

CATHODIC PROTECTION OF CARBON STEEL IN 0.1N NaCl SOLUTION UNDER FLOW CONDITIONS USING ROTATING CYLINDER ELECTRODE

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ABSTRACT

The effect of applied current on protection of carbon steel in 0.1N NaCl solution (pH=7) was investigated under flow conditions (0-0.262 m/s) for a range of temperatures (35-55°C) using rotating cylinder electrode. Various values of currents were applied to protect steel from corrosion, these were $I_{app}=I_{corr}$, $I_{app}=2I_{corr}$, and $I_{app}=2.4I_{corr}$, under stationary and flow conditions. Corrosion current was measured by weight loss method. The variation of protection potential with time and rotation velocity at various applied currents was assessed. It is found that the corrosion rate of carbon steel increases with rotation velocity and has unstable trend with temperature. The protection current required varies with temperature and it increases considerably when the rotation velocity was increased. The protection potential decreases appreciably (shifts to more negative) with time and with increasing rotation velocity. Also it shifts to more positive with increasing temperature.

Keywords: cathodic protection, steel, impressed current flow, salt

الخلاصة

لقد تم دراسة تأثير تيارات مسلطة على الفولاذ الكربوني في محلول تركيز الملح فيه ٠,١ مولاري وتحت ظروف جريان (٠ - ٢٦٢ م/ثا) ودرجات حرارة (٣٥-٥٥°م) باستخدام قطب الاسطوانة الدوارة. سلطت قيم مختلفة لتيارات الحماية لحماية الفولاذ الكربوني من التآكل، تم تسليط تيار التآكل، ضعف تيار التآكل و ٢,٤ من تيار التآكل تحت سرع ودرجات حرارة مختلفة، تم ملاحظة تغير فولتية الحماية مع الوقت ومع السرع في مختلف التيارات المسلطة. وجد ان معدل التآكل للفولاذ الكربوني يزداد مع السرع ويكون تغيره مع درجات الحرارة غير ثابت وان تيارات الحماية المطلوبة تختلف مع درجات الحرارة وتزداد عند زيادة سرع الدوران، وفولتية الحماية تقل (تصبح اكثر سالب) مع زيادة الوقت ومع زيادة السرعة وتصبح أكثر موجب مع زيادة درجات الحرارة.

INTRODUCTION

Corrosion in aqueous solutions is an electrochemical reaction that involves charge transfer oxidation (loss of electrons) and reduction (gain of electrons). Corrosion is a metal dissolution process with the metal ions going into solution [Fontana and Greene 1986].

There are many methods for corrosion prevention, one mean of controlling is by the use of cathodic protection. Cathodic protection is an electrochemical technique in which a cathodic protective potential is applied to an engineering structure in order to prevent corrosion from taking place [Perez 2004]. Cathodic protection can be applied in practice to protect metals such as steel, copper, lead and brass against corrosion in all soils and in almost all aqueous media [Uhlig 2008].

The principle of cathodic protection is either in connecting an external anode to the material to be protected from corrosion or passing of an electrical DC current. So that all area of the metal surface becomes cathodic and therefore do not corrode. The external anode may be a galvanic (sacrificial) anode or it may be an impressed current anode where the current is impressed from external DC source. Cathodic protection requires a source of direct current and an auxiliary electrode (anode) of noble material (such as graphite) located some distance away from the protected structure. The direct current (DC) source is connected with its positive terminal to the auxiliary electrode and its negative terminal to the structure to be protected; in this way, current flows from the electrode through the electrolyte to the structure. The applied voltage is not critical, it need only be sufficient to supply an adequate current to all parts of the protected structure. In waters of high resistivity, the applied voltage must be higher than in environment of low resistivity [Uhlig 2008].

Cooling water used industrially removes heat from production processes. It is one of the major applications for water and is a major factor in sitting plants and processes. It often contains some salts that enhance the corrosion of metals. Cooling systems suffer many forms of corrosion and failure [Roberge 2008]. The open recirculating cooling water system is one of the most vital units of a petroleum refinery [Barhai 2010].

It is well known that the rate controlling step in most natural water corrosion process is the cathodic half reaction. The most important cathodic process in

half reaction is generally limited by the speed at which oxygen can reach the surface of the metal. This oxygen is transported from the bulk water to the surface across the boundary layer by diffusion. The boundary layer is defined as the region over which the property of interest, (velocity or oxygen concentration), is affected by the interface. For example, the oxygen concentration will vary from a minimum at the surface to bulk concentration at the outside edge of the boundary layer. This results in the concentration gradient and promotes the transport of oxygen [Smith 1989]. If the corrosion process is under cathodic diffusion control then agitation increases the corrosion rate. This effect generally occurs when an oxidizer is present in small amounts, as is the case for dissolved oxygen in acids or water [Fontana and Greene 1986].

The mechanism of cathodic protection is simply understood by reference to the following reactions.



Making the surface more negative and increase the concentration of electrons which accelerates the rate of cathodic reaction and decreases the rate of the anodic reaction. (i.e the rate of the anodic reaction becomes zero and the whole surface of the metal becomes cathodic [Shreir 1976].

Temperature of the medium governs the solubilities of the corrosive species in the fluid, such as oxygen (O_2), carbon dioxide (CO_2), chlorides, and hydroxides. Temperature increases the rate of almost all the chemical reactions. When the rate determining step is the activation process, the temperature changes have the greatest effect [Scott 1999]. In open systems, the effect of temperature is complex in that the diffusivity of oxygen increases, but solubility decreases with temperature increase [Fotana 1986, Scott 1999, Uhlig 1976].

