Analysis of static electric field characteristics of ships in flowing medium

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Abstract. At present, the model of ship corrosion electrostatic field mainly analyzes the electrostatic field distribution in the static medium under the given boundary conditions, without considering the actual corrosion of the metal on the ship's surface in the flowing seawater, and the relationship between the electrochemical corrosion of the metal and the flow of the medium is very large, which results in a large error between the simulation results and the actual measurement results. In this paper, the relationship between corrosion electrostatic field and flow rate in flowing medium is theoretically deduced. Firstly, the distribution of liquid flow rate is analyzed, the thickness of boundary layer on the surface of metal plate is calculated, then the mass transfer process in flowing electrolyte is calculated by combining the flow rate distribution of metal surface medium, and the corrosion current density on the metal surface under the control of mass transfer process is calculated. Finally, the corrosion current density on the metal surface under the control of mass transfer process is calculated. The equivalent source model of electric field is established based on the current density, and the distribution of corrosion electrostatic field in the medium is analyzed. The correctness of the conclusion is verified by the finite element simulation and the ship model experiment.

1. Introduction

When all kinds of ships are sailing in the sea water, the potential difference is formed in the sea water due to the difference of electrode potential of metal materials composed of hull and propeller. When the two materials pass through the sea water, the main shaft and the hull, electrochemical corrosion will occur, and the electrostatic field will be generated in the sea water, which is inevitable. At present, the modeling methods of electrostatic field mainly include equivalent source method, finite element method and boundary element method. The medium conditions of simulation are assumed to be static state [1-3]. In practice, the flow state of seawater environment will directly affect the size of electrostatic field [4]. The relative speed of ship and sea water will change with the sea condition and speed. The propeller surface as cathode will accelerate the mass transfer process of oxygen molecules to the propeller surface and accelerate the corrosion of ship hull with the increase of rotating speed, and the relative speed of sea water and ship hull will generate greater surface shear stress on the ship hull surface, resulting in the damage of ship hull surface. The oxidation products of the raw metal will fall off and expose the bare steel due to stress, which will further corrode the hull [5]. In addition, the
conductivity in seawater is realized by the directional movement of conductive ions in seawater. The flow of seawater will destroy the movement state and the distribution state of ion concentration, resulting in the uneven distribution of current density in the medium. For the sea water domain, it can be regarded as a constant flow field for research. Because the static electric field intensity is proportional to the current density at any position in the sea water, the uneven distribution of the current density caused by the sea water flow will directly affect the distribution of the static electric field intensity.

The above analysis shows that by introducing the theoretical basis of electrochemical corrosion of metals in flowing medium, the actual analysis and solution of the hull model are carried out, and the expression of corrosion current density obtained by the solution is improved and optimized to the current equivalent source model, so that the calculation results can better reflect the distribution of corrosion electrostatic field in the actual flowing sea water.

2. Electrostatic field generated by metal plate model in flowing medium

In order to study the corrosion electrostatic field of ships in seawater, the relationship between the corrosion electrostatic field and the flow velocity in laminar media is theoretically deduced. According to the theory of viscous flow and turbulent flow in modern hydrodynamics, when the solid metal is placed in the flowing medium, the flow state of the medium within a certain range from the metal surface due to the resistance generated by the metal surface presents a ladder like distribution, and the flow state of the medium in the transition area is approximately a laminar flow state [6,7]. In reference [8] and [9], the local equivalent of the surface wall of a complex object to a plate model is carried out by using the theory.

2.1. The boundary layer when the velocity of medium flows parallel to the plate

In order to study the mass transfer process on the surface of the plate, two metal plates in the medium are first connected by wires to form a circuit in the medium. In order to facilitate the calculation, the flow direction of the fluid is parallel to the electrode surface and starts to contact the metal plate surface at the origin of the coordinate, and the diffusion layers on the surface of the two metal plates do not interfere with each other. Because of the existence of the viscosity coefficient of seawater, the solution of the fluid boundary layer on the metal surface is needed before the solution of the corrosion current.

