A REVIEW ARTICLE ON CORROSION IN OIL & GAS INDUSTRY

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***Abstract*— One of the most frequent occurrences we witness in our everyday lives is corrosion. We all must have noticed that some objects made of iron are covered with an orange or reddish-brown colored layer at some point in time. Rusting is a type of corrosion that occurs chemically and leads to the production of this coating. In general, it is a process through which a refined metals converted into more stable compounds such as metal oxides, metal sulfides and metal hydroxides. This is now a very challenging situation in the refinery industry. The major portion of the global economy is dependent on the oil and natural gas industry and billions of dollars is invested to reduce the corrosion in the refinery industry. In view of the above some methods or approaches must be adopted to prevent the corrosion. Corrosion resistant is suitable at a temperature of 100^0C to prevent sweet corrosion and is stable and shows no technical issues but the performance of the corrosion resistant is limited with rise in the temperature. This is a critical issue to control the sweet corrosion in drilling operation, deeper wells at high temperature and pressure. Till now no such article or patent literature has been published on corrosion inhibitor. And for this reason, a thorough review on corrosion inhibitor at high temperature is very much important. In this review article the corrosion issues at different sectors have been presented. As well as, the sources of the corrosion problem and the corrosion resistant approaches such as engineering design, cathodic protection, the use of corrosion inhibitors and metal coating will be discussed.**

Keywords - Corrosion, Oil and Gas industry, Corrosion inhibitor, high temperature corrosion.

I. INTRODUCTION

Any given substance, often a metal, can undergo corrosion, which is a chemical or electrochemical process that gradually degrades the material and its properties. Particularly in the transportation system and in the production of natural gas process, corrosion is considered to be one of the primary failure reason. These corrosion-related failures during the past few decades have raised different issues as energy security, decreased production rates, monetary losses, and environmental damage. In the global economy the main interest of focus is now on refinery industry. Not only are refined petroleum products a vital supply of energy for homes and businesses, but they are also vital for boosting transportation sectors. Different types of product like plastic, industrial fabrics, paints, dyes, medications, fertilizers, and a variety of other consumer goods and some by-products such as ammonia and sulphur are made from the refined oils. The presence of this segment in any nation is critical not as it were for the nation but moreover for neighboring nations. In spite of these benefits, the refining industry is regarded as high-risk since refineries are huge and complex sites that carry out various operations such as working at high levels of pressure and temperature. Corrosion is one of the major problems that affects most the industries throughout the world, resulting several issues to the global economy. During the petroleum and natural gas processing it can occur at any point or at any time.

Landolt. D, [1] expressed that though the corrosion is a chemical reaction process but it significantly changes the physical properties and behaviour of metals and alloys. And to prevent this problem billions of dollars are being invested in refinery sectors. According to Ruschau, G.R., Al-Anezi [2] approximately 0.20–0.40 US dollars are spent on the prevention of corrosion for each barrel of crude oil, as because it has been found that 30% of the failures in the exploration and production processes are caused by internal corrosion. According to National Association of Corrosion Engineers (NACE), [3] the annual cost of corrosion in US refineries is more than 3.7 billion dollars. According to a report of Canadian Association of Petroleum Producers 2009, [4] internal corrosion is responsible for major pipelines failure. Another report by Singh, B., Krishnathasan, K [5] confirmed that corrosion caused around 15% of onshore and up to 50% of offshore pipeline failures, which is of great threat to the oil and gas industry. Various types of erosion happen in different portions of petroleum refineries depending on the interaction between the material and the environment. Hassan-Beck. H., Firmansyah, T., Suleiman, M.I., Matsumoto, T., Musharfy, M. A.L., Chaudry, A.H., Rakib, M. A.,[6] explained that the existence of hydrogen sulfide (H_2S) and ammonia (NH_3) makes a suitable environment for the stripping unit, rendering it susceptible to various forms of deterioration. Patrick, B.N., [7] explained although corrosion and failure may occur anywhere in the oil sector, examples of refinery failure receives the greatest attention because of their size and severity. Different studies by Nesˇic´ , S.,[8], and Nesˇic´ , S., Lee, K.L.J., [9] describes some important factors which influence the corrosion in pipelines :

i) The chemistry of water,

ii) The process of corrosion is slowed down at the metal surface by the development of protective scales,

iii) The pH level, as an internally corrosive environment exists in pipelines with low pH levels and vice versa,

iv) The corrosive gases (CO_2 and H_2S),

v) The rise in CO2 partial pressure typically leads to an rise in corrosion,

vi) The impact of acetic acid (HAc) since acid causes a fall in the pH level,

vii) Increase in the flow velocity can harm the protective scale formation,

viii) The existence of sulphate-reducing bacteria.

