

**INTERNATIONAL JOURNAL OF CURRENT RESEARCH IN
CHEMISTRY AND PHARMACEUTICAL SCIENCES**

(p-ISSN: 2348-5213; e-ISSN: 2348-5221)

www.ijcrops.com

DOI:10.22192/ijcrops

Coden: IJCROO(USA)

Volume 3, Issue 9 - 2016

Research Article



DOI: <http://dx.doi.org/10.22192/ijcrops.2016.03.09.005>

Inhibitory action of piperazine derivatives on mild steel corrosion in hydrochloric acid solutions

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Abstract

Derivatives of piperazine (Tert-butyl-4-(2-(ethoxycarbonyl)benzofuran-5-yl)-piperazine-1-carboxylate, Ethyl 5-(piperazin-1-yl)benzofuran-2-carboxylate and 3tert-butyl 4-(2-carbamoylbenzofuran-5-yl)piperazine-1-carboxylate) were used as corrosion inhibitors for mild steel in hydrochloric acid solution. The inhibition efficiency depended on the concentration and type of the piperazines. The inhibition efficiency ranged between 90 and 94 % at the highest concentration (25 mM), and between 44 and 62% at the lowest concentration (5 mM) of inhibitor in 1 M HCl solution. Inhibition efficiency decreased with rise in temperature, this corresponded to surface coverage of the metal by the inhibitor. Potentiodynamic polarization measurements have been carried out at room temperature, which clearly reveal the fact that all investigated inhibitors are of mixed type and they inhibit corrosion of mild steel by blocking the active sites of the metal surface. The results also showed that, the inhibitors were adsorbed on the mild steel surface according to Langmuir adsorption isotherm.

Keywords: Corrosion, Mild steel, Hydrochloric acid, piperazines, Langmuir adsorption, Temkin's adsorption isotherm.

Introduction

Acidization of petroleum oil and gas well is one of the important techniques for enhancing oil production. It is brought about by forcing a solution of 15-28% HCl into the well to open channels and to increase flow of oil and gas. Hydrochloric acid is the major acidizing agent. To reduce the corrosive attack of the acid, inhibitors are incorporated with the acid solution during the process of an acidization¹. The use of acid solution during pickling and industrial cleaning leads to corrosive attack on mild steel. Therefore, corrosion of mild steel and its inhibition in acidic solutions have attracted the attention of number of investigators²⁻⁵. The protection of mild steel against corrosion can be achieved by adding a small concentration of organic compounds to environment⁶. A survey of literature reveals that the applicability of organic compounds as corrosion inhibitors for mild steel in acidic media has been recognized for a long time. Use of hazardous chemical inhibitors is totally reduced

because of environmental regulations. Chromates, phosphates, molybdates etc. and a variety of organic compounds containing hetero atoms like nitrogen, sulphur and oxygen have been investigated as corrosion inhibitors⁷⁻⁹. A survey of literature reveals that the applicability of organic compounds as corrosion inhibitors for mild steel in acidic media has been recognized for a long time. Compounds including surfactants¹⁰, aromatic hydrazides¹¹, organic dyes¹²⁻¹⁴, drugs¹⁵, poly (4-vinylpyridine)¹⁶, thiosemi-carbazide¹⁷ and heterocyclic compound such as triazole¹⁸⁻¹⁹ derivatives, bipyrazolic²⁰ derivatives, pyrazolones²¹ and thiazole²² type organic compounds were reported as inhibitors. Therefore, The present paper explain a study of corrosion protection action of piperazine derivatives on mild steel corrosion in 1, 2 and 3M hydrochloric acid solution using weight loss and electrochemical techniques. Different concentrations of inhibitor were

prepared and their inhibition efficiency in acidic media was investigated.

Experimental

Materials preparation

Mild steel contains Fe = 99.746; Mn = 0.100; C = 0.058; Al = 0.033; Si = 0.010; Cr = 0.008; Cu = 0.004; Ni = 0.0029; Mo = 0.002% were used in this study. Each sheet, which was 0.12 cm in thickness, was mechanically press-cut into coupons of dimension 3.5 x 3 cm with small hole of about 5 mm diameter near the upper edge. These coupons were used in the "as cut" condition, inhibition efficiency without further polishing, but were de-greased in absolute ethanol, dried in acetone, weighed and stored in a moisture-free desiccator prior to use.

