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Evaluation of corrosion in metallic pipelines caused by petroleum derivatives. Case study: Angolan Distributor

Evaluación de la corrosión en ductos metálicos por derivados del petróleo. Estudio de caso: Distribuidora angolana

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Abstract: The oil sector in Angola, which has been growing in recent decades, faces significant challenges related to the corrosion of metal structures, particularly in the pipelines and storage tanks of fuel distribution companies. Corrosion, accelerated by environmental agents and transported petroleum derivatives, has resulted in high maintenance costs and environmental risks. This study proposes the combination of impressed current cathodic protection and corrosion sensors monitoring as a solution to control and reduce in-tube corrosion. The methodology included a literature review, interviews with company professionals, and experiments with metal pipe samples exposed to different environmental conditions. The results indicated that the combination of the proposed methods is more efficient than the coating method currently used, offering both internal and external protection for pipelines, reducing maintenance costs, and increasing operational safety. The study area, located near the Atlantic Ocean, presents a highly corrosive environment due to the marine atmosphere and sandy soil. It is concluded that the implementation of these methods can extend the structures lifespan, while minimizing economic and environmental impacts, and ensuring greater safety for the company and the surrounding community.

Keywords: power resources, oil industry, petroleum technology, pipelines transportation

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Resumen: El sector petrolero en Angola, en crecimiento en las últimas décadas, enfrenta desafíos significativos relacionados con la corrosión de estructuras metálicas, particularmente en los conductos y tanques de almacenamiento de empresas distribuidoras de combustible. La corrosión, acelerada por agentes ambientales y por los propios derivados del petróleo transportados, ha generado altos costos de mantenimiento y riesgos ambientales. Este estudio propone la combinación de métodos de protección catódica por corriente impresa y monitoreo por sensores de corrosión como solución para controlar y reducir la corrosión intra tubo. La metodología incluyó revisión bibliográfica, entrevistas con profesionales de la empresa y experimentos con muestras de tubos metálicos expuestos a diferentes condiciones ambientales. Los resultados indicaron que la combinación de los métodos propuestos es más eficiente que el método de revestimiento con pinturas actualmente utilizado, ofreciendo protección interna y externa de los conductos, reducción de costos de mantenimiento y aumento de la seguridad operativa. El área de estudio, ubicada cerca del océano Atlántico, presenta un ambiente altamente corrosivo debido a la atmósfera marina y al suelo arenoso. Se concluye que la implementación de estos métodos puede prolongar la vida útil de las estructuras, minimizando impactos económicos y ambientales, y garantizando mayor seguridad para la empresa y la comunidad circundante.

Palabras clave: recursos energéticos, industria petrolífera, tecnlogía del petróleo, transporte por tubería

Introduction

The oil industry is a cornerstone of the Angolan economy, with significant growth in recent decades (González, 2025). However, this sector faces major technical challenges, particularly the corrosion of metal structures such as pipelines and storage tanks, which, despite representing the safest and most economical means for petroleum and gaseous products transportation, pose considerable environmental and operational risks (Popescu & Gabor, 2021).

In the oil and gas industry, gases and fluids can cause serious corrosion problems (Cueli *et al.,* 2022; Solovyeva *et al*., 2023; González *et al.,* 2023; Vakili *et al*., 2024). Corrosion is a spontaneous electrochemical process in which metals undergo oxidation when interacting with reactive species existing in the environment (Martínez-Pérez, 2023), returning to thermodynamically more stable states. In the oil industry, this phenomenon intensifies due to the presence of water, CO_2, H_2S, oxygen, and salts, which act as electrolytes and promote simultaneous oxidation and reduction reactions. The interaction between these agents and operating conditions such as temperature, pressure, pH, and flow turbulence bring about different corrosion mechanisms, including uniform, localized, erosive or CO_2 corrosion, as well as H_2S embrittlement (Alamri *et al.,* 2020; Azam *et al.,* 2021).

In gas pipelines, corrosion concentrates in effusion regions, such as low-inclination sections, elbow joints, flanges, valves, separators, and areas near pumps or compressors. It is influenced by flow velocity, liquid retention, temperature, and H_2S and CO_2 partial pressures (Liao *et al.,* 2022). Corrosive behavior depends on parameters such as temperature, pressure, flow velocity, fluid pH, and soil corrosivity; these factors influence the integrity of buried oil pipelines, gas pipelines, and tanks (Khakzad *et al.,* 2022). The means of exposure includes both the inside of these equipments, in contact with formation water and fluids containing CO_2 and H_2S, and the outside, exposed to corrosive soils. Within these means, exposure conditions vary according to fluid and soil chemical composition, temperature, pressure, and flow, which determine the corrosion type and severity. Among the main failure mechanisms are hydrogen damage, stress corrosion cracking, corrosion cracking, and microbiologically induced corrosion (Wasim & Djukic, 2022).

