

The Adsorption and Corrosion Inhibition of Non-Ionic Surfactant on Carbon Steel Surface in Hydrochloric Acid

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Abstract The effect of non-ionic surfactant, namely Polyethylene glycol methyl ether (PEGME), on the corrosion rate of mild steel in aerated 1N HCl by gravimetric method. The effect of PEGME on the corrosion rate was determined at various temperatures and concentrations. The strong adsorption ability of the surfactant molecules leads to formation of a mono-layer, which isolates the surface from the environment and thereby reduces the corrosion attack on the surface. Adsorption followed the Langmuir isotherm with negative values of ΔG^0_{ads} , suggesting a stable and a spontaneous inhibition process. The inhibition efficiency increases with increase in inhibitor concentration but decrease with rise in temperature. The maximum percentage inhibition efficiency (IE %) approached 90.50% in presence of 80 ppm of the inhibitor molecules.

Keywords Polyethylene glycol methyl ether, Carbon steel, Surfactant, Adsorption isotherm, Acid hydrochloric

1. Introduction

Acid inhibitors find wide applications in the industrial field as a component in pretreatment compositions, in cleaning solutions for industrial equipment and in acidization of oil wells. Many organic compounds containing oxygen, nitrogen and sulphur atoms have been used as corrosion inhibitors for carbon steel in various aggressive environments [1–10]. The addition of high molecular weight organic compounds such as surfactants to combat corrosion of carbon steel has found wide application in many fields. The surfactant inhibitor has many advantages such as high inhibition efficiency, low price, low toxicity and easy production [11–13]. The adsorption of the surfactant on the metal surface can markedly change the corrosion-resisting property of the metal [14, 15], and so the study of the relationship between the adsorption and corrosion inhibition is of great importance.

Ionic surfactants have been used for the corrosion inhibition of iron and other metals [16, 22] in different corroding media. Recently, many nonionic surfactants have been widely used as corrosion inhibitors for iron in acidic media [23–26]. However, as a nonionic surfactant, been reported that these compounds possess high inhibition efficiencies for steel corrosion [27–31]. The objective of the

present work is to investigate the inhibition action of non-ionic surfactant, namely Polyethylene glycol methyl ether (PEGME) in 1N HCl at 30–60°C, so as to study inhibitive mechanism of PEGME for mild steel in hydrochloric acid

2. Materials and Methods

2.1. Organic Compound

Polyethylene glycol methyl ether (PEGME) is used as the inhibitor. The nonionic surfactant was produced from Sigma-Aldrich. Fig. 1 shows the molecular structure of the PEGME). The main functional group is hydroxyl, which may be easily protonated in acidic solution.



Figure 1. Polyethylene glycol methyl ether (PEGME)

2.2. Materials

Tests were performed on a mild steel of the following composition, presented in table 1.

Table 1. Chemical composition (wt. %) of mild steel

Eléments	wt. %
C	0,21
Si	0,38
P	0,09
S	0,05
Mn	0,05
Al	0,01
Fe	Balance

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2.3. Solutions

The acidic solution 1N HCl was prepared by dilution of Analytical Grade 97% 1N HCl with distilled water. Appropriate concentrations of acids were prepared by using triple distilled water. The concentration range of inhibitor (PEGME) employed was varied from 10 to 80 ppm.L⁻¹.

2.4. Gravimetric Technique

The mild steel sheets of 3,5cm × 1cm × 0.1cm were abraded with a series of emery paper (grade 320-500-800) and then washed with distilled water and acetone. After weighing accurately, the specimens were immersed in 30 ml beaker, which contained 30 ml hydrochloric acid with and without addition of different concentrations of PEGME. All the aggressive acid solutions were open to air. After 6 h, the specimens were taken out, washed, dried, and weighed accurately. Experiments were carried out in triplicate. The average weight loss of three parallel mild steel sheets could be obtained. Then the tests were repeated at different temperatures and 1N HCl concentration.

3. Results and Discussion

3.1. Effect of PEGME on the Corrosion Rate

The gravimetric study allows the calculation of several corrosion parameters [32-35] by means of the mathematical relationships given below. The corrosion rate (CR) of carbon steel investigated in this study was calculated using the following equation [36]:

$$CR = \frac{w}{St} \quad (1)$$

Where W is the average weight loss of three parallel mid steel sheets, S the total area of the specimen, and t is immersion time. With the calculated corrosion rate, the inhibition efficiency (IE) of PEGME on the corrosion of mid steel was calculated as follows [37]:

$$IE \% = \frac{W_0 - W}{W_0} \times 100 \quad (2)$$

Where, W₀ and W are, respectively, the value of the average weight loss, without and with the addition of the inhibitor.