All chemicals and reagents used were of analytical grade and used as source without further purification. The aggressive media were, respectively, 1, 2 and 3 M HCl solution. Piperazine and its derivatives were used as inhibitor in the concentration range 5, 10, 15, 20 and 25 mM.

Gravimetric Method

Room Temperature

The test specimens were immersed in 1 to 3 M HCl solution with and without inhibitors. Only one specimen was suspended by a glass hook, in each beaker containing 230 ml of the test solution and was open to air at room temperature for 24 h. After the immersion, the surface of the specimen was cleaned with double distilled water, followed by rinsing with acetone and the sample was weighed again in order to calculate inhibition efficiency (%). Triplicate experiments were performed in each case and the calculated mean values of the weight loss data are presented in figure 1.

Effect of Temperature

This experiment was done at temperatures 313, 323 and 333K. In this experiment, 250ml beakers were used. The weighed mild steel coupon was inserted into a beaker containing 230ml of 1M acid concentrations, with the help of a thread and was put in a thermo stated water bath. The coupons were removed after 3hrs. The coupons were washed several times double distilled water with bristle brush, again rinsed with distill water and dried in acetone and then reweighed. This experiment was repeated with various concentrations of inhibitor in 1M HCl.

The differences in weight of the coupons were taken as the weight loss which was used to compute the corrosion rate by given relationships;

$$\text{Corrosion rate (mpy)} = \frac{543w}{rAt} \quad (1)$$

Where W is weight loss (g), r is the density of specimen (gcm^{-3}), A is surface area of the specimen (cm^2) and t is the exposure time (days). The inhibition efficiency of piperazine derivatives were calculated using the expression:

$$y\% = \left(\frac{W_0 - W_1}{W_0} \right) \times 100 \quad (2)$$

Where W_0 and W_1 are the weight loss of mild steel in the absence and presence of inhibitor in HCl medium at the same temperature. The degree of surface coverage (θ) was also calculated using the equation:

$$\theta = \left(\frac{W_0 - W_1}{W_0} \right) \quad (3)$$

Inhibition efficiency (%), energy of activation (E_a), heat of adsorption (Q_{ads}), free energy of adsorption (G_{ads}°), enthalpy of adsorption (H_{ads}°) and entropy of adsorption (S_{ads}°) were calculated.

Polarization studies

For polarization study, metal specimens having an area of 0.25 cm^2 were exposed to corrosive solutions. Mild steel was used as a working electrode, SCE was used as reference electrode and auxiliary graphite electrode was placed in 100 ml of corrosive media through which external current was supplied automatically from computerized polarization instrument. The change in potential was measured by potentiostat/galvanostat (Gamry-Make, USA) on potentiostat mode with 5 mV/s scan rate. Polarization study was done with and without inhibitors in 1.0 M HCl.

Results and Discussion

The results are presented in Tables 1 to 2 and Figs. 1 to 10. To assess the corrosion rate of mild steel in HCl with and without piperazine derivatives. The corrosion rate of mild steel in HCl was increased with the acid concentration which was depicted in figure 1.

