Summarize the Corrosion and Protection of Drum-Shaped Filter in Nuclear Power Plant

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Abstract—The drum-shaped filter of the pressurized water reactor nuclear power plant is prone to corrosion due to the influence of sea water, moist air and other factors all year round, which puts a burden on the economic and safe operation of nuclear power plants. In this paper, the corrosion forms and causes of different parts of the drum-shaped filter are analyzed and expounded, and protective measures are put forward.

1. Introduction

As a clean and efficient energy, nuclear power has been highly valued by China with the development of the economy. While seawater circulation system equipment is facing corrosion problems owing to the nuclear power plants built in coastal areas.

Circulating water filtration system is a system for filtering seawater used in nuclear power plants. The drum-shaped filter is a relatively large device in the circulating water system of nuclear power plants. The working environment of the drum-shaped filter is seawater, but the presence of salt ions and chloride ions makes the seawater highly electrolytic, resulting in the corrosion of the drum-shaped filter. During the overhaul inspection of the nuclear power plant, Lin et al [1] found that there was rust on the contact part of the strainer and the skeleton, and the fastening bolts of the skeleton and the strainer showed slight corrosion pits. The damage to the coating resulted in pitting pits on the surface of the skeleton. The largest pit radius is about 2 cm and the depth is about 4 mm. After the strainer was removed, it was found that the stainless steel strainer was rusty, and there were flaky yellow rust spots on the edges, irregular sporadic corrosion in the middle of the individual stencils, and corrosion of the fastener bolts. Due to the reason that part of the drum-shaped filter was below the liquid level which belonged to the full immersion zone, while the other part belonged to the splash zone, resulting in the ineffective cathodic protection for drum-shaped filter during operation and corrosion of the bottom skeleton of the drum mesh. Liu [2] from Shandong Nuclear Power Co., Ltd. found that the corrosion phenomenon of the drum-shaped filter is localized corrosion, and the localized corrosion form can be represented as pitting corrosion, galvanic corrosion and crevice corrosion. Ma [3] from Fujian Fuqing Nuclear Power Co., Ltd. found that the carbon steel coating was damaged during the installation of the drum network. The seawater entered the coating and directly contacted the carbon steel body, which not only caused strong corrosion of the bare metal, but also gradually eroded the surrounding intact coating gradually. The carbon steel body and even the metal matrix inside part of the coating form corrosion pits in a short time. Stainless steel ferrite pollution induces galvanic corrosion, pitting corrosion, stress corrosion, etc. At the same time, the applied current cathodic protection system fails to be put into operation in time, resulting
in galvanic corrosion. If protective measures are not taken on the drum-shaped filter screen, the drum-shaped filter screen will be severely corroded, which will bring hidden safety risks to the stable operation of the nuclear power plant. In recent years, there have been many reports on the corrosion of drum-shaped screens in nuclear power plants, but there are few analyses on the corrosion forms and causes of different parts of drum-shaped screens, and lack the corrosion protection measures for drum-shaped screens. This paper proposes corrosion protection methods such as metal protective coating, cathode protection of sacrificial anode, applied current cathodic protection, and metal surface passivation treatment by analyzing the mechanism and form of equipment corrosion, which ensure the safe operation and economic benefits of nuclear power plants.

2. DETAILED INTRODUCTION OF DRUM-SHAPED FILTER EQUIPMENT

Drum-shaped filter is one of the main filtration equipment in the circulating water filtration system. It is mainly composed of rotating cylindrical skeleton, stainless steel mesh, drive device, sealing device, flushing system, protection device and other parts. Supported by two hubs on the main shaft, it is used to intercept suspended dirt in the seawater that is larger than the diameter of the mesh after being processed by the grid, and remove the intercepted dirt out of the water surface to remove it to ensure the normal operation of subsequent equipment such as circulating water pumps, important plant water pumps and condensers. The general design size of the drum-shaped filter is 19m in diameter and 4m in width. Under normal operating conditions, the drum screen rotates continuously, and the rotation speed increases according to the increase of the water level difference before and after the strainer. The main frame of the skeleton adopts A-shaped structure to improve the rigidity and stability. The cross beam adopts the variable cross-section and other strengthen design. The drum skeletons are all detachable which is convenient for transportation. The main technical parameters of the drum-shaped filter are shown in Table I [4].

