EVALUATION OF THE SACRIFICIAL ANODE CATHODIC PROTECTION OF CARBON STEEL IN 0.5M NACL USING EXPERIMENTAL DESIGN

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ABSTRACT

This study examined the effect of Temperature (T); flow rate(F); and pH ; on the zinc consumption as sacrificial anode in cathodic protection of steel pipe carrying saline solution (i.e., 0.5 M NaCl) using a 2^3 factorial design. Rates of zinc consumption during cathodic protection were measured by weight loss technique and it ranges from $7.5x10^{-3}$ to $98.9x10^{-3}$ g/cm^2.day. For the system under investigation, the cell responsible for cathodic protection is Zn/NaCl/Fe

It was found that both temperature and flow rate increases the zinc consumption while pH decreases it sharply.It was found also that the interaction between the temperature and pH is the dominant term compared with other interactions.

الخلاصة

هذه الدراسة اختبرت تأثير درجة الحرارة ،سرعة جريان سائل المحلول الملحي وحامضيته على استهلاك الزنك كمضحي انودي في عمليه الحماية الكاثوديه لأنبوب حديدي بأستعمال تقنية تصميم التجارب.ان معدلات استهلاك الزنك اثناء عمليه الحماية الكاثودية تم قياسها بتقنية الفقدان بالوزن و كانت مدياتها تتراوح بين 0.0075 و 0.0989 غم/سم2.يوم. الخلية الكهروكيميائية المسؤوله عن الحماية الكاثودية في النظام قيد الدراسة كانت زنك/محلول ملحي/حديد.لوحظ ان درجة الحرارة و سرعة جريان السائل تزيد من استهلاك الزنك كمضحي انودي بينما حامضية السائل تقلل من ذلك بشدة.كذلك لوحظ ان التداخل بين درجة الحرارة و حامضية السائل هي السائدة مقارنة مع بقية التداخلات.

KEY WORD
Sacrificial anode, Cathodic protection, Seawater, Factorial design.

INTRODUCTION

Without some forms of protection, Steel is very susceptible to degradation in chloride- containing environments. To prolong the lifetime and functioning capability of steel, one of the most effective forms of protection is sacrificial anode cathodic protection. Sacrificial anode protection is called "sacrificial" because the anode is thought of as " sacrificing" itself to protect the structure. This type of protection utilizes a galvanic cell consisting of an anode made from a more active metal than the structure , so this method is also called galvanic anode protection. Sacrificial anodes require no external power. The protection current comes from the electrochemical cell created by the connection of the anode material to the more noble or electrically positive metal of the structure [Ulig, 2000]. In a galvanic couple between dissimilar metals, the galvanic current cathodically protects the more noble metal and preferentially dissolves the more active metal. Electrons flow from the active sacrificial anode to the noble cathode structure. The anodic reaction at the cathode structure, for example:

$$Fe \rightarrow Fe^{+2} + 2e$$

, is reduced by surplus of electron provided by the sacrificial anode . At the same time, the reduction of dissolved oxygen by reaction:

$$O_2 + 2H_2O + 4e \rightarrow 4OH^-$$

Or the evolution of hydrogen:

