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Ai-ping WANG

Min DU

Qing-zhang WANG

Sheng-shan CAO

Ji-xing SUN

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Construction of Three-Dimensional Finite Element Model for Complicated Cathodic Protection System

WANG Ai-ping[1*], DU Min[2], WANG Qing-zhang[2], CAO Sheng-shan[3], SUN Ji-xing[3]
(1. Institute of Material Science and Engineering, 2. College of Chemistry and Chemical Engineering, 3. Department of Mathematics Ocean University of China, Qingdao 266100, Shandong, China)

Abstract: When condensers with carbon steel waterbox and titanium tube structure were protected by SACP in an ocean beach power plant, while seawater were used to be cooling water, carbon steel was under-protected and Titanium was over-protected, because their protective potential are less than −0.85V (vs. SCE) and more than −0.75V (vs. SCE) separately. In order to optimize the SACP design, potential distribution of two materials must be obtained during the SACP process. In the lab, carbon steel waterbox and Titanium tube model (Q235-Ti model) were set up. A series of electrochemical techniques (steady polarization, galvanostatic charge technique) were used to obtain reasonable boundary condition and surface form of two materials during the SACP process. The experiments were carried out to validate 3-D potential distribution under one anode SACP condition by finite element method (FEM). The calculation results were consistent with measuring results. The results can be used to provide a theoretical foundation to design an optimal cathodic protection.

Kerwords: condenser; cathodic protection; FEM; potential distribution
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1 Introduction

Seawater is used to be cooling water in beach power plant. Condensers, as the main part of cooling system, were consisted with carbon steel waterbox and titanium tube. Carbon steel and titanium compose galvanic couple, so galvanic corrosion always happened and caused vast economic loss to power plant.

Cathodic protection (CP) is one of the most widely used methods of protecting metallic structure against corrosion. It can prevent or reduce the corrosion of any metal or alloy exposed to an aggressive environment. Basically, this technique is accomplished by impress current cathodic protection (ICCP) or sacrificial anode cathodic protection (SACP)[1]. The use of sacrificial anodes has also been studied to provide cathodic protection for condenser in seawater.

Carbon steel was always under-protection and titanium was over-protection in cathodic protection, because their protective potential are less than −0.85V (vs. SCE) and more than −0.75V (vs. SCE) respectively. Hydrogen embrittlement for titanium occurs easily under over-protection.

In order to avoid above phenomena, it is very necessary to design reasonable SACP system to obtain the reasonable current density and potential distributions across the protected surface. Mathematical model of potential distribution was build to suggest optimums SACP system including the optimum anode location and impressing current of anodes. Numerical

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method is versatile in handling problem of complex structure in complex environment[2-4].

Q235-Ti model was designed according to condenser structure in a beach power plant. The area ratio of Q235 to Ti was 55∶1 in Q235-Ti model and the size of Q235 water-box was 200 mm×200 mm×400 mm and Ti tube was 400 mm long.

Finite element method (FEM) was applied to calculate 3-D potential distribution of the Q235-Ti model in this paper.

2 Mathematical Model

When the electrolyte can be considered to be homogeneous, the calculation of potential distribution on a cathodically protected structure in seawater first requires the solution of Laplace's equation for the distribution of potential in the bulk of seawater[5-13]:

$$\Delta^2 E = 0 \tag{1}$$

In order to obtain a complete solution to this equation, the potential is required to satisfy certain conditions specified for the anode and cathode surface. Since the sacrificial anodes can be assumed to operate at a constant value, the surface condition pertaining to the anodes can be stated simply in the form.

$$E = E_{anode} \tag{2}$$

The complexity of physical, chemical, and biological phenomena occurring on the cathode surface (carbon steel and titanium tube) does not permit a simple relationship of current density and potential, especially in complex structure consisted of different metals. For Q235, such a relation is governed almost entirely by the properties of calcareous deposits formed on the steel surface during cathodic protection[1]. For titanium, multilayer titanium oxides are formed easily in cathodic polarization, and configuration of surface does not change evidentially.