The corrosion rate curves of mid steel with the addition PEGME in 1N HCl at various concentrations are shown in Fig. 2. The curves in Fig. 2 show that the corrosion rate values (mg.cm⁻².h⁻¹) of mild steel in 1N HCl solution containing PEGME decrease as the concentrations of the inhibitor increase, whereas the corrosion inhibition increases with the nonionic surfactant concentration.

The inhibition efficiency reaches a maximum value of ca. 90.50% in the presence of 80 ppm of in figure 2 that shows the significant decrease in the corrosion rate (CR) upon addition of PEGME to the aggressive corrosion solution to reach a PEGME showing the effectiveness of the latter as a corrosion inhibitor for carbon steel in the present work conditions. This is better visualized minimum value when as

less as 80 ppm PEGME concentration is attained.

This tremendous change in the corrosion rate values had a very strong impact on the inhibition efficiency, which in its turn increases with increasing PEGME concentrations as depicted from table 2 and plotted in figure 3 reaching the highest value of ca. 90.50% at an PEGME concentration of 80 ppm.

Table 2. Gravimetric results for the corrosion parameters of carbon steel corrosion in 1N HCl with various concentrations of PEGME obtained at 303 K

[PEGME] (ppm)	CR (mg.cm ⁻² .h ⁻¹)	IE (%)	Θ
Blank	0,42	--	--
10	0,21	49,17	0,49
20	0,13	69,70	0,70
30	0,11	73,14	0,73
40	0,09	76,90	0,77
50	0,07	83,33	0,83
60	0,06	85,70	0,86
70	0,05	88,10	0,88
80	0,04	90,45	0,91

Table 3. Effect of temperature on the mild steel corrosion for various concentrations of PEGME in 1N HCl

[PEGME] (ppm)	T(k)	IE (%)	Θ
Blank	303	-	-
	313	-	-
	323	-	-
	333	-	-
20	303	69.70	0.70
	313	67.40	0.67
	323	65.30	0.65
	333		
60	303	85.70	0.86
	313	82.20	0.82
	323	77.20	0.77
	333	69.70	0.70
80	303	90.45	0.90
	313	85.70	0.86
	323	83.30	0.83
	333	76.30	0.76

A plausible explanation of these results is that the increasing inhibitor's concentrations reduces the carbon steel exposed surface to the corrosion media through the increasing number of adsorbed molecules on its surface which hinders the direct acid attack on the metal surface. Fig. 1 shows that the molecular weight of PEGME is high, thus PEGME can relatively easily adsorb on the mild steel surface by Van der Waals force. In addition, the main hydrophilic part -(OCH₂CH₂) of PEGME attacks the mid steel surface while the main hydrophobic part -(OCH₂CH₂) extends to the solution face. In addition, PEGME may chemisorb at steel/solution interface via hydrogen bond between the OH groups in PEGME molecules and water

molecules adsorbed on the surface. When PEGME adsorbed on metal surface, coordinate bond may be formed by partial transference of electrons from the polar atom (O atom) of PEGME to the metal surface, in Fig. 4. It shows that inhibition efficiency decreased at higher temperatures. This behavior indicates desorption of inhibitor molecule [38]. However, at higher inhibitor concentration, the decrease in IE (%) is small.

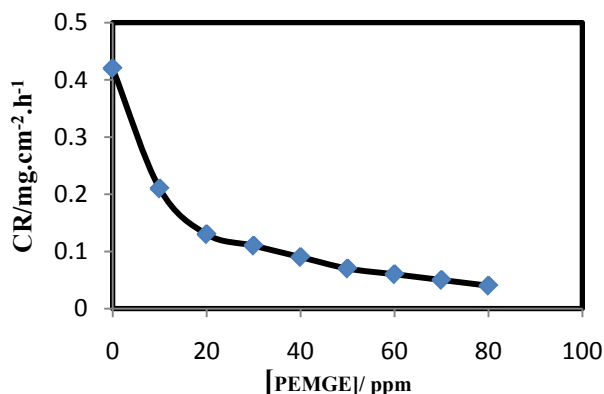


Figure 2. Variation of the corrosion rate (CR) of carbon steel with the concentration of PEGME in 1N HCl at 303 K

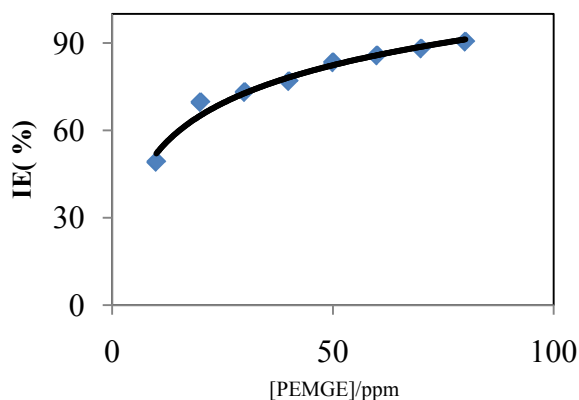


Figure 3. Variation of the inhibition efficiency IE(%) of carbon steel corrosion with the concentration of PEGME in 1N HCl at 303 K