The limiting current is defined as the maximum current that can be generated by a given electrochemical reaction, at a given reactant concentration, under well-established hydrodynamic conditions, in the steady state. This definition implies that the limiting rate is determined by the composition and transport properties of electrolytic solution and by the hydrodynamic conditions at the electrode surface.

aerated waters is oxygen reduction. The rate of this
Nesic et.al.[1995] using rotating cylinder electrode, studied the effect of velocity on the limiting current density. For temperature of 22°C and Re up to 26000, the cathodic polarization curves showed that the limiting current density increases with velocity increase.

Konsowa and El-Shazly [2002] studied the effect of flow and temperature on the rate of zinc consumption during cathodic protection of a copper pipeline carrying saline water by measured the loss in weight. They found that the rate of zinc consumption increases with increasing solution flow rate and temperature. Also the authors concluded that the cathodic protection in saline water is controlled by the rate of diffusion of dissolved oxygen towards the walls of the copper tube.

Scantlebury [2006] studied corrosion of mild steel in marine environments under cathodic protection. Electrochemical studies at the two protection potential namely -780 and -1100 mV were examined by different techniques. DC polarization experiments was carried out for mild steel in natural

sea water and 18.5g/L NaCl solution to evolve corrosion current density. He concluded that mild steel does not corrode under the protection potentials, viz., -780 and -1100 mV.

Sami and Ghalib [2008] studied cathodic protection system for low carbon steel pipe. They investigated the influence of temperature and distance between cathode and anode on the minimum cathodic protection current that would provide a full cathodic protection for steel tube immersed in sea water for temperature range 30-50°C and distance between pipe (cathode) and graphite electrode (anode) of (10-20cm). The experimental results indicated that cathodic protection current density increases with increasing temperature.

The aim of present work is to study the impressed current cathodic protection of steel specimen in 0.1N NaCl solution at various temperatures under flow conditions using weight loss and electrochemical technique (limiting current density) to determine the cathodic currents and potentials required to obtain high protective percents.

EXPERIMENTAL WORK

Figure. 1 shows the experimental apparatus that was used for performing the experimental work.

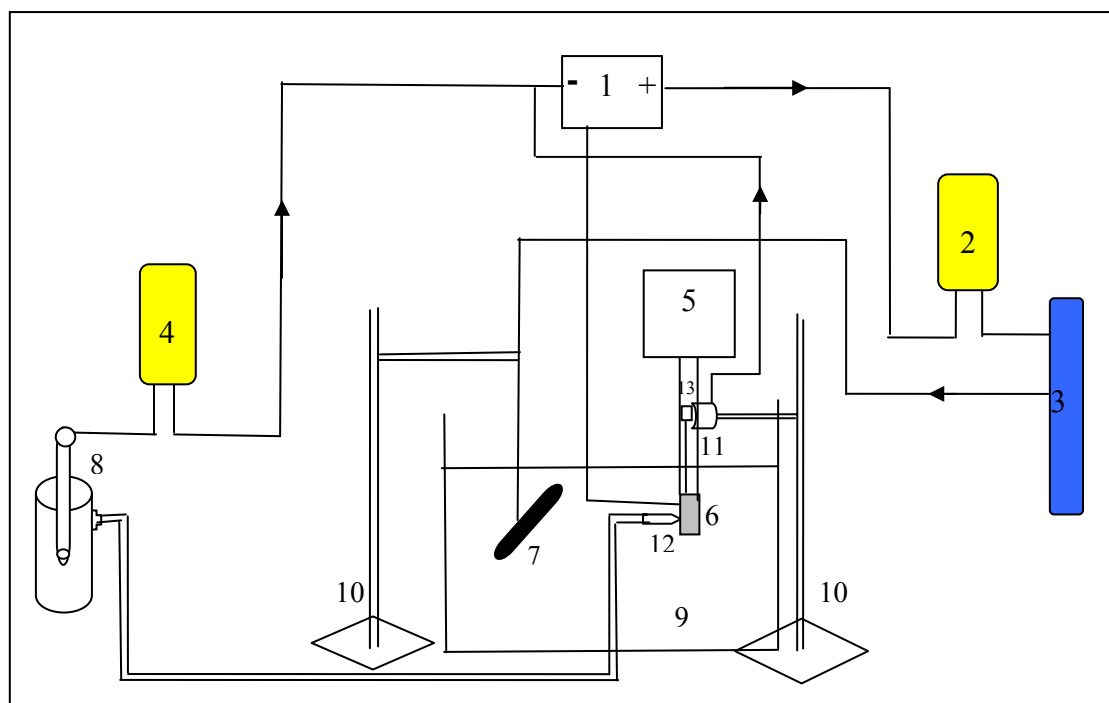


Fig. 1 Experimental apparatus 1) power supply, 2) ammeter, 3) resistance box, 4) voltmeter, 5) stirrer, 6) working electrode (specimen), 7) graphite electrode (anode), 8) calomel electrode (reference electrode), 9) water bath, 10) stand, 11) brush, 12) Luggin capillary, 13) metal for electrical connection with specimen

The experimental apparatus was composed of mechanical agitator to obtain different rotational velocities, water bath to obtain different solution temperatures, carbon steel specimen 3 cm long and 2.5 cm outside diameter (cathode) attached to the rode of agitator, power supply to apply the required protection potential, digital ammeter to measure the current, digital voltmeter to measure the potential, variable resistance (rheostate) to control the current flow, graphite electrode as auxiliary electrode (anode) and saturated calomel electrode (SCE) as reference electrode. Digital balance of high accuracy (4 decimal places of gram) to measure the weight loss. The electrical connection between cathode (specimen) and the cell was attained using brush.