The analyzed company proximity to the Atlantic Ocean generates a highly corrosive atmosphere that holds a high concentration of chlorides and high relative humidity (Natesan *et al.*, 2008). In coastal zones, exposed materials suffer greater damage due to atmospheric corrosion (Viña *et al*., 2021; Castañeda-Valdés *et al*., 2024). In addition to external damage, transported products, such as gasoline, diesel, and liquefied gas, contribute to internal corrosion as well. Even applying anticorrosive coatings, costs are high and durability is limited, hence pipeline incidents are mainly caused by corrosion and external interference (Popescu & Gabor, 2021).

Pipelines containing sulfur compounds are exposed to acid corrosion, in which dissolved H_2S promotes anodic and cathodic reactions. The origin and development of this type of corrosion in the oil industry requires the presence of water, acidic conditions (low pH), apart from operational factors such as flow velocity, turbulence, and the presence of CO_2, dissolved salts, and other impurities that modulate the corrosive attack severity and the formation of corrosive deposits (Alamri, 2020). In this context, impressed current cathodic protection has proven effective in reducing corrosion, although it can affect the integrity of coatings, requiring continuous monitoring through sensors that provide real-time data. Therefore, this study proposes integrating cathodic protection and continuous monitoring to develop more efficient and sustainable methods to control corrosion in metallic pipelines, in order to increase operational reliability, reduce maintenance costs, and minimize environmental impacts.

This study results have significant implications for both industrial practice and scientific research. The actual implementation of the proposed methods can reduce maintenance costs, extend the structures lifespan, and minimize environmental and safety risks associated with corrosion.

From a scientific point of view, the study contributes to the growth of knowledge on corrosion protection methods in marine and industrial environments as it offers a basis for future research and applications in similar contexts. The relevance of this study lies in its contribution to improving the management of critical infrastructure in the oil sector, promoting sustainability and operational safety. Furthermore, the results obtained can be the foundation of future research and applications in similar contexts, both in Angola or other countries facing similar challenges.

1.1. Location of the study area

The fuel distribution company, which is operational, is composed of several storage systems and pipeline channels that transport petroleum derivatives. It is located in a coastal zone, at 758 m from the sea.

- Pipeline distance from the discharge area to the storage area: 758 m.

- Industrial zone dimensions:
Perimeter: 1.50 km
Area: 140,346 m²

Materials and methods

This study was developed with the aim of proposing effective methods for corrosion control in the pipelines of a fuel distribution company in Angola. To achieve this objective, the research was structured into three main stages: literature review, data collection, and experimental analysis. The adopted methodology was designed to guarantee the obtention of reliable and relevant data that allow a comprehensive evaluation of the protection methods proposed.

2.2. Literature review

The first stage included a literature review on corrosion mechanisms, protection methods, and emerging technologies for corrosion control. Scientific sources, technical standards (ISO 8501-1 and NACE RP-07-75), and case studies in industrial and marine environments were considered. The literature confirms that fatigue resistance is linked to the ultimate tensile strength of the pipe material (Jiang *et al*., 2019) and that impurities in captured CO_2 can generate corrosive species (Morland *et al*., 2019). Olabisi and Chukwuka (2020) point out that contamination intensifies submarine pipelines degradation. These findings evidence the limitations of conventional methods such as anticorrosive coatings, justifying the adoption of alternatives like impressed current cathodic protection and corrosion sensors monitoring.

2.3. Data collection

Data collection was carried out at the fuel distribution company, covering three main approaches:

2.4. Interviews with professionals

Semi-structured interviews were conducted with company professionals, including maintenance technicians and engineers, in order to understand the currently used protection methods, the challenges faced, and maintenance practices. The results revealed that the predominant method applied is coating with anticorrosive paints, such as Maza, Zarcón, and Eurotex, which, despite their widespread use, have a limited durability in highly corrosive environments.

2.5. Direct observation

Direct observation of the facilities allowed identifying the areas most affected by corrosion, such as pipelines exposed to the marine atmosphere and storage tanks. Images and notes on the structures condition were recorded, enabling a qualitative analysis on the corrosion impact.

Figure 1. Corroded pipeline.

2.6. Sample collection

Samples from metal tubes with physicochemical properties similar to those of the pipelines used in the company were collected. These samples were exposed to different environmental conditions: one was buried at a one-meter depth and another remained exposed on the surface, simulating the corrosive environments found in the study area. The samples were monitored during 60 days, and changes on their surfaces were documented through photographs and laboratory analysis.

Figure 3. Sample a) exposed on the surface. b) when buried.

