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Corrosion Control Methods in Oil and Gas Pipelines and Their Limitations

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Abstract: Corrosion in oil and gas pipelines is a significant challenge for the industry, leading to failures, leaks, and ruptures that can have severe consequences. These incidents can cause significant environmental damage and financial losses for affected companies. As a result, corrosion control has become crucial for ensuring the safety of infrastructure and maintaining the smooth operation of the oil and gas industry. This review study provides a detailed examination of the corrosion control methods used in the oil and gas industry, detailing the most common methods such as coating, corrosion inhibitors, cathodic protection, and biocides. Each method is evaluated in terms of its effectiveness, cost, and associated challenges, including the sustainability of long-term solutions and their environmental impact. The study also discusses the specific limitations of each approach, providing insights into the best practices and improvement strategies to optimize corrosion management in this critical sector.

Key words: Corrosion, oil and gas pipelines, oil and gas industry, corrosion inhibitor, cathodic protection, coating, biocide.

1. Introduction

Corrosion of oil and gas pipelines is a serious problem for the oil and gas industry, being the main cause of failures occurring in the process of production and transportation [1]. This widespread phenomenon can lead to ruptures and leaks of oil and gas, causing significant disruptions in the supply. The consequences of corrosion are of particular concern, as they lead not only to significant damage to the environment, but also to substantial financial losses, not to mention health and safety issues for workers and surrounding communities. The average annual cost of corrosion control is $7 billion, with 38% of the cost being capital expenditures, 52% being operational and maintenance costs, and 10% being breakdown costs. The global corrosion monitoring market was valued at $280.8 million in 2022 and is projected to reach $564.1 million by 2030, representing an annual growth rate of 9.1% [2]. Corrosion of pipelines is caused by H_2S (hydrogen sulfide), CO_2 (carbon dioxide), chlorides, and acids. H_2S, in the presence of moisture, creates an acidic environment that leads to corrosion. Seawater and brine produce hydrochloric acid, which also causes corrosion. Deep-sea oil and gas extraction, with its high pressure and temperature, accelerate this process. Therefore, corrosion management is crucial to prevent such crises and ensure the smooth operation of the industry.

Corrosion processes in the oil and gas industry are one of the most complex and pressing challenges faced by modern engineers and researchers. Despite extensive efforts to develop effective corrosion prevention strategies, it is nearly impossible to completely eliminate this phenomenon [3]. Even with protective coatings in place, degradation can occur under harsh operating conditions. However, implementing comprehensive

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corrosion reduction measures can significantly reduce the economic losses associated with damaged pipelines and equipment [4]. Various protection methods are used to combat pipeline corrosion in the oil and gas sector, including cathodic protection, organic coating, and the use of high-quality corrosion-resistant alloys [5]. Over decades of research and development, numerous technologies have been created to control and minimize corrosion damage. Corrosion inhibitors are essential for protecting equipment from corrosion in the oil and gas industry. To achieve maximum inhibition effectiveness, their concentration must exceed a certain threshold. In addition, film-forming inhibitors are more effective in protecting low-carbon steel in acidic environments by creating molecular and hydrocarbon layers that prevent water from contacting the surface. However, despite significant progress, the effectiveness and limitations of various methods for protecting oil and gas pipelines remain a subject of intense debate and research in the scientific literature.

The purpose of this article is to provide a comprehensive analysis and systematization of scientific research data on corrosion protection methods for oil and gas pipelines operating in aggressive environments. The article will also address the main limitations affecting the efficiency of pipelines in order to improve and optimize corrosion control methods.