In weight loss, before each experiment the specimen was washed by tap water followed by distilled water, dried with clean tissue, immersed in annular acetone for 5 minutes, rinsed with water and dried with clean tissue. The specimen then was stored in vacuum desiccator over high activity silica gel until use for 24 h before use. Then it was weighted to nearest 0.1 mg. The carbon steel specimen was immersed in corrosion rate (CR) was calculated by the solution (0.1 N NaCl) at a particular temperature to corrode freely before applying the impressed current (cathodic protection) to measure the corrosion rate at stationary condition at different temperature (35, 45 and 55 °C). The corrosion rate was measured at different speeds (25, 90, 120 and 200 rpm) at constant temperature of 45°C. After each test, the specimen was washed with tap water, immersed in acetone for 5 minute and washed with distilled water, then dried with paper tissue, dried and kept for 24 h in desiccator over high activity silica gel. Finally it was weighed using the digital balance. From the weight loss the corrosion rate (CR) was calculated by using:

$$CR(gmd) = \frac{\text{weightloss}(g)}{\text{Area}(m^2) \times \text{Time}(d)} \quad (3)$$

Where CR represents corrosion rate in g/m².d.

The protection percent (pp) was calculated as:

$$PP\% = \frac{CR_0 - CR}{CR_0} \times 100 \quad (4)$$

Here CR₀ and CR are the corrosion rate in absence and in presence of impressed current respectively.

A 12 liter of 0.1N NaCl solution was used in polarization experiments. The specimen was connected to -ve terminal of power supply to serve as cathode and graphite to +ve terminal to serve as anode. When the bath reached the required temperature, the specimen was immersed and the electrical circuit was switched on. The power supply was set at 5 V (applied voltage). The specimen (working electrode) was cathodically polarized from a particular potentials (-1.3 to -1.5 V) to the corrosion potential (where $i_{app.} = 0$) by changing the applied current using rheostat. The current was recorded for step changes in potential. Two minutes were allowed for steady state to be reached after each potential increment [Pickett 1974]. The capillary tube was placed at distance 1-2 mm from cathode (specimen) and connected to calomel electrode to measure the specimen potential. Thus polarization curve can be drawn and the limiting current can be obtained. In impressed current cathodic protection experiment the area of anode (graphite) immersed in water was 3 times the area of cathode (working electrode) to ensure the limiting current density occurs on cathode.

For the case of flow conditions experiments the specimen was attached to the agitator rod. A brush was used to ensure the electrical connection between cathode and the -ve terminal of power supply.

The limit current density (i_L) was also obtained from weight loss measurement as follows:

$$N_{Fe} = (\Delta w/M)/(A.t) \quad (5)$$

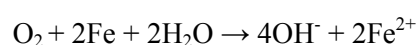
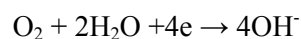
where Δw represents weight loss, M is the molecular weight of carbon steel (iron), A is the area in m² and t is the time in second, N_{Fe} is the moles of Fe lost per unit area per unit time (gmole/m².s)

$$i_{Fe} = z F N_{Fe} \quad (6)$$

where i_{Fe} is the corrosion current density in (A/m²), F is Faradays constant (96487 coulomb/equivelant), z is the number of electron freed by corrosion reaction (for iron z=2).

$$I_{Fe} = i_{Fe} \times A$$

according to equ. (1) & (2)



2 mole of Fe requires 1 mole of O_2

$$\text{Hence } N_{O_2} = \frac{1}{2} N_{Fe}$$

$$\text{Since } N = \frac{i}{ZF}$$

$$\frac{i_{O_2}}{z_{O_2} \times F} = \frac{1}{2} \frac{i_{Fe}}{Z_{Fe} F}$$

$$\frac{i_{O_2}}{4F} = \frac{1}{2} \frac{i_{Fe}}{2F}$$

$$i_{O_2} = i_{Fe}$$

$$\text{hence } I_{Fe} = I_{O_2} = I_{corr.} \text{ at } E_{corr.}$$

Since the system is neutral (PH=7) and hydrogen current is not present in the limiting current region [Uhlig 2008, Shreir 1976] hence

$$i_{O_2} = i_L$$

Since the current plateau is not well defined, thus the method given by [Gabe and Makanjola 1986] was adopted to obtain i_L as in Fig..2

$$i_L = \frac{i_1 + i_2}{2}$$

Where i_1 and i_2 are the currents associated with E_1 and E_2 respectively.

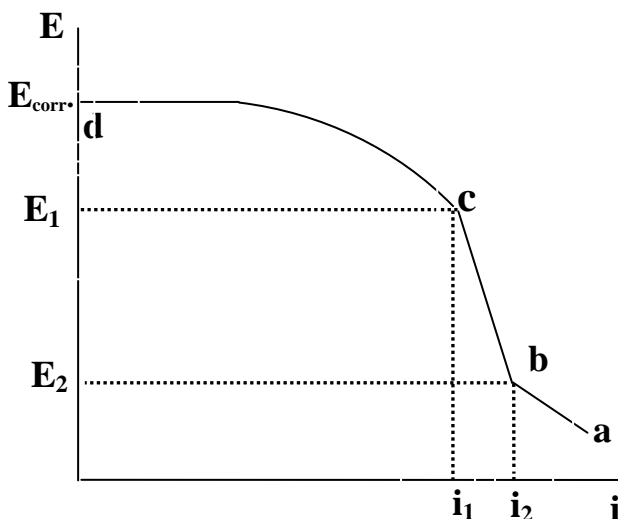


Fig.2 Typical polarization curve on carbon steel in 0.1N NaCl

After measuring $i_{corr.}$, different values of applied current were impressed to cathode at each temperature for 4 h to protect the metal and the potential was recorded at every 15 min to obtain the protection potential change with time. The values of applied current that were used to protect the metal at stationary and flow conditions at 45°C were $I_{app}=I_{corr.}$, $I_{app}=2I_{corr.}$ and $I_{app}=2.4I_{corr.}$ to determine the protection percent for different values of rotation velocity at 45°C. The distance between anode and cathode was 30 cm.

was obtained from weight loss measurements for 4 h time of exposure. Since $I_{corr.}$ is lower than I_L where the later is for clean surface while $I_{corr.}$ for 4 h includes the corrosion product effect that reduces the corrosion rate [Mahato et. al. 1968, Slaiman and Hasan 2010], so applying $I_{corr.}$ is not expected to protect the clean surface and it is needed to apply higher values.