The current density on cathode surface can be expressed mathematically as following when in fixed pressure, temperature, velocity of medium, initial surface condition, and seawater chemical property.

$$i = -\kappa \frac{\partial E}{\partial n} \tag{3}$$

Where κ is the conductivity of seawater, E is the potential of cathode surface measured by a reference electrode adjacent to the surface, n is normal vactor in the direction of current flow.

If the polarization is at steady condition, the relation of i and E on metal/electrolyte interface can be expressed as following.

$$i = \frac{1}{R_p}(E - E_c) \tag{4}$$

Where R_p is called polarization resistance and E_c is the open circuit potential of the protected metal.

So the equation as following is obtained by two equations above.

$$-\kappa \left.\frac{\partial E}{\partial n}\right|_r = \frac{1}{R_p}(E - E_c) \tag{5}$$

To obtain mathematical model. The Laplace's equation need be solved with boundary conditions reflecting the relationship between the potential and the current density and how this relation changes with time, at same time it is necessary to retrieve polarization data compatible with actual state of the structure.

In Q235-Ti model, Q235 steel and titanium have different cathodic polarization characteristics, the relationship between the potential and the current density and how this relation changes with time are different. Two different equations must be used in boundary condition.

$$-\kappa \left.\frac{\partial E}{\partial n}\right|_{r1} = \frac{1}{R_{P1}}(E - E_{c1}) \tag{6}$$

$$-\kappa \left.\frac{\partial E}{\partial n}\right|_{r2} = \frac{1}{R_{P2}}(E - E_{c2}) \tag{7}$$

Where $\Gamma 1$ represents surface of Q235 steel and $\Gamma 2$ represents Titanium, E_{c1}, E_{c2} are the open circuit potential of the Q235 steel and Titanium respectively, R_{p1}, R_{p2} are the polarization resistance of Q235 steel and Titanium respectively.

3 Experimental Results

In order to achieve mathematical models of SACP, the critical aspect of solving the Laplace's equation is appropriate boundary condition by polarization curve, which is a non-linear relationship between the two main variables, polarization potential and polarization resistance.

Q235 and Ti specimens with exposed surface ar-

ea of 1 cm^2 were embedded in araldite. The specimens were given a metallographic polishing prior to each experiment, followed by washing with distilled water and acetone. Polarization measurements were carried out using a three-electrode configuration, saturated calomel electrode (SCE) was used as reference electrode, a platinum electrode as counter one. In the paper, potential values compare to SCE. HDV-7 potentiostat was used in steady polarization experiments. Electrochemistry measurements were performed using M6e (ZAHNER, Germany) electrochemistry workstation. Cathodic polarization for the two metals was carried out in different potential scale according to practical potential in CP.

1) Boundary condition experiments about Q235 [14-20] were following.

In the experiments, the changes in corrosion current density with time from weak polarization were obtained after potentiostatic polarization at −0.800 V, −0.850 V, −0.900 V in seawater. Potentiodynamic measurements were performed at a potential scanning rate of 1 mV · s^{-1}. The calculated R_p were list in Table 1.

2) Boundary condition experiments about Ti were following.

Titanium is prone to passivation in seawater. Multilayer titanium oxides were formed easily and intermediate resistance was steady[22]. The open circuit potential moved towards less negative values continuously. Galvanostatic charge technique was used to measure electrochemical parameter of Ti after polarized at −0.65V, −0.70V and −0.75V respectively. The date fitting process for galvanostatic charge curve was programmed by MATLABE computer language based on linear regression. The calculated R_p were list in Table 2.

The design protection current densities for Q235 and Ti were 90 mA/m^2 and 55 mA/m^2 respectively. Al-

Tab. 1 Variation of R_p with polarization time for Q235 in seawater after polarized at different potential calculated by dynamic polarization curves

Polarization	Potential −0.800V							
Time/h	13	25	37	39	42.5	44.5	48.5	
R_p / kΩ · cm^2	19.608	15.891	10.331	9.759	9.894	9.811	6.015	
Polarization	Potential −0.850V							
time/h	6	11.5	24	30.5	35	47.5	54.5	59.5
R_p / kΩ · cm^2	6.973	9.122	9.795	14.979	18.226	20.901	21.6	22.105
Polarization	Potential −0.900V							
time/h	5	12	24	48	60	144	192	280	384
R_p / kΩ · cm^2	2.260	2.935	2.609	6.245	10.422	15.858	17.478	20.982	18.890