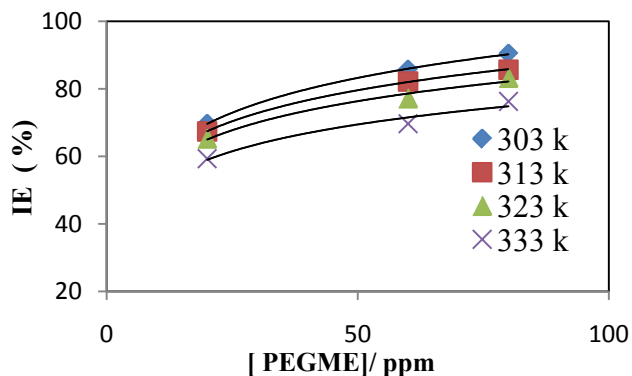


Figure 4. Effect of temperature (298 K–333 K) on the inhibition efficiency IE (%) of carbon steel corrosion in a (various concentrations of PEGME + 1N HCl) solution

3.2. Effect of Temperature

Generally speaking, the corrosion increases with the rise

of temperature. This result supports the idea that the adsorption of inhibitor components onto the steel surface is physical in nature. Thus, as the temperature increases, the number of adsorbed molecules decreases, leading to a decrease in the inhibition efficiency. The values of inhibition efficiencies at different temperatures obtained from weight loss data for the various inhibitor concentrations in 1N HCl shown.

3.3. Adsorption Isotherm

It is widely acknowledged that the adsorption isotherms provide useful insights into the mechanism of corrosion inhibition. The surface coverage, Θ , was calculated according to the following equation [39]:

$$\Theta = \frac{CR_{unhib} - CR_{inhib}}{CR_{unhib}} \quad (3)$$

The surface coverage values (Θ) for the inhibitors were obtained from the weight loss measurements for various concentrations at different temperatures. It is necessary to determine empirically which adsorption isotherm fits best to the surface coverage data in order to use the corrosion rate measurements to evaluate the thermodynamic parameters pertaining to inhibitor adsorption. We supposed that the adsorption of this inhibitor followed the Langmuir adsorption:

$$C = \frac{\Theta}{1-\Theta} = K_{ads} \quad (4)$$

Rearranging Eq.(5) gives:

$$\frac{C}{\Theta} = \frac{1}{K_{ads}} + C \quad (5)$$

Where, K_{ads} is the equilibrium constant of the inhibitor adsorption process, and C is the inhibitor concentration. The best-fitted straight line was obtained for the plot of C/Θ vs C with slopes very close to 1. The strong correlation ($R^2 > 0.999$) suggested that the adsorption of the inhibitor molecules in 1N HCl on the metal surface obeyed to the Langmuir's adsorption isotherm (Fig.5) [40]. As the adsorption isotherm in 1 N HCl is of Langmuir-type with slope of almost unity, monolayer of the inhibitor species must have been attached to mild steel surface without lateral interaction between the adsorbed species. The values of K_{ads} were calculated from the intercepts of the straight lines on the C/Θ - axis. The K_{ads} was related to the standard free energy of adsorption, ΔG°_{ads} according to the following equation [41]:

$$\Delta G^\circ_{ads} = -RT \ln (55.5 K_{ads}) \quad (6)$$

In the above expression, 55.5 is the concentration of water in solution in mol.l^{-1} [42]. The values of ΔG°_{ads} were calculated from the above equation and summarized in Table 4 where, R is the molar gas constant and T is temperature. The negative values of ΔG°_{ads} indicate that the adsorption process is spontaneous and the adsorbed layer on the mild steel surface is stable.

The negative values of ΔG°_{ads} indicate spontaneous adsorption of the inhibitor molecules on the carbon steel surface while their magnitude suggests the strong

interaction between inhibitor molecules and the metal surface [43–45]. Generally, the energy values of -20 kJ mol^{-1} or less negative are associated with an electrostatic interaction between charged molecules and charged metal surface, physisorption; those of -40 kJ mol^{-1} or more negative involve charge sharing or transfer from the inhibitor molecules to the metal surface to form a coordinate covalent bond, chemisorption [46].