RESULTS AND DISCUSSION

Table 1 lists the experimental results for the stationary conditions.

Table 1 protection percent at various temperatures and applied currents ($A_{specimen} = 2355 \text{ mm}^2$).

Temp. (°C)	$I_{app.}$ (mA)	C.R (g/m ² .d)	PP%
35	0	22.549	-
	$I_{corr.}=1.99$	6.543	69.88
	$2I_{corr.}=3.97$	2.786	86.70
	$2.4I_{corr.}=4.76$	0.805	96.38
45	0	25.270	-
	$I_{corr.}=2.41$	5.636	78.22
	$2I_{corr.}=4.83$	3.413	87.1
	$2.4I_{corr.}=5.79$	0.249	99
55	0	24.49	-
	$I_{corr.}=2.29$	4.341	82.3
	$2I_{corr.}=4.59$	2.366	90.62
	$2.4I_{corr.}=5.51$	0	100

Table 2 lists the values of corrosion rate and protection percent for different rotational velocities at 45°C.

Table 2 Effect of rotation speed on the cathodic protection percent ($A_{\text{specimen}}=2355\text{mm}^2$).

Speed (m/s)	$I_{\text{app.}}$ (mA)	C.R (g/m ² .d)	PP%
0.033	0	31.310	-
	$I_{\text{corr.}}=3.04$	11.301	64.56
	$2I_{\text{corr.}}=6.08$	2.689	99.2
0.118	0	59.418	-
	$I_{\text{corr.}}=5.65$	23.499	60.59
	$2I_{\text{corr.}}=11.3$	3.255	94.49
0.157	0	94.895	-
	$I_{\text{corr.}}=8.88$	34.068	62.8
	$2I_{\text{corr.}}=17.76$	4.407	95.42
0.262	0	154.440	-
	$I_{\text{corr.}}=14.76$	59.931	62.39
	$2I_{\text{corr.}}=29.52$	15.348	90.27

Corrosion rate and corrosion potential

The best indication for cathodic protection is by weight loss. The corrosion rate from the experimental results of metal specimen at different temperatures without impressed current and cathodic current density are shown in Fig.3. The results show that increasing temperature leads to unstable trend of corrosion rate and corrosion current. Unstable trend was also noticed by previous workers [Mahato et.al. 1968, Mahato et.al. 1980, Hassan 2003]. From this figure it can be seen that the corrosion rate at 45°C is higher than at 35°C and the corrosion rate at 55°C is slightly lower than at 45°C this can ascribed to the lower concentration of O_2 at 55°C than 45°C. Increasing the temperature will increase the rate of oxygen diffusion to the metal surface and decrease the viscosity of water which will aid the oxygen diffusion. All these factors enhance the corrosion rate. On the other hand, increasing temperature decreases the oxygen solubility the factor that restrains the corrosion [Henry and Scott 1999] as shown in table 3.

Table 3 Values of oxygen Diffusivity and solubility at different temperatures (Audin 1972, Sense 2001)

T(°C)	$D \times 10^9$ (m ² /s)	Solubility (mg/l)
30	2.374	7.5
40	3.010	4.389
50	3.562	5.399
60	4.834	4.49

Figures 5 to 8 show the polarization curves at 45°C and different speeds. It can be seen as the

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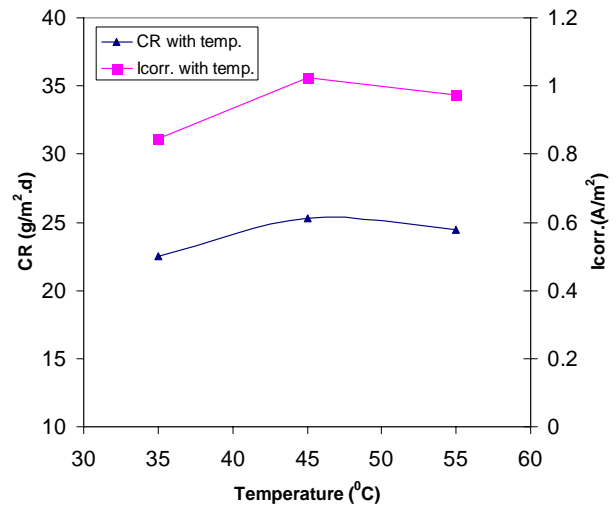


Fig. 3 Corrosion rate and Icorr. vs. temperature for free corrosion at stationary conditions

Polarization results

The typical polarization curves for carbon steel in 0.1N NaCl solution (pH=7) at temperatures of 35°C, 45°C and 55°C are shown in Fig.4. The most important characteristic of the cathodic polarization is the limiting current density of oxygen reduction (i_L). The corrosion potentials (E_c) were also determined from the polarization curves when the applied current becomes zero, i.e, open circuit potential (or free corrosion potential). It can be seen that i_L for 55°C (1.2 mA) is lower than that for 35°C (2.5 mA) and 45°C (1.7 mA). The i_L for 45°C is lower than for 35°C this is because of higher concentration of O_2 at 35°C.

