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Analysis of Corrosion and Scaling Factors in Light Hydrocarbon Cooling Systems and Corresponding Control Strategies

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Abstract: Light hydrocarbon cooling units are pivotal heat exchange equipment in oil and gas extraction, refining, storage, and transportation production, primarily responsible for the core processes of cooling and condensing light hydrocarbon media and separating and purifying gas-liquid phases. The long-term stable operation of these units directly affects the quality of light hydrocarbon products, production efficiency, and equipment service life. Under actual oil and gas production conditions, influenced by multiple factors such as complex medium composition, fluctuating water quality conditions, unstable operating parameters, and inadequate material adaptability of the equipment, light hydrocarbon cooling units commonly face the intertwined issues of severe corrosion and scaling. This directly results in reduced heat exchange efficiency, corrosion-induced leaks in pipelines and tube bundles, and a significant increase in unit maintenance frequency. Under extreme conditions, it can easily trigger safety incidents, causing substantial economic losses to oil and gas production enterprises. Based on the actual production conditions at the Tahe Oilfield, this paper systematically explores the core inducing factors of corrosion and scaling in light hydrocarbon cooling units, delves into the microscopic mechanisms of corrosion and scaling, clarifies their mutually catalytic and vicious cycle synergistic relationship, and formulates targeted integrated control strategies encompassing source prevention, process control, and post-maintenance management. These strategies cover key aspects such as medium pretreatment, equipment material optimization, process parameter adjustment, chemical agent dosing, and routine maintenance management, aiming to enhance the safe, stable, and efficient long-term operation of light hydrocarbon cooling units.

Keywords: Light hydrocarbon cooling unit; Corrosion mechanism; Scaling factors; Control strategies; Electrochemical corrosion

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1. Introduction

Light hydrocarbons are important by-products in the exploitation of oil and gas resources, characterized by flammability, explosiveness, volatility, and high component activity. The cooling and separation process is

a critical preliminary step for the recovery, upgrading, and efficient utilization of light hydrocarbons. Light hydrocarbon cooling units primarily rely on circulating cooling water or specialized refrigerants to exchange heat with light hydrocarbon materials, reducing the temperature of the light hydrocarbon medium below the dew point critical value to achieve effective gas-liquid phase separation and produce qualified light hydrocarbon products that meet industrial standards. Currently, domestic oil and gas development is gradually shifting towards deep wells, ultra-deep wells, and the exploitation of complex oil and gas reservoirs with high sulfur content. The complexity of exploitation conditions directly leads to the continuous deterioration of light hydrocarbon medium components, with a significant increase in the content of corrosive, harmful components such as sulfur ions and chloride ions. Meanwhile, the units are subjected to harsh operating environments with frequent fluctuations in temperature and pressure for extended periods, making equipment corrosion and scaling increasingly prominent year by year and becoming a core bottleneck restricting the efficient operation of light hydrocarbon recovery units. According to statistics from oil and gas field surface production operation and maintenance, over 60% of various shutdown failures in light hydrocarbon cooling units are directly or indirectly caused by corrosion and scaling issues, with corrosion perforation and scaling blockage failures being most frequent in the core tube bundles of heat exchangers and cooling transmission pipelines. Taking the circulating cooling water system associated with light hydrocarbon recovery at the Tahe Oilfield No. 2 United Station as an example, severe scaling attachment on the inner walls of pipelines occurs during long-term operation of the unit, with frequent corrosion perforation failures in heat exchangers and surface evaporators, significantly reducing equipment heat exchange efficiency and directly interfering with the continuity of the entire light hydrocarbon recovery production process. Corrosion damage can cause continuous thinning of equipment pipe walls and failure of sealing structures, easily leading to safety hazards of light hydrocarbon medium leakage; scaling damage directly reduces heat exchange conduction efficiency, increases production energy consumption, and induces local corrosion under scale, forming a vicious cycle of “corrosion promoting scaling and scaling exacerbating corrosion.” Based on the practical pain points in field production, this paper systematically teases the core causes and mechanisms of corrosion and scaling in light hydrocarbon cooling units in conjunction with their operational characteristics, establishing a scientific and comprehensive prevention and control system to provide technical support for precise fault prevention and control and production optimization and regulation of the units. This has significant practical engineering importance for reducing production costs and reinforcing the safety defensive line of oil and gas production.