$$2H_2O + 2e \rightarrow H_2 \uparrow + 2OH^-$$

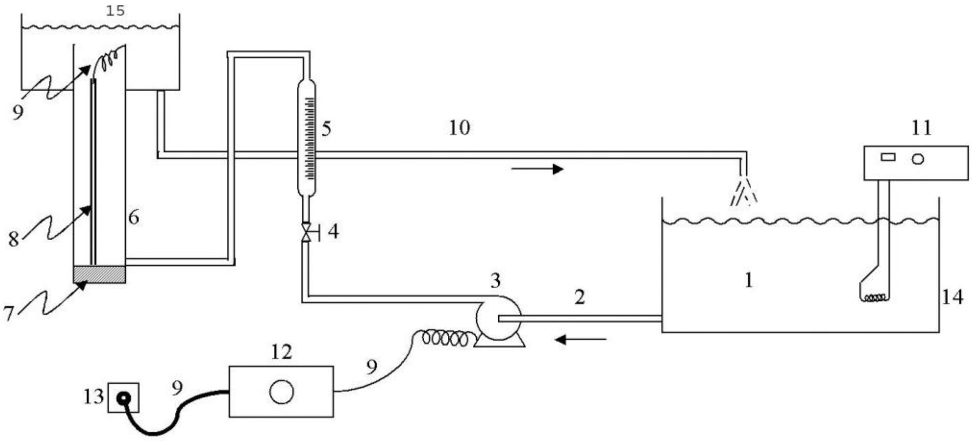
is accelerated . The cathode structure is cathodically protected, and the same electrochemical reactions are present at the cathode as when polarization is provided by impressed current.[Davies,2003].

The aim of the present work is to study the effect of different operating parameters such as temperature, flow rate and pH on the rate of zinc consumption during cathodic protection of a steel pipe carrying 0.5M NaCl solution adopting 2^3 factorial design. Cathodic protection was carried out by extending a zinc strip along the steel tube to ensure uniform current and potential distribution along the wall tube.

APPARATUS AND PROCEDURE

The apparatus (fig.1) consists of an insulated 6 liters storage reservoir, 210 watt pump of capacity 11.4-54.6 lit/min and a vertical pipeline. The pipeline was made of low carbon steel of chemical composition: C%=0.1648; si%=0.254; Mn%=0.51; s%=0.0062; Cr%=0.0253; Ni%=0.009; Cu%= 0.1511; V%=0.0034; Fe% the remainder.

The tube dimensions were: 13.5 cm length; 2.68cm inside diameter and 0.31 cm thick. A zinc strip of 12.5 cm length and a 1 cm width, 0.6 cm thick was extended along the axis of the low carbon steel tube. The zinc strip was fixed at the inlet and was electrically connected by a wire to the low carbon tube outlet.



1. Electrolyte (seawater)	2. Feed forward Pipe	3. Pump	4. Valve	5. Rota meter
6. Tube steel	7. Rubber stopper	8. Zinc strip	9. Copper wire	10. Feedback pipe
11. Heater or chiller	12. Variac	13. Electric source	14. Insulated vessel	15. Overflow

Fig (`1): Schematic diagram of apparatus used in sacrificial anode test system

Before each run, a weighed zinc strip was fixed inside a low carbon pipe and 6 liter of 0.5 M NaCl solution after adjusting its pH was placed in the storage tank. The solution was circulated between the pipeline and the storage tank by the pump. Solution flow rate was measured by a rotameter placed after the pump and adjusted by a valve. Temperature was controlled by thermostat heater or chiller, duration of experiments was fixed at 4 h’s . After each run, the zinc strip was rinsed in distilled water, dried and reweighed.

Experimental Design and Analysis:

Factorial design [Balton, 1984 and Armstrong, 1990] is an experimental technique by which factors involved in a process can be identified and their relative importance assessed. It is thus a means of separating those factors that are important from those that are not, and identifying the interactions, if any, between the factors chosen. Thus the construction of a factorial design involves the selection of parameters and the choice of responses. A 2^3 factorial design was used to determine the effect of temperature , flow rate and pH, on the zinc consumption used as sacrificial anode in protection of iron pipe carrying seawater (0.5M NaCl solution). To observe a significant weight loss (zinc consumption) for each experiment, duration time was fixed at four hours. The factors and the levels are shown in table (1). The matrix of the factorial design is shown in table (2).

Table (1) Factors and levels used in the 2^3 factorial design.