| TABLE I. TECHNICAL PARAMETERS OF THE DRUM-SHAPED FILTE | diameter | 19 m | Net hole size | 4.2 mm | Effective width | 4.0 m | Flushing water volume | 96.14 m³/h |
|----------------------------------------------------------|---------|------|---------------|-------|----------------|------|----------------------|-----------|
| Strainer Line speed (high)                               | 15 m/min|      | Maximum water flow | 19 m³/s |
| Strainer Line speed (Low)                                | 5 m/min |      | Total speed ratio | 5600   |
| Maximum flow rate                                        | 0.8 m/s |      | Maximum lifting volume | 10 t |

| Operating maximum internal and external water level difference | 500 mm |
| Operating maximum internal and external water level difference | 1500 mm |

The material of the Strainer is 316 stainless steel, the skeleton is Q345 carbon steel, and the material of the drum-shaped filter of the nuclear power plant meets the national standard. As the representative of martensitic steel, 316 stainless steel has good mechanical properties, yield strength reaches 480Mpa, and tensile strength is about 177Mpa. Due to the addition of Mo element, its corrosion resistance is better, but corrosion also occurs in harsh corrosive environments. The chemical composition is shown in Table II. Q345 steel is a low-alloy high-strength steel with a wide range of applications (C<0.2%). Yield strength is 345Mpa, tensile strength is between 450Mpa-630 Mpa, its comprehensive mechanical properties are excellent, plasticity and welding performance are good, it is widely used in lifting transportation machinery, bridges, ships, power station equipment and other withstand higher loads Engineering and welding structural parts. However, it also has deficiencies, such as low surface hardness, poor wear resistance and corrosion resistance, which limits its application to a certain extent. The chemical composition of Q345 carbon steel is shown in Table III.
TABLE II. CHEMICAL COMPOSITION OF 316 STAINLESS STEEL

| element | C  | Mn | Si  | P  | S  | Ni  | Cr  | Mo  | Fe  |
|---------|----|----|-----|----|----|-----|-----|-----|-----|
| constituents (wt.%) | 0.08 | 2.0 | 1.0 | 0.045 | 0.03 | 10.0-14.0 | 16.0-18.0 | 2.0-3.0 | bal |

TABLE III. CHEMICAL COMPOSITION OF Q345 STEEL

| element | C   | Mn | Si  | P  | S  | Ni  | V  | Ti  | Cr  | Cu  | Mo | Fe  |
|---------|-----|----|-----|----|----|-----|----|-----|-----|-----|----|-----|
| constituents (wt.%) | 0.18 | 1.70 | 0.50 | 0.03 | 0.025 | 0.50 | 0.15 | 0.20 | 0.30 | 0.3 | 0.1 | bal |

3. CORROSION CHARACTERISTICS AND FACTORS OF SEAWATER

The working environment of the drum-shaped filter of a nuclear power plant is a marine environment. The marine environment is a complex and changeable system. Seawater contains a variety of salts such as NaCl, MgCl, KCl, and various sulfates. The surface salt content is generally at Between 3.2% and 3.75%, the salt content increases slightly with increasing water depth. When the material is in different positions of seawater, the surface temperature of the material is different, the oxygen content of the seawater in contact with it is different, and the stress of the material is different. In addition, there are some other factors such as sea creatures, pH, electrical conductivity, and seawater flow velocity. The effect of seawater intake and drum-shaped filter corrosion is negligible. This paper takes the raw seawater intake of Hongyanhe Nuclear Power Plant as an example. According to the literature, the annual maximum seawater temperature of Hongyanhe Nuclear Power Plant's drum-shaped filter is 24.4 °C, the annual minimum temperature is -1.8 °C, and the annual average temperature is 10.9 °C. The monthly seawater temperature of Hongyanhe Nuclear Power Plant is shown in the Table IV and the seawater conditions as shown in the Table V [5].