The method of corrosion mitigation starts with selecting the correct metal while designing the plant to handle the aggressive substances utilized in refineries. Speight, J.G. [10] advised that to diminish the corrosion rate of the uncovered metal surface, the suitable coating, injection of corrosion inhibitors, evacuation of destructive components from crude oil, and other strategies must be utilized all through the plants life.

Researchers have been hustling to create green corrosion inhibitors that are compelling at high temperatures, eco-friendly, non-toxic, and biodegradable. Ulaeto, S.B., Rajan, R., Pancrecious, J.K., Rajan, T.P.D., Pai, B.C., [11] analyses for the development of smart coating as it will give a few benefits to refinery units it can react to changes in pH, temperature, and other imperative variables that are basic for corrosion mitigation. Sharma, V., Goyat, M.S., Hooda, A., Pandey, J.K, Kumar, A., Gupta, R., Upadhyay, A.K., Prakash, R., Kirabira, J.B., Mandal, P., Bhargav, P.K., [12] explained about the recent popular superhydrophobic coating and nano based CNT coating which will give a high level of resistance to the corrosive environment found in refineries.

II. CORROSION AT REFINERY UNITS

A petroleum refinery is a huge industrial complex where crude oil is converted into usable items such as gasoline, diesel fuel, kerosene, and asphalt using unceasing processing units. Refineries typically process 100,000 to 2,000,000 barrels of crude oil per day into petroleum items. Basic refineries utilize desalter overhead refining, liquid catalytic splitting, and hydrotreating units to handle rough oil to usable items. Speight, J.G., [13] elaborate that most processing units in an oil refinery are susceptible to typical corrosion issues due to their interaction with aggressive compounds, flow rate, and operating temperature.

A. Storage Tank

At the first stage the crude oil is transferred to the storage tanks, before it transferred to the refinery units. The maximum size of the storage tank can be approximately 50 feet in height and 100 feet in width depending upon the working capacity of the storage. Most storage tanks are designed to withstand different pressure and temperature levels. However, corrosion may happen independently of a structure's size, shape, or purpose. Typically, a thermally insulating coating is applied to their exterior. The storage tank inside walls might corrode, though, if that safeguard fails. If H_2S gas present in the storage tank starts react with the other corrosion product, forms a compound called iron sulphide which is an ignition for the corrosion. In addition with that corrosion may also occur if water is accumulate at the bottom of the tank.

Impurities in the crude oil cannot be prevented and that happens immediately when it pumped from the reservoir. Facilities used to store crude oil are colonized by both anaerobic and aerobic microbes. Syafaat, T.A., Ismail, M.C., [14] expressed that metabolic products of aerobic and anaerobic microbes develops the results in major problems like corrosion and fuel biodeterioration. G.J. Licina, G. Nekoksa [15] discover that that the presence of water and organisms within the storage tank can cause biocorrosion, which can rise the corrosion rate of a metal by up to 1000 times. When there's a metal spillage, the fetched of repair will be very high, and the treatment will be greatly troublesome.

To control the corrosion in storage tanks, a liner on the inner walls and dividers are included to anticipate contact between metal shells and any collected water or other destructive dregs.

B. Desalting unit

Water that is present in crude oil sent to the refinery having some inorganic salt with very small amount which dissolved within it like magnesium, chloride, and calcium chloride. Humooudi, A., Hamoudi, M.R., Maruf, B., [16] said that desalters can expelled inorganics from unrefined oil to diminish fouling and corrosion in other handling units. Desalination can be achieved through - two techniques: chemical desalting and electrical desalting. Chemical desalting involves the addition of water and demulsifiers to the crude and heated to bond salts and other contaminants to the water. Chemicals like ammonia are frequently employed in both methods to reduce the impact of corrosion. The majority of desalting chemicals are either demulsified or or used to adjust the pH of the wastewater.