Factor	Low level	High level
T: temperature, ºC	15	45
F: Flow rate ,L/h	300	900
pH: pH of solution	2	8

Table (2) Matrix of the 2^3 factorial design zinc consumption in sacrificial anode used in steel protection *

Exp. No.	Factor T	Factor F	Factor PH	Zinc Consumption (mg/cm²)
1	-1	-1	-1	7.94
2	+1	-1	-1	13.89
3	-1	+1	-1	11.12
4	+1	+1	-1	16.48
5	-1	-1	+1	2.16
6	+1	-1	+1	3.210
7	-1	+1	+1	2.56
8	+1	+1	+1	3.72

*-1, Low level of the factor; +1, high level of the factor.

Result and Discussion:

The results for the zinc consumption as weight loss in (mg/cm^2) during cathodic protection are listed in table (2). Based on the data [Khalid, 2006], the main effects of the factors under study and their interaction were calculated, table (3).

Table (3) Effects and interactions of the selected factors on the zinc consumption used as sacrifice in cathodic protection of steel.*

Factor	Main Effect or interaction
T	3.40
F	1.70
pH	-9.40
TXF	-0.12
TXpH	-2.30
FXpH	-1.22

* T indicates Temperature (°C); F, Flow rate (L/h); pH, acidity of the solution.

Table (3) shows that an increase in the both the temperature of the solution and its flow rate results in an increase in zinc consumption. while the pH of the solution sharply reduces, the zinc consumption within the range studied.

IN other words: The relative importance of main effect coefficients in present investigation indicates that the effect of temperature, flow rate, and pH with coefficient 3.4, 1.7 and -9.4 respectively is not the same (i.e., Temperature and flow rate lead to increase zinc consumption while PH of the solution induces a retarding influence). With factors combined effects, as measured by (TXF),(TXpH) , and (FXpH) are appreciably pronounced in reducing zinc consumption, but still (TXpH) term is the dominant term. According to previous explanation , it can be stated that: The alkaline conditions promoted by cathodic protection in seawater deposit calcareous scales on the surface, while reduce corrosion rates and necessary cathodic protection currents. i.e.,

The reduction reactions:

$$O_2 + 2H_2O + 4e \rightarrow 4OH^- \quad \dots (1)$$

And

$$2H_2O + 2e \rightarrow H_2 \uparrow + 2OH^- \quad \dots (2)$$

Increase pH at the protected surface by generation of OH^- during cathodic polarization . To some degree this is beneficial, because the ferrous alloys are resistant to mildly alkaline solutions in which a protective oxide film is stable. Also generation of OH^- in seawater. deposits calcareous seals by reaction with dissolved calcium and magnesium ions:

$$Ca^{+2} + HCO_3^- + OH^- \rightarrow H_2O + CaCO_3 \quad \dots (3)$$

$$Mg^{+2} + 2OH^- \rightarrow Mg(OH)_2 \quad \dots (4)$$

Seal deposition causes a continuous decrease in limiting current density for O_2 reduction as scale thickness increases. The current necessary for cathodic protection decreases correspondingly.

To develop a response surface equation to predict the zinc consumption during cathodic protection, the data were analyzed using a commercially available package (statistica). A 2^3 fractional design was used for response surface analysis. The design was chosen because it allows the estimation of complex response functions up to the quadratic order [Box, 1978]. The design of selected experiments as well as the zinc consumption values is shown in table (2). To follow the levels adopted in this design, the factors studied needed to be decoded. The decoding formula was as follows:

$$Coded\ \ variable = \frac{(uncoded\ \ value - 0.5x(high\ \ value + low\ \ value)}{0.5x(high\ \ value - low\ \ value)} \quad \dots (5)$$

The polynomial equation obtained, correlates the temperature(x_1), the flow rate (x_2) and the pH of the seawater (x_3) with the amount of zinc consumption (y) was:

$Y= 7.64+1.7x_1 +0.86x_2-4.7x_3-0.06x_1x_2-1.15x_1x_3-0.61x_2x_3$ … (6)

Where x_1 , x_2 and x_3 are in their coded values.

Equation (6) is statistically acceptable with a correlation coefficient of 0.98.