2. Main influencing factors and mechanisms of corrosion and scaling in light hydrocarbon cooling units

2.1. Main Influencing factors and mechanisms of corrosion

2.1.1. Medium component factors

The complex and variable composition of light hydrocarbon media is the core source factor inducing corrosion in cooling units, with harmful components such as acidic corrosive gases, chloride ions, and sulfides having the most prominent corrosive effects on equipment metal substrates, with significantly different corrosion modes for each component type. Firstly, acidic gas corrosion. Light hydrocarbon media generally contain acidic corrosive gases such as CO_2 and H_2S, which are also the core inducing factors for frequent electrochemical corrosion in the units. CO_2 dissolves in the free water of the medium to form carbonic acid, which ionizes to produce a large amount of hydrogen ions. Hydrogen ions undergo reduction

reactions on the metal surface of the equipment, directly causing anodic dissolution and damage to the metal, gradually forming local corrosion pits. The core corrosion chemical reaction mechanism is clear, with the anodic reaction being $Fe - 2e^- = Fe^{2+}$, the cathodic reaction being $2H^+ + 2e^- = H_2\uparrow$, and the overall reaction being $Fe + H_2CO_3 = FeCO_3 + H_2\uparrow$. Under high CO_2 concentration conditions, a $FeCO_3$ corrosion product film forms on the metal surface. If the film structure is loose and lacks density, it is prone to detachment, directly exacerbating local pitting and pit corrosion damage to the equipment. After H_2S dissolves in water, it forms hydrosulfuric acid, which not only directly reacts with the metal substrate to generate FeS corrosion products but also precipitates active hydrogen atoms that penetrate into the metal, inducing hydrogen-induced cracking and sulfide stress corrosion cracking damage, which is extremely harmful to high-strength steel equipment. The produced fluid from the Tahe Oilfield contains a large amount of CO_2 and H_2S components, forming a typical H_2O-CO_2-H_2S-Cl^- composite corrosion system, which is the core reason for the frequent corrosion failures of local light hydrocarbon cooling equipment. Secondly, chloride ion corrosion. Chloride ions in light hydrocarbon media mainly originate from formation brine and oilfield injected water. Chloride ions have strong penetrability and can directly destroy the protective passive film on the metal surface of equipment, inducing pitting and crevice corrosion damage to the equipment. Chloride ions easily accumulate at structural defects in the passive film, causing local potential imbalances and forming anodic corrosion points, which gradually develop into deep pitting. When the chloride ion concentration exceeds 1000 mg/L, the pitting rate significantly increases, easily causing tube bundle perforation failures and simultaneously exacerbating the risk of stress corrosion cracking in stainless steel equipment. Thirdly, corrosion by other components. Organic acids such as formic acid and acetic acid, as well as free oxygen, present in light hydrocarbon media, can also promote corrosion damage. Organic acids directly erode and damage the protective film on the metal surface, while free oxygen induces oxygen absorption corrosion, accelerating the formation and accumulation of iron rust. The oxygen-exposed environment in open-type circulating cooling water systems significantly amplifies the harm of electrochemical corrosion [1].

2.1.2. Equipment material factors

The corrosion resistance of equipment materials directly determines the corrosion rate and service cycle. Currently, commonly used materials for light hydrocarbon cooling units mainly include carbon steel, low alloy steel, stainless steel, and some non-metallic materials, with significant differences in their suitability for different operating conditions and corrosion resistance. Carbon steel and low alloy steel are inexpensive and easy to process, widely used in basic components such as cooling pipelines and heat exchanger shells. However, they generally have weak corrosion resistance and are prone to electrochemical corrosion in corrosive media containing acidic gases and chloride ions. The $FeCO_3$ and FeS corrosion product films they generate have poor density and cannot block the continuous erosion of corrosive media. No. 10 and No. 20 carbon steels and 16Mn low alloy steel are the main materials with high corrosion failure rates on site. Stainless steel materials, including types 304 and 316L, can form a dense oxide passive film on their surfaces and have good corrosion resistance under normal operating conditions. However, the passive film is prone to damage under high chloride ion and high-temperature conditions, inducing pitting and crevice corrosion. Improper welding process control can also cause intergranular corrosion. Even 316L stainless steel, which has better corrosion resistance, still has a risk of stress corrosion cracking under strongly corrosive, rich amine solution conditions. Non-metallic materials such as fiberglass-reinforced plastic and high-density

