5]. For this reason, they are widely used in paint and pigment industries, coating systems, polymer composites, printing inks, electrochemical sensors, photocatalytic systems, and organic electronic devices [6-8]. Metal phthalocyanines are also studied as thermally and chemically stable materials with excellent optical and electronic properties in various sensor, photovoltaic, and electronic applications.

Among these compounds, copper phthalocyanine (CuPc) is considered one of the most important industrial pigments. CuPc is distinguished by its intense blue color, high dispersion stability, resistance to solvents, excellent lightfastness, and thermal stability [2,6,9]. Its α- and β-polymorphic forms significantly influence pigment color intensity, particle morphology, crystallinity, and dispersion behavior. In particular, the β-CuPc form is thermodynamically more stable and suitable for application in high-temperature polymer and coating systems [9,10]. CuPc pigments are widely applied for coloring coatings, plastics, and high-molecular-weight organic materials due to their resistance to heat, light, and weathering.

In recent years, considerable attention has been devoted to modifying conventional metal phthalocyanines with heteroatom-containing functional

ISSN 3030-3907

groups in order to improve their physicochemical properties [11-13]. Such modifications alter the electron density distribution in the molecular structure, enhance intermolecular interactions, and improve compatibility with polymer matrices, coating systems, and composite materials. In particular, modification with phosphorus-containing fragments makes it possible to enhance the thermal stability, oxidation resistance, adhesion properties, and flame-retardant performance of CuPc pigments [13,14].

The effectiveness of phosphorus-containing functional groups is primarily explained by the high bond energies of P-O, P-N, and in some cases P=O bonds. These bonds slow down thermal degradation at elevated temperatures, promote the formation of carbonized residues, and facilitate the formation of thermally protective layers around pigment molecules [14,15]. Phosphorus modification also promotes the formation of stable condensed-phase residues, which helps to limit heat transfer and reduce the release of combustible gases in polymer composites. For example, phosphorus-containing hyperbranched copper phthalocyanine compounds of the DOPO-CuPc type have been used as flame-retardant additives for epoxy resins, resulting in increased limiting oxygen index (LOI) values and improved UL-94 ratings up to the V-0 level [14].

Phosphorus-modified copper phthalocyanine pigments are important not only for improving flame retardancy but also for enhancing adhesion interactions between pigments and coating surfaces. Phosphorus-containing groups are capable of forming hydrogen bonds, coordination interactions, or dipole–dipole interactions with metals, oxidized surfaces, or polar functional groups in polymer matrices [11,13]. As a result, CuPc-P pigments improve dispersion stability in coating materials, reduce particle agglomeration, and enhance the mechanical and thermal durability of coating layers.

Although numerous studies have been conducted on conventional CuPc pigments, the thermal decomposition stages, DTG peaks, DSC thermal effects, and degradation mechanisms of macrocyclic structures in phosphorus-containing CuPc derivatives have not yet been systematically investigated [4,5,15]. In particular, detailed information regarding the interaction of phosphorus fragments with the CuPc macrocycle, decomposition temperatures of peripheral groups, carbonized residue content, and the thermal range of the main destruction stage remains limited. Therefore, thermal analysis of CuPc-P pigments provides an important scientific basis for the development of high-temperature-resistant pigments, functional coatings, and polymer composite materials.

Thermal analysis techniques such as thermogravimetric analysis (TGA), differential thermogravimetry (DTG), and differential scanning calorimetry (DSC) represent essential instrumental approaches for comprehensive evaluation

ISSN 3030-3907

of pigment behavior under thermal conditions [5,15]. TGA determines mass loss as a function of temperature, while DTG enables identification of major decomposition stages based on mass-loss rate. DSC records endothermic and exothermic heat effects, providing information about phase transitions, moisture release, chemical rearrangements, and non-oxidative degradation processes. Evaluation of phthalocyanine pigments using TGA and DSC methods is widely recognized as an effective approach for assessing their suitability for high-temperature applications.

From this perspective, the main objective of the present study is to determine the thermal stability and decomposition characteristics of phosphorus-modified copper phthalocyanine pigment (CuPc-P) using TGA-DTG-DSC techniques. The study analyzes the initial mass-loss region, decomposition stage of phosphorus-containing peripheral fragments, principal degradation range of the macrocyclic phthalocyanine core, and the residual mass formed at elevated temperatures. The obtained results provide a basis for evaluating phosphorus-containing CuPc pigments as promising components for heat-resistant coatings, polymer composites, flame-retardant materials, and functional pigment systems.