The effect of solution temperature and pH on zinc consumption for the solution flow rate at its minimum and maximum level (i.e., 300 and 900 L/h) respectively can be seen in figure (2 and 3).

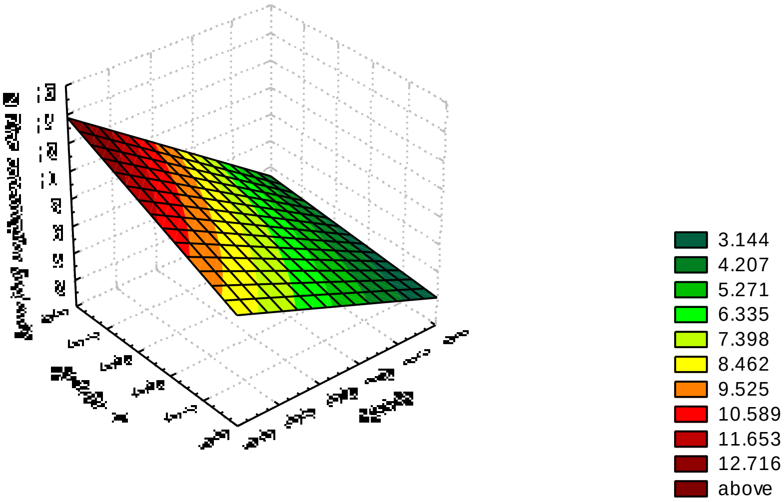


Fig (2) Effect of solution temperature and pH on zinc consumption as sacrificial anode; F= 300 L/h (-1).

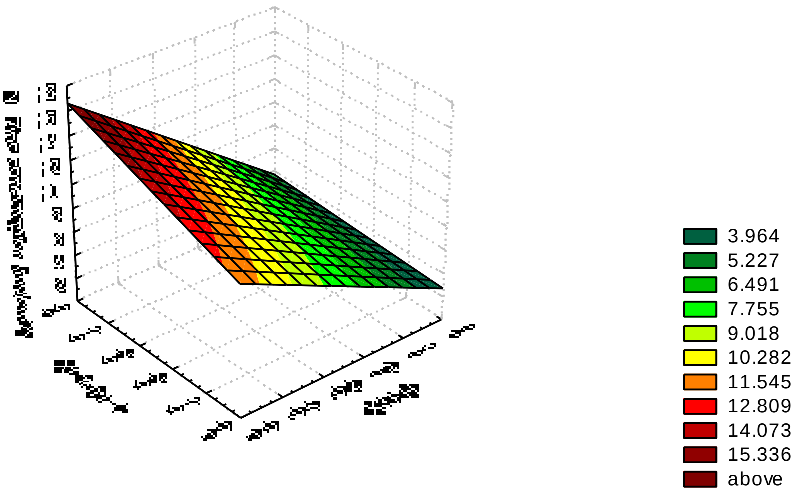


Fig (3) Effect of solution temperature and pH on zinc consumption as sacrificial anode; F= 900 L/h (+1).

It is clear from figure (2) that when the solution pH is at its maximum level, 12 (coded +1), the zinc consumption is about 3.144 mg/cm^2 .This amount increases as the temperature increased and the solution pH shifted toward acidic (i.e. pH=2, coded -1), until it reaches about 13mg/cm^2 at pH=2 and the temperature is 45°C . This means that the zinc consumption increases about 4 times with pH shifting .Same behavior can be seen in figure (3), but in this case the zinc consumption is more pronounced with flow rate increase to 900 L/h.

Conclusions

Temperature and flow rate of the solution were found to some extent affect the zinc consumption as sacrificial anode in cathodic protection of steel in sea water,but the pH of the solution was found to be significantly the dominant.the correlation of temperature,flow rate,pH of the solution and the amount of zinc consumption as sacrificial anode can be adequately described by equation (6).Finally experimental design techniques such as factorial design proved to be useful for the identification and correlation of the significant factors that affect cathodic protection of steel by zinc consumption.

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