According to the concept of fluid boundary layer, it is impossible to get the thickness of boundary layer accurately, because the viscous effect of medium will be considered in the boundary of thin plate surface, and its effect will gradually decrease with the increase of the vertical distance from the plate, and the velocity component \( u \) will gradually approach the main body velocity \( u_0 \). It is pointed out in most literatures on fluid mechanics that the vertical effect of velocity component \( u \approx 0.99 u_0 \) can be considered the straight distance \( z \) is specified as the thickness of the boundary layer \( \delta_0 \). The thickness of fluid boundary layer \( \delta_0 \) is

\[
\delta_0 \approx 5 \frac{\nu x}{u_0}
\]

where \( \nu \) is the kinematic viscosity coefficient of the medium, and the kinematic viscosity coefficient of sea water is generally 0.01~0.02 cm\(^2\)/s. \( u_0 \) is the flow rate of the main medium.

2.2. Solution of current density of plate surface corrosion

When calculating the mass flow due to diffusion, we should first know the thickness of the diffusion layer. We can deduce the expression of the thickness \( \delta_z \) of the diffusion layer as follows
\[ \delta_0 \approx \left( \frac{D_i}{\nu} \right)^{1/3} \delta_0 = 5D_i^{1/3} \nu^{1/6} x^{1/2} u_0^{-1/2} \]  

where \( D_i \) is the diffusion coefficient of the particle \( \nu \); \( \delta_0 / \delta \approx Sc^{-1/3} \) is the Schmidt number.

When electrochemical reaction occurs on the metal surface, the reaction process is mainly on the surface of the metal plate, which will lead to the concentration difference of the reaction particles in the diffusion layer. It is mentioned in reference [10] that oxygen will form a diffusion boundary layer in the fluid boundary layer in the process of mass transfer. The thickness of the diffusion layer is generally much smaller than that of the boundary layer. Because the thickness of the diffusion layer is very small, the concentration of reactants in the diffusion layer can be regarded as a uniform linear distribution

\[
J(x, z) = \frac{nF}{\lambda_i} \left\{ D_0^{2/3} u_0^{1/2} \nu^{-1/6} x^{-1/2} (c_0 - c_s) + \frac{1.33 u_0^{1/2} z^2}{16 \nu^{1/2} x^{3/2}} \left[ \frac{0.22 \nu / D_i}{1.3} \right] c_0 \int_0^z \sqrt{\frac{z}{x}} \exp(-0.22\nu \omega^3 / D_i) d\omega + c_s \right\}
\]

where \( c_0 \) is the concentration of oxygen in the medium; \( c_s \) is the concentration of oxygen after the reduction reaction on the surface of the plate; and \( \lambda_i, n \) are respectively the number of reactions and electron transfers of \( i \) substances in the electrochemical reaction; \( F = 96500 \) is the Faraday constant; \( \omega \) is the velocity component in the direction \( z \).

### 2.3. Electrostatic field produced by metal plate model in seawater

Three components of electrostatic field in medium can be calculated by using \( E = -\nabla \varphi \)

\[
Ex = -\frac{\partial \varphi_2}{\partial x} = \sum_{i=0}^{W/d_1} \sum_{n=0}^{L/d_2} Jdx \left( x - x_n \right) \left\{ \frac{1}{R_1^3} + \sum_{m=0}^{\infty} \gamma_{32} \left[ \frac{\gamma_{23}}{R_1^3} - \frac{1}{R_2^3} + \frac{\gamma_{23}}{R_3^3} - \frac{\gamma_{23}}{R_4^3} \right] \right\}
\]

\[
Ey = -\frac{\partial \varphi_2}{\partial y} = \sum_{i=0}^{W/d_1} \sum_{n=0}^{L/d_2} Jdx \left( y - y_n \right) \left\{ \frac{1}{R_1^3} + \sum_{m=0}^{\infty} \gamma_{32} \left[ \frac{\gamma_{23}}{R_1^3} - \frac{1}{R_2^3} + \frac{\gamma_{23}}{R_3^3} - \frac{\gamma_{23}}{R_4^3} \right] \right\}
\]

\[
Ez = -\frac{\partial \varphi_2}{\partial z} = \sum_{i=0}^{W/d_1} \sum_{n=0}^{L/d_2} \frac{Jdx}{4\pi \sigma_2} \left( \frac{z - z_0}{R_1^3} + \sum_{m=0}^{\infty} \gamma_{32} \left[ \frac{\gamma_{23}}{R_1^3} \right] \left[ \left( z - z_0 \right) + 2(m + 1)(H + h) \right] \right)
\]

where \( \varphi_2 \) is the potential generated by the point charge in seawater; \( \sigma_2, \sigma_3 \) is the conductivity of seawater and seabed respectively; \( \gamma_{23} = \frac{\sigma_2 - \sigma_3}{\sigma_2 + \sigma_3} \); \( J \) is the corrosion current density; \( H \) is the depth...
of seawater; \( h \) is the distance between the metal plate and the water surface; the position of the point charge is \( \left( x_0, y_0, z_0 \right) \).