polyethylene have excellent corrosion resistance but low mechanical strength and poor temperature and pressure resistance, making them suitable only for simple operating conditions with low pressure and temperature. Titanium alloy materials have excellent comprehensive corrosion resistance but are expensive and have high construction costs, making them difficult to promote on a large scale.

2.1.3. Operating parameter factors

Fluctuations in process parameters such as operating temperature, operating pressure, and medium flow rate in the unit significantly regulate the corrosion reaction rate. An increase in temperature can double-boost the corrosion reaction, not only increasing the solubility of acidic gases such as CO_2 and H_2S and enhancing the corrosive activity of the medium, but also accelerating the electron transfer rate in electrochemical corrosion and speeding up anodic dissolution of the metal. Experimental data show that under the operating conditions of a Q345 steel heat exchanger, the corrosion current density is highest and corrosion is most severe at 180°C. Temperature fluctuations can also induce thermal stress in the metal, exacerbating stress corrosion cracking. An increase in operating pressure raises the solubility of acidic gases and strengthens the destructive effect of chloride ions on the passive film. The normal operating pressure of light hydrocarbon cooling units is 1.5–3.0 MPa, with the corrosion rate under high-pressure conditions being 2 to 3 times higher than that under atmospheric pressure. Imbalanced control of the medium flow rate also poses significant hazards. A low flow rate easily causes the deposition and scaling of corrosion products and impurities, inducing under-deposit corrosion; a high flow rate can erode and strip the protective film and corrosion product film on the metal surface, causing erosion corrosion. The optimal controlled flow rate on site is 1.0-2.0 m/s, with both higher and lower flow rates exacerbating corrosion damage [2].

2.1.4. Process design factors

Unreasonable process design is an important inducing factor for local corrosion. The tube bundle and tube sheet welding joints of shell-and-tube heat exchangers adopt a corner joint structure, with welds protruding to form triangular dead corners, easily causing the accumulation and deposition of impurity scale layers and inducing under-deposit corrosion; vertical heat exchangers have a higher risk of scaling and corrosion compared to horizontal heat exchangers; open-type circulating cooling water systems are prone to sediment accumulation and water oxygen exposure problems, significantly exacerbating electrochemical corrosion, while closed-type circulating processes can effectively alleviate such damage. Meanwhile, unreasonable equipment installation layouts and excessive flow dead corners in the medium can cause local retention of corrosive media, continuously inducing local corrosion failures of the equipment.

2.2. Main influencing factors and mechanisms of scaling

2.2.1. Medium and water quality component factors

Impurities in light hydrocarbon media and ions in circulating cooling water quality are the material basis for equipment scaling, with different ion components forming different types of scale and varying degrees of harm. Firstly, carbonate scale. Circulating cooling water and formation water contain a large amount of Ca^{2+}, Mg^{2+}, and HCO_3^- ions. During process temperature increases and pressure decreases, HCO_3^- decomposes to generate CO_3^{2-}, which combines with calcium and magnesium ions to precipitate calcium carbonate and magnesium carbonate, attaching to heat exchange surfaces to form hard and dense carbonate scale, which is also the most common scale type on site. Software calculations show that the calcium carbonate scaling

tendency is most severe for unsoftened circulating water in the Tahe Oilfield. Secondly, sulfate scale. When the medium contains SO_4^{2-}, it combines with Ca^{2+} to generate calcium sulfate precipitate, which has strong adhesion and is hard, making it difficult to remove with conventional cleaning and significantly reducing heat exchange efficiency. Thirdly, sulfide and elemental sulfur scale. H_2S in light hydrocarbon media combines with Fe^{2+} generated by corrosion to form ferrous sulfide precipitate, while H_2S in regeneration gas oxidizes to form elemental sulfur deposition and scaling. The proportion of elemental sulfur in some scale samples from air coolers on site reaches 78%. Fourthly, other mixed scale types. Sediment, iron rust, organic matter, and silicon-aluminum impurities in the medium deposit to form mud scale, organic matter scale, and silica scale, which are loose in texture but easily block pipelines and heat exchanger flow channels [3].

