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Corrosion of Oil and Gas Pipelines: A Review of the Common Control Methods and their Limitations

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ABSTRACT

Corrosion of oil and gas pipelines remains a critical issue in the industry. It leads to pipeline failures, leaks, and ruptures, and these can have severe consequences such as environmental damage and loss of revenue. This study reviewed the most common corrosion control methods used in the oil and gas industry and the limitations of these methods in mitigating the corrosion of oil and gas pipelines. From the study, cathodic protection, coating, corrosion inhibitors and biocides were identified as the common corrosion control methods. The application of these corrosion control methods is mostly affected by sub-surface conditions such as high temperatures and pH aside from other limitations like high cost, environmental, health and safety concerns.

Keywords: Biocides; Cathodic, Coating; Corrosion Inhibitors; Hydrogen Sulphide

1. Introduction

Corrosion of oil and gas pipelines remains a critical issue in the industry. It is seen as the main cause of failure in the oil and gas production process, mainly in the transportation of oil and gas. Corrosion is defined as the deterioration of materials due to a chemical reaction with the environment, reducing the material's strength, durability, and integrity[1]. Corrosion of oil and gas pipelines is a common problem that can lead to pipeline failures, gas and oil leakage, and interruption in oil and gas supply. Again, it can have severe consequences such as environmental damage, revenue loss and results in health and safety issues[2]. Corrosion in pipelines can be caused by various factors, including the presence of hydrogen sulphide (H_2S), carbon dioxide (CO_2), and dissolved acidic chloride environments. For example, when H_2S combines with moisture, it can create an acidic environment that can cause corrosion in pipelines[3]. Acidic chloride environments, on the other hand, can occur when seawater or brine is used in oil and gas production, causing chloride ions to react with water and produce hydrochloric acid, leading to corrosion[4]. In deep offshore oil and gas operations, the presence of high-pressure, high-temperature (HPHT) wells have also increased the rate of corrosion of pipelines[5].

It is almost impossible to eliminate corrosion in the oil and gas industry, however, corrosion can be mitigated to save the industry a lot of revenue. Various corrosion mitigation techniques are used in the oil and gas industry to prevent pipeline corrosion. Over the years, various researchers have worked on various corrosion control methods[6-10], however, these methods and their limitations with regard to the corrosion of oil and gas pipelines are scattered in the literature. The aim of this paper is to consolidate the various research findings by bringing to light the various corrosion control methods that are employed in protecting oil and gas pipelines exposed to corrosive environments and finally bring to bear the limitations of applying these techniques.

2. Overview Oil and Gas Pipeline Corrosion

Fluid flowing from oil and gas pipelines has a combination of chemicals including CO_2, H_2S, organic acids, bacteria, sand, and water[11-15]. CO_2 and H_2S gases contribute mostly to oil and gas pipeline deterioration. CO_2 present in oil and gas will dissolve in water to produce carbonic acid (H_2CO_3). This acid dissolves steel to produce iron carbonate and hydrogen as represented by Equation 1. Despite the weakness of carbonic acid, it is extremely corrosive to carbon steel. This type of corrosion is referred to as sweet corrosion. This sweet corrosion is widespread in natural gas pipelines and it can be prevented by injecting corrosion inhibitors (they are not effective at high temperatures); using martensitic stainless steels (>12% Cr); and controlling pH by caustic injection[16].

$$Fe_{(s)} + CO_{2(g)} + H_2O_{(l)} \rightarrow FeCO_{3(s)} + H_{2(g)} \quad (1)$$

H_2S can cause general and pitting corrosion and hydrogen attack. H_2S can be emitted through cracks into the environment and cause the death of people and damage to the environment. Generally, corrosion that results from H_2S is called sour corrosion. Sour corrosion occurs when H_2S in excess of 100 ppm is present in oil and gas. Sour corrosion can be prevented by controlling pH using caustic injection; injecting H_2S scavengers and corrosion inhibitors; using organic and cement coatings; and choosing alloys according to standards for preventing Sulphide Stress Cracking (SSC)[17].

Corrosion can be grouped into internal and external. Internal corrosion in the oil and gas industry occurs when the inner surface of the pipe encounters corrosive fluids which are generally caused by water, carbon dioxide (CO_2) and hydrogen sulphide (H_2S), and also can be aggravated by microbiological activity[18]. The internal corrosion process is influenced by several factors, including the composition and temperature of the transported fluid, the presence of corrosion contaminants and the material properties of the pipeline. The most common form of internal corrosion in oil and gas pipelines is termed "general corrosion", where the corrosive environment gradually attacks the entire inner surface of the pipe. Additionally, localized corrosion, such as pitting or Stress Corrosion Cracking (SCC) can also occur in areas with high stress or varying fluid flow rate[19]. Internal corrosion can lead to production reduction as corrosion by-products accumulate in the pipeline, and in the event of a through-wall failure, can cause extensive hazards to people and damage to assets and the environment[20]. Internal corrosion can be mitigated through chemical treatments, such as the use of corrosion inhibitors and biocides, internal coating applications, process control, and consistent monitoring and inspection[21].