C. Crude oil distillation unit

Crude oil is separated into useful products by the crude oil distillation unit which are then further processes in to different units. Waheed, M.A., Oni, A.O., [17] elaborated different components of distillation unit like heat exchanger network, pre-flash drum, atmospheric distillation, and vacuum distillation. Perforated trays in the distillation column allow vapours to rise to the top. The separation of light hydrocarbons from heavier ones requires high temperatures. The higher boiling heavy hydrocarbons will be collected as liquids at the bottom of the column. The principle of vacuum distillation is similar to that of atmospheric distillation, unless the larger diameter column is used to maintain the steam velocity at low pressure. Despite an effective desalting operation, corrosion agents can also be transmitted from the desalter, causing serious corrosion problems to the unit [17]. In atmospheric and vacuum distillation columns, sulphurous corrosion and from nitric acid occurs at similar temperatures. Bhowmik, P.K., Shamim, J.A., Emam Hossain, M., [18] explained that corrosion by nitric acid is mainly located in the high-speed zone of a Crude oil distillation unit at temperatures ranging from 220^0C to 400°C. However, when the temperature exceeds 400 ° C, nitric acid corrosion decreases. Above 120 ° C, hydrogen chloride can be formed by decomposition of sodium chloride (NaCl), calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$). At this temperature, Water vapor in the header system condenses in water, which absorbs hydrogen chloride to produce hydrochloric acid. Water can absorb ammonia, which then can mix with hydrogen chloride to form ammonium chloride. These salts are highly acidic and have the ability to create a coating on the surface. Pitting corrosion may occur when moisture facilitates the formation of these acidic salts.

D. Hydrogen unit

Impurities such as sulphur and nitrogen need to be eliminated from Petroleum refineries need to uphold the steadiness and lessen the corrosive nature of fractions. As per Papavinasam, S., [19] if these contaminants are not eliminated, they will have an adverse effect on the refinery's machinery catalysts, and affect the quality of the end product. All hydro processing facilities, however, serve the same fundamental purpose: to eliminate chemically, sulphur that is chemically connected to hydrocarbons. removal, the most commonly used catalysts are cobalt molybdenum and nickel molybdenum oxides on alumina supports. These catalysts work by promoting the hydrogenation of sulphur compounds to form hydrogen sulphide at high temperature, which can then be easily removed from the hydrocarbon stream. After cooling, the item leaves the reactor and goes into a liquid/gas separator.

III. PHYSICOCHEMICAL BASICS OF CORROSION AT REFINERY UNITS

Corrosion of metal apparatus and buildings in a refinery units happen in a extend of environment and stages over assorted circumstances. Groysman, A., [20] categories corrosion in oil refineries and petrochemical plants as:

- Low temperature corrosion which is considered at a temperature of below 100^0C which takes place in the presence of electrolytes, generally aqueous solutions of electrolytes and water, such as dissolved corrosive gases like H_2S, HCl, and NH_3, or dissolved salts like NaCl and Na_2SO_4;
- High temperature corrosion which is mainly considered at a temperature above 100^0C which is mainly takes place due to nonelectrolytes (mainly gaseous H_2 and H_2S, NA corrosion, oxidation by oxygen in furnaces, hot ash corrosion);
- Intermediate temperature (100 _C<T<200 _C) corrosion which can occur either in the presence of electrolytes or non-electrolytes depending on substances and conditions.

IV. SOURCES OF CORROSION IN REFINERIES

Bhowmik, P.K., Shamim, J.A., Emam Hossain, M., [18] explained that corrosion in refining operations can stem from various sources, which can be categorized into three main groups: corrosion caused by components of crude oil, corrosion resulting from chemicals used in refining processes, and environmental corrosion. To understand corrosion phenomena in refineries, it's essential to first grasp the physicochemical properties of crude oil and natural gas. Crude oil consists of a liquid mixture of hydrocarbons, varying from volatile to nonvolatile compounds. While crude oil itself isn't inherently corrosive, it may contain impurities and components with nitrogen, sulphur, and oxygen, which can lead to corrosion. The natural gas present in crude oil mainly consists of nitrogen, carbon dioxide (CO_2), hydrogen sulfide (H_2S), and water. These gases can contribute to metal corrosion at any stage of the manufacturing process.