2.2.2. Operating parameter and other factors

Operating parameters significantly regulate the formation and growth rate of scaling. An increase in temperature reduces the solubility of salts and accelerates crystallization reactions. The solubility of calcium carbonate significantly decreases with increasing temperature, making it prone to precipitation and scaling; a decrease in pressure causes CO_2 to escape and the medium pH value to rise, promoting the precipitation and scaling of carbonates; a low medium flow rate accelerates the deposition and scaling of impurities, while a high flow rate induces erosion corrosion, with corrosion products becoming cores for scaling, forming a vicious cycle. In addition, a large inner wall roughness of equipment, an imbalanced medium pH value, and an excessively high concentration ratio of circulating cooling water all increase the probability of scale formation. A high pH value promotes the precipitation and scaling of calcium and magnesium ions, while a low pH value inhibits scaling but exacerbates corrosion.

2.3. Synergistic mechanism of corrosion and scaling

Corrosion and scaling in light hydrocarbon cooling units are not independent damages; instead, they mutually catalyze and synergistically exacerbate each other, forming an irreversible vicious cycle. Corrosion reaction products such as $FeCO_3$ and FeS become cores for the crystallization and deposition of salt impurities, accelerating the rapid growth and attachment of scale layers; after the scale layer covers the metal surface, it forms a local oxygen-deficient, high-chloride ion closed environment, inducing severe under-deposit corrosion, and the medium retention effect further amplifies the corrosion damage. In the open circulating cooling water system of the Tahe Oilfield, sediment scaling deposition induces under-deposit electrochemical corrosion, and the iron rust generated by corrosion promotes the secondary deposition of sediment. This vicious cycle directly accelerates equipment failure and scrapping, significantly shortening the actual service life of the equipment.

3. Control strategies for corrosion and scaling in light hydrocarbon cooling units

3.1. Strengthening medium pretreatment to reduce corrosion and scaling

Triggers at the Source Medium pretreatment is a core measure for preventing corrosion and scaling at the source, primarily by purifying the light hydrocarbon medium and optimizing the quality of circulating water to remove corrosive components and scaling ions. Before entering the cooling unit, the light hydrocarbon medium undergoes additional processes such as dehydration, deacidification, and precise filtration. The alcohol-amine method is employed to remove acidic gases like H_2S and CO_2, while filter element

sedimentation filtration removes mechanical impurities. Molecular sieve dehydration reduces the water content of the medium, thereby minimizing the material basis for corrosion reactions and scaling deposition from the source. The circulating cooling water undergoes softening and deoxygenation treatments, utilizing ion exchange and reverse osmosis processes to remove calcium and magnesium scaling ions. Thermal and chemical combined deoxygenation eliminates dissolved oxygen corrosion. The concentration ratio of the circulating water is strictly controlled between 3 and 5 times. After implementing circulating water pretreatment and process modifications at the joint station of the Tahe Oilfield, corrosion and scaling issues have been effectively alleviated.

3.2. Optimizing equipment material selection to enhance corrosion and scale resistance

Equipment materials are precisely matched based on the corrosion grade of the medium and operating conditions. Carbon steel and low-alloy steel are selected for low-sulfur and low-chlorine, mildly corrosive conditions to control costs. For high-sulfur and high-chlorine, severely corrosive conditions, 316L stainless steel and duplex stainless steel are chosen, while titanium alloy tube bundles are used for special, highly corrosive conditions. Carbon steel equipment surfaces are coated with epoxy resin or polytetrafluoroethylene anti-corrosion coatings or protected with fiberglass-reinforced plastic linings. Surface strengthening treatments such as zinc-aluminum co-diffusion and nickel-phosphorus plating enhance the corrosion resistance of the substrate. The welding process for stainless steel equipment is optimized, with strict control over welding heat input to avoid intergranular corrosion. Heat exchangers use internally extended welding joints to eliminate dead corners in welds, reducing scaling deposition and under-deposit corrosion [4].