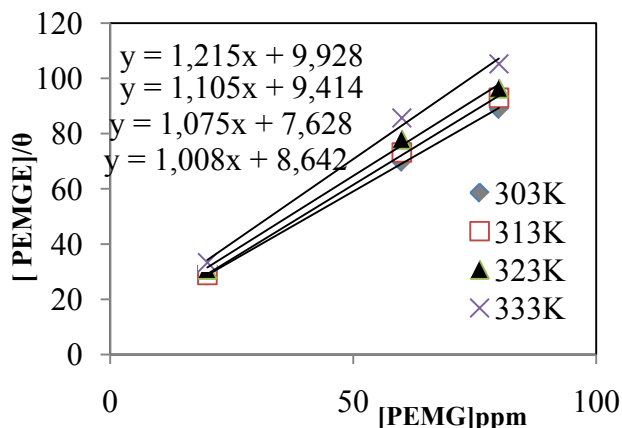


Figure 5. Langmuir's adsorption isotherm plot for the adsorption of PEMGE at different concentrations in 1N HCl on mild steel surface

From this estimation, it can be concluded that the inhibitor molecules are physically adsorbed on the charged steel surface thus creating an electrostatic interaction. In acid solution, PEMGE dissolves to form cations, R^+ by being protonated at the hetero atom. The protonated PEMGE can be adsorbed on the mild steel surface on previously adsorbed chloride ions. Organic compounds containing O and N are able to adsorb on the metal surface even at high concentration of chloride ions [47–49]. The chloride ions (from the electrolyte) on the electrode surface provide a better electrostatic condition, which promotes a direct adsorption of cations on the surface through its polar group.

The adsorption heat, ΔH°_{ads} , can be calculated according to the Van't Hoff equation [50] (7). The adsorption heat is obtained by plotting $\ln K_{ads}$ and $1/T$ (Fig 3). The adsorption heat could be approximately regarded as the standard heat of

adsorption, ΔH°_{ads} , under experimental conditions. According to the thermodynamic basic equation, the standard entropy of adsorption ΔS°_{ads} could be calculated from the following equation [51]:

$$\ln K_{ads} = \frac{-\Delta H^\circ_{ads}}{RT} + \text{constante} \quad (7)$$

ΔH°_{ads} is the standard heat of adsorption, under experimental conditions. According to the thermodynamic basic equation, the standard entropy of adsorption ΔS°_{ads} could be calculated from the following equation [52]:

$$\Delta G^\circ_{ads} = \Delta H^\circ_{ads} - T\Delta S^\circ_{ads} \quad (8)$$

All the obtained thermodynamic parameters are listed in Table 4. Review of these data divulges that the thermodynamic parameters ΔH°_{ads} and ΔS°_{ads} of dissolution reaction of mild steel 1N HCl in the presence of PEMGE are higher than in the absence of inhibitor. The positive sign of enthalpies ponder the endothermic nature of mild steel dissolution process i.e. dissolution of steel is difficult [53]. The shift towards negative value of entropies (ΔS°_{ads}) in the inhibited solutions imply that the activated complex in the rate determining step represents association rather than dissociation, meaning that disordering decreases on going from reactants to the activated complex [54].

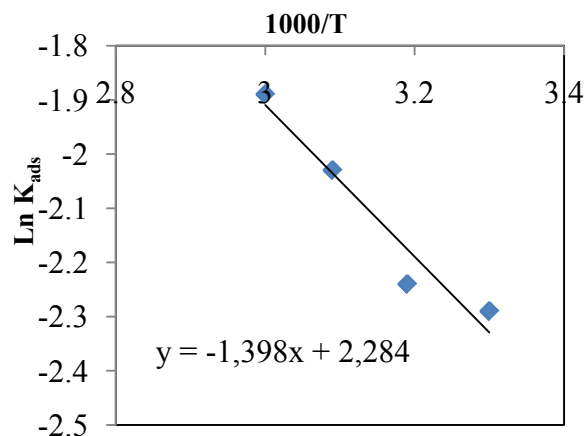


Figure 6. Arrhenius plots for mild steel corrosion in 1N HCl solution with PEMGE at different temperatures

Table 4. Thermodynamic parameters for the adsorption of PEMGE in 1N HCl on mild steel surface at different temperatures

T (K)	$k_{ads}(\text{mg.cm}^{-2}.\text{h}^{-1})$	$\Delta G^\circ_{ads}(\text{KJ.mol}^{-1})$	$\Delta H^\circ_{ads}(\text{KJ.mol}^{-1})$	$\Delta S^\circ_{ads} (\text{KJ.mol}^{-1})$	R^2
303	$10,07.10^{-2}$	-4,34	6.92	$37, 20. 10^{-2}$	0.999
313	$10,62.10^{-2}$	-4,62		$36, 90.10^{-2}$	0.999
323	$13,10.10^{-2}$	-5,40		$38,1410^{-2}$	0.996
333	$15,06.10^{-2}$	-5,90		$38,5010^{-2}$	0.995

3.4. Kinetics Parameters

The kinetics of the corrosion rate of carbon steel as a function of PEGME concentration might be assumed to obey the following equation [55]:

$$\log CR = \log k + B \log [PEGME] \quad (9)$$

Where k is the rate constant ($\text{mg. cm}^{-2} \cdot \text{h}^{-1}$) and B is the reaction constant which is a measure of the inhibitor efficiency in this case.

