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Experimental Study on Corrosion of Stainless Steel in Low Temperature Multi effect Seawater Desalination

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Abstract: Starting from the corrosion mechanism, this paper analyzes the characteristics of various types of stainless steel and selects the best performance composite plate composite plate stainless steel. Analyze and select the most suitable corrosion detection method based on specific practical multi working conditions, discuss the interference factors that affect metal corrosion during experimental simulation, and the advantages of newly developed sheet metal. The new development of composite board panels, with the substrate and composite materials applying their respective capabilities for MED, will bring breakthrough progress to the scientific research and engineering application of composite boards.

Keywords: seawater desalination; corrosion mechanism of stainless steel; composite board lamination; corrosion rate

Introduction

China's freshwater resources are seriously insufficient, while seawater resources are very abundant. Seawater desalination technology is an important method to solve the shortage of freshwater resources [1,2], which can convert seawater into freshwater. Thermal low-temperature multi effect distillation (LT-MED) technology is one of the mainstream processes in current seawater desalination technology, which has the characteristics of low corrosion rate, low scaling risk, high thermal power efficiency, and low energy consumption [3,4].

The evaporator is an important unit of LT MED, and its shell is welded from stainless steel plate (S32304) with a thickness of generally about 8 mm. However, due to its high cost, its application in practical engineering is limited. In order to solve this problem, it is urgent to develop and research a new type of composite plate as a substitute for steel plate. This new type of composite plate needs to have the following characteristics: (1) the substrate needs to meet mechanical requirements, and it is advisable to choose ordinary carbon steel with lower prices; (2) The new composite plate cladding needs to use corrosion-resistant stainless steel, which has corrosion resistance; (3) The composite plate needs to meet the service life requirements of the evaporator, and the thickness of the corrosion-resistant stainless steel cladding needs to be considered.

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1 Classification of metal corrosion

1.1 Classification by corrosive environment

According to the environment in which corrosion occurs, the metal can be divided into dry gas corrosion, corrosion in electrolyte, corrosion in non electrolyte, and corrosion in molten metal. Dry gas corrosion includes room temperature dry gas corrosion above dew point and oxidation corrosion in high-temperature gas [5]; Corrosion in electrolyte, also known as wet corrosion, is electrochemical corrosion; Corrosion in non electrolyte solutions belongs to chemical corrosion, and a small amount of water can change the nature of corrosion; The corrosion of molten metal, also known as

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physical corrosion, is usually caused by physical action.

The operating conditions of a low-temperature multi effect evaporator (MED) are complex, and the operating environment of the top, side, and bottom plates that make up the MED is also complex. For MED, the top plate is immersed in salt mist for a long time, while the bottom plate is immersed in seawater for a long time. For the side plate, it has a unique gas vapor operating environment that combines the top plate and side plate. In addition, the temperature, pressure, oxygen density, seawater salinity, and microbial distribution in different parts of MED are all different and will change over time.

1.2 Classification by corrosion mechanism

According to the mechanism of corrosion, it can be further divided into chemical corrosion and electrochemical corrosion. In specific environments, there is a direct chemical interaction between metals and oxidants, and electron transfer occurs directly between metals and oxidants, causing a change in the surface of metals. This process is called chemical corrosion, which does not generate current. Electrochemical corrosion refers to the corrosion that occurs when a metal loses electrons and is oxidized. The metal undergoes a primary cell reaction with the electrolyte, and during the electrochemical corrosion process, an electric current is generated, which is the biggest difference from chemical corrosion.

1.3 Classification by corrosion morphology

According to the classification of corrosion forms, metal corrosion can be divided into uniform corrosion, localized corrosion, and corrosion fracture under stress [6].

Uniform corrosion is generally distributed throughout the entire surface of the metal, with uniform erosion, low risk, and easy control. When using seawater resistant stainless steel plate as the material for MED composite plate, the designed service life is generally 30 years, and the thickness is controlled at around 8 mm.

Localized corrosion, also known as uneven corrosion, can be both localized and compositional, making it more prone to damage and failure of mechanical products, and more harmful than comprehensive corrosion. Local corrosion is the main influencing factor on the design thickness of MED plates, so the actual material selection should simulate the actual operating conditions and focus on studying local corrosion.

Metal materials generally work in corrosive environments and under stress, and stress corrosion is common and sudden. Usually, MED boxes have a relatively large volume, and there are various connection methods for box components, each of which experiences different stresses. To ensure the overall performance of the MED box, corrosion fracture under stress should also be included in the range of composite material selection and be one of the key research areas.