MATERIALS AND METHODS.

The thermal behavior of the phosphorus-containing modified metal phthalocyanine pigment was investigated using combined thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) techniques. Thermal measurements were carried out over a temperature range from 30 to 800 °C under an inert nitrogen atmosphere to prevent oxidative degradation during heating.

Approximately 5-10 mg of finely powdered sample was placed into a standard alumina crucible and subjected to controlled heating at a constant rate of 10 °C/min. The nitrogen gas flow was maintained throughout the experiment to ensure stable inert conditions and reproducible thermal data.

The TGA technique was used to monitor the mass loss of the sample as a function of temperature, allowing identification of different decomposition stages and evaluation of thermal stability. Simultaneously, DSC measurements were performed to record endothermic and exothermic thermal events associated with structural transformations, phase changes, and decomposition processes occurring during heating.

The obtained thermal curves were analyzed to determine the onset temperature of degradation, the temperature corresponding to maximum mass-loss rate, and the amount of residual mass remaining at elevated temperatures. These parameters were used to assess the thermal resistance and stability of the phosphorus-modified metal phthalocyanine pigment.

RESULTS AND DISCUSSION.

ISSN 3030-3907

The thermogravimetric analysis revealed that the thermal degradation of the phosphorus-containing modified phthalocyanine pigment proceeds through a multistage decomposition pathway. This behavior indicates that the pigment structure contains several thermally active fragments, including adsorbed low-molecular components, phosphorus-containing peripheral groups, and the highly conjugated phthalocyanine macrocycle.

The first mass-loss stage was observed in the temperature range of 50-150 °C. This initial process can be mainly attributed to the removal of physically adsorbed moisture, residual solvent traces, and weakly bound volatile components from the pigment surface. The mass loss in this region was relatively low and accounted for approximately 2-4 %, indicating that the synthesized pigment contained only a limited amount of volatile impurities.

The second degradation stage occurred in the range of 200-350 °C. This region is associated with the partial decomposition of phosphorus-containing peripheral substituents and weakly bonded functional fragments attached to the phthalocyanine framework. The corresponding mass loss was approximately 10–18 %, confirming that the introduced phosphorus-containing groups participate in the early stage of thermal transformation. However, the relatively gradual character of this mass decrease suggests that these functional groups do not destabilize the main macrocyclic core.

The main decomposition stage was detected within 350-550 °C. This stage represents the most intensive mass-loss region and is related to the destruction of the phthalocyanine macrocyclic system. The mass loss in this temperature interval reached approximately 40-55 %, which confirms the breakdown of the conjugated aromatic structure and cleavage of the main chemical bonds within the pigment molecule. The high decomposition temperature of this stage indicates that the modified pigment possesses considerable thermal resistance.

At temperatures above 600 °C, the mass decreased slowly, suggesting the formation of thermally stable carbonized and inorganic residues. These residues may include copper-containing species, phosphorus-derived fragments, and carbonaceous structures formed during high-temperature degradation. The presence of a stable residue at elevated temperatures demonstrates the potential suitability of the phosphorus-modified phthalocyanine pigment for applications requiring thermal durability.

The DSC curve provided additional information on the heat effects accompanying the thermal transformation of the pigment. The thermal events observed in the DSC profile were consistent with the mass-loss stages identified by TGA, confirming the reliability of the proposed degradation mechanism.

ISSN 3030-3907

An endothermic effect observed in the range of 100-150 °C can be attributed to the evaporation of moisture and the release of volatile components. This process does not involve significant chemical degradation and is mainly related to physical desorption from the pigment surface.

An exothermic effect appeared in the range of 300-420 °C. This thermal event may be associated with structural rearrangement, partial decomposition of phosphorus-containing functional groups, and the initial cleavage of chemical bonds in the modified pigment structure. The exothermic nature of this process suggests that degradation may be accompanied by secondary condensation, oxidation-like rearrangement, or formation of more thermally stable intermediate structures.

At higher temperatures, the DSC data confirmed the progressive degradation of the macrocyclic phthalocyanine framework. The absence of abrupt thermal collapse at lower temperatures indicates that the pigment maintains its structural integrity over a relatively wide temperature interval. Therefore, the DSC results support the conclusion that the phosphorus-modified pigment exhibits enhanced thermal stability.