2. Methods of Corrosion Control on Oil and Gas Pipelines

2.1 Cathodic Protection

The protection of buried pipelines transporting gas and oil relies on insulating coatings and CP (cathodic protection), which reduces corrosion and prevents damage by providing electrochemical protection [6]. It reduces the potential differences between the anodic and cathodic zones of the pipeline by using a buried external anode that induces a current flow, thus aligning these zones at the same potential. This prevents the existence of anodic sites on the pipeline, making it entirely cathodic. Cathodic protection systems for pipelines are an effective technology for preventing corrosion (Fig. 1). They transform the pipeline into a secure element within a controlled electrochemical cell, thereby ensuring the durability and reliability of the infrastructure. Wang [7] examined the impact of AC (alternating current) on pitting corrosion and SCC (stress corrosion cracking) of X70 pipeline steel under CP conditions. The results showed that corrosion and stress corrosion cracking (SCC) are inhibited by a PC of -0.775 V_{SCE} without AC. However, PCs of -0.95 V-ECS and 1.2 V-ECS promote cathodic reactions, causing a positive shift in the DC (direct current) potential and increasing the cathodic current. AC induces local anodic dissolution, initiating corrosion pits between 0.6 and 2 μm. Furthermore, AC increases the susceptibility to stress corrosion cracking of X70 steel at -0.775 V-ECS, even with a low AC of 1 mA/cm^2, due to anodic dissolution and hydrogen release. Chen [8] conducted a corrosion analysis study of protected pipelines exposed to AC interference, developing tools to assess PC requirements. Numerical models simulated the current distribution, which were validated by laboratory experiments. The results show that AC interference increases corrosion rates and decreases PC efficiency, with a dependence on the metal type. C1018 steel exhibits corrosion rates 1.85 to 3.65 times higher than X60 steel. To limit corrosion under an AC disturbance of 50 A/m^2, PC current densities of 1.45 A/m^2 for C1018 steel and 0.18 A/m^2 for X60 steel are required, increasing to 2.98 A/m^2 and 2.2 A/m^2 respectively at 500 A/m^2, highlighting the importance of PC at high AC levels.

2.2 Coatings

Anti-corrosion coatings play a crucial role in protecting materials, particularly pipelines, from the damaging effects of corrosion. By creating a protective layer, these coatings act as an effective barrier between the material and the environment, preventing corrosion-related damage. Over the years, numerous different

Fig. 1 Installation of a pipeline equipped with cathodic protection in a trench [9].

coating materials and formulations have been developed, each designed to provide effective protection against corrosion. The selection of these materials is crucial for extending the lifespan and integrity of underground infrastructure, preventing leaks and structural damage that can have significant environmental and safety implications. Therefore, the development of coatings specifically adapted to different soil conditions remains an area of ongoing research and application.

Anti-corrosion coatings are divided into three categories: organic, inorganic, and metallic [10]. Organic coatings, the most common, form a continuous, adaptable film on the substrate, providing an effective barrier against corrosion due to their excellent adhesion. Inorganic coatings, often ceramic, are resistant to high temperatures and corrosive environments. They are preserved due to their chemical stability and create protective oxide layers. Metal coatings, on the other hand, use sacrificial mechanisms, such as zinc, which is predominantly corroded to protect the substrate, or barrier mechanisms, such as stainless steel, which prevent the migration of corrosive agents.

Nanocomposite coatings, using TiO_2 nanoparticles synthesized by the sol-gel method, are essential for treating metallic surfaces in the oil and gas industry. Fadl et al. [11] created a PDMAS/TiO_2 nanocomposite by mixing these nanoparticles with PDMAS (polydimethylaminosiloxane), which acts as a multifunctional modifier for an epoxy coating. The test results obtained showed improved anti-corrosion, mechanical, chemical, electrical, thermal and Ultra Violet characteristics for the hybrid epoxy PDMAS/ TiO_2 nanocomposite coating. Cao et al. [12] developed a pH-sensitive, self-healing, anti-corrosion epoxy-based coating. The triazinylic corrosion Inh (inhibitor) was introduced into a MCM-41 (mesoporous molecular sieve) by vacuum impregnation. PEI (Polyethyleneimine) and sodium PSS (polystyrene sulfonate) were applied to the surface by LBL (layer-by-layer) self-assembly. Nanocapsules with the self-healing anti-corrosion coating Inh@MS/PEI/PSS-EP were then added to the epoxy coating. The coating actively releases ammonium inhalide in an alkaline environment. After 30 days of immersion, the corrosion resistance of the modified coating is three orders of magnitude greater than that of pure epoxy.