A. Corrosion due to naphthenic acid (NA)

One of the most common corrosive agents found in crude oil is naphthenic acid (NA), which has significant effects on refinery equipment. To tackle the issue of NA corrosion, it's important to first understand the structure and behavior of these chemicals. According to the literature, naphthenic acids are aliphatic acids that can have zero to three cycloalkene rings, an alkyne chain, and a terminal carboxylic acid group. Alvisi, P.P., Lins, V.F.C., [21] explained that at room temperature, naphthenic acids are not corrosive; however, their corrosiveness increases at the temperatures typically encountered during refining. Naphthenic acids become corrosive to carbon steel between 200 and 220 °C, reaching their highest activity at 350 °C. Above 400 °C, their corrosiveness decreases due to decomposition at elevated temperatures. The corrosivity of naphthenic acids is linked to their Total Acid Number (TAN), which measures acidity and is expressed in milligrams of KOH needed to neutralize the acids in one gram of crude oil. Crude oil with a Total Acid Number (TAN) exceeding 0.5 is considered corrosive when processed in a fractional distillation column, while crude oil with a TAN greater than 1.5 is regarded as corrosive to vacuum distillation towers.

B. Corrosion due to H_2S

While CO_2 and H_2S are highly soluble in water in natural gas, their concentrations can differ between samples. When CO_2 leads to corrosion, it is referred to as sweet corrosion, whereas corrosion caused by H_2S is called sour corrosion. According to NACE, the extent of corrosion is influenced by factors such as partial pressure, natural gas acidity (pH), and other variables including the environment, temperature, and flow velocity. H_2S corrosion can present itself as general (uniform) corrosion, localized pitting corrosion, or hydrogen embrittlement. The latter can lead to cracks in the metal, releasing H_2S gas into the environment, which poses serious environmental and health risks for workers. Temperature plays a crucial role in H_2S corrosion, with significant corrosion occurring in the distillation unit when temperatures exceed 400 °F. Popoola, L., Grema, A., Latinwo, G., Gutti, B., Balogun A., [22] observed that when H_2S and moisture interact with metals, they lead to deterioration, particularly evident in drill pipes used in the oil industry. The mechanism of H_2S corrosion is not completely understood. However, it can generally be described by two primary reactions: (i) the oxidation of iron (anodic reaction) and (ii) the reduction of aqueous H_2S (cathodic reaction). The rate of corrosion due to H_2S is influenced by various interconnected factors, including flow velocity, temperature, H_2S partial pressure, exposure time, and concentrations of dissolved salts and organic acids (like NaCl and CH_3COOH). Other important aspects include the concentration and dissociation of H_2S, the chemistry of steel, the nature of deposits on the metal surface (such as corrosion products, scales, and wax), the presence of oxygen, and the fluid chemistry (including pH, water cut, phase ratios, organic acids, and oil wettability). While these factors are all interrelated, making it challenging to isolate the impact of any single factor, H_2S corrosion has been thoroughly investigated by Abayarathna, D., Naraghi, A., Obeyesekere, N., [23] in the oil and gas sector.

C. Corrosion due to CO_2

CO_2 corrosion, often referred to as sweet corrosion, is the most prevalent type of corrosion in the oil and gas industry. As per Usman, B.J., Ali, S.A., [24] around 60% of failures in this sector are attributed to corrosion caused by CO_2.

According to research by Garcia-Arriaga, V., Alvarez-Ramirez, J., Amaya, M., Sosa, E., [25] indicates that CO_2 corrosion represents about 10–30% of the maintenance budget for oil refineries and natural gas industries. CO_2 becomes corrosive only when it dissolves in water to create carbonic acid, which then reacts with iron. The phenomenon of sweet corrosion in steel has been thoroughly investigated by Crolet, J.L., Bonis, M.R., [26] over the years to gain a better understanding of its mechanisms, as several different mechanisms have been suggested. The intensity of CO_2 corrosion is influenced by several factors that impact the formation and characteristics of the carbonate film. Perez, T.E., [27] suggested some factors which include:
Temperature;

- Partial pressure of CO_2;
- pH;
- water content and chemistry of water;
- flow type and its velocity;
- The presence of oxygen, organic acids and H_2S.

It was found that the severity of corrosion increases with higher flow velocity, elevated partial pressure of CO_2, greater water content, and lower pH levels.