External corrosion occurs when the pipeline's outer surface is exposed to the environment, including moisture, oxygen, soil composition and the presence of corrosive substances such as dissolved acidic chlorides. External corrosion can be prevented by using coatings, cathodic protection and monitoring systems[22, 23]. External corrosion is manifested in different forms, such as uniform corrosion which is the general and localised corrosion which is characterized by small pits or holes on the metal surface[23] and Stress Corrosion Cracking (SCC), which is due to the combined effects of tensile stress and environments with a high level of hydrogen sulphide (H_2S)[24]. The extent and rate of external corrosion depend on the pipeline's material, protective coatings, cathodic protection and environmental conditions. External corrosion of oil and gas pipelines is a time-dependent damage mechanism and the degree of external corrosion strongly depends on the age of the pipeline and whether and how they are externally protected. It is usually prevented by coatings and Cathodic Protection (CP) systems[25].

3. Corrosion Mitigation Techniques for Oil and Gas Pipelines

3.1 Cathodic Protection

Cathodic Protection (CP) is the electrical solution to the corrosion problem. In other words, it provides electrochemical support to oil and gas pipelines[26]. CP attempts to minimise the potential or voltage difference naturally occurring between various areas on the pipe. The potential differences between these various locations are known as anodic and cathodic areas on the pipe. CP is accomplished by providing an external anode, buried in the ground adjacent to the pipeline and inducing current flow such that the anodic and cathodic areas on the pipe are driven to the same common potential. At this condition, the individual anodic and cathodic sites of the pipe itself no longer exist. Rather now the pipe is entirely cathodic and participates in the main induced corrosion cell between the newly buried anode, the soil, and the pipe[27]. The two main ways of achieving cathodic protection include the Impressed Current Cathodic Protection (ICCP) system and the Sacrificial Anodes Cathodic Protection (SACP) system[28].

3.1.1 Impressed Current Cathodic Protection Method (ICCPM)

The impressed current system generates electrons using an external DC power source. As illustrated in Fig. 1, an impressed current cathodic protection system consists of a rectifier, anodes, reference electrodes and a controlling unit. The required positive current is provided by the rectifier and delivered by the anodes to protect the pipeline. During this process, the reference electrodes track the protection level and the controlling unit regulates the produced current accordingly. Eventually, the metal structure becomes negatively charged, which ultimately leads to a decrease of potential below a certain threshold value. This threshold value is traditionally accepted that the steel is cathodically protected when it has a potential of -800 mV, or more negative[29].

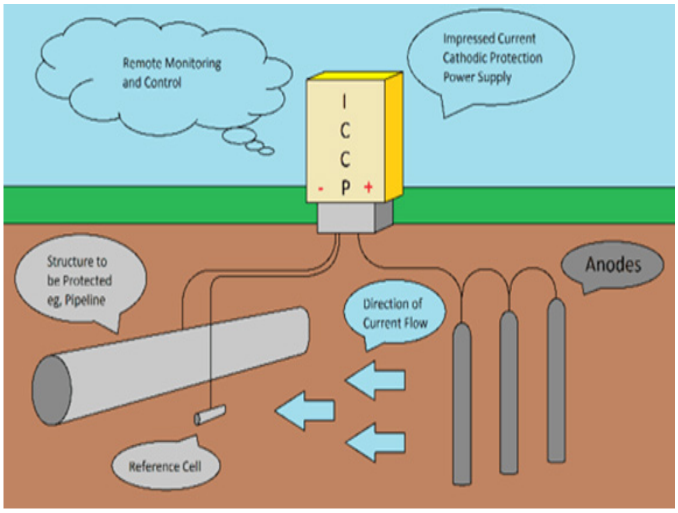

Figure 1: Impressed Current Cathodic Protection System[30].

The utilization of the external power source allows an impressed current cathodic protection system to generate comparatively higher current output and tends to use larger voltage differences than any sacrificial anode system. The larger voltage available with impressed current permits remote anode location, delivering a more efficient current distribution pattern along the protected structure. Especially in low conductive environments, these larger voltages are found useful[31]. The selection of the right type of external DC power source is crucial in ICCP which tends to be versatile, robust, effective and cost-efficient[32].

3.1.2 Sacrificial Anode Cathodic Protection System

Sacrificial Anode Cathodic Protection System (SACPS) is greatly employed to protect oil pipelines, marine, and some domestic structures[33]. It involves the connection of a more negative electrochemical metallic anode with the intended structure to be protected via a wire to complete the circuit[34]. Generally, aluminium (Al), zinc (Zn), and magnesium (Mg) are the metals mostly employed for sacrificial cathodic protection of metals[35]. The basis of the SACPS is that the potential difference between the steel pipeline to be protected and a second metal in the same environment causes the driving voltage. If no anodes were attached to the pipeline, then over time the steel would begin to interact with electrolytes and oxygen dissolved in underground or seawater. Eventually, the steel would undergo corrosion to revert to a naturally occurring ore, such as iron oxide. In such cases, sacrificial anodes can be used to prevent both offshore and onshore pipelines from corroding in this manner[29].