TABLE IV. INTRODUCTION OF SEAWATER TEMPERATURE

| month | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|
| temperature (°C) | -0.8 | -1.0 | 1.8 | 5.9 | 11.2 | 16.7 | 22.0 | 24.4 | 22.2 | 16.4 | 8.4 | 3.3|

TABLE V. INTRODUCTION OF SEAWATER QUALITY

| seawater quality | Numerical value | seawater quality | Numerical value |
|-----------------|----------------|-----------------|----------------|
| K⁺              | 380            | Cl⁻             | 18000          |
| Na⁺             | 10000          | SO₄²⁻           | 2500           |
| Ca²⁺            | 400            | HCO₃⁻           | 150            |
| Mg²⁺            | 1200           | CO₃²⁻           | 0              |
| Fe²⁺            | 0.2            | NO₃⁻            | 0.02           |
| Fe³⁺            | 0.2            | NO₃⁻            | 3              |
| NH₄⁺            | 0.2            | F⁻              | 0.8            |
| Cu²⁺            | <0.05          | I⁻              | 0.06           |
| Al³⁺            | <0.02          | PO₄³⁻           | 0.05           |
| Mn²⁺            | 0.01           | S²⁻             | 0.02           |
| Zn²⁺            | 0.02           | others          | ---            |
| Pb²⁺            | <0.01          | pH              | 7.8            |
| Sr²⁺            | 7              | Ba²⁺            | 0.04           |
| Soluble SiO₂    | 2              | Total alkalinity | CaCO₃          | 130 |
Seawater is rich in Cl-ions, which can hinder or destroy the passivation of metals, so that most metals in seawater will suffer severe corrosion. Cl-ions have a penetrating and destructive effect on the passivation membrane, and Cl-ions are easily adsorbed on the metal surface, and can form complexes with metal cations, which increases the probability of corrosion of the filter screen 316 stainless steel. As the concentration of Cl-ions increases, the self-corrosion potential impedance modulus and polarization resistance of mesh 316 stainless steel continue to decrease, resulting in an increase in corrosion current density and an increase in corrosion rate. In addition to the typical salt ions and chloride ions in seawater, in order to kill algae and prevent other marine organisms from entering the filter screen, a chlorination equipment is usually installed in the seawater filtration system to inject sodium hypochlorite solution, and Sodium hypochlorite solution is further accelerated by the corrosion of the equipment material because of its strong oxidation.

Different equipment materials and seawater contact conditions have different effects on corrosion. The seawater working conditions are divided into marine atmospheric zone, splash zone, tidal zone, full immersion zone and sea mud zone. Corrosion rate in the splash zone is the most intense because of seawater splashing and dry and wet alternation. The corrosion rate in each zone is: splash zone>full immersion zone>tide zone>atmosphere zone>sea mud zone.[1]

Analysis of the key corrosion factors affecting the corrosion of Q345 steel, Lin.et.al [6] used the salt spray experiment, constant temperature and humidity experiment to study the corrosion law of Q345 steel under different chloride ion content, temperature and humidity. The results show that the corrosion rate of Q345 steel shows the trend of increasing and decreasing with the increase of the mass fraction of chlorine ion in the environment. when the chloride ion content is 1.75%, the corrosion rate reaches a maximum value. The corrosion rate of Q345 steel with the change of temperature shows that the corrosion rate of Q345 steel increases with the increase of temperature, and the corrosion rate increases greatly at 35°C-40°C. The relative humidity has a linear relationship with the corrosion rate of Q345 steel. The results of the study indicate that the key corrosion factors that affect the corrosion of Q345 steel are chloride ion mass fraction, humidity, and temperature. [7]