D. Corrosion due to ammonium chloride (NH_4Cl)

In the refining industry today, corrosion caused by ammonium chloride (NH_4Cl) is a major contributor to equipment and piping failures. This type of corrosion leads to significant costs related to materials, maintenance, and repairs, resulting in a serious impact on refineries. It can compromise the structural integrity of facilities and threaten equipment safety. NH_4Cl corrosion has been observed in various areas, including hydro processing effluent systems, overhead systems in crude distillation, and fractionation columns in thermal and catalytic conversion units. Sun, A., Fan D., [28] explained NH_4Cl leads to either general or localized corrosion, often resulting in pitting. Carbon steel is the most widely used construction material in the processes mentioned earlier. However, its corrosion rate is typically considered unacceptably high in the presence of NH_4Cl. Many common alloys, like austenitic stainless steels, are not viable alternatives in these environments because they are prone to chloride stress corrosion cracking (Cl-SCC). The performance of duplex stainless steels has been inconsistent, with some cases reporting pitting corrosion and stress corrosion cracking due to the combined effects of chlorides and sulfides. So far, only nickel alloys have shown satisfactory performance in these conditions.

E. Corrosion due to oxygen (O_2)

Groysman, A., [29] described the role of oxygen: it acts as an oxidizing agent and as a depolarizing agent, which enables it to continually consume electrons during the oxidation (corrosion) of iron. Issa, B., Bazhin, V.Y., Telyakov, N.M., Telyakov, A.N., [30] expressed that the levels of dissolved oxygen in the oil or accompanying water, along with the temperature, significantly affect the corrosion of carbon steel and low alloy steels. Oxygen can enter equipment and processing streams through various means, such as loose seals or connections in pumps and vacuum systems, during transportation, while being stored in tanks, during different operations (like filling and emptying tanks and vessels), and during shutdowns. Corrosion caused by dissolved oxygen leads to pitting in different equipment. Furthermore, when oxygen concentrations exceed 50 ppm, it can oxidize glycols and amines in relevant units, creating corrosive byproducts. It can also react with hydrocarbons during regeneration in high-temperature adsorption beds, generating water, affecting the efficiency of inhibitors, impacting the resistance of stainless steels to chloride stress corrosion cracking (Cl-SCC), and contributing to galvanic corrosion. Corrosion products, primarily rust, can be dislodged during equipment start-up, leading to contamination of hydrocarbon streams and clogging of heat exchangers, strainers, and piping. Consequently, oxygen is detrimental not just because of corrosion but also due to fouling.

V. MITIGATION METHODS

In a harsh environment, it is essential to safeguard metallic equipment from corrosion by employing mitigation strategies like applying coatings or injecting corrosion inhibitors. These methods should be integrated into the refinery's engineering design.

A. Engineering design

When designing a refinery, it’s essential to take into account factors that may cause corrosion. For instance, by thoughtfully designing the equipment's geometry, one can manage fluid velocity and prevent the buildup of sour water, which helps minimize issues related to erosion and corrosion. Selecting an appropriate construction material for the challenging environment of refinery processes is also crucial. It's important to recognize that there is no single perfect material that can resist every type of medium under all conditions. Carbon steel can be utilized in areas where low-temperature corrosion occurs, except in cases where aqueous corrosion from inorganic contaminants is present. For an example, Speight, J.G., [10] discussed environments with HCl or H_2S require the use of more resistant alloys. Effectively removing corrosive contaminants through processing units like desalters and hydrotreaters helps reduce low-temperature corrosion issues. In areas exposed to high-temperature corrosion, more resilient materials such as stainless steel, nickel alloys, and copper alloys are necessary. Fan, D., Fort, W.C, Horvath, R.J., [31] elaborated that titanium is widely used across various industries and sectors. Initially, titanium alloys found their application in the chemical and biochemical industries because of their excellent corrosion resistance in different environments. When titanium prices dropped in the 1960s, it became economically feasible to use due to its strong resistance to aggressive media like brackish, saline, and cooling water, as well as hydrocarbons containing H_2S, HCl, NH_3, and organic acids commonly found in oil refineries. Since 1967, titanium-based equipment—including heat exchangers, vessels, pipes, tanks, and valves—has been employed in petroleum refining. The growing adoption of titanium in petroleum refining and petrochemical plants from 1970 onwards can be attributed to its high corrosion resistance, low density, high strength, and a minimal number of failure incidents.

In the refinery industry, polymeric materials and composites play a significant role due to their excellent chemical resistance against various gases and solvents. However, they are generally considered to have lower temperature resistance and mechanical properties compared to metals. In petroleum refinery systems, polymeric materials are utilized for gaskets, seals, sumps, rings, pipes, and tanks that interact with water, cooling water, seawater, firefighting water, as well as acid and alkali solutions, soil, and atmospheric conditions. Along with choosing the right materials, it's important to install corrosion monitoring equipment, like electrical resistance probes, at various locations in the refinery to provide continuous updates on the corrosion status.