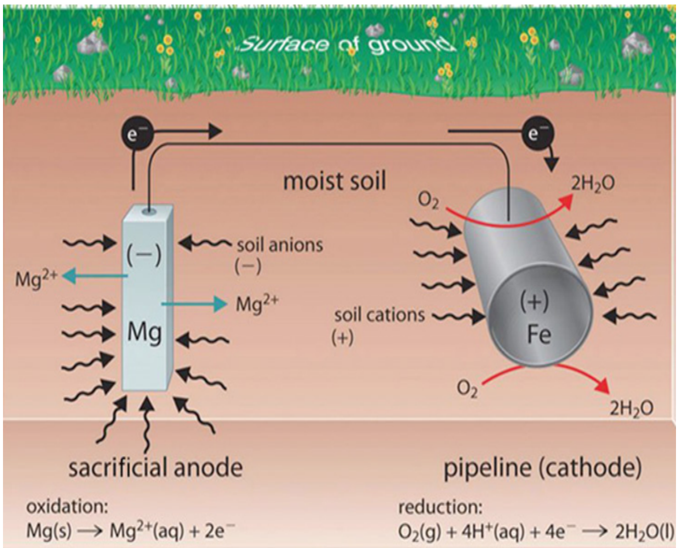

Figure 2: A Simple SACP System[36].

During pipeline installation, the anodes are either clamped or welded to the steel surface to ensure permanent contact between the two types of metal. The two metals will have different electrochemical potentials, meaning a galvanic cell is generated between the two metals due to their voltage difference. In this cell, the pipeline acts as a cathode, as a partner to the sacrificial anode. A redox reaction can then occur between the two metals, with electron transfer occurring from the anode to the cathode, dictated by their difference in electrochemical potentials[37]. The cathode undergoes reduction, becoming more negatively charged due to electron donation from the anode, and the anode on the other hand undergoes oxidation, with positively charged metal ions (cations) forming at its surface. These cations will undergo reactions with dissolved oxygen in seawater (in the case of offshore) or underground (in the case of onshore), leading to the formation of metal oxides (corrosion) at the surface of the anode. The favourable difference in electrochemical potential between the sacrificial anode and the pipeline prevents corrosion from occurring on the pipeline surface itself - instead, only the attached anode undergoes corrosion, and thus it is given the term "sacrificial anode" (Fig. 2)[29].

3.2 Coating

Coatings are a natural choice to create a barrier to the corrosive environment in soils. Over the years, there have been different coating materials and formulations used to protect pipelines. For example, in the 1940s and 1950s, coal tar, wax, and vinyl tape were used; in the 1960s, asphalts were used; and in the 1970s to the present day, fusion-bond epoxy (FBE) was and is being used. Polyethylene (PE) tape and extruded PE jacket material also have been used from the early 1950s to the present day. Though many types of coatings have been applied on buried pipelines, the three main coatings commonly used for pipelines under H_2S and acidic chloride environments are coal tar, FBE coating, and three-layer PE (3LPE) coatings[38].

3.2.1 Coal Tar Enamel Coating

Coal Tar Enamel (CTE) protective coating systems have been used to protect underground and subsea pipelines from corrosion for decades. Its ease of application, low cost, compatibility with cathodic protection, and proven performance in the field for over 80 years make it a popular choice for pipeline companies worldwide. Its resistance to water absorption, hydrocarbons, soil chemicals, and bacteria is excellent. The CTE coating system has evolved into a sophisticated application of primers, multiple grades of plasticized enamel, and high-strength-resin-bonded glass fibre wraps. These improvements have resulted in a CTE coating system with greater bendability, improved handling characteristics, an increase in the temperature exposure range from -28 °C to 80 °C, and a lower safe handling temperature of -10 °C[39].

3.2.2 Fusion-Bond Epoxy Coating

Out of various organic coatings, epoxies have the strongest resistance to oxygen, moisture, and acidic chlorides, which are important constituents of soil. Also, they are highly insulating with very low conductivity and high dielectric resistance. That is why epoxies are the preferred choice where strong corrosion resistance is the main requirement. There are many ways by which the epoxy coatings can be applied: brush, spray, using liquid epoxies, or electrostatically spraying the fine epoxy powder on a heated pipeline, which immediately melts it and fuses instantly[40]. Fusion-bond epoxy coatings are thermosetting compounds, which, once set, cannot be remelted. The most important requirements of the coating are surface cleanliness, proper heating, and sufficient cure. The first step is the blast cleaning of the pipe, followed by heating the pipe uniformly using an induction furnace. This is followed by electrostatic spraying of Fusion-bond epoxy powder, which immediately melts and fuses. The hot-coated pipe is quenched immediately. The temperature at the pipe surface usually ranges from 180 °C to 210 °C. The coating thickness depends upon the pressure of the epoxy powder, electrostatic voltage, and conveyor belt speed[41].