4. ANALYSIS OF CORROSION MECHANISM

Galvanic corrosion, also known as contact corrosion, refers to the electrochemical corrosion that occurs when two different metals are in contact with each other while being in an electrolyte. The metal material constitutes a spontaneous battery. In the drum net, the skeleton Q345 carbon steel wrapped paint was damaged, resulting in carbon Q345 steel and filter mesh 316 stainless steel contacting under seawater conditions, because there is a potential difference between the two metals to form galvanic corrosion, The potential difference makes the galvanic current flow between Q345 carbon steel and 316 stainless steel. The negative potential carbon steel intensifies the corrosion while the applied current cathodic protection system fails to protect, the galvanic corrosion intensifies, and the bottom skeleton of the drum network corrodes.

Crevice corrosion belongs to electrochemical corrosion, which refers to the local corrosion that occurs in the metal surface, crevices and other hidden areas in the corrosive medium. Crevice corrosion often occurs in the holes of the drum-shaped filter, gasket contact surfaces, lap joints, under deposits and fastener gaps. Corrosion-resistant metals that rely on oxide films or passivation layers are prone to crevice corrosion in oxygen-containing media. When the filter screen rotates into the sea water, there is a very small gap (0.02mm-0.12mm) between the joint of the drum net and the fastening between the mesh and the skeleton. The sea water will infiltrate into these areas and stay and cause crevice corrosion. The skeleton Q345 steel has yellow corrosion. The basic characteristic of the corrosion of metal materials in the seawater medium is electrochemical corrosion. The presence of oxygen in seawater is rich, and the metal reacts electrochemically in the electrolyte. Taking the drum-shaped filter metal material as an example, the electrochemical reaction formula is:

$$\text{Fe} + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2\text{OH}^- \quad (1)$$
In the process of corrosion, the electrode potential of Fe is relatively negative, so an oxidation reaction occurs. Under the action of polar water molecules, metal cations will detach from the surface of the metal material and enter the solution, which may form hydrated metal cations with water molecules $\text{Mn}^{+} \cdot \text{mH}_2\text{O}$, oxygen in the air in a neutral or alkaline solution gets electrons, a reduction reaction occurs, generating hydroxide ions. Therefore, formula (1) can be expressed by the following two reaction formulas:

$$\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \quad (2)$$

$$\frac{1}{2} \text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2\text{OH}^- \quad (3)$$

Pitting, also known as pitting corrosion, is a form of corrosion that focuses on a small area of the metal surface and penetrates deep into the metal. It usually occurs on metals or alloy materials that have self-passivation properties. The small-scale rust of the strainer mesh is due to the pitting corrosion caused by the adsorption of chloride ions to the surface of 316 stainless steel.

5. PROTECTIVE MEASURES

The corrosion of the drum-shaped filter is the result of the combined effect of galvanic corrosion, crevice corrosion and pitting corrosion. Therefore, the protection of the drum network can be reduced and controlled by the relevant methods.

For the galvanic corrosion protection measures between the strainer and the frame, the bolt fastener and the strainer, the current connection between the frame Q345 carbon steel and 316 stainless steel can be isolated, such as coating the metal on the frame or shaft Q345 carbon steel Insulation coating. Gao et al. adopted an external current cathodic protection system. It includes three independent potentiostats. The drum-shaped rotating strainer is divided into three corrosion areas, which are the inner area of the strainer, the outer area of the strainer, and the symmetrical areas on both sides. Each potentiostat adjusts its output current according to the potential signal fed back by the corresponding reference electrode in combination with the preset potential value, so that the potential of each corrosion area remains consistent at the reference potential, ensuring that all parts of the drum-shaped filter are reached. The best cathodic protection potential can achieve the purpose of inhibiting metal corrosion.