2.7. Experimental analysis

The experimental study was carried out in the laboratory, emphasizing the evaluation of impressed current cathodic protection effectiveness and the corrosion sensors monitoring. Cathodic protection is appreciated for extending pipelines and engineering components lifespan by significantly reducing the corrosion rate (Giourntas *et al.,* 2020). However, in coated pipelines, cathodic disbonding is identified as the main cause of coating degradation. A detailed understanding of this phenomenon, along with the evaluation of coating resistance and precise monitoring of the protection level, is essential to minimize failures and ensure long-term structural integrity (Xu *et al*., 2020).

2.8. Impressed current cathodic protection

To test cathodic protection, an experimental system was assembled consisting of a 9 V battery, a copper conductor, a graphite anode from a cylindrical gouging electrode (graphite + copper), with dimensions of 10 mm in diameter and 300 mm in length, an ASTM A106 Grade B carbon steel cathode, 80 mm long and 20 mm in diameter, which represent the metal to be protected, and an electrolyte consisting of a 3.5 % NaCl solution, simulating seawater. The sample remained connected to the system for three days, and the reduction of corrosion was evaluated visually and quantitatively.

2.9. Corrosion sensors monitoring

Monitoring was carried out using corrosion coupons, test pieces manufactured from the same material as the pipelines installed at different points and removed after three months. A strip-shaped coupon with dimensions of 3" × ½" × 1/16" (76.2 mm × 12.7 mm × 1.6 mm) was used as a standard widely employed in gas and oil pipelines internal monitoring systems. This non-electrochemical method is widely used in the upstream oil and gas sector to effectively track internal corrosion activities and patterns (Ameh *et al*., 2017). Furthermore, real-time monitoring with internal coupons has proven to be a reliable tool for predicting internal corrosion with an accuracy equivalent to direct measurement, allowing the pipeline operator to act proactively and effectively (Cáceres *et al*., 2019). The corrosion rate was calculated based on the coupons mass loss, using the formula:

Corrosion rate: $\frac{K.\Delta M}{A_c.T_e.\rho}$ [1]

Where:
K: constant (8.76 x 10^4)
ΔM: mass difference before and after exposure (g)
A_a: exposed area of the coupon (cm^2)
T_e: exposure time (hours)
ρ: material density (g/cm^3)

2.10. Data processing

The collected data were organized and analyzed using Microsoft Excel for numerical processing and analysis, and Microsoft Word for documenting and presenting the corrosion study results. Images taken to the samples were processed to quantify the extent of corrosion, and the results from the interviews were categorized to identify patterns and trends.

3. Results and discussion

The results obtained in this study allowed evaluating the effectiveness of the proposed methods for corrosion control in the Fuel Distribution Company's pipelines. The data analysis was divided into three main axes:

- Qualitative and quantitative evaluation of corrosion in the exposed samples;
- Effectiveness of impressed current cathodic protection;
- Performance of corrosion sensors monitoring.

The discussion of results is based on scientific evidence and comparisons to previous studies, highlighting the outcomes' practical and theoretical implications.

3.1. Evaluation of corrosion in exposed samples

Metal pipe samples exposed to different environmental conditions showed different behaviors regarding corrosion. The sample exposed on the surface (sample A) showed a significantly higher degree of corrosion than the buried sample (sample B). This difference is a consequence of the marine environment, characterized by a high relative humidity, the presence of dissolved salts in the air and water, and direct exposure to sea spray, factors that accelerate the corrosion of carbon steel. The buried sample (sample B), although in contact with soil moisture, was not directly exposed to airborne salts or marine spray, thus presenting a lower corrosion rate. This evidences that the intensity of external corrosion is directly related to exposure to the aggressive marine environment.

Figure 4. Oxidation degree of the sample. a) Sample A. b) Sample B.

3.2. Visual inspection and laboratory analysis

Visual inspection and laboratory analysis indicated that sample A presented uniform corrosion (Grade A according to ISO 8501-1), with oxide formation and material loss, while sample B showed minimal signs of corrosion. This confirms that the subsoil corrosiveness is less aggressive than the surface's in marine environments. That is because the subsoil, in spite of having moisture and ions responsible for corrosion, the oxygen and aggressive salts concentration is limited, therefore reducing carbon steel oxidation rate. In contrast, the surface in marine environments is constantly exposed to oxygen, high humidity, and salts dissolved in the air and water, factors that accelerate and intensify corrosion.

These results concur with Silva *et al.* (2015), who point out that corrosion in coastal atmospheric environments is aggravated by chlorides and humidity, while corrosion in subsoil depends on soil composition and its moisture content. Variations in atmospheric temperature contributes to corrosion, as it influences relative humidity and condensation on the metal surface, facilitating the salts dissolution and oxidation. In the exposed sample, these fluctuations accelerate the corrosive processes, while the buried sample is less affected due to the soil's higher thermal stability. The difference between samples reinforces the need for protection methods adapted to each environment's specific conditions.