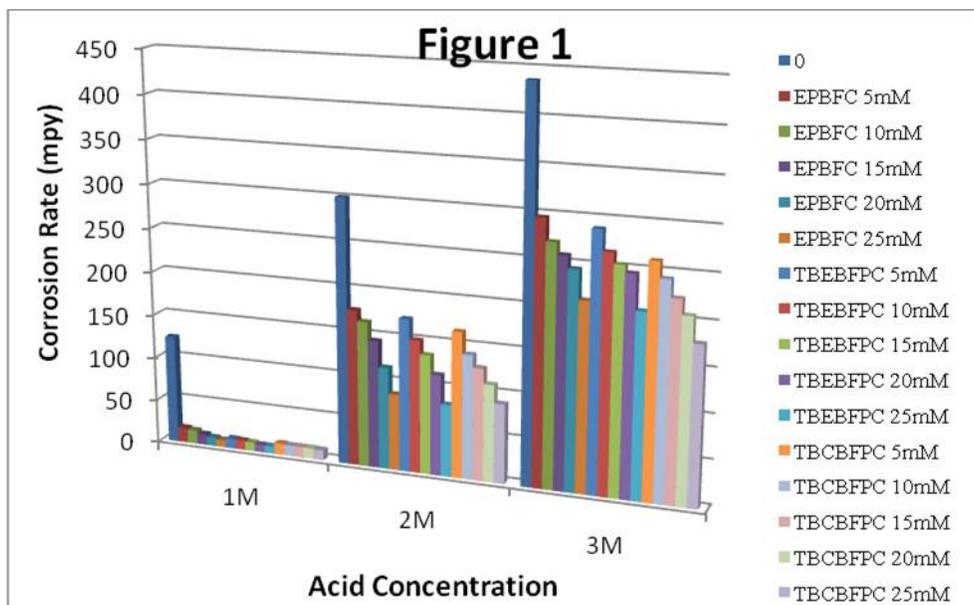


Figure 1: Corrosion rate of mild steel in HCl with and without inhibitors for 24 h at 301 K.

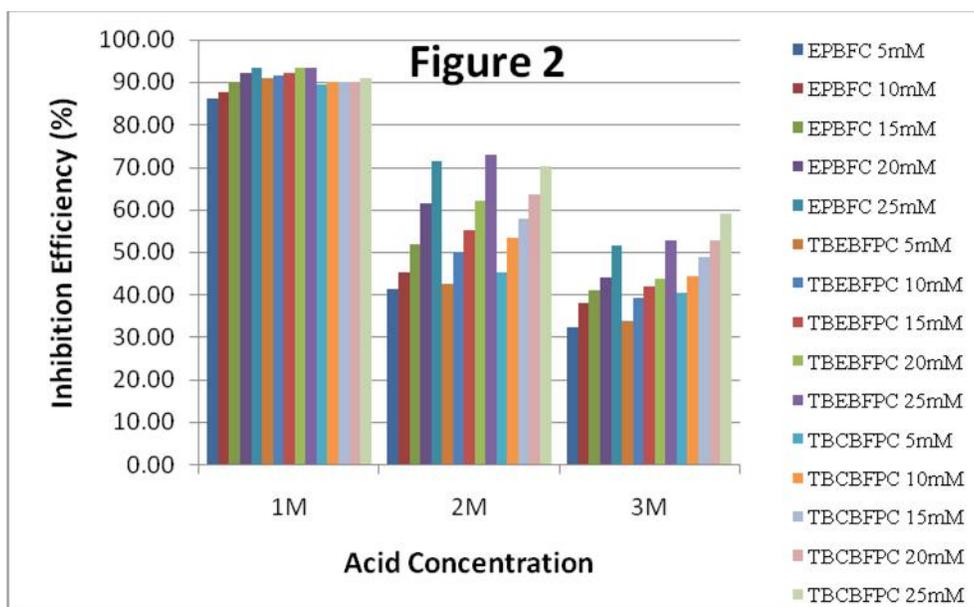


Figure 2: Effect of inhibition efficiency of Piperazines for mild steel at different acid and inhibitor concentrations for 24 h at 301 K.

At constant inhibitor concentration, the inhibition efficiency decreased with the increase in acid concentration. At 25 mM inhibitor concentration, the inhibition efficiency of benzimidazole was 94.77, 73.39 and 55.45 with respect to 1.0, 2.0 and 3.0 M acid concentrations respectively. At constant acid concentration, the inhibition efficiency of the

Benzimidazole increased with the inhibitor concentration, e.g. with EPBFC in 1.0 M HCl the inhibition efficiency was found to be 86.27, 87.58, 90.20, 92.16 and 93.46 with respect to 5, 10, 15, 20 and 25 mM inhibitor concentrations respectively (Figure 2).