For the corrosion electrostatic field of iron plate in the medium, the distribution of current density on the surface of iron plate can be reasonably assumed according to the current density on the surface of copper plate. According to the method of generating electrostatic field on the surface of copper plate in the medium, the electrostatic field generated when the metal is galvanically corroded in the sea water can be calculated by the superposition principle.

3. Finite element simulation of electrostatic field in flowing medium

In the study of the corrosion electrostatic field under the condition of flowing medium, the seawater medium can be regarded as a constant flow field, and the distribution of the electric field in the medium can be calculated indirectly by the current density distribution in the medium. It is assumed that the oxygen concentration in seawater is 0.01 mol/L. The change of velocity results in the increase of electric field amplitude, and the increase of electric field modulus decreases with the increase of velocity. The main reason is that the larger the velocity of medium, the thinner the boundary layer on the hull surface, and the smaller the change of the thickness of boundary layer with the change of velocity. The variation curve of corrosion electrostatic field amplitude and mode value with flow velocity at 1 m below the center of ship model is shown in Figure 1.

![Fig. 1. Simulation of the relationship between three components of electric field and velocity of flow](image)

4. Electrostatic field experiment of ship model corrosion in flowing medium

In order to verify the theoretical and simulation results, the distribution of electrostatic field at different velocity is verified by the ship equivalent hull model.

In the process of ship model measurement, the electrostatic field is measured through the characteristic curve. The sensor is fixed at the bottom of the pool. The measurement process is divided into forward measurement and backward measurement. The sensor layout and measurement path are
shown in Figure 2. The transverse distance between the ship model and the sensor is 1.5m, which is about the length of a ship model. The experimental results can be approximate to the far-field measurement of electrostatic field.

In the process of making the ship model, the hull and propeller materials are the same as the real ship. The hull material is 921A steel, and the propeller copper material is B10, so as to reduce the error caused by the hull material itself. In the process of experimental measurement, the flow state of the medium is simulated by controlling the water output of the circulation pipe.

Fig. 2 Measurement processes on different paths, The hull with paint coating and the copper propeller constitute the galvanic corrosion system in the medium. The ship model is placed in a pool with conductivity, and the draft of the ship model in the medium is about. During the experiment, the ship model is moved by electric motor, and the forward and backward speeds are both. The static electric field generated when the ship model moves forward and backward under the conditions of and two kinds of medium flow is compared respectively, and the results are shown in Fig. 3 and Fig. 4.

(a) Actual measurement path  
(b) Schematic diagram of measurement path

Fig. 2. Measurement processes on different paths

(a) $E_x$
(b) $E_y$
(c) $E_z$
(d) $|E|$

Fig. 3. Electrostatic field at different velocities in advance
It can be seen from Fig. 3 and Fig. 4 that the variation rule of corrosion electrostatic field passing through the characteristic curve at different flow rates is basically the same. The main reason for the time displacement is that the difference between the measurement acquisition time and the time when the ship model starts moving in the actual measurement process results in different sampling periods.

From the point of view of electric field amplitude, the change of the peak value of electrostatic field at different velocity is not obvious, and the three components of electric field and the magnitude of mode value are basically the same, which shows that when the coating on the hull surface is well protected, it is less affected by the change of medium flow state. The main reason is that due to the existence of coating on the hull surface, the medium penetrates into the hull surface through the coating gap and reacts with the metal As a result, the corrosion electrostatic field will be generated. At the same time, the existence of the coating is not conducive to the transmission of conductive ions in the sea water circuit. Therefore, the increase of the flow rate will not significantly change the corrosion electrostatic field between the shell with the coating and the propeller.

5. Conclusion
In this paper, a simple plate model is established to obtain the corrosion current density of the metal surface in the flowing medium, and the curve of the corrosion electrostatic field at any position in the medium with the flow rate of the medium is obtained. The results are verified by finite element simulation and experiment, and the following conclusions are obtained:

(1) Generally, with the increase of flow rate, the electrostatic field in the medium will increase with the increase of flow rate;

(2) When the coating on the hull surface is well protected, the electrostatic field is less affected by the change of medium flow state.
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