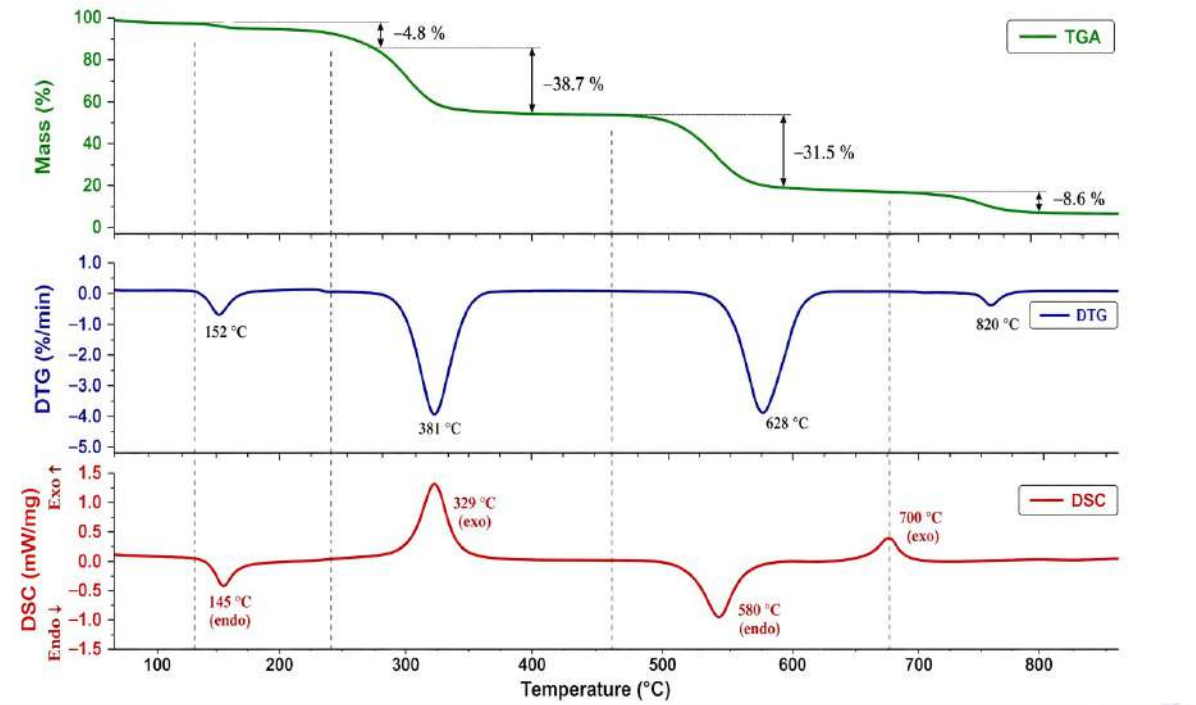


Figure 1. Combined TGA–DTG–DSC curves of phosphorus-modified copper phthalocyanine pigment (CuPc–P), showing mass-loss stages, derivative decomposition peaks, and heat-flow transitions associated with the thermal degradation of the modified macrocyclic structure

Table 1. Thermal degradation characteristics of phosphorus-modified copper phthalocyanine pigment (CuPc–P) determined from combined TGA–

ISSN 3030-3907

DTG–DSC measurements, showing temperature intervals, mass-loss values, thermal effects, and corresponding decomposition processes.

Table 3

Thermal degradation stages of phosphorus-modified copper phthalocyanine pigment (CuPc-P) based on combined TGA-DTG-DSC analysis

Stage	Temperature range (°C)	TGA mass loss (%)	DTG peak temperature (°C)	DSC thermal effect	Proposed process description
Stage I	50–200	≈ 4.8 %	152 °C	145 °C (endo)	Removal of physically adsorbed moisture and release of volatile impurities
Stage II	200–450	≈ 38.7 %	381 °C	329 °C (exo)	Decomposition of phosphorus-containing substituents and peripheral functional groups
Stage III	450–700	≈ 31.5 %	628 °C	580 °C (endo)	Progressive destruction of phthalocyanine macrocyclic structure
Stage IV	>700	≈ 8.6 %	820 °C	700 °C (exo)	Carbonization and formation of thermally stable inorganic residues

The obtained thermal analysis results demonstrate that the presence of phosphorus-containing functional groups has a significant influence on the thermal behavior of the modified phthalocyanine pigment. Phosphorus modification contributes to the stabilization of the pigment structure through several possible mechanisms.