2 Qualitative selection analysis of the types of composite plate cladding stainless steel

In the process of seawater desalination, composite plate cladding works in complex environments with high salinity, high temperature, and seawater erosion. Moreover, there are a wide variety of microorganisms in seawater, and their life activities can cause certain corrosion to composite plates. This requires special stainless steel materials to resist metal corrosion caused by special and complex environments.

2.1 Classification and characteristics of stainless steel

Stainless steel, also known as stainless steel, is a type of steel that is resistant to weak acid corrosive media such as air, steam, and water, or has rust resistance. Stainless steel can be divided into martensitic stainless steel, austenitic stainless steel, ferritic stainless steel, precipitation hardening stainless steel, and austenitic ferrite duplex stainless steel according to their microstructure; According to the main chemical composition of stainless steel, it can be divided into Cr stainless steel, Cr-Ni stainless steel, Cr-Ni-Mo stainless steel, ultra-low carbon stainless steel, high Mo stainless steel, and high-purity stainless steel. The classification and characteristics of stainless steel are shown in Table 1.

2.2 Qualitative selection analysis of corrosion-resistant stainless steel for composite laminates

The operating conditions of composite plate with corrosion-resistant stainless steel are high temperature, high salinity, and seawater erosion. In order to prevent the composite plate from being corroded less or less, and to meet the actual service life of seawater desalination evaporators, it must have high corrosion resistance and special structural properties. The comparison of selecting different corrosion-resistant stainless steels as composite plate cladding corrosion-resistant stainless steels is shown in Table 2.

According to Table 2, the structural performance of duplex stainless steel is superior to that of single stainless steel, and it has the dual advantages of ferrite and austenitic stainless steel, making it the best choice as a corrosion-resistant stainless steel for composite plate cladding.

2.3 Qualitative selection analysis of corrosion-resistant duplex stainless steel grades

In recent years, with the increasing number of low-temperature multi effect distillation seawater desalination projects, the development of new corrosion-resistant stainless steel has become an urgent task. Zhou Bo [7] developed a new type of seawater corrosion resistant stainless steel that can meet the requirements of using corrosion-resistant duplex stainless steel as a composite plate for seawater desalination equipment through continuous optimization of alloy element

Table 1 Classification and characteristics of stainless steel

Classification of stainless steel	Characteristic
Martensitic stainless steel	(1) Good corrosion resistance in oxidizing media, but not in strong acid, molten alkali, or oxygen deficient seawater; (2) Low resistance to local corrosion, high sensitivity to hydrogen embrittlement, and not suitable for use in environments where local corrosion may occur; (3) Mainly used for steam engine blades, tableware, surgical instruments, etc.
Austenitic stainless steel	(1) Has excellent corrosion resistance, comprehensive mechanical properties, process and welding performance; (2) Chromium nickel austenitic stainless steel is corrosion-resistant in oxidizing media and not corrosion-resistant in reducing media; (3) In less corrosive media such as nitric acid, acetic acid, and oxalic acid, the corrosion resistance of chromium manganese type austenitic stainless steel is equivalent to that of chromium nickel type. However, in highly corrosive high-temperature media such as nitric acid, sulfuric acid, and phosphoric acid, its corrosion resistance is worse than that of chromium nickel type; (4) Poor resistance to pitting and crevice corrosion in chloride containing environments.
Ferritic stainless steel	(1) The characteristics include high thermal conductivity, low expansion coefficient, good oxidation resistance, and resistance to stress corrosion; (2) Can be used to manufacture components that are resistant to atmospheric, water vapor, water, and oxidative acid corrosion.
Precipitation hardening stainless steel	Corrosion resistance, high mildness, and precipitation hardening can be achieved through aging treatment to achieve ultra-high strength.
Austenitic ferrite bi-directional stainless steel	(1) It possesses both the excellent toughness and weldability of austenitic stainless steel, as well as the high strength and resistance to chloride stress corrosion cracking of ferritic stainless steel; (2) It has high resistance to pitting corrosion, which is related to the type and composition of added alloying elements, but not to the duplex structure of duplex stainless steel.

Table 2 Comparison of corrosion-resistant stainless steel selection

Classification of stainless steel	Corrosion resistance characteristics
Martensitic stainless steel	Low resistance to local corrosion, such as sensitivity to point corrosion, intergranular corrosion, and stress corrosion, and high sensitivity to hydrogen embrittlement;
Austenitic stainless steel	Poor resistance to pitting and crevice corrosion in chloride containing environments;
Ferritic stainless steel	Poor resistance to pitting and crevice corrosion; Low yield strength;
Precipitation hardening stainless steel	High structural strength, corrosion resistance performance does not meet the requirements;
Austenitic ferrite bi-directional stainless steel	It has the corrosion resistance of both ferrite and austenitic stainless steel, and its structural performance is superior to that of a single entity.

formula, melting process, and heat treatment system through a series of experimental research. This stainless steel ensures a good combination of material strength and toughness. Based on Zhou Bo's research, we can compare its new seawater corrosion resistant stainless steel formula, choose the existing grades and formulas of duplex stainless steel, or develop a new type of stainless steel. The selected or developed corrosion-resistant stainless steel needs to undergo practical engineering experiments and economic feasibility analysis before it can be put into practical production applications.