Temperature had significant influence on the metal corrosion rates. The effect of change in temperature on the corrosion rates of mild steel in 1.0 M HCL was examined. It was found that, the corrosion rate of mild steel increased with increase in temperatures (Figure 3). Corrosion rate was measured in 1.0 M HCl containing 5, 10, 15, 20 and 25mM inhibitor concentration at solution temperature of 313, 323 and 333 K for an immersion period of 3 h. It shows that the increase in corrosion rate may be due to the

adsorptions of the adsorbed molecules-inhibitor and /or aggressive at higher temperature and thus exposing the fresh metal surface to further attack ²⁴ [20] which results in intensification of the kinetics of electrochemical reaction ²⁵ [21] and thus explains the higher corrosion rate at elevated temperature. In 1.0 M HCl solution with 25 mM TBECBFPPC concentration, the inhibition efficiency was found to be 93.59, 91.81 and 87.26 at 313, 323 and 333 K respectively (Figure 4).

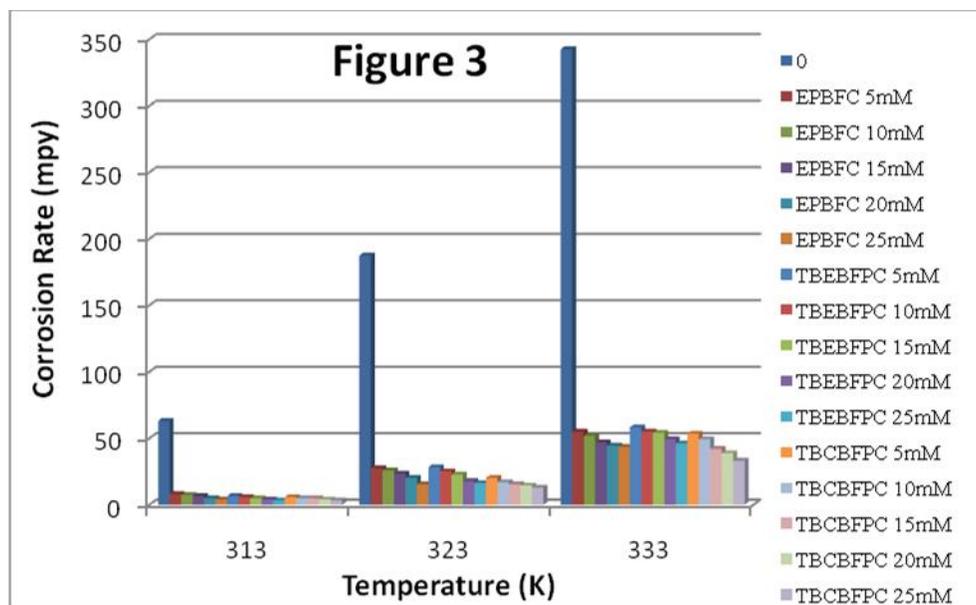


Figure 3: Corrosion rate of mild steel in HCl with & without inhibitors at various temperature for 3h.

