EMERGING TRENDS AND FUTURE DIRECTIONS IN THE SYNTHESIS AND UTILIZATION OF ENVIRONMENTALLY BENIGN CORROSION INHIBITORS

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Annotation: This article analyzes modern methods for obtaining corrosion inhibitors based on alternative (green) chemical substances, as well as the influence of aggressive environments on the corrosion formation process, particularly in pipeline flow systems used in the oil and gas industry.Pipeline flows in the oil and gas sector are classified into three main categories: the upstream, midstream, and downstream sectors.The upstream sector includes the processes of exploration, identification, and extraction of crude oil and natural gas from onshore (subsurface) and offshore (subsea) fields.The midstream sector covers the long-distance transportation of oil and gas to processing facilities or consumer regions, as well as their storage and initial processing stages.The downstream sector comprises the refining of crude oil at oil refineries, the production of various petrochemical products at petrochemical plants, and the delivery of these products to consumers.At these stages, the prospects for using environmentally friendly (green) corrosion inhibitors to prevent corrosion processes are examined.

Key words: Green corrosion inhibitors; environmentally friendly inhibitors; pipeline flow systems; oil and gas industry; upstream; midstream; downstream; corrosion prevention; aggressive environments; CO_2 and H_2S corrosion; sustainable inhibitor technologies; corrosion control; eco-friendly materials; green chemistry.

Аннотация: В данной статье проанализированы современные методы получения ингибиторов коррозии на основе альтернативных (зелёных) химических веществ, а также влияние агрессивной среды на процесс образования коррозии, особенно в трубопроводных потоковых системах, применяемых в нефтегазовой промышленности.Трубопроводные потоки в нефтегазовой отрасли классифицируются по трём основным направлениям: верхний сектор (upstream), средний сектор (midstream) и нижний сектор (downstream).Сектор upstream включает процессы поиска, выявления и добычи сырой нефти и природного газа из наземных (подземных) и морских (подводных) месторождений.Сектор midstream охватывает транспортировку нефти и газа на дальние расстояния к пунктам переработки или районам потребления, а также их хранение и начальные стадии переработки.Сектор downstream включает переработку сырой нефти на нефтеперерабатывающих

ISSN 3030-3907

заводах (НПЗ), производство различных нефтехимических продуктов на нефтехимических предприятиях и доставку этих продуктов потребителю.На этих этапах анализируются перспективы применения экологически чистых (зелёных) ингибиторов коррозии для предотвращения коррозионных процессов.

Ключевые слова: Зелёные ингибиторы коррозии; экологически чистые ингибиторы; трубопроводные потоковые системы; нефтегазовая промышленность; upstream; midstream; downstream; предотвращение коррозии; агрессивные среды; коррозия CO_2 и H_2S; устойчивые ингибиторные технологии; контроль коррозии; экологически безопасные материалы; зелёная химия.

Annotatsiya: ushbu maqolada muqobil (yashil) kimyoviy moddalarga asoslangan korroziya ingibitorlarini olishning zamonaviy usullari, shuningdek, agressiv muhitning korroziya hosil bo'lish jarayoniga, xususan, neft va gaz sanoatida qo'llaniladigan quvur oqimi tizimlariga ta'siri tahlil qilingan.Neft va gaz sohasidagi quvur oqimlari uchta asosiy toifaga bo'linadi: yuqori, o'rta va quyi oqim tarmoqlari.Yuqori oqim sektoriga qidiruv, identifikatsiya qilish jarayonlari kiradi, quruqlikdagi (er osti) va dengizdagi (dengiz osti) konlaridan xom neft va tabiiy gaz qazib olish.O'rta oqim sektori neft va gazni qayta ishlash ob'ektlariga yoki iste'molchilar hududlariga uzoq masofalarga tashishni, shuningdek ularni saqlash va dastlabki qayta ishlash bosqichlarini qamrab oladi.Quyi sektorga neftni qayta ishlash zavodlarida xom neftni qayta ishlash, neft-kimyo zavodlarida turli xil neft-kimyo mahsulotlarini ishlab chiqarish va ushbu mahsulotlarni etkazib berish kiradi consumers.At ushbu bosqichlar, korroziya jarayonlarining oldini olish uchun ekologik toza (yashil) korroziya ingibitorlaridan foydalanish istiqbollari ko'rib chiqiladi.