2.3 Corrosion Inhibitors

The use of corrosion inhibitors is one of the most widespread control methods in industry. However, many of these inhibitors are prohibited due to their toxicity and the hazards they pose to the environment.

In recent years, environmentally friendly natural corrosion inhibitors have emerged, offering corrosion protection with minimal impact on the environment and human health [13]. They are extracted from plants, agricultural waste, or biopolymers and contain organic compounds such as alkaloids, flavonoids, tannins, saponins, and polyphenols. Corrosion inhibitors are chemical agents added in low concentrations to corrosive environments, with the aim of reducing or preventing the interaction between metals and their corrosive surroundings. Among the various methods for controlling corrosion, the use of inhibitors stands out for its cost, effectiveness, and practicality, particularly in acidic aqueous conditions. These inhibitors exert their action by reacting with corrosive elements present in the systems, thereby neutralizing harmful chemical substances that can cause damage to the metal.

The corrosion of metals in acidic environments presents a challenge, driving the search for environmentally friendly and sustainable inhibitors. Tan et al. [14] reported that, compared to traditional copper corrosion inhibitors, PFAE (Pyracantha fortuneana alcohol extracts) derived from natural plants are environmentally friendly inhibitors of copper corrosion. Experiments showed that PFAE effectively inhibits corrosion in a sulfuric acid (H2SO4) solution. At a concentration of 600 mg/l, the efficacy is greater than 95%, and after immersion for 4 hours, the copper retains more than 80% of its corrosion resistance. Morphological analysis confirmed a decrease in copper surface roughness upon the addition of PFAE. Simulations showed that the six active components of PFAE had high corrosion resistance activity. Haddou et al. [15] investigated the efficacy of three extracts of *Cannabis sativa* L. (ethanolic extract, hexanic extract, and dichloromethane extract) in inhibiting the corrosion of mild steel in an acidic medium (1 M HCl). The results show that the inhibition efficacy increases with concentration, reaching 91% for the EET (ethanolic extract), 89% for the EHX (hexanic extract), and 83% for the EDM (dichloromethane extract) at 308 K for 0.8 g/L. EET, EHX, and EDM act as mixed-type, primarily anodic inhibitors, via adsorption onto the metal surface, following the Langmuir isotherm model. The adsorption equilibrium constants are 3.0143 M (EET), 5.1245 M (EHX), and 2.2009 M (EDM), respectively. The EET exhibits the highest Ea (activation energy) of 101.70 kJ/mol, while the EHX and EDM extracts have Ea values of 79.05 kJ/mol and 82.93 kJ/mol, respectively, all higher than that of the control at 30.23 kJ/mol. This indicates that these extracts effectively inhibit corrosion. Simulations show that the catechin dihydrate in EET, linoleic acid in EHX, and naringenin in EDM interact strongly with the metal surface.

2.4 Biocides

A biocide is a substance or microorganism intended to control harmful organisms such as bacteria, viruses, and parasites by chemical or biological means. Biocidal products can be chemical mixtures, pure active substances, or articles impregnated with active substances, such as disinfectant wipes. Biocides used in small quantities to control the growth of microorganisms on oil and gas pipelines must possess bactericidal, algicidal, and fungicidal properties [16]. Their effectiveness depends on the type of microorganism and the application conditions. In practice, they are often combined with other corrosion control methods, such as coatings and pipe cleaning, to reduce biofilm growth and microbiological corrosion. Biocides must be selective, effective in the presence of toxic compounds, non-corrosive, biodegradable, and economical.

Corrosion is amplified by the presence of biofilms on metallic surfaces, enabling novel electrochemical reactions that would not exist without microorganisms [17]. Furthermore, the interactions between the biofilm and the metallic sublayer are also modified by the metabolic by-products of the bacteria.