3.3. Impressed current cathodic protection effectiveness

The impressed current cathodic protection experiment showed promising results. A gouging graphite anode (graphite + copper) and an ASTM A106 Grade B carbon steel cathode were used, connected to a 9 V battery, providing necessary current to activate the protection. After three days of exposure, the sample showed a 95 % reduction in corrosion formation, as evaluated by visual inspection and quantitative analysis, indicating that the current supplied by the battery was suitable to minimize corrosion in this test.

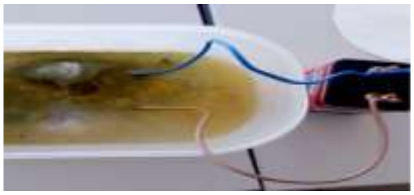

Figure 5. Color of the solution.

3.4. Visual inspection and laboratory analysis

Visual inspection and laboratory analysis showed that sample A displayed uniform corrosion, classified as Grade A according to ISO 8501-1, with oxide formation and material loss on the surface. In contrast, sample B showed minimal signs of corrosion, confirming that the subsoil, although corrosive, is less aggressive than the surface in marine environments. Even though the subsoil is humid and contains corrosive ions, oxygen and aggressive salts availability is lower than in marine surfaces, which reduces carbon steel oxidation rate. These results are consistent with studies such as those by Ramos-Gómez *et al.* (2019), which underline the importance of proper anode selection to maximize cathodic protection efficiency.

3.5. Corrosion sensors monitoring performance

The corrosion coupons used for monitoring, which were made from ASTM A106 Grade B carbon steel to match the simulated pipelines material, provided accurate data on the corrosion rate. After three months of exposure, the coupons installed at different points in the pipelines presented an average corrosion rate of 0.025 mm/year, classified as low according to NACE RP-07-75. This is significantly lower value than the ones observed in unprotected pipelines, which can reach up to 0.254 mm/year in highly corrosive environments.

The coupons analysis also allowed identifying variations in the corrosion rate according to location. For instance, coupons installed on the pipelines' lower generatrix, where there is greater accumulation of moisture and debris, showed slightly higher corrosion rates than coupons installed on the top. These data highlight the importance of strategic sensor positioning for effective monitoring.

4. Discussion

The proposed methods proved to be superior to the conventional methods, such as coating with anticorrosive paints, currently used by the company. While paints offer surface and aesthetic protection, their durability is limited in highly corrosive environments, requiring frequent maintenance and generating high costs. In contrast, impressed current cathodic protection and corrosion sensors monitoring provide a lasting and economical solution, with the bonus of allowing internal corrosion control.

From an economic point of view, impressed current cathodic protection, along with corrosion sensor monitoring, is justified by the reduction in operational and maintenance costs. By prolonging pipelines lifespan and preventing internal failures, these methods decrease the need for frequent repairs and premature replacements, which also prevents financial losses associated with leaks, production stops, and accelerated deterioration. This presents a superior economic return compared to conventional methods based solely on anticorrosive coatings (Wainwright, 1953).

4.1. Limitations and recommendations

Although the results are promising, it is important to note some limitations of the study. The exposure period of the samples (60 days) and the coupons (90 days) may not fully capture the long-term effects of corrosion. It is recommended to conduct long-term studies to validate the results and evaluate the proposed methods durability. Furthermore, large-scale implementation requires substantial initial investments, which may represent a challenge for companies with limited resources.

5. Conclusions

The influence of petroleum derivatives on the corrosion of pipelines belonging to a Fuel Distribution Company located 758 m from the Atlantic Ocean was analyzed, and effective methods to control and reduce this phenomenon were proposed.

The main agents causing corrosion in the studied pipelines include gases (CO_2, NO_2, SO_2), acids (H_2SO_4, H_2S), marine atmosphere, natural waters, soil, and chemical impurities.

Current protection methods, such as paint coatings, have limited effectiveness, high costs and insufficient durability.

Laboratory experiments demonstrated the combination of conventional methods with innovative techniques, such as impressed current cathodic protection and corrosion sensors monitoring, as the most viable alternative to protect pipelines in corrosive environments.

The implementation of these methods can prolong pipelines lifespan, prevent premature replacements, reduce production stops, and ensure greater work safety.

The combination of traditional and innovative methods is essential for effective corrosion control, promoting sustainability and operational safety.

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Author's Contribution according to CRediT Taxonomy

Lisandra Poll Legrá: Conceptualization/Methodology/Supervision/Visualization/Writing – review & editing

Jacob Cassuada Gomes: Conceptualization/Methodology/Data curation/ Resources/Investigation/ Writing – original draft