Kalit so'zlar: yashil korroziya ingibitorlari; ekologik toza ingibitorlar; quvur liniyasi oqim tizimlari; neft va gaz sanoati; yuqori oqim; o'rta oqim; quyi oqim; korroziyaning oldini olish; agressiv muhit; CO_2 va H_2S korroziyasi; barqaror inhibitor texnologiyalari; korroziyani nazorat qilish; ekologik toza materiallar; yashil kimyo.

Introduction

In the oil and gas industry, corrosion-prone operations are conventionally classified into three principal sectors: upstream, midstream, and downstream. The upstream sector encompasses activities related to the exploration, characterization, and extraction of crude oil and natural gas from subterranean or subsea reservoirs.The midstream sector involves the transportation of crude and partially processed hydrocarbons over long distances, their storage, initial processing, and large-scale commercial distribution. The downstream sector includes the refining

ISSN 3030-3907

of crude oil at petroleum refineries, the manufacture of a wide range of petrochemical products (such as lubricants, fertilizers, antifreeze agents, and others), and the subsequent delivery of these products to end users. Corrosion is encountered throughout all stages of oil and gas operations, posing significant safety hazards and resulting in substantial economic burdens.[1]

There are no universally accepted criteria for classifying corrosion inhibitors; however, a clear and rational classification system is essential for both research and practical implementation. One of the most widely adopted approaches is to categorize inhibitors according to their inhibition mechanisms, such as anodic, cathodic, or mixed-type inhibitors. Another well-established approach—which is also employed in this chapter—is classification based on chemical composition, broadly distinguishing between inorganic and organic species. Owing to the wide structural diversity of organic molecules, organic inhibitors may further be subdivided into more specific families of compounds.

Traditionally, various metal salts have been extensively utilized as corrosion inhibitors for different metals and alloys. Among the most recognized examples are chromates, vanadates, molybdates, tungstates, silicates, phosphates, and rare-earth species. Chromium-based inhibitors, particularly hexavalent chromates (CrO_4^{2-} and $Cr_2O_7^{2-}$), represent classical and long-established corrosion-protection systems. Hexavalent chromium (Cr(VI)), also known as an anodic passivator, exhibits strong oxidizing properties, promoting the formation of protective oxide films on metal surfaces and thereby enhancing passivation. Typically, Cr(VI) species are introduced directly into corrosive environments as inhibitor anions or employed in the preparation of surface-conversion coatings, such as chromate conversion layers.

Due to its low cost and excellent mechanical stability, steel remains the most widely used material for oil and gas pipelines. When manufacturing requirements are fully met, this type of steel can withstand normal and high operational loads over extended service periods. According to industry standards, steel grades are classified based on their production technology, chemical composition, and heat-treatment conditions, which collectively determine their mechanical properties. Among the commonly used industrial steels, the 1Cr, 9Cr, and 13Cr grades hold particular importance.

Of these, 1Cr steel is the most extensively applied owing to its economic advantage. Although this grade exhibits a certain level of resistance to sulfide stress cracking (SSC), it remains susceptible to uniform corrosion [2]. Under non-aggressive environmental conditions, pipelines manufactured from such steels can operate reliably for decades even without dedicated corrosion-protection measures [3].

ISSN 3030-3907

However, in practical field environments, the combination of elevated temperatures, high pressures, and the presence of corrosive gases such as CO_2 and H_2S substantially accelerates corrosion processes, leading to a significant increase in maintenance and operational costs.