Tab. 2 Variation of the R_p with polarization for Ti in seawater time after polarized at different potential calculated by the galvanostatic charge curves

Polarization	Potential −0.650V								
time/h	3	18	29	55	78	102	119	135	142
R_p / kΩ · cm^2	13.6	6.5	4.3	4.7	9.6	4.5	3.7	8.3	5.7
Polarization	Potential −0.700V										
time/h	13	19	21	37	44	61	85	97	110	120	133
R_p / kΩ · cm^2	14.5	13.5	7.6	2.6	3.2	2.8	3.8	3.5	2.4	3.6	2.6
Polarization	Potential −0.750V									
time/h	7	19	25	43	60	69	86	91	110	
R_p / kΩ · cm^2	14.3	14.4	10.5	7.7	6.2	5.9	10.8	5.9	5.1	

Zn-In sacrificial anode was used for CP system. Fig. 1 depicts location of the sacrificial anode in Q235-Ti model.

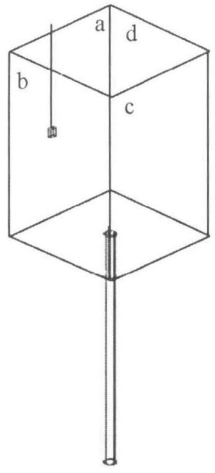

Fig. 1　The sketch of sacrificial anode in Q235-Ti model (□ denote Al-Zn-In sacrificial anode)

The side which attached the sacrificial anode was defined as the a-side. And the rest sides in anticlockwise were defined as b, c, d. Fig. 2 shows potential distributions by measuring in a, b, c, d sides in Q235-Ti model in turns.

In Q235-Ti model, cathode potential and current provided by anode rapidly decrease with time at the beginning of polarization. After about 100 h, the current density decreases slowly and reaches apparent steady-state value at approximate 240 h.

4　Mathematic Model Analysis and Calculated Result

The boundary of the Q235-Ti model was discretized into tetrahedron unit as shown in Fig. 3. Appropriate function was applied for discrete structure surface and its environment. Through analysis of each unit and synthesis in the whole area, the FEM was used to obtain the numerical solution of mathematical model.