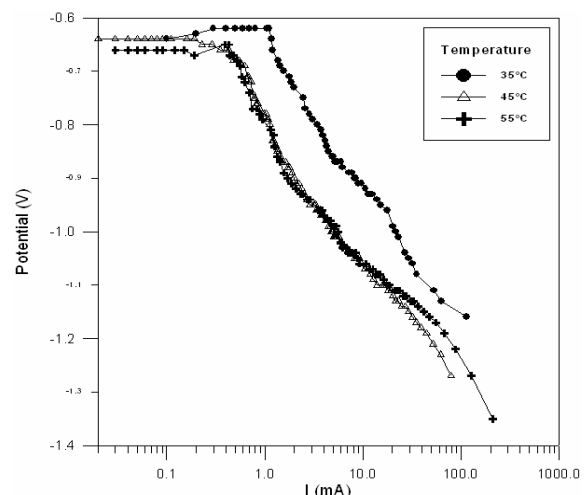


Fig.4 Polarization curve at stationary conditions at different temperatures

velocity increases I_L is increased, for example at speed of 0.033, 0.118, 0.157 and 0.262 m/s, I_L is 5, 14.5, 19.5 and 22 mA respectively. This can be attributed to the increase in oxygen supply from the bulk of the solution to the metal surface leading to higher I_L [Mahato et.al 1968, Mahato et.al 1980, Foroulis 1979, Hasan 2003].

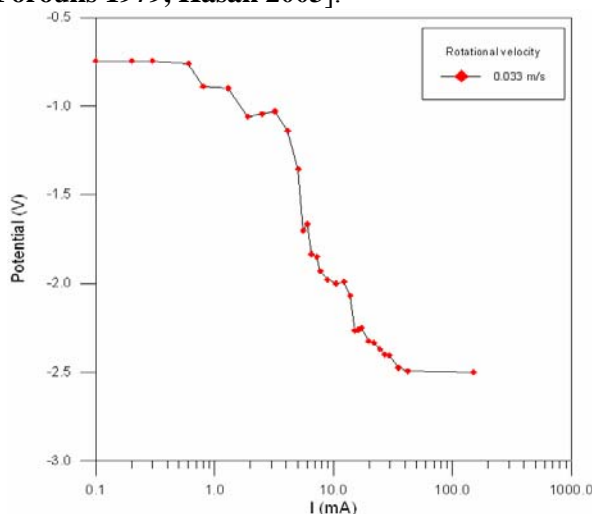


Fig.5 Polarization curve at velocity of 0.033 m/s at temperature=45°C

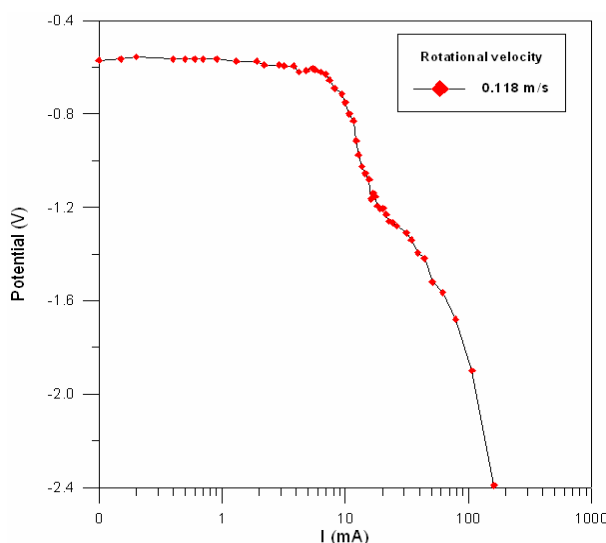


Fig. 6 Polarization curve at velocity of 0.118 m/s at temperature= 45°C

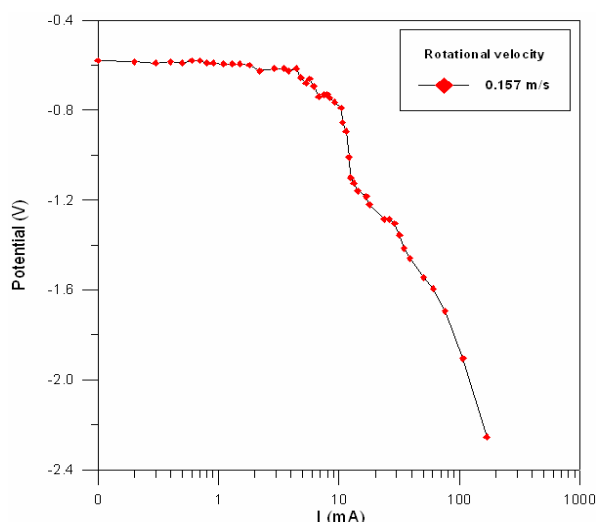


Fig.7 Polarization curve at velocity of 0.157m/s at temperature=45°C

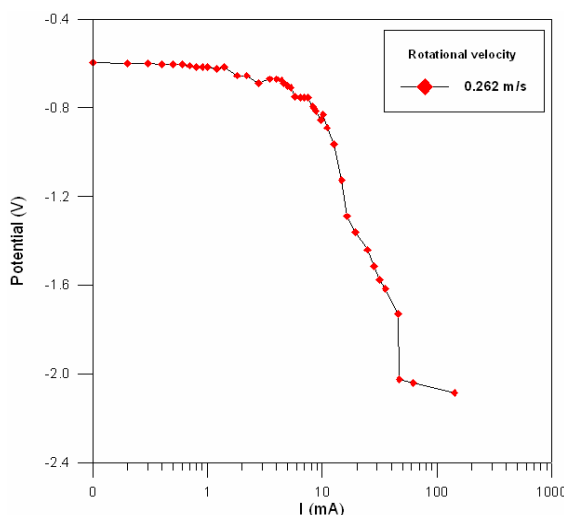


Fig. 8 Polarization curve at velocity of 0.262 m/s at temperature=45°C

Impressed current results

A metal in an aqueous environment, can be protected by impressing an electric current at its surface, delivered by a DC generator to polarize the potential to a value more negative than the equilibrium potential. Fig.9 shows the corrosion rate versus temperature at different applied currents values. The results in this figure indicate that as the applied current increases, the corrosion rate decreases this means the metal is protected by impressed current. For example the corrosion rate at 35°C is 22.549 g/m².d before applying protection current. When applying corrosion current (1.99 mA) is 6.543 g/m².d, at double corrosion current (3.97 mA) is 2.786 g/m².d and at current greater is 0.805 g/m².d.