3.2.3 Multilayer Coating

The purpose of multilayer coating is to enhance the damage resistance of the single-layer coatings. It involves the application of adhesive layer and polyethylene (PE) layers to the pipeline surface. The temperatures required to coat an adhesive layer and PE layers are, respectively, 220 °C and 238 °C, and the two coatings must be applied within a small-time interval of 13-25 seconds (depending upon the pipe surface temperature). The purpose of the inner layer (adhesive layer) is to have strong adhesion to the pipe, while the outer layer(polyethene) is expected to be very tough to have high impact resistance[41]. More recently, superhydrophobic coatings have emerged as corrosion inhibitors for use in the marine environment since they lessen the reaction between dissolved corrosive species and steel substrates by significantly reducing the water-solid contact area, as shown in Figs. 3 and 4[42].

3.3 Corrosion Inhibitors

Corrosion Inhibitors (CIs) are substances which when added in small concentrations to corrosive media decrease or prevent the reaction of the metal with the media[44]. Among the techniques, corrosion inhibition is the most economical, practical, and convenient technique to control corrosion on metals in aqueous acidic environment. CIs work by reacting with the corrosive media in the pipeline and effectively neutralizing the harmful chemicals[45]. CIs control the pipeline dissolution as well as the acid consumption. CIs are adsorbed on the metal surface, forming a protective barrier, and interact with anodic or/and cathodic reaction sites to decrease the oxidation or/and reduction of corrosion reactions. Most of the well-known inhibitors are organic compounds containing electronegative functional groups and π-electrons in conjugated double or triple bonds and hence exhibit good inhibitive properties by supplying electrons through π-orbitals. There is also a specific interaction between functional groups containing heteroatoms like nitrogen, sulphur, oxygen having free lone pair of electrons, and the metal surface, which play an important role in inhibition. When both features combine, increased inhibition can be observed[46]. However, many of these compounds are toxic and do not fulfil completely the requirements imposed by the environmental protection standards[47].

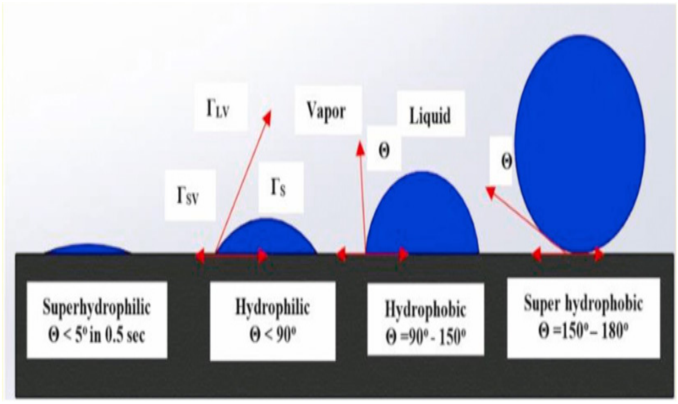

Figure 3: Schematic Illustration of Hydrophilic, Super Hydrophilic, Hydrophobic, and Superhydrophobic Surfaces in 2D[43].

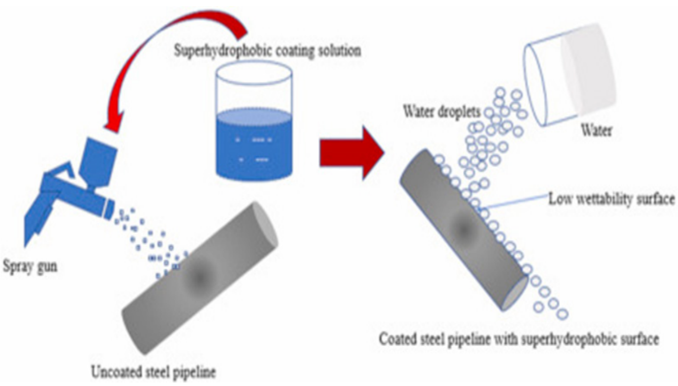

Figure 4: Superhydrophobic Coating of Pipelines[43].

A new generation of CIs has been developed with low environmental impact without compromising on their inhibitor efficiency. The new generation of CIs replaces toxic chemicals with the so-called "Green chemicals". These inhibitors are derived from natural sources and are biodegradable, making them a safer alternative to traditional inhibitors. The inhibition must meet the following requirements: maximum protection action and minimum consumption; absence of influence on technological process proceeding, quality of product and work of catalyst, soluble and dispersible in water and brine, pass to an organic phase in insignificant amounts only, ability to prevent the formation of pitting and prevent the hydrogenation of steel pipes in case of the presence of H_2S[47-48]. Fig. 5 shows how CIs are applied in a pipeline.