A plot of $\log CR$ against $\log [PEGME]$ based on the data given in table 5 is displayed in figure 7. The resulting graph has a good linearity ($R^2 = 0.98$) showing that the kinetic parameters can indeed be calculated using equation (9). The values of B (calculated from the slope of the graph) and k (derived from the y-intercept) are given in table 5 as well.

Table 5. Kinetic parameters of carbon steel corrosion in 1N HCl with various concentrations of PEGME obtained at 303 K

[PEGME] (ppm)	20	60	80
$\log [PEGME]$	1.30	1.78	1.90
$CR_{inh} (\text{mg.cm}^{-2} \cdot \text{h}^{-1})$	0.13	0.06	0.04
	0.14	0.08	0.06
	0.15	0.09	0.07
	0.17	0.13	0.10
$-\log CR_{inh}$	0.88	1.22	1.40
	0.85	1.10	1.22
	0.82	1.05	1.16
	0.76	0.88	1.00
K		$75 \cdot 10^{-2}$	
		$89 \cdot 10^{-2}$	
		$92 \cdot 10^{-2}$	
		$82 \cdot 10^{-2}$	
B		-0.36	
		-0.54	
		-0.59	
		-0.82	

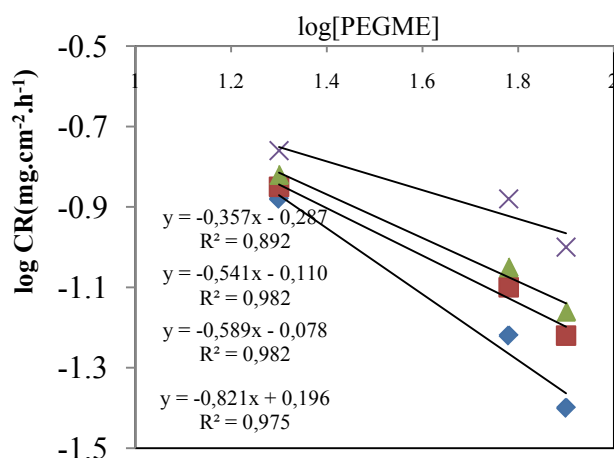


Figure 7. Variation of $\log CR$ with $\log [PEGME]$ for carbon steel corrosion in HCl at different temperatures

The inverse proportionality of the corrosion rate (CR) to the inhibitor concentration $[PEGME]$ is shown here as a

negative sign of (a) and the good inhibitory properties of (PEGME) can be concluded from its relatively high value [56]. **Table 5.** Kinetic parameters of carbon steel corrosion in 1N HCl with various concentrations of PEGME obtained at 303 K.

Kinetic parameters are of great importance to study the inhibition mechanism. The kinetic functions for dissolution of mild steel without and with the addition of various concentrations of PEGME were obtained by applying the Arrhenius equation and the alternative formula of the Arrhenius equation is the transition state equation [57]:

$$\log (CR) = \frac{-E_a}{2.303RT} + A \quad (10)$$

$$CR = \frac{RT}{N_h} \exp \left(\frac{\Delta S_a}{R} \right) \exp \left(\frac{-\Delta H_a}{RT} \right) \quad (11)$$

Where, E_a is the apparent effective activation energy, R is the molar gas constant and A is Arrhenius pre exponential factor. Where, h is Planck's constant, N is Avogadro's number, ΔS_a the entropy of activation, and ΔH_a the enthalpy of activation. Accordingly, $\ln(CR)$ against $(1/T)$ and $\ln(CR/T)$ against $(1/T)$ were plotted, as displayed in figure 8 and figure 9, respectively. All graphs show, both in the absence and presence of PEGME excellent linearity as expected from equations (10) and (11), respectively. The intercepts of the lines in figure 6 permit the calculation of the values of the pre-exponential factor (A) and the slopes which equal $(-E_a/RT)$ allowed the determination of the activation energy (E_a) both in the absence and presence of the inhibitor, respectively.

On the other hand, the obtained straight lines in figure 9 have a slope of $(-\Delta H_a/R)$ and an intercept of $(\ln[R/N_h] + \Delta S_a/R)$, each. Consequently, the values of ΔH_a and ΔS_a were calculated, respectively. All of these results are tabulated in table 6.