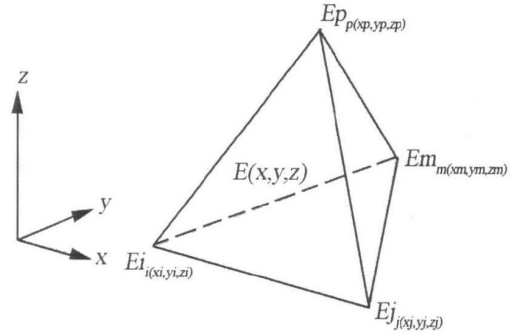

Fig. 3　The sketch of tetrahedron

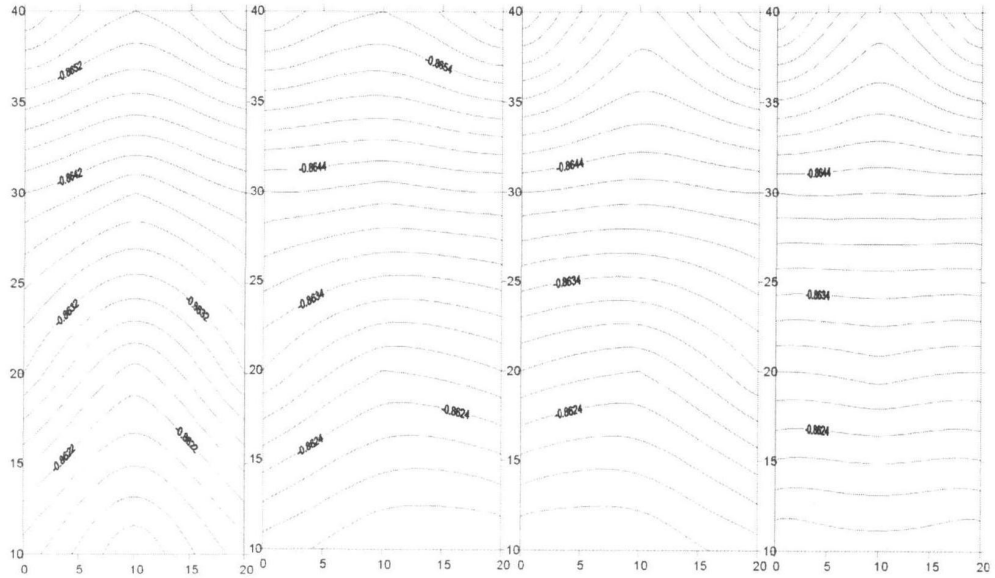

Fig. 2　The distribution of potential in water box with one anode (cm · V)

In the numerical procedure for calculating potential distributions the R_p can be either a constant or a variable of E. If R_p is a constant which is a good approximation in many activation controlled polarizations the constant is R_p assigned to all elements on the interfaces The potential distribution is obtained by solving Equation (1) only once However R_p in many corrosion systems is not a constant but is a function of E. In this case the potential distribution was obtained by iteration of R_p. After a period of protection in Q235-Ti model new R_p values were selected for individual elements on the surfaces based on the new potentials at the metal surfaces This procedure is repeated automatically by computer until the potential closely match the previous iteration and at this point the solution has converged.

Fig 4 shows the calculated Q235 surface potential distribution by mathematical model on Q235-Ti model in SACP system in seawater. Side b is symmetry of an equivalence relation to side d. Potential distribution of side b is same as side d. Potential distribution of underside of Q235 waterbox was depicted in Fig 4e

Fig 5 shows the Ti-tube potential distribution. Application of the mathematical model were used to calculate the potential distribution of Q235-Ti model with one anode and two anodes in dilution seawater whose conductivity is the 1/10 of that of seawater by diluting with deioned water the results of potential distribution in mathematical model were consist with potential distribution by measurement

5 Conclusions

FEM formulation was successfully used to calculated potential distribution in cathodic protection in complex construction based upon Laplace's equation.