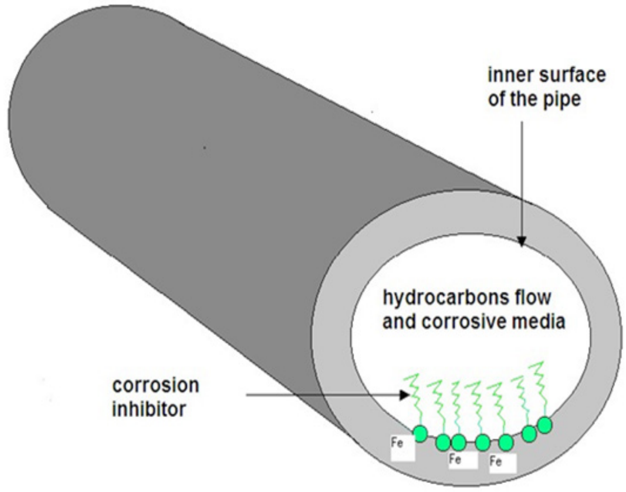

Figure 5: Corrosion Inhibitor Adsorbed into a Metal Surface[47].

3.4 Biocides

Biocides are chemicals that are used in small amounts to control the growth of bacteria and other harmful organisms that aid corrosion in oil and gas pipelines[49]. Generally, biocides are required to behave as bactericidal, algicidal and fungicidal for disinfecting any system, however, such broad-spectrum compounds are not easily available. Therefore, in a practical application of biocide, the microorganism to be killed and its operating conditions play an important role in deciding the type of biocide and its appropriate dosage[50]. Biocides are often used in combination with other corrosion control measures, such as coatings and regular flushing of facility piping dead legs. This integrated approach helps to minimize the growth of biofilms and control microbiologically influenced corrosion more effectively[51-52]. Typical properties of a biocide are selectivity against target microorganisms; capacity to maintain its inhibitory effects in the presence of toxic compounds and under operating conditions of the system; lack of corrosivity; biodegradability; and low cost. Biocides are classified into oxidizing and non-oxidizing.

3.4.1 Oxidising Biocides

Four main oxidizing biocides extensively used in the industry are Chlorine, Bromine, Ozone and Hydrogen Peroxide.

Chlorine Releasing Agents

Chlorine-releasing agents include chlorine, sodium hypochlorite and hypochlorous acid. Chlorine is one the most used bactericide and algaecide in microbial induced corrosion problems. The hydrolysis of chlorine results in hydrochloric (HCl) and hypochlorous (HOCl) acids. Hypochlorous acts as a biocide but it is highly dependent on pH. It is reported that hypochlorous acts best in a pH range of 6.5-7.5. Another compound which is used instead of gaseous chlorine is chlorine dioxide (ClO_2), which is more cost-effective as a lesser amount of ClO_2 is required, as compared to gaseous chlorine, to treat a similar problem[53]. ClO_2 has a stronger oxidation capacity than chlorine and usually does not produce toxic and harmful byproducts [54].

Bromine

Bromine forms hypobromous acid (HOBr) which serves as biocide. Hypobromous is stable over a larger pH range than hypochlorous. With a lower volatility, the biocidal action of bromine is longer as compared to chlorine. Mostly bromine is introduced to MIC problems using solid brominated hydantoins such as bromo-chloro-dimethyl-hydantoin (BCDMH) and bromo-chloro-ethyl methyl-hydantoin (BCEMH), lower concentrations of which are found effective in controlling planktonic bacteria efficiently. In terms of biocidal effect and biofilm removal, bromo-chloro-dimethyl-hydantoin is more efficient than bromo-chloro-ethyl methyl-hydantoin[53].

Ozone

Ozone has gained popularity as a biocide due to several advantages. It is highly oxidative[54] and works well against many bacterial species and microbial biofilms, with minimum or no residuals as it is produced and consumed simultaneously. It does not cause any degradation in the structural metals (aluminium, steel *etc*.). With 0.01-0.05 mg/l ozone in the system, biofilm formation can be prevented. 0.2 mg/l of ozone is sufficient to protect a system from organic contamination, and 0.2-1 mg/l of ozone is required to clean the system with biological deposits (biofouling). Also, ozone is more cost-effective than chlorine and bromine[53]. However, the stability of ozone is poor; it is easy to decompose when used, efficacy time is short, and free radicals generated by ozone can attack the surface of materials, therefore, easily damaging the equipment[54].

Hydrogen peroxide

Hydrogen peroxide is a strong oxidizing biocide with high efficiency, high performance, convenient to use, pollution-free, non-toxic and minimally corrosive [54]. Hydrogen peroxide is relatively a cheaper and stable biocide, and it is usually applied when metals are exposed to water for longer periods. It is reported that a 50-100 ppm concentration of hydrogen peroxide can effectively inhibit microbial growth and biofilm formation in the system[55].