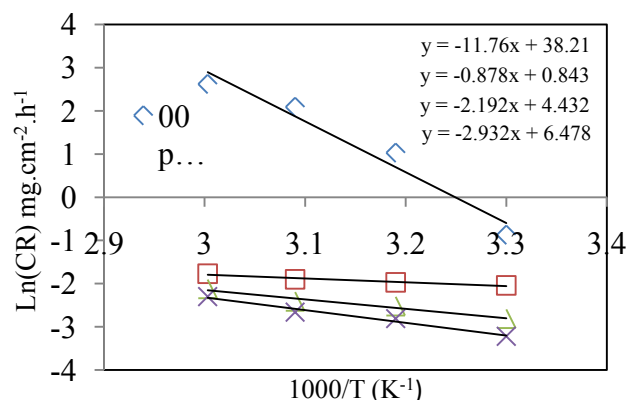


Figure 8. Arrhenius plots for mild steel corrosion in 1N HCl solutions without and with PEGME

As can be depicted from table 6, the activation energy in both solutions is greater than a value of 10 kJ.mol^{-1} owing to a surface-reaction process, either, in the absence or presence of (PEGME). It is noteworthy that the concentration changes the apparent activation energies values. This change may be explained by the modification of the corrosion process mechanism in the presence of

adsorbed inhibitor molecules [58-59]. The literature has discussed the variation of the apparent activation energy, E_a , in the presence and absence of inhibitor. Higher values for E_a were found in the presence of inhibitors [60-61]. Other studies showed that, in the presence of inhibitor, the apparent activation energy was lower than that in the absence of inhibitor [62-63]. However, in our study, the data shows that the activation energy (E_a) of the corrosion of mild steel in 1 N HCl solution in the presence of PEGME is lower than that in the free acid solution.

Table 6. Kinetic-thermodynamic corrosion parameters for mild steel corrosion in absence and presence of various concentrations of PEGME

Inhibitor (ppm)	E_a (KJ.mol ⁻¹)	ΔH_a (KJ.mol ⁻¹)	ΔS_a (J.mol ⁻¹)	$E_a - \Delta H_a$ (KJ.mol ⁻¹)
Blank	97.77	94.90	+0,9.10 ⁻³	2.87
20	07.30	04.60	-1,10.10 ⁻³	2.70
60	18.20	15.80	-0,65.10 ⁻³	2.40
80	24.40	21.60	-0,40.10 ⁻³	2.80

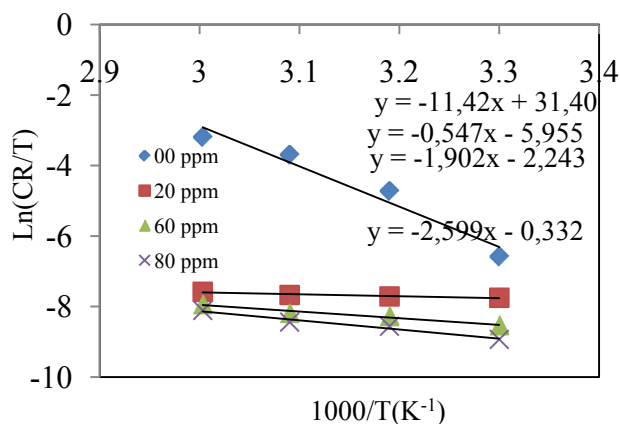


Figure 9. Transition-state plots for carbon steel corrosion rates (CR) in 1N HCl in the presence and absence of PEGME

The positive signs of enthalpies (ΔH_a) obtained in both systems reflects the endothermic nature of dissolution process. The shift towards negative value of entropies (ΔS_a) in the inhibited solutions imply that the activated complex in the rate determining step represents association rather than dissociation, meaning that disordering decreases on going from reactants to the activated complex [64].

4. Conclusions

In this study, we have investigated the influence of PEGME the corrosion behaviour of mild steel in 1N HCl solution using weight loss method. The principal results of the present work can be summarized as follows:

The nonionic surfactant, polyethylene glycol methyl ether displayed good corrosion inhibition for mild steel in 1M HCl solution.

The inhibition efficiency of PEGME increases with the increase of inhibitor concentration.

The percentage inhibition efficiency of PEGME is temperature-dependent and the adsorption of the inhibitor molecules on mild steel surface obeys the Langmuir adsorption isotherm model.

The PEGME inhibits the corrosion of mild steel in 1N hydrochloric acid by physisorption on the cathodic sites that are constituted by the cementite phase.