The crevice corrosion and pitting corrosion of the main shaft are electrochemical corrosion behaviors. After research, Yang et al. decided to use Interzone 954 epoxy coating for the overall treatment of the drum mesh main shaft, the old coating on the surface is removed using a power tool, the substrate is polished to St3 level, and the surface roughness of the substrate is guaranteed to be 50~75μm. After the coating is cured, check the coating quality to ensure that there are no defects such as pinholes and sagging. Before coating, the surface treatment must be performed in strict accordance with the design process requirements.

For the pitting behavior of 316 stainless steel mesh, the 316 stainless steel mesh can be protected according to the principle of electrochemical passivation. Electrochemical passivation principle is to create a dense passivation film on the metal surface, isolate the metal and the external corrosion environment, to improve the stability and homogeneity of the metal. Wang research found that the corrosion resistance of metals after electrochemical passivation treatment has increased by three levels. Therefore, the stainless steel materials such as mesh, bolt fasteners, pressure plates and other corroded parts of the drum net are disassembled, pickled and rusted, and then passivated to form a protective film $\geq 10$nm to improve the corrosion resistance of the filter screen.

For the Q345 steel parts of the drum-shaped filter, a new anti-corrosion and repair technology is proposed. The laser cladding technology prepares the surface coating to improve the corrosion resistance of the equipment parts. Laser cladding is under the action of high-energy laser beam (energy density: $10^4$~$10^9$W/cm$^2$), the reinforced layer powder and the substrate are rapidly heated and melted, and the laser beam is removed and cooled rapidly to finally obtain a surface of metallurgical bonding coating strengthen technology. According to the actual needs of the workpiece, laser cladding can be used to prepare metal or non-metallic material coatings of various design components, mainly used to prepare surfaces with high temperature resistance, wear resistance, corrosion resistance, fatigue resistance,
oxidation resistance, etc. coating. Liu et al [10] used laser cladding technology to prepare Fe₄₀Mn₂₀Ni₁₀Co₁₀Cr₂₀ on the Q345 steel substrate. The research shows that laser cladding high-entropy alloy coating Fe₄₀Mn₂₀Ni₁₀Co₁₀Cr₂₀ has good comprehensive mechanics and corrosion resistance. Bao et al [11] used laser cladding technology to prepare FeCrNiCoCuₐ (x=0,1,2,3) high-entropy alloy coatings with different aluminum contents on the surface of Q345 steel. Studies have shown that in 3.5% NaCl solution, the corrosion current density of the coating decreases first and then increases with the increase of Al content, and the coating has the best corrosion resistance when x=2 (FeCrNiCoCu₂). Laser cladding to prepare corrosion-resistant alloy coatings is expected to provide a reference for the corrosion protection of nuclear power plant drum-shaped filter and other seawater circulation equipment.

6. CONCLUSIONS
As of January 2020, Chinese mainland has 47 nuclear power units in operation, ranking third in the world. As an important circulating water system in nuclear power plants, it is concerned that the corrosion of drum-shaped filter poses a threat to the safe operation of the nuclear power unit. The corrosion protection of the drum-shaped filter is to reduce the electrochemical reaction speed between the material and the environmental conditions. Therefore, improving materials, changing the environment, preparing anti-corrosion coating, isolating equipment from corrosive media, or reducing the exchange of ions, oxygen, and water between materials and the environment are corresponding measures. Each corrosion control measure (anticorrosive coating, electrochemical protection, surface treatment, corrosion inhibitor, etc.) has its own advantages/disadvantages. The choice of corrosion protection measures depends on the specific use conditions of the equipment, and corrosion monitoring technology is also an important part of corrosion control [12]. Safety evaluation and life prediction are the key steps to ensure safety. Environmental protection, low cost, safety, easy construction and high performance are the general trends in the development of corrosion protection technology.

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