3.4.2 Non-oxidizing Biocides

Non-oxidizing biocides are used more than oxidizing biocides because they are more effective in the eradication of fungi, algae and bacteria. Unlike oxidizing biocides, they are independent of pH. The non-oxidizing biocides groups include aldehydes (formaldehyde, glutaraldehyde), acrolein, quaternary ammonium compounds, methylene bisthiocyanate, Tetrakis hydroxymethyl phosphonium sulphate (THPS) and isothiazolones[56].

Glutaraldehyde

Glutaraldehyde is the most common component of commercial biocides with powerful antibacterial and antifungal activity. It is stable over large pH and temperature ranges. The chemical is highly effective in treating sulphate-reducing bacteria in biofilms; however, Glutaraldehyde may cause compatibility issues with the system being treated owing to its soluble and insoluble nature in water and oil respectively. Glutaraldehyde does not react with strong acids and alkalis but reacts violently with ammonia and amine-containing substances, which causes exothermic polymerization reaction of an aldehyde, and thus its deactivation[56-57].

Quaternary Ammonium Compounds (QUATS)

Quaternary Ammonium Compounds (QUATS) are positively charged biocides and corrosion inhibitors which behave as detergents. For its biocidal activity, it dissolves the lipid cell membrane, which leads to loss of the cell contents of the microorganism. It also prevents the formation of polysaccharide secretions during bacterial colonization, thus showing antibacterial activity. Generally, they are usually diluted by water, hydroxides and alcohols which improves their penetration capacity and biocidal properties. Quaternary ammonium compounds are reported to be biodegradable and thus require no chemical deactivation after their use. QUATS mostly work best in an alkaline environment[53, 56].

Methylene bisthiocyanate

Methylene bis(thiocyanate) (MBT) is effective against algae, fungi and bacteria including Sulphate Reducing Bacteria (SRB). It is unstable in alkaline medium, due to hydrolysis[56].

Tetrakis hydroxymethyl phosphonium Sulphate

It is characterized by low toxicity and interacts with other chemicals used in aqueous environments, a particular advantage of this compound is its ability to remove residual iron sulphide in pipelines[56].

Isothiazolones

Isothiazolones are mainly composed of oxygen, nitrogen and sulphur, and are popular for their biocidal control of SRB [53]. Isothiazolones are used only in an alkaline medium, at pH < 7 they lose biocidal properties, moreover, these compounds can be used in combination with other chemicals without changes in performance. An exception is an environment containing hydrogen sulphide, which causes deactivation of isothiazolones[56]. Isothiazolones are popular in controlling the biofilm development of both bacteria and algae due to higher control over microbial growth and their metabolism[53].

4. Limitations of the Corrosion Control Methods

4.1 Limitation of Cathodic Protection

Cathodic protection is a proven corrosion control method used to protect underground and undersea metallic structures, including oil and gas pipelines. When properly designed and implemented, cathodic protection systems can provide long-term protection for oil and gas pipelines. For example, offshore pipelines are often protected with aluminium alloy or zinc bracelet anodes that can last for 30 years or longer[58]. According to Naveen et al[59]. patch repair with CP can enhance the life of repairs to about 20+ years. Notwithstanding the effectiveness, some of the limitations as far as cathodic protection is concerned are the high capital cost of operation, environmental concern, limited applicability in high-temperature environments and cathodic disbandment.

4.1.1 High Capital Cost of Operation

The installation of cathodic protection itself can be costly, and the specific details of how structures are constructed can also add to the complexity. In addition to this cost, the system also requires routine maintenance, including a periodic visual inspection[60]. The adverse effects of pipeline failures due to corrosion include high cost of cathodic protection system maintenance[34]. The total life cycle cost of the system can vary depending on factors such as the size of the pipeline and the cost of materials and labour. For example, one study estimated the life cycle cost of a cathodic protection system for one mile of 30-inch ductile iron pipe to be under $2 310 000[61].

4.1.2 Environmental Concern

One of the primary environmental concerns associated with Impressed Current Cathodic Protection Systems (ICCP) is their carbon footprint. The Impressed Current Cathodic Protection systems typically require an external power source, which is often derived from electricity generated by fossil fuels. As a result, the operation of these systems can contribute to greenhouse gas emissions, such as carbon dioxide (CO_2), which is a significant driver of climate change[62]. A study conducted by Princeton University investigated the environmental impact of fossil fuel infrastructure and cathodic shielding on groundwater quality. The study found that natural gas pipelines designed to resist microbial corrosion using ICCP systems could increase the presence of toxic metals such as arsenic in groundwater. The electrical current used in impressed current cathodic protection systems could stimulate biogeochemical processes that release arsenic from the surrounding aquifer, leading to groundwater contamination[63]. The most serious drawback of CTE coatings is the emission of carcinogenic vapours during its applications, which not only threatens the workers carrying out the application but also pollutes the environment. For these reasons, many countries have completely banned the use of this system[39].