REFERENCES

- [1] N. Dkhireche, R. Abdelhadi, M. Ebn Touhami, H. Oudda, R. Tourir, M. Sfaira, B. Hammouti, O. Senhaji, R. Taouil, *Int. J. Electrochem. Sci.*, 7 (2012) 5314.
- [2] B. Mernari, H. El attari, M. Traisnel., F. Bentiss and M. Lagrenée, (1998), *Corrosion*, Vol. 40, p. 391. Ref brribri ss bentiss.
- [3] M. Lagrenée, M. Traisnel, B. Mernari, F. Benstiss, H. El Attari, *Journal of Applied Electrochemistry* 29 1073-1078, (1999).
- [4] M. El Achouri, S. Kertit, M. Salem, E.M. Essassi, M. Jellal, (1998), *Bull. Electrochem.*, Vol. 14 No.12, pp.462–8.23.
- [5] B. El Mehdi, B. Mernari, M. Traisne, F. Bentiss, M. Lagrenée, *Mater. Chem. Phys.*, 77 (2003) 489–496.
- [6] F. Bentiss, C. Jama, B. Mernari, H. El Attari, L. El Kadi, M. Lebrini, M. Traisnel, M. Lagrenée, *Corros. Sci.*, 51 (2009) 1628– 1635. 25.
- [7] K. Adardour, O. Kassou, R. Tourir, M. Ebn Touhami, H. ElKafsaoui, H. Benzeid, E. Essassi, M. Sfaira *J. Mater. Envir. Sci.*, 1 (2010) 129.
- [8] Y. Elkacimi, M. Achnin, Y. Aouine, M. Ebn Touhami, A. Alami, R. Tourir, M. Sfaira, D. Chebabe, A. Elachqar, B. Hammouti, *Portugaliae Electrochem. Acta* 30, 53 (2012).
- [9] K. Adardour • R. Tourir • M. Elbakri • Y. Ramli • M. Ebn Touhami • H. El Kafsaoui • C. Kalonji Mubengayi • E. M. Essassi, *Res Chem Intermed* DOI 10.1007/s11164-012-0934-x,.
- [10] H. El Attari, A. El Bribri, L. Mhaidra, F. Bentiss and M. Siniti, *American Journal of Engineering Research*, Volume-4, Issue-3, pp-44-51.
- [11] A.A. Abdel Fattach, K.M. Atia, F.S. Ahmed, M.I. Roushdy, *Corrosion Prevention and Control* 33 (3) (1986) 67.
- [12] M. Elachouri, M.S. Hajji, M. Salem, S. Kertit, E.M. Essassi, *Corrosion Science* 37 (1995) 381.
- [13] M. Elachouri, M.S. Hajji, M. Salem, S. Kertit, J. Aride, R. Coudert, E. Essassi, *Corrosion* 52 (1996)103.
- [14] I.L. Rozenfeld, *Corrosion Inhibitors*, McGraw-Hill, New York, 1981.
- [15] B.A. Abd-El-Nabey, E. Khamis, M.Sh. Ramadan, A. El-Gindy, *Corrosion* 52 (1996) 671.
- [16] A.K. Maayta, M.B. Bitar, M.M. Al-Abdallah, *Brit. Corros. J.* 36 (2001) 133.