B. Blending

As opportunity crude oil gains popularity, managing high acid content continues to pose significant corrosion control challenges for refineries. Saxena, R.C., Seal, D., Goyal H.B., [32] reported one solution that is blending, which involves mixing heavy and light crude oil to effectively reduce the acid concentration in the feed and subsequently lower the corrosion rate. However, each type of crude oil has different compositions and properties, leading to varying degrees of compatibility in crude oil blends. Some oils are naturally incompatible due to the insolubility of asphaltenes in lighter, more paraffinic crudes. However, Dettman, H.D., Li, N., Wickramasinghe, D., Xu, Z., Chen, X.N., Elliott, G.R.D., Luo, J., [33] reported that blending can introduce additional challenges during refining if the crude being mixed contains high levels of sulfur compounds or other corrosive substances.

C. Metal coating

Metal coating is a technique used to decrease corrosion rates by applying a thin layer of material to the metal surface. Cheng, L., Lou, F., Guo, W., [34] describes how this coating helps prevent corrosion by either managing electrochemical reactions or creating a barrier between the metal and its harsh environment. The effectiveness of a coating in enhancing a metal's corrosion resistance depends on several properties. These include the coating's resistance to water, chemicals, abrasion, weather, bacteria, fungi, and extreme temperatures. Coatings can be categorized into three main groups based on the type of base material used: organic, inorganic, and metallic. In recent years, numerous coatings have been developed to address the specific and varied requirements of the oil and gas industry. These coatings enhance operational safety and also offer opportunities to boost the efficiency of various refinery processes. The high-performance composite coating system (HPCC) is an advanced composite solution that represents the latest innovation in anti-corrosion coatings. This system consists of a single-layer, powder-coated multicomponent design that includes an FBE base coat, a medium-density polyethylene outer layer, and a tie layer made of chemically modified polyethylene adhesive. All three components are applied through an electrostatic powder coating process. The tie layer combines adhesive with FBE, featuring a varying concentration of FBE. Guan, S. W., Gritis, N., Jackson, A., Singh, P., [35] explained that HPCC system offers excellent adhesion to pipe surfaces, with strong shear resistance, flexibility at low temperatures, resistance to impact and cathodic disbandment, and extremely low moisture permeability.

D. Cathodic protection

Cathodic protection (CP) is a corrosion control method that transforms a metal surface into the cathode of an electrochemical cell. The principle behind using cathodic protection (CP) is that organic coatings are the main approach for controlling corrosion on metal structures, while CP is employed alongside these coatings to minimize defects that may arise during application and use. Majbor, K.A. sattar, Alias, Q.M., Tobia, W.F., Hamed, M.A., [36] suggested the application of Cathodic protection (CP) to both the inner and outer surfaces of aboveground storage tanks used in refineries for oil products and/or water. While pure hydrocarbon fluids are typically non-corrosive, internal surfaces may still face corrosion risks in tanks where sediments, water, and other contaminants are present. This has been observed in practice. Cathodic protection (CP) is effective only when all four essential components—anode, cathode, electrolyte, and complete electrical circuit—are present. If any of these components are absent, the CP process stops. It's important to understand that while the corrosion rate of metal structures under CP is never zero, it remains very low and poses minimal risk of corrosion. CP system can be categorising as:

- Sacrificial (or galvanic) anode cathodic protection (SACP),
- Impressed current cathodic protection (ICCP).

In the sacrificial anode cathodic protection (SACP) method, reactive metals like aluminium, zinc, or magnesium are attached to a metal structure. These metals corrode instead of the structure, generating a protective current that helps prevent corrosion on the main metal. As a result, all the corrosion occurs on the sacrificial anode. Conversely, impressed current cathodic protection (ICCP) utilizes an anode connected to a direct current power source. This anode can be made from materials like graphite, mixed metal oxides, or high silicon cast iron. It is designed to be inert or have a low consumption rate and can be surrounded by carbonaceous backfill to enhance efficiency and reduce costs.