3 Selection and analysis of corrosion detection methods for corrosion-resistant stainless steel

3.1 Stainless steel corrosion detection method

At present, the main corrosion detection methods for stainless steel include quality method, electrochemical measurement method, and surface analysis method [8].

The quality method is a commonly used method for studying metal corrosion, which is divided into weight loss method and weight gain method. Qida [9] et al. studied the corrosion behavior of copper nickel alloy and HAl77-2 brass in 1 m/s flowing seawater using weight loss method and

dynamic potential polarization curve; Ai Yingying [10] studied the seawater corrosion resistance of martensitic aging stainless steel after different heat treatment processes by combining the weight loss method with the dynamic potential polarization curve; Liang Jun [11] et al. investigated the corrosion behavior of 316L/625 composite pipe materials in seawater through methods such as weight loss analysis and galvanic corrosion testing.

Electrochemical measurement is an important method for studying the process and mechanism of metal corrosion, especially suitable for metal materials that produce passivation films on stainless steel. Electrochemical methods have become an important method for measuring metal corrosion due to their advantages such as fast measurement speed, short cycle, high sensitivity, and ease of on-site monitoring. Electrochemical measurement techniques mainly include self corrosion potential analysis, potentiodynamic polarization curve analysis, electrochemical impedance spectroscopy (EIS), and electrochemical noise analysis. Zeng Chusheng [8] studied the corrosion resistance of 316L stainless steel under different conditions using immersion experiments and Tafel polarization curve method, and verified the corrosion process by analyzing its corrosion mechanism and AC impedance method; Dong Xiaoshuai [12] studied the effects of Cl - concentration and acidity on the corrosion rate and pitting resistance of TTS443 stainless steel using Tafel polarization curve method and electrochemical impedance spectroscopy. Che Juntie [13] et al. calculated the data fitting results using the weak polarization zone three-point method through computer numerical fitting, and explored the welding process conditions that can enhance the seawater corrosion resistance of austenitic stainless steel welding joints. The weak polarization zone three-point method can simultaneously measure the Tafel constant and self corrosion current of corroded metals, and is the most commonly used method for measuring corrosion rate in weak polarization measurement technology.

The characteristics of various electrochemical analysis methods are described in Table 3.

Table 3 Analysis methods of electrochemical measurement techniques

Analysis methods	Feature description
Self corrosion potential	Characterize the corrosion state of metals and use it in conjunction with other detection methods.
Dynamic potential polarization curve analysis method	The curve of the relationship between corrosion current density and polarization potential. When the polarization potential deviates sufficiently from the self corrosion potential, the Tafel line extrapolation method is used to measure the corrosion rate of the metal; When the polarization potential deviates significantly from the self corrosion potential, the linear polarization method is used to measure the corrosion rate of the metal.
Electrochemical impedance spectroscopy	Analyze electrode process dynamics, double layer and diffusion by obtaining changes in the response potential or current of the measuring electrode; It can be used to study electrode materials, solid electrolytes, conductive polymers, and corrosion protection mechanisms.
Electrochemical noise analysis	Can be used for continuous monitoring of corrosion; Higher requirements for instrument performance and usage environment, only suitable for laboratory analysis.

Surface analysis technology, also known as corrosion imaging, has intuitive and empirical properties and can be divided into macroscopic and microscopic analyses. It is widely used in corrosion rate research, especially in failure analysis [14]. Macro analysis can be conducted by visually observing the morphological differences of metal materials before and after corrosion and before and after the removal of corrosion products; Microscopic analysis involves comparing and analyzing the microscopic changes before and after metal corrosion using various analytical instruments. Common instruments and techniques include optical metallographic microscopy, scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray photoelectron spectroscopy (XPS).