3.3. Optimizing process design and operating parameters to improve operating conditions

The core of process modification involves upgrading open circulating cooling water systems to closed-loop systems, adding volumetric expansion tanks to prevent pump cavitation and reduce sedimentation and water aeration corrosion. Heat exchangers are equipped with spiral flow disturbance elements to enhance medium agitation, eliminating flow dead zones and inhibiting scaling deposition. Operating parameters are reasonably controlled, with temperatures maintained between 40 and 60°C, pressures kept within the designed rated range, and medium flow rates managed between 1.0 and 2.0 m/s. Frequent equipment start-ups and shutdowns are avoided to reduce temperature and pressure fluctuations, lowering the risk of stress corrosion cracking. Equipment installation layouts are optimized to avoid areas prone to impurity accumulation and water stagnation.

3.4. Precise addition of chemical agents for synergistic control of corrosion and scaling

Corrosion inhibitors, scale inhibitors, and biocides are added as needed to achieve chemical prevention and control. Mixed-type corrosion inhibitors are selected for electrochemical corrosion conditions, mercaptan-based inhibitors for sulfur-containing media, and imidazoline-based inhibitors for chloride pitting conditions, with reasonable control over the addition amount ranging from 50 to 200 mg/L. Organic phosphonic acid and polycarboxylic acid-based high-efficiency scale inhibitors are chosen to chelate and disperse calcium and magnesium ions, inhibiting salt crystal deposition, with the addition amount controlled between 20 and 100 mg/L. Oxidizing and non-oxidizing biocides are alternately added to inhibit microbial growth and microbial

corrosion, enhancing the synergistic effect of the agents and avoiding reduced prevention and control effectiveness due to agent reactions.

3.5. Strengthening routine operation and maintenance management to promptly address hidden dangers and defects

A regular equipment inspection mechanism is established, utilizing ultrasonic testing, corrosion coupons, and endoscopic inspection to routinely monitor equipment wall thickness, corrosion rates, and scaling thickness. The composition of the medium and water quality are regularly tested to dynamically adjust prevention and control measures. Chemical acid cleaning and high-pressure water jet physical cleaning are conducted as needed to selectively remove different types of scale layers, with strict control over cleaning concentration and time to avoid cleaning-induced corrosion. Routine maintenance and replacement of vulnerable components, such as seals and valves, are carried out, and equipment operation logs are established. Emergency response plans for corrosion perforation and pipeline blockage are formulated to quickly address sudden failures, reducing downtime losses and safety risks [5].

4. Conclusion

Corrosion and scaling in light hydrocarbon cooling units are influenced by the coupling of multiple factors, including medium composition, equipment material, operating parameters, and process design. Corrosion and scaling exhibit significant synergistic catalytic effects, forming a vicious cycle of defect mechanisms. Medium components such as acidic gases and chloride ions are the core triggers for corrosion, while calcium and magnesium ions and impurity deposition are the fundamental sources of scaling. Inadequate material adaptation, parameter fluctuations, and process defects further amplify the harm of these defects. With the continuous development of complex oil and gas reservoirs, the corrosive properties of light hydrocarbon media will continue to intensify. Future efforts should focus on developing green, low-cost corrosion and scale inhibition composite agents, developing new composite equipment materials with corrosion and scale resistance, establishing online early warning systems for corrosion and scaling based on intelligent monitoring technologies, deepening research on the microscopic mechanisms of the synergistic effects of corrosion and scaling, continuously optimizing prevention and control technology systems, and promoting the green, efficient, and intelligent safe operation of light hydrocarbon cooling units.

Disclosure statement

The authors declare no conflict of interest.

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