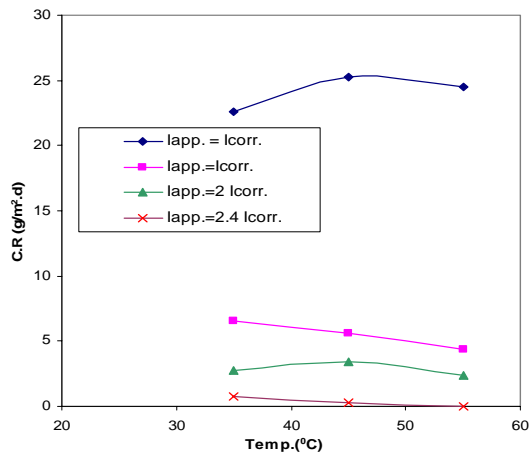


Fig. 9 Corrosion rate vs. temperature at stationary conditions

It is important to determine the amount of current or potential that needed to be applied to protect a structure and to make sure that the anode can provide that current uniformly across the structure at a reasonable DC output voltage [Varmani and Clemena 1998]. The relation between applied current and corrosion rate at different temperature is shown in Fig.10. It is clear that as the current for cathodic protection increases the corrosion rate decreases. The oxidizing of iron releasing electrons and ferrous ions, which dissolve in the solution surrounding the steel. The electrons are deposited on the steel surface, lowering the potential. In reduction current, electrons released by iron at the anode flow towards higher potential (cathodic) sites, where they combine with water and oxygen molecules to form hydroxyl ions. The corrosion reaction will only continue if there is cathodic reaction to accept released electrons, so these corrosion reactions can be stopped if oxygen and water are not available at the cathodic sites on the steel [Bentur et.al 1997].

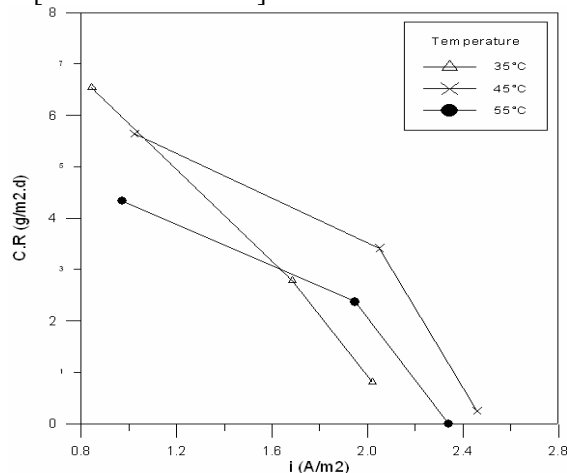


Fig.10 Corrosion rate vs. $I_{applied}$ at stationary conditions

oxygen concentration leads to shift E_c to more

The protection percent at three temperatures (35°C, 45°C and 55°C) with applied current is shown in Fig. 11. From this figure it can be seen that the protection increases as the temperature increases, for example when applying corrosion current the protection percent are 69.88%, 78.22% and 82.3% for 35°C, 45°C and 55°C respectively while when applying current density equal to $2I_{corr}$. the protection percent are 86.70%, 87.1% and 90.62% for 35°C, 45°C and 55°C respectively, so for higher current ($I_{app}=2.4I_{corr}$) it is 96.38%, 99% and 100%. The protection percent increased with increasing impressed current (I_{app}) due to the increased reduction of O_2 at the metal surface leading to decrease the corrosion of metal. Fig. 11 also reveals that the protection percent varies with temperature with unstable trend depending on O_2 solubility and diffusivity [Shreir 2000, Mahato et.al.1980].

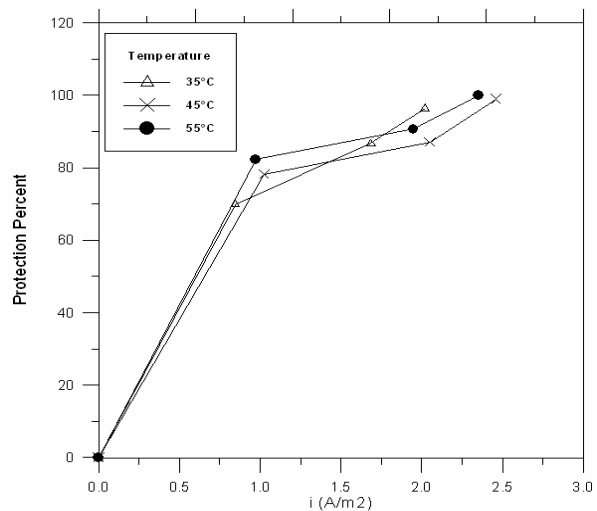


Fig. 11 I_{app} . vs. protection percent at different temp. under stationary conditions

Protection Potential

Figure 12 shows effect of time on the protection potential of carbon steel pipe immersed in 0.1 N NaCl at different temperatures. The figure shows that the potential decreases with time, where the potential is recorded at each 15 min for an experiment time of four hour long. Precisely the potential becomes rapidly more negative in the first hour, and then the curve reaches asymptotic value at -990 mV, -990 mV and -1070 mV vs SCE which represent the protection potential for 55°C, 45°C and 35°C respectively. Numerous studies have demonstrated that E_c is generally influenced by the oxidizer concentration. Several investigators [Foroulis 1979, Atia 1996, Al-mashta 1996, Kim 1998 and Ross 1966] showed that decreasing

negative values. It is evident that E_c falls with increasing temperature this because E_c are affected by both anodic and cathodic process. The anodic (activation controlled) process is simulated by increasing bulk temperature to greater extent than that of cathodic (concentration controlled) process [Shreir 1976 and Steigerwald 1968]. The corrosion potential become more negative with time, because the oxygen level at the steel interface can be depleted over time when subject to constant current density [Enos et.al 1997]. This figure indicates that at applied current of $I_{app.}=I_{corr.}$ the higher the temperature is the more positive protection potential. The decrease in the potential with time can be ascribed to the fact that at low temperature the depletion of O_2 is higher due to its high reduction on the metal surface leading to more negative the protection potential.