3.2 Analysis of factors to consider when selecting an appropriate corrosion rate

There are many factors that affect the selection of appropriate corrosion rate measurement methods, mainly including the following aspects:

(1) The first type of corrosion caused: in a multi operating environment, determine the type of corrosion that causes the composite plate to fail first, generally pitting corrosion;

(2) Multiple operating conditions: The operating condi-

tions of MED evaporators are complex and require simulation of actual multiple operating conditions;

(3) Economic feasibility: Determine the actual economic feasibility of the measurement method, with the general quality method having the lowest measurement cost;

(4) If electrochemical method is used to determine the corrosion rate, the most suitable method is the weak polarization zone three-point method.

3.3 Analysis of interference factors in corrosion rate measurement

3.3.1 Temperature interference

The temperature of seawater varies in different regions and times, and the chemical reaction rate of metal corrosion will accelerate with the increase of seawater temperature. Generally, for every 10 ℃ increase in temperature, the corrosion rate will increase to twice the original [15]. Therefore, different temperatures of seawater can lead to differences in the measured corrosion rate.

3.3.2 Interference of seawater flow velocity

The flow rate of seawater is one of the factors that interfere with the corrosion rate. In experimental simulations, when seawater enters the LT MED at a certain flow rate, the composite plate cladding will be subjected to certain erosion, which can affect the corrosion rate of the composite plate cladding. The interference of seawater flow rate on the multilayer corrosion of composite plates is as follows:

(1) When the seawater flow rate is too high, it will cause turbulence and physical erosion of metals. For example, when the seawater flow rate reaches 95 m/s, the seawater flow rate will increase the corrosion rate of titanium [16]; Turbulence can increase dissolved oxygen in seawater and promote the occurrence of metal corrosion reactions.

(2) The flow rate of seawater can also erode the metal corrosion film layer, causing cavitation corrosion [17].

3.3.3 Interference of dissolved oxygen

During the actual simulation experiment, the dissolved oxygen concentration in seawater entering the MED evaporator is constantly changing, which has certain interference with the measurement of corrosion rate of corrosion-resistant stainless steel. Low temperature or low salinity can increase the dissolved oxygen content in natural seawater, thereby accelerating the electrochemical corrosion reaction of composite plate cladding corrosion-resistant stainless steel [18]. However, the increase in dissolved oxygen in seawater also enhances the formation of passivation films on corrosion-resistant stainless steel, reducing the sensitivity of incoming water to local corrosion. Therefore, the influence of dissolved oxygen on the corrosion rate of corrosion-resistant stainless steel in composite laminates cannot be arbitrarily determined, and specific analysis is still needed.

3.3.4 Microbial interference

There are a large number of microorganisms in seawater. When metals are immersed in seawater for a period of time, a layer of "biofilm" will attach to their surface. These biofilms themselves and the metabolites produced by their life activities can affect the metal corrosion process, thereby interfering with the measurement of the actual metal corrosion rate. The common attached organisms in seawater mainly include two types: non hard shelled organisms and hard shelled organisms [19]. These organisms often attach to metal surfaces and can cause corrosion to metals through chemical, physical, electrochemical, and material science reaction processes [20]. When measuring the corrosion rate of metals, marine microorganisms interfere with it as follows:

(1)The biofilm attached to the metal surface will form gaps with the metal surface, and electrolyte solutions such as seawater will cause the metal inside the gap and the metal outside the gap to form a short-circuit primary battery, resulting in gap corrosion [21];

(2) Microbial metabolism produces a large amount of inorganic acids or anaerobic reactions produce organic acidic secretions, which can corrode the coatings and coatings on metal surfaces;

(3) Some microorganisms precipitate hydrogen gas on the surface of metals, causing hydrogen embrittlement of metal materials;

(4) Microbial metabolism can cause differences in the concentration of dissolved oxygen inside and outside the attached biofilm, resulting in an oxygen concentration cell and accelerating metal corrosion. Iron bacteria, sulfate reducing bacteria, etc. are the main participants in microbial corrosion [22–24];

(5) Polymers with multiple functional groups secreted by microorganisms can directly undergo complexation reactions with metal ions, interfering with the determination of corrosion rate.

4 Conclusion and outlook

Through the analysis of corrosion-resistant stainless steel materials in composite plates, it was found that in order to develop new composite plate materials, it is necessary to consider non single corrosion resistance performance and meet the requirements of multiple working conditions for

seawater desalination MED; The substrate mainly serves as the stiffness and strength of the composite plate, while the composite material mainly meets the corrosion resistance performance of the composite plate under multiple working conditions; In the case of complete corrosion of the composite material, it is considered to leave a certain margin, so that when the MED reaches the upper limit of its service life, the substrate can still maintain the structural stability performance of the MED, ensuring the safety of MED equipment operation; Compared with a single corrosion-resistant stainless steel plate, the substrate and composite materials each have their own capabilities, which has certain economic rationality.

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