E. Corrosion inhibitors

Internal corrosion is one of the most hazardous forms of corrosion that can happen in refineries, as it is challenging to maintain and inspect cost-effectively. To prevent expensive alloy upgrades, a practical solution is to manage internal corrosion using corrosion inhibitors. Corrosion inhibitors are compounds that, when applied in low concentrations within a corrosive environment, slow down the corrosion process by creating a film that shields the exposed metal surface from the corrosive agents. Brzeszcz, J., Turkiewicz, A. [37] expressed that substances deemed suitable as corrosion inhibitors in the oil and gas industry should possess the following physical and chemical properties:

- stability;
- inability to precipitate in the form of residue; and
- inability to form emulsion

As well as the influential factors for the effectiveness for various agent is given by:

- The type of material which interacts with the inhibitor;
- The aggressiveness of the environment (for example, the presence of redox species and pH of the environment);
- The place where the inhibitor is applied (refinery, drilling equipment, gas and oil pipelines, etc.);
- The type of transferred or stored fuel.

Given the wide range of corrosion inhibitors available, it is crucial to select the appropriate one based on the specific corrosive media and operating conditions. In contrast, inorganic corrosion inhibitors consist of salts from metals like copper, zinc, arsenic, and nickel, with arsenic compounds being the most prevalent. These inhibitors have both advantages and disadvantages. Tamalmani, K., Husin, H., [38] discussed the performances of inorganic corrosion inhibitor at high temperatures for extended periods and are generally cheaper than organic inhibitors. However, their effectiveness tends to diminish in acid solutions stronger than 17% HCl, and they may produce toxic arsine gas as a byproduct of corrosion. Umoren, S.A., Solomon, M.M., [39] focused on polymeric materials, both natural and synthetic, as potential alternatives to inorganic corrosion inhibitors. Polymers consist of long chains of monomers and can take on various structures, such as linear, branched, hyperbranched, rotaxanes, comb-like, and dendrimeric cross-links. Compared to traditional small molecule corrosion inhibitors, polymers offer superior film-forming abilities, multifunctionality, solubility, adjustable viscosity, more attachment points to metal surfaces, cost efficiency, and environmental friendliness.

The use of ‘ ‘green” corrosion inhibitors is becoming more popular. Because they must be evaluated from a safety, health, and environmental standpoint, there is no clear and acceptable definition of ‘ ‘green” corrosion inhibitors. Corrosion inhibitors should have a low toxicity (preferably nontoxic), be biodegradable, and contain no harmful elements or substances. In other words, the corrosion inhibitors currently in use must meet all equipment’ s safety and risk requirements, as well as reliability and quality assurance assessments.

VI. FUTURE SCOPE

Future research should aim to create innovative smart superhydrophobic coatings that integrate corrosion inhibitors and possess self-healing properties. These coatings should be capable of repairing their anticorrosion, antibiofouling, and self-healing functions independently or with minimal influence from external factors like UV light. It is essential to develop more environmentally friendly and cost-effective superhydrophobic coatings, particularly for widespread industrial use. Recent studies have evaluated the anti-corrosion performance of various superhydrophobic coatings over only short durations (up to two months), indicating a future need for enhanced coatings that can endure harsh corrosive environments for longer periods. Ijaola, A.O., Farayibi, P.K., Asmatulu, E., [40] reviewed new superhydrophobic coatings that are much needed to protect industrial-grade carbon steel (such as X80 and X90), which is primarily used for transporting crude oil under high pressure and temperature.

VII. CONCLUSION

Corrosion in refinery operations costs the petroleum industry billions of dollars to manage and control. In this study, we conducted a thorough review of the corrosion challenges faced in petroleum refineries. Key topics addressed include refinery units, the physicochemical principles of corrosion in these units, sources and mechanisms of corrosion, and current mitigation strategies such as engineering design, cathodic protection, the application of corrosion inhibitors, and metal coatings. The review highlights that corrosion in refineries has not received as much attention in scientific literature compared to other corrosion issues in the petroleum sector.

We identified critical knowledge gaps, including inaccurate prediction models, inadequate data on ammonium bisulfide (NH4HS) corrosion, and the need for developing smart coatings and environmentally friendly high-temperature corrosion inhibitors. We propose that future research should prioritize improving prediction models for refinery corrosion, creating innovative nanomaterials and superhydrophobic coatings, developing effective high-temperature corrosion inhibitors (above 100 °C), and gathering more data on ammonium bisulfide, ammonium chloride, and hydrogen sulfide (sour) corrosion.

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