Types of Corrosion Encountered in Oil and Gas Production

In the oil and gas industry—particularly within production pipelines—corrosion predominantly occurs under either sweet conditions (corrosion induced by CO_2) or sour conditions (corrosion induced by H_2S). In certain cases, corrosion may also arise due to oxygen when the applied treatment methods fail to achieve sufficient deaeration, allowing residual oxygen to remain in the system.

Under these corrosive environments, and as a result of their interaction with pipeline materials, several major forms of corrosion can develop. These include: uniform (general) corrosion, galvanic (bimetallic) corrosion, crevice corrosion, pitting corrosion, intergranular corrosion, erosion–corrosion, stress corrosion cracking, acid-induced corrosion, under-deposit corrosion, and microbiologically influenced corrosion (MIC).

Table 1

Conventional Corrosion Inhibitors

Advantages	**Disadvantages**
Economic efficiency	Environmental restrictions
Wide applicability (universal property)	Hazardous to human health
Rapid action	Requires high concentration
Chemical stability	Potential to damage metal surfaces
Fast-acting	Non-renewable raw materials

A common characteristic of the corrosion types mentioned above is the presence of an aqueous (moist) environment, meaning that the liquid phase directly interacts with the metal surface. In this study, corrosion induced by CO_2 and H_2S and their associated mechanisms are given primary focus due to their prevalence in oil and gas operations. However, for the sake of providing a general overview, brief information on other forms of corrosion is also presented. The effectiveness of corrosion inhibitors is primarily determined by their ability to adsorb onto the metal surface. Adsorption can occur through two distinct mechanisms: physical adsorption (physisorption) and chemical adsorption (chemisorption). Physical adsorption arises from electrostatic forces between inhibitor molecules and the charged metal surface [4]. At this stage, an inhibitor film is formed on the metal surface via van der Waals interactions. Subsequently, this protective layer is further stabilized through chemisorption , as this process involves the formation of strong chemical bonds between the metal surface and the adsorbed inhibitor molecules[5].

ISSN 3030-3907

Table 2

Green Corrosion Inhibitors

Advantages	**Disadvantages**
Environmentally sustainable	**Efficiency is variable.**
Non-hazardous to human health	It requires a high concentration
Broad availability of raw materials	Sensitive to temperature
Non-destructive to metal surfaces	Complex separation process
Sourced from locally renewable materials	Long-term stability is low

Upon adsorption onto the metal surface, corrosion inhibitors impede the ingress of ions and molecules, thereby decelerating corrosion processes. They also occupy active sites on both anodic and cathodic regions, effectively interrupting the sequence of electrochemical reactions. The resulting physical barrier, together with the electric double layer formed at the metal–solution interface, exerts a significant influence on electrochemical behavior. Heteroatoms present in the inhibitor (O, N, S, P) establish strong interactions with the metal surface, blocking corrosion-prone sites. The stability of adsorption is determined by these interactions as well as the inhibitor's overall physicochemical properties, including functional groups, electron density on donor atoms, p-orbital characteristics, and molecular electronic structure[6].

Corrosion inhibitors generally consist of surfactants, solvents, intensifiers, amines, quaternary ammonium compounds, acetylenic alcohols, and various nitrogen-containing heterocyclic structures. Surfactants ensure uniform distribution in acidic media and promote stable dispersion, while enhancing metal surface wetting, which contributes to high protective efficiency. Solvents decrease inhibitor viscosity and improve chemical stability. Intensifiers enhance the protective performance of acidic inhibitors under conditions such as elevated temperature, strong acids, or prolonged exposure. However, these additives often present environmental concerns due to their high toxicity[7].

Corrosion inhibitors typically contain functional groups that incorporate one or more heteroatoms (O, N, S, P), which facilitate strong binding of the inhibitor to the metal surface. The interaction with the metal is a critical step, as it enables the adsorption of inhibitor molecules onto the metal surface, representing the initial stage of corrosion protection. In the oil and gas industry, various organic and chemically structured compounds are employed for corrosion prevention. This study specifically examines the prospects of using water-soluble, environmentally friendly "green" corrosion inhibitors.

ISSN 3030-3907

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ISSN 3030-3907