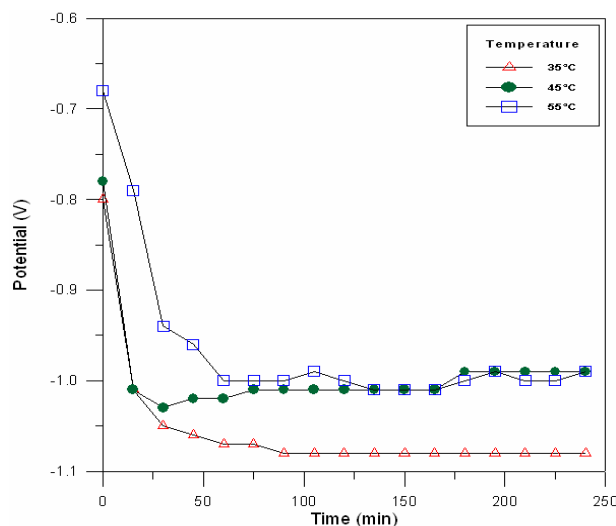


Fig. 12 Potential vs. time at $I_{app.} = I_{corr.}$ at stationary conditions

Figure 13 shows that the potential become more negative with increasing time at different applied current values at temperature of 35°C. The corrosion potential become more negative with time, because the oxygen level at the steel interface can be depleted over time when subjected to constant current density [Enos et.al 1997]. It can be seen that as the current increases, the potential becomes more negative because high $I_{app.}$ leads to high O_2 reduction, shifting the potential to more negative [Foroulis 1979, Hasan 2003]. The corrosion potentials for current applied and higher current is approximately similar while for lower current are less negative. The decrease in potential is rapid during the 90min for $I_{app.}=1.99$ mA while for $I_{app.}=3.97$ mA and $I_{app.}=4.763$ mA the decrease in potential is rapid during 30 min.

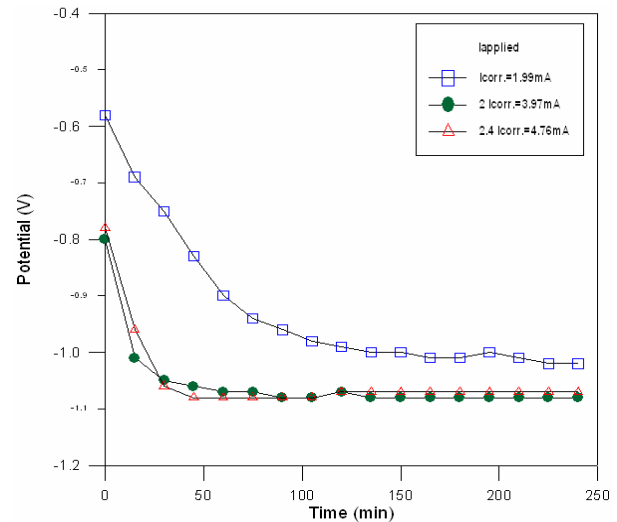


Fig.13 Potential vs. time at 35°C

Figure 14 shows the effect of rotational velocity on the corrosion rate of carbon steel specimen for different applied currents. It is clear that the corrosion rate decreases with increasing applied current and increases with increasing velocity. The increase in the rate of carbon steel dissolution with increasing solution velocity can be attributed to the decrease in the thickness of the hydrodynamic boundary layer and diffusion layer across which dissolved O_2 diffuses to the metal wall [Fahien 1983, Brodkey and Harshy 1989] with a consequent increase in the rate of O_2 transfer from bulk solution to the surface, since:

$$N_{O_2} = K C_{O_2} = (D/\delta) C_{O_2} \quad (7)$$

Where K is the mass transfer coefficient (m/s), D is the diffusivity of dissolved O_2 (m^2/s) and C_{O_2} is the concentration of O_2 in the solution bulk, δ is the diffusion layer thickness. In other word increasing velocity will increase the amount of oxygen arriving to the surface leading to higher corrosion rate. Increasing velocity leads to decrease the thickness of diffusion layer that represents the main resistance to oxygen transport [Welty 2001, Brodkey and Harshy 1989]. It is to be noticed from Fig. 14 that at high applied current values the effect of velocity on the corrosion rate is lower, however, the corrosion rate increases considerably with velocity when $I_{app.}=0$ while it increases little at $I_{app.}=I_{corr.}$