4.1.3 Limited Applicability in High-Temperature Environments

Traditional cathodic protection systems, ICCP and SACP may become less effective as the pipeline temperature increases. High temperatures can alter the electrochemical reactions occurring at the metal surface, affecting the formation and stability of protective films. Consequently, Cathodic Protection (CP) systems may struggle to provide adequate corrosion control under these conditions [61]. High temperatures can also increase the rate of corrosion on pipelines, which can make it more difficult to maintain adequate CP. For example, Liu et al[64]. investigated the effect of temperature on the corrosion and cathodic protection of X65 pipeline steel in a 3.5% NaCl solution. The study found that with an increase in temperature, the corrosion rate increased, and the corrosion potential and electrochemical impedance decreased. Elevated temperatures can reduce the efficiency of cathodes, which can make it more difficult to maintain adequate cathodic protection. This can occur because the current density on the cathode needs to exceed the oxygen replenishment rate to arrest corrosion, and high temperatures can reduce the oxygen replenishment rate[65].

Another study conducted by Cheng et al[66]. on the stress corrosion cracking of X80 pipeline steel in a simulated soil solution found cathodic protection to be an effective method for protecting pipelines from corrosion. They recommended that temperature effects on cathodic protection should be considered when designing and implementing corrosion protection systems for pipelines. Practical examples of the effects of high temperatures on cathodic protection systems can be seen in the Gulf of Mexico, where pipelines are exposed to high temperatures due to the warm waters. A study conducted by NACE International in 2014 found that high temperatures can cause accelerated corrosion on pipelines, leading to failures and leaks. From the study, it was revealed that high temperatures can cause changes in the soil chemistry, which can affect the performance of cathodic protection systems under such environment. Pojtanabuntoeng et al[67]. found that high temperatures can cause changes in the chemical composition of crude oil, which can affect the performance of cathodic protection systems. Their study also revealed that high temperatures can change pipeline's physical properties, which can affect the ability of cathodic protection systems to provide adequate corrosion protection.

4.1.4 Cathodic Disbondment

Cathodic disbondment is recognized as the main cause of coating degradation in coated pipelines with cathodic protection. It refers to the separation or detachment of the protective coating from the pipeline surface due to the electrochemical reactions occurring during cathodic protection. This can expose the bare steel substrate to the surrounding environment, increasing the risk of corrosion[68].

4.2 Limitations of Coating

Limitations and defects can manifest themselves at various times in the life of a coating. Before application, they can take the form of settlement and skinning, during application as runs and sags, shortly after application as solvent popping and orange peel, and during service as blistering and rust spotting. To determine the cause and mechanism of coating failure, all possible contributory factors must be evaluated together with a detailed history from the time of application to the time the failure was first noted. Many coating failures require further evaluation and analysis to be carried out by a qualified chemist or coating specialist, often using specialised laboratory equipment[69]. The following are some of the limitations of coating.

Complexity of designing efficient pipeline coating formulations: The design of efficient pipeline coating formulations is complex and requires consideration of many factors, such as climate, properties of the substrate travelling through the pipeline, product flammability, and rate of flow[22].

Flammability limitations: Both the fluid in the pipeline and the coating material prior to curing may be extremely flammable, which creates a potential fire hazard at the work site[22].

Temperature limitations: Some coating processes, such as Chemical Vapour Deposition (CVD), require high temperatures to be applied, which can limit the base materials that can be coated[70].

Surface preparation limitations: The minimum surface preparation standard for the oil and gas pipeline body is SSPC-SP 10 Near-White Blast Cleaning with SSPC-SP 11 Bare Metal Power Tool Cleaning for the ends of the pipeline where the joint coatings are applied[71].

Size limitations: Coating processes are limited by the size of the reaction chamber, which can limit the size of the parts that can be coated. The coating process requires a reaction chamber where the coating material is applied to the parts being coated. If the reaction chamber is too small, it may not be possible to coat larger parts[72].

Limited durability in acidic environments: The durability of coatings in acidic environments is limited, and the coatings may require frequent replacement[73].

4.3 Limitations of Corrosion Inhibitors

Corrosion inhibitors are effective in various environments, including those with high levels of hydrogen sulphide, chloride, carbon dioxide, oxygen, bacteria, water cut, strong acids, and brines[74]. Corrosion inhibitors can also improve pipeline-pumping efficiency by making the inside of the pipeline smoother. This reduces operational costs associated with pumping petroleum products[75]. While corrosion inhibitors have demonstrated significant potential in mitigating corrosion in oil and gas pipelines, they come with inherent limitations that warrant attention and further research. Awareness of these challenges can facilitate the development of improved corrosion inhibition strategies and complementary techniques to ensure the long-term integrity of critical pipeline infrastructure. Some of the identified limitations of inhibitors are as follows.

4.3.1 Ineffective under High Temperature and Pressure Conditions

Corrosion inhibitors might demonstrate reduced efficiency or even become entirely ineffective under extreme conditions such as high temperatures, elevated pressures, and aggressive chemical environments present in certain pipeline sections. These conditions cause the protective film formed by corrosion inhibitors to break down or fail to form adequately, leading to accelerated corrosion rates[76].