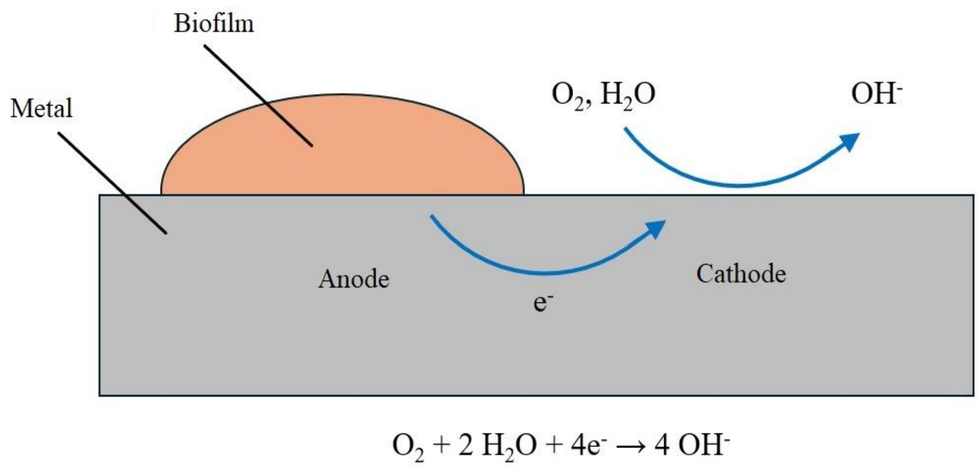

Fig. 2 Diagram representing the mechanism of corrosion caused by microorganisms [17].

3. Limitations of Corrosion Control Methods

Cathodic protection is a corrosion control method used to protect underwater and underground metal structures, such as pipelines. When properly designed, these systems provide long-term protection, particularly through the use of aluminum or zinc anodes, which can last up to 30 years. However, they have limitations, including high costs, environmental concerns, limited applicability at high temperatures, and cathodic dissolution. Installing cathodic protection is an expensive and complex process that requires regular maintenance, such as visual inspections. Corrosion-related pipeline accidents lead to high costs for the protection system. The total cost of the life cycle depends on the size of the pipeline, as well as the materials and labor used.

Traditional cathodic protection systems lose their effectiveness as the temperature of the pipeline increases. High temperatures alter the electrochemical reactions on the metal surface, impairing the formation and stability of protective films [18]. This makes it difficult to control corrosion and increases its rate, making it difficult to keep systems in working order.

Coatings limitations and defects can occur at various stages: before application (deposits, films), during application (drips, sagging), after application (bubbles, orange peel effect), and during operation (bubbles, rust) [19]. It is crucial to assess all contributing factors and analyze the application history to identify the cause of failure. Limitations include coating formulation issues for pipelines, flammability and temperature issues, surface preparation requirements, size limitations, and limited durability in acidic environments.

Corrosion inhibitors are effective in various corrosive environments, but they have significant limitations, including ineffectiveness at high temperatures and pressures, difficulties in applying them to long pipelines, limited resistance to extreme pH levels, and limited compatibility with other chemicals [1]. These limitations require further research to develop strategies for inhibition and ensuring the integrity of pipeline infrastructure.

Biocides play an important role in the oil and gas industry for preventing pipeline corrosion, although they have limitations such as environmental impact, health risks, and microbial resistance [20]. Their effectiveness depends on a better understanding of microbial ecology, but there are still challenges in terms of resource optimization and management.

4. Conclusion

This article discusses the most common corrosion control methods used to reduce corrosion in oil and gas pipelines. It also analyzes the various limitations associated with these methods and provides an in-depth analysis of the effectiveness of each method and the challenges that arise during its implementation. Among the analyzed methods, cathodic protection and coatings are the most effective, providing long-lasting benefits and significant cost savings for the industry, despite their relatively high maintenance costs. In contrast, biocides and inhibitors, although used to limit internal corrosion, pose a significant health risk to workers and have a significant environmental impact. Additionally, they have a shorter lifespan compared to other methods, making them less cost-effective despite their high operating costs. By analyzing these methods and their limitations, this article aims to provide a comprehensive overview of current methods and potential improvements in the field of corrosion control.

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