First, phosphorus atoms may participate in the formation of additional coordination or intermolecular interactions with the central metal ion and neighboring functional groups. These interactions can restrict molecular mobility and delay thermal degradation.

ISSN 3030-3907

Second, phosphorus-containing fragments may promote the formation of thermally stable protective residues during heating. Such residues can act as a barrier layer, slowing down further decomposition of the organic macrocyclic structure.

Third, phosphorus groups can reduce the rate of destructive thermal processes by stabilizing the conjugated phthalocyanine framework and suppressing rapid bond cleavage at elevated temperatures.

As a result, the decomposition temperature of the phosphorus-modified pigment is expected to be higher than that of unmodified phthalocyanine analogues. The multistage degradation behavior, relatively high main decomposition temperature, and formation of stable high-temperature residues indicate that the modified pigment can be considered a promising functional material for heat-resistant coatings, polymer composites, and corrosion-protective systems.

CONCLUSION.

The combined TGA-DTG-DSC investigation confirmed that the phosphorus-modified copper phthalocyanine pigment (CuPc-P) exhibits a complex and stepwise thermal degradation pattern. The first stage, occurring below approximately 200 °C, was mainly associated with the release of physically adsorbed moisture and low-molecular volatile components, indicating good stability under moderate heating conditions.

The principal degradation region was observed in the 200-450 °C interval, where the decomposition of phosphorus-containing peripheral fragments and substituent groups became dominant. Further heating above 450 °C led to gradual destruction of the conjugated phthalocyanine macrocycle, confirming that the aromatic core remains relatively stable until high-temperature exposure.

At temperatures exceeding 700 °C, the mass loss slowed considerably, suggesting the formation of thermally resistant carbonized and inorganic residues. This behavior indicates that phosphorus modification contributes to the stabilization of the CuPc structure by promoting protective residue formation and delaying complete thermal decomposition.

Overall, the results demonstrate that phosphorus incorporation enhances the thermal resistance of copper phthalocyanine pigments. Therefore, CuPc-P can be considered a promising functional pigment for heat-resistant coatings, polymer composites, and advanced materials intended for operation under elevated-temperature conditions.

REFERENCES

1. Yusupov, M., & Kadirkhanov, J. (2023). In E3S Web of Conferences (Vol. 390). EDP Sciences.

ISSN 3030-3907

2. Gregory P. High-Technology Applications of Organic Colorants. Springer, 1991.
3. McKeown N.B. Phthalocyanine Materials: Synthesis, Structure and Function. Cambridge University Press, 1998.
4. Achar B.N., Fohlen G.M., Parker J.A. GC–MS studies on degradation of copper phthalocyanine sheet polymer. Journal of Analytical and Applied Pyrolysis, 2005.
5. Seoudi R., El-Bahy G.S., El Sayed Z.A. FTIR, TGA and optical studies of phthalocyanine complexes. Journal of Molecular Structure, 2005.
6. Eshkalak S.K., et al. A novel surface modification of copper(II) phthalocyanine blue pigment. Dyes and Pigments, 2018.
7. Schmidt A.M., et al. Phthalocyanines: An old dog can still have new phototricks. Molecules, 2021.
8. Cranston R.R., et al. Thin-film formation, microstructure, and physical properties of metal phthalocyanines. RSC Advances, 2021.
9. Herbst W., Hunger K. Industrial Organic Pigments: Production, Properties, Applications. Wiley-VCH, 2004.
10. Zollinger H. Color Chemistry: Syntheses, Properties, and Applications of Organic Dyes and Pigments. Wiley-VCH, 2003.
11. Chen Z., et al. Preparation of copper phthalocyanine/SiO_2 composite particles and improved stability. Materials, 2019.
12. Szwajca A., et al. Quantum chemical stability analysis of phthalocyanine-shaped molecules. Molecules, 2024.
13. Safonova E.A., et al. Phosphorus(V) crown-phthalocyanine as a promising functional phthalocyanine system. Dyes and Pigments, 2024.
14. Zheng P., Wang R., et al. A phosphorus-containing hyperbranched phthalocyanine flame retardant for epoxy resins. Scientific Reports, 2021.
15. Pająk A., et al. The thermal properties and flammability of pigmented elastomeric materials containing phthalocyanine pigments. Journal of Thermal Analysis and Calorimetry, 2014.

ISSN 3030-3907