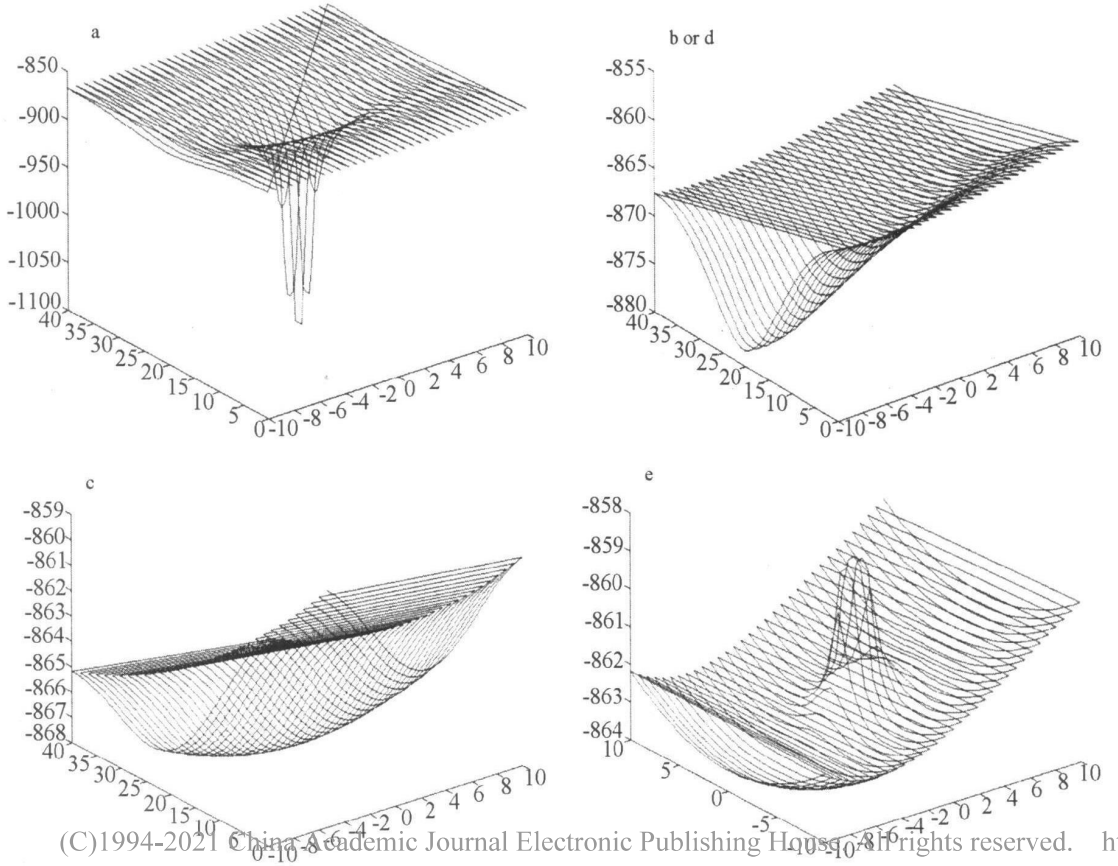

Fig 4 Potential distribution for Q235 surface by calculation(cm· mV)

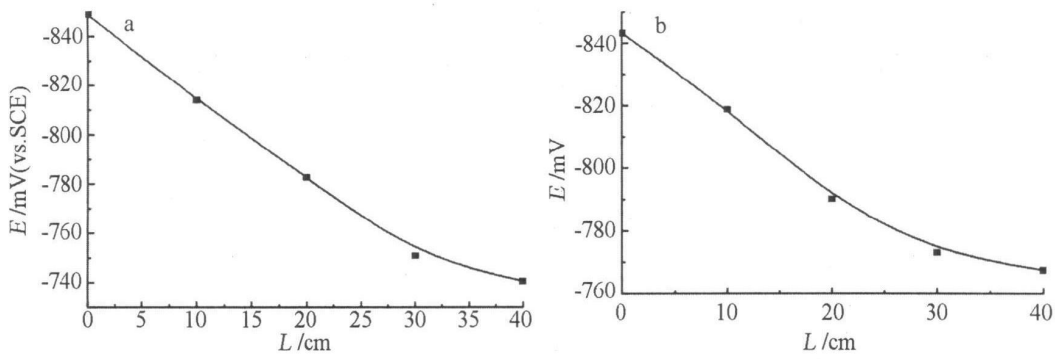

Fig 5　Potential distribution for Ti-tube　a) measured data　b) calculated data

Mathematical model of 3-D for water-box model was constructed. Mathematical model is feasible and available by comparing measured data and calculated data.

The use of modeling to simulate the detailed behavior of a SACP system reduces the uncertainty of the system's performance.

FEM can be applied to calculate 3-D potential distribution of the Q235-Ti model under different SACP conditions such as anode numbers, anode position etc. Computer modeling may also be used to predict potential in inaccessible part. For examples, potentials distribution for condenser in beach power plant can be predicted based on mathematical model.

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复杂阴极保护体系三维有限元建模研究

王爱萍[1*]，杜 敏[2]，王庆璋[2]，曹圣山[3]，孙吉星[3]

(中国海洋大学 1.材料科学工程研究院，2.化学化工学院，3.数学系，山东 青岛 266100)

摘要： 滨海电厂常以天然海水作冷却水，其碳钢水室和钛管凝汽器在实施阴极保护过程中，要求钢电位应低于 −0.85V(vs. SCE)，电位过正则碳钢保护不足，而钛的电位则须高于 −0.75V(vs. SCE)，电位过负则易使钛管发生氢脆损伤.研究牺牲阳极阴极保护，需先得出两种金属在阴极保护过程中的电位分布.本文在设计室建立碳钢水室钛管模型，根据该实验体系阴极保护过程的的(稳态极化和恒电流极化)测定获得两种金属有效的边界条件，用有限元(FEM)计算在一个牺牲阳极阴极保护状态得到三维电位分布.计算结果和测量结果基本一致，为优化阴极保护设计提供了理论依据.

关键词： 凝汽器；阴极保护；有限元；电位分布