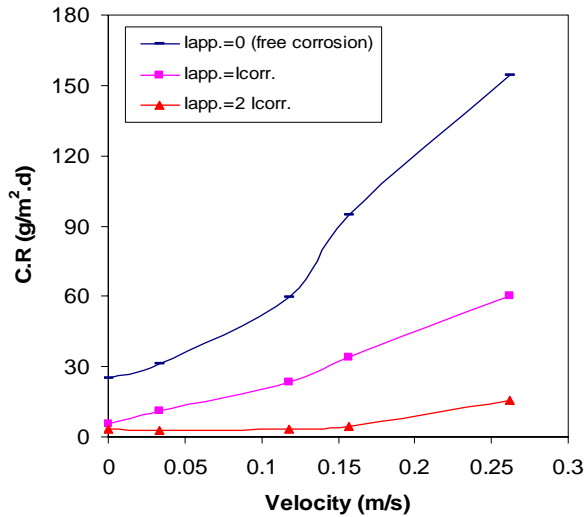


Fig.14 Effect of applied current by weight loss on the corrosion rate at 45°C

Figure 15 shows the protection percent versus applied current at stationary and flow conditions at 45°C. It is evident that as the applied current increases the percent of cathodic protection increases. In neutral solutions the cathodic corrosion process is usually the reduction of oxygen. The kinetics of this cathodic process are controlled by the rate at which oxygen can diffuse to the surface of metal, which is slower than the rate of consumption of oxygen by the cathodic reaction. Thus, the rate of this reaction remains constant unless the rate of supply of oxygen to the surface of metal is increased by increasing fluid flow rate. However, if the flow rate is increased the limiting current for the reduction of oxygen is increased and the current required to maintain the metal at the protection potential is increased. At stationary conditions the highest protection percent attained is 99% when $I_{app}=5.79$ mA. For a velocity of 0.033 m/s the highest protection percent is 99.2% when $I_{app}=6.08$ mA, for 0.118 m/s the highest protection percent is 94% when $I_{app}=11.3$ mA, for 0.157 m/s the highest protection percent is 95% for $I_{app}=17.8$ mA, and for 0.262 m/s the highest protection percent is 90.3% for $I_{app}=29.52$ mA. Hence the higher the velocity is the higher the required current for protection.

CATHODIC PROTECTION OF CARBON STEEL IN 0.1N NaCl SOLUTION UNDER FLOW CONDITIONS USING ROTATING CYLINDER ELECTRODE

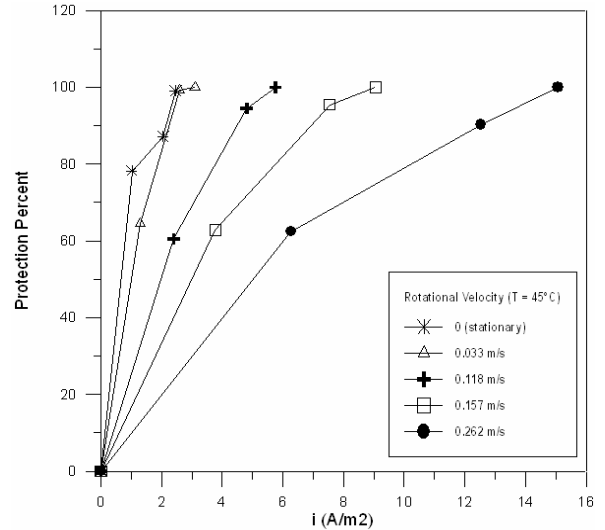


Fig.15 I_{app} . vs. PP% at different speed and constant temp. 45°C

Figure 16 shows the variation of corrosion potential with time for different values of velocity at 45°C. This figure indicates that the corrosion potential more negative with time. Also the higher the velocity is the lower the protection potential due to high applied current required for protection.

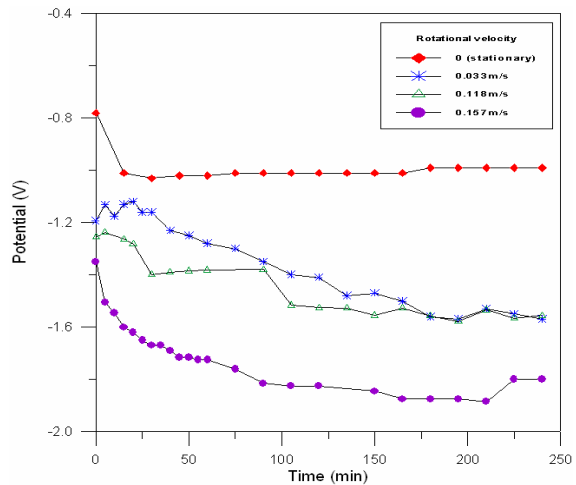


Fig.16 Corrosion Potential vs. time at $I_{app}= 2I_{corr}$. at temperature=45°C



Conclusions

- 1- The corrosion rate of carbon steel specimen exhibits unstable trend with temperature.
- 2- Increasing velocity (0-0.262 m/s) leads to increase the corrosion rate from 25.27 gmd to 154.44 gmd at $i_{app}=0$ and i_{corr} increases from 2.41 mA to 14.76 mA at 45°C.
- 3- The impressed current required for cathodic protection depends on temperature and rotational velocity. Applying $I=2I_{corr}$ gives protection percent between 90 to 99% depending on temperature and velocity.
- 4- The higher the rotational speed is the higher the cathodic currents required for protection.
- 5- The higher the impressed cathodic protection current is the lower the effect of velocity on the rotational speed will be.
- 6- The protection potential shifts to more negative values with time where it decreases by 40-68% depending on temperature. Also it shifts to more -ve with increasing velocity.
- 7- The lower the temperature is the more negative protection potential will be.

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NOMENCLATURE

A: Area (m^2)
D: Diffusivity (m^2/s)
E_c: corrosion Potential (V)
F: Faradays constant (96487 coulomb/equivalent)
i: Current density (A/m^2)
I_{app}: Applied current (mA)
I_{corr}: Corrosion current (mA)
I_L: Limiting current (mA)
K: Mass transfer coefficient (m/s)
M: Molecular weight (g/mole)
mA: mil ampere
t: time of exposure (hours)
V: Volts
Δw: weight loss (g)

Subscript

C: Corrosion
Corr: Corrosion
L: Limiting

Abbreviations

C.R: Corrosion rate ($g/m^2.d$)
PP: Protection percent
SCE: Standard Calomel Electrode

Greek Letters

δ: diffusion layer thickness (m)