- [17] R. Fuchs-Godec, V. Dolecek, *Colloids Surf. A* 244 (2004) 73.
- [18] R.F.V. Villamil, P. Corio, J.C. Rubim, M.L. Silvia Agostinho, *J. Electroanal. Chem.* 472 (1999) 112.
- [19] S.S. Abd El Rehim, H.H. Hassaan, M.A. Amin, *Mater. Chem. Phys.* 78 (2002) 337.
- [20] A.K. Maayta, N.A.F. Al-Rawashdeh, *Corros. Sci.* 46 (2004) 1129.
- [21] R. Guo, T. Liu, X. Wei, *Colloids Surf. A* 209 (2002) 37.
- [22] V. Branzoi, F. Golgovici, F. Branzoi, *Mater. Chem. Phys.* 78 (2002) 122.
- [23] M. Elachouri, M.S. Hajji, M. Salem, S. Kertit, J. Aride, R. Coudert, E. Essassi, *Corrosion* 52 (1996) 103.
- [24] A.S. Algaber, E.M. El-Nemma, M.M. Saleh, *Mater. Chem. Phys.* 86 (2004) 26.
- [25] M.M. Osman, M.N. Shalaby, *Anti-Corros. Methods Mater.* 44 (1997) 318.
- [26] M.M. Osman, A.M.A. Omar, A.M. Sabagh, *Materials Chemistry and Physics* 50 (1997) 271.
- [27] F. Hanna, G.M. Sherbini, Y. Brakat, *British Corrosion Journal* 24 (1989) 269.
- [28] M.M. Osman, M.N. Shalaby, *Materials Chemistry and Physics* 77 (2002) 261.
- [29] F.N. Speller, *Corrosion Causes and Prevention*, McGraw-Hill, New York, 1951.
- [30] M.M. Osman, M.N. Shalaby, *Anti-Corrosion Methods and Materials* 44 (5) (1997) 318.
- [31] D. Gobi, N. Bhuvaneshwaran, S. Rajeswarai, K. Ramadas, *Anti-Corrosion Methods and Materials* 47 (6) (2000) 332.
- [32] A. El bribri, M. Tabyaoui, H. El Attari, K. Boumhara, M. Sinit, B. Tabyaoui *J. Mater. Environ. Sci.* 2 (2) (2011) 156-165.
- [33] M. Elachouri, M.S. Hajji, M. Salem, S. Kertit, J. Aride, R. Coudert, E. Essassi, *Corrosion* 52 (1996) 103.
- [34] M. Bouklah, N. Benchat, B. Hammouti, A. Aouniti, S. Kertit, *Mater. Lett.* 60 (2006) 1903.
- [35] M.M. Osman, A.M.A. Omar, A.M. Sabagh, *Materials Chemistry and Physics* 50 (1997) 271.
- [36] A. El bribri, H. El attari, M SINIT and M. Tabyaoui *Mor. J. Chem.* 3 N°2 (2015) 286 297.
- [37] H. Elmsellem, H. Bendaha, A. Aouniti, A. Chetouani, M. Mimouni, A. Bouyanzer, *Mor. J. Chem.* 2 N°1 (2014) 1-9.
- [38] F. El-Hajjaji, R.A. Belkhmira, B. Zerga, M. Sfaira, M. Taleb, M. Ebn Touhami, B. Hammouti, *J. Mater. Environ. Sci.* 5 (1) (2014) 263-270.
- [39] Chris O. Akalezi, Conrad K. Enenebaku, Emeka E. Oguzie, *J. Mater. Environ. Sci.* 4 (2) (2013) 217-226.
- [40] L.B. Tang, G.N. Mu, G.H. Liu, *Corros. Sci.* 45 (2003) 2251.
- [41] E. Khamis, *Corrosion* 46 (1990) 476.
- [42] A. El Awady, A. Abd El Naby, S. Aziz, *J. Electrochem. Soc.* 139 (1992) 2149.
- [43] E. Cano, J.L. Polo, A. La Iglesia, J.M. Bastidas, *Adsorption* 10 (2004) 219.
- [44] G. Moretti, F. Guidi, G. Grion, *Corros. Sci.* 46 (2004) 387.
- [45] D. Do, *Adsorption Analysis: Equilibria and Kinetics*, Imperial College Press, 1998, pp. 10–60.
- [46] S.A. Ali, A.M. El-Shareef, R.F. Al-Ghamdi, M.T. Saeed, *Corros. Sci.* 47, 2659 (2005).
- [47] L. Tang, X. Li, Y. Si, G. Mu and G. Liu, *Mater. Chem. and Phys.*, 95 (2006) 29.
- [48] E. E. Ebenso. *Mater. Chem. and Phys.*, 79 (2003) 58.
- [49] G. E., Badr, *Corros. Sci.*, 51 (11), (2009) 2539.
- [50] T.P. Zhao, G.N. Mu, *Corros. Sci.* 41 (1999) 1937.
- [51] L.B. Tang, G.N. Mu, G.H. Liu, *Corros. Sci.* 45 (2003) 2251.
- [52] Badiea A. Mohammed, Kikkeri N. Mohana, *Monatsh Chem/Chemical Monthly* 140 (2009) 1–8.
- [53] Chandra Bhan Verma, M.A. Quraishi, E.E. Ebenso *Int. J. Electrochem. Sci.*, 9 (2014) 5507 – 5519.
- [54] I Bockris, J.O.M., Reddy, A.K.N. *Modern Electrochemistry*, vol. 2, Plenum Press, New York, 1977, p.1267.
- [55] I. Ahamad. R. Prasad and M.A. Quraishi *Corros. Sci.* 52 (2010) 1472–1481.
- [56] Sami Ben Aoun, *Der Pharma Chemica*, 5(3) (2013), 294-304.
- [57] Deng X. Li, H. Fu, G. Mu, *Corros. Sci.* 50 (2008) 2635–2645.
- [58] O. Riggs, I.R. Hurd, M. Ray, *Corrosion* 23, (1967) 252.
- [59] Szauer T., Brandt A., *Electrochim. Acta* 26 (1981) 1209.
- [60] S.N. Banerjee, S. Misra, *Corrosion* 45, 780 (1989).
- [61] Q.H. Cai, Y.K. Shan, B. Lu, X.H. Yuan, *Corrosion* 49, 486 (1993).
- [62] A. Zarrouk, A. Chelfi, A. Dafali, B. Hammouti, S.S. Al-Deyab, I. Warad, N. Benchat, M. Zertoubi, *Int. J. Electrochem. Sci.* 5, 696 (2010).
- [63] J. Marsh, *Advanced organic chemistry*, 3rd edn. (Wiley Eastern, New Delhi, 1988).
- [64] J.O.M Bockris, A.K.N, Reddy, *Modern Electrochemistry*, vol. 2, Plenum Press, New York, 1977, p.1267.