4.3.2 Challenging Applications in Long-distance Pipeline

The uniform distribution of corrosion inhibitors in long-distance pipelines can be challenging, especially in areas with low flow rates or stagnant conditions. Achieving an even distribution is critical to ensure comprehensive corrosion protection along the entire pipeline length[77].

4.3.3 Limited Resistance to Extreme pH Conditions

In pipelines where the pH deviates significantly from neutral, corrosion inhibitors may lose their effectiveness, requiring alternative corrosion control methods. For instance, the performance of sodium nitrite inhibitors at different pH values was examined by using different electrochemical techniques. The study found that the effectiveness of the inhibitor decreased as the pH increased[78].

4.3.4 Limited Compatibility with Other Pipeline Chemicals

The possible reaction between corrosion inhibitor and biocide can lead to degradation of the chemicals and result in inadequate protection of the pipeline. Hence, it is quite essential to study the possible interference between corrosion inhibitors and biocide. The interaction of these compounds could lead to reduced corrosion protection and even cause adverse effects on pipeline integrity[79].

4.4 Limitations of Biocides

Biocides have been widely applied in the oil and gas industry to remedy oil and gas pipeline corrosion, but the long-term performance of biocide treatments is hard to predict or optimize due to a limited understanding of the microbial ecology affected by biocide treatment. Biocides help mitigate microbiologically influenced corrosion (MIC) and maintain the integrity of pipelines. However, the application of biocides for corrosion protection is not without its limitations. Some of the limitations of biocide application include environmental impact, health hazards, short life, optimisation challenges, microbial resistance and transportation and storage challenges[80].

4.4.1 Environmental Impact

Biocides can have toxic effects on the environment, including aquatic organisms and soil microorganisms. Some biocides can transform into more toxic or persistent compounds, and hardly anything is known about their environmental impact and toxicity[81].

4.4.2 Health Hazards

Biocides can cause inhalation toxicity, which can lead to respiratory problems. People who use biocidal products may be exposed to biocides through inhalation, especially if the products are sprayed or trigger-type formulations. Biocides can cause skin irritation and other skin problems[82].

4.4.3 Short Lifespan

The lifespan of biocides can vary depending on several factors, including the type of biocide, the dose used, and the storage conditions. According to a study on the long-term efficacy of biocides on a souring microbial community, souring control failed after 7 days at a dose of 100 ppm regardless of the biocide type[83]. The shelf life of biocides can also vary depending on the product and storage conditions. A webinar on the shelf life of agrochemicals and biocides suggests that during storage, biocidal products lose efficacy, but the extent of the loss depends on the product and storage conditions. Some biocides, particularly oxidizing biocides, have a short lifespan and may not provide long-term control of microbial growth during fluid storage and transportation. This can lead to the re-establishment of microbial populations and the potential for pipeline corrosion and other issues[84].

4.4.4 Optimisation Challenges

Optimizing the use of biocides in oil and gas pipelines can be challenging. Factors such as solubility, pH, salinity, thermal stability, and compatibility with other chemicals need to be considered when selecting the appropriate biocide. Additionally, regulatory requirements and downstream processes/disposal also play a role in biocide selection[85].

4.4.5 Microbial Resistance

Studies have shown that biocide exposure can induce mechanisms of resistance in bacteria. Biocide use exposes microbes to sub-inhibitory concentrations of antiseptics, disinfectants, and preservatives, leading to the emergence of antibiotic resistance in bacteria[86]. Prolonged and indiscriminate use of biocides can lead to the development of microbial resistance, rendering them less effective in controlling microbial growth and biofilm formation[56].

4.4.6 Transportation and Storage Challenge

Biocides may have safety concerns associated with their transportation and storage. Some biocides can contain substances of concern with allergic, ecotoxic, carcinogenic, or other harmful properties. Proper handling, storage, and transportation practices are necessary to ensure the safety of personnel and the environment[87].

5. Conclusions

The objectives of this paper were to review the most common corrosion control methods used in mitigating corrosion of oil and gas pipelines and the limitations of these techniques. From the review, it can be concluded that:

Cathodic protection and coating techniques are the most effective methods for mitigating corrosion of oil and gas pipelines. They have a longer life span and can save the industry a lot of money when applied properly, though the cost of operations for both is projected to be very high.

Biocides and inhibitors are very effective techniques when it comes to internal corrosion mitigation, however, they pose danger to workers when they are not handled properly. Again, the environmental impact of biocides and inhibitors can be very high when overused or underused. Life span is very short as compared to cathodic protection and coatings despite their high cost of operation.

The intricate interplay of factors such as temperature, pressure, pH, fluid composition, and pipeline materials can lead to diverse corrosion mechanisms, including sulphide stress cracking, and pitting corrosion.

Safeguarding oil and gas pipelines against corrosion in H_2S and acidic chloride environments demands a multi-faceted approach by combining cathodic protection and coating methods.

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