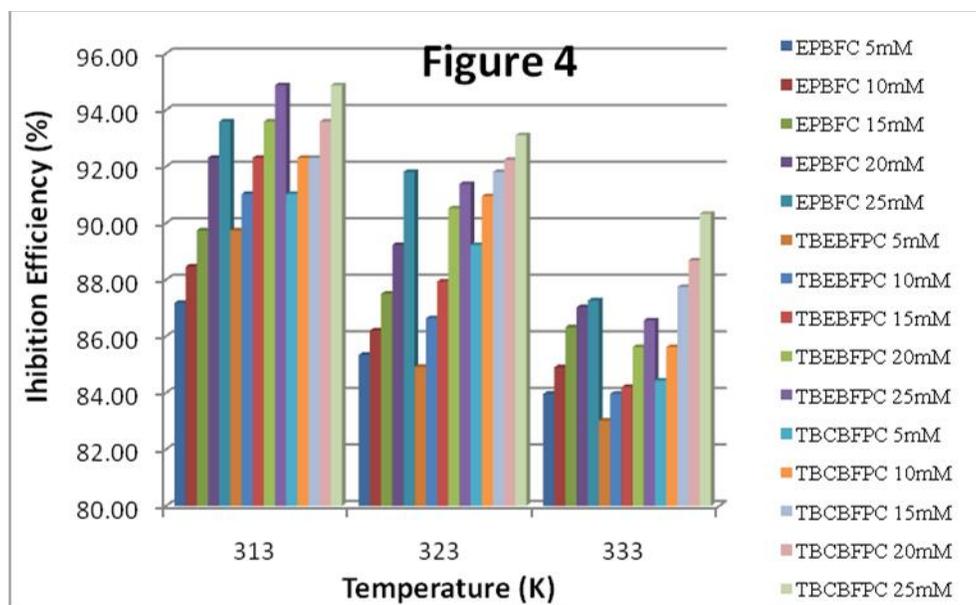


Figure 4: Effect of inhibition efficiency of piperazines for mild steel in 1M HCl at various temperature for 3h.

In the present study general type of corrosion occurs predominately and less pitting. Plotting of $\log \frac{1}{1-C}$ versus $\log C$ (%), straight lines were obtained, indicating that the adsorption of the added inhibitors followed the Langmuir adsorption isotherm (Figure 5a, 5b, 5c). Therefore, adsorption of these compounds is assumed to occur uniformly over the metal surface. Plot a graph versus $\log C$ gives straight line (Figure 6a, 6b, 6c) showing that the adsorption of the compound on the mild steel surface from 1 M HCl obeys also Temkin's adsorption isotherm. It is also found that the degree of adsorption of the inhibitors increases with their concentration.

The values of the free energy of adsorption (G_{ads}^0) were calculated with the slope of the following equation²⁶.

$$\text{Log} C = \text{Log} \left(\frac{n}{1-n} \right) - \text{Log} B \quad (4)$$

Where

$$\text{Log} B = -1.74 - \left(\frac{\Delta G_{ads}^0}{2.303RT} \right) \text{ and } C \text{ is the inhibitor}$$

concentration. The mean G_a^0 values are negative almost in all cases and lie in the range of -8.38 to -11.91 kJ. mol⁻¹ shown in Table-1. The most efficient inhibitor shows more negative G_a^0 value. This suggests that they be strongly adsorbed on the metal surface. This statement was supported by the work of Talati and Darji²⁷. The values of heat of adsorption (Q_{ads}) were calculated by the following equation.

$$Q_{ads} = 2.303R \left[\text{Log} \left(\frac{n_2}{1-n_2} \right) - \text{Log} \left(\frac{n_1}{1-n_1} \right) \right] \times \left[\left(\frac{T_1 T_2}{T_2 - T_1} \right) \right] \quad (5)$$

From Table -1, it is evident that in all cases, the (Q_{ads}) values are negative and ranging from -5.72 to -46.85 kJ. mol⁻¹. The negative values show that the adsorption, and hence the inhibition efficiency, decreases with a rise in temperature.

Mean ' E_a ' value was calculated by using equation (6) for mild steel in 1M HCl is 72.79 kJ.mol⁻¹ while in acid containing inhibitor, the mean E_a values are found to be higher than that of an uninhibited system (Table 1). Higher values of E_a in the presence of the imidazoles which acts as inhibitor is a good indication of strong inhibiting action of the imidazoles by increasing the energy barrier for the corrosion process. Higher values of E_a in the presence of extract can also be correlated with the increase in thickness of the double layer that enhance the E_a of the corrosion process²⁸. The values of E_a calculated from the slope of an Arrhenius plot (Figure 5-a,5-b) and using equation (6) are almost similar. Energy of activation (E_a) has been calculated from the slopes of $\log p$ versus $1/T$ (p = corrosion rate, T = absolute temperature) and also with the help of Arrhenius equation.

$$\text{Log} \frac{P_2}{P_1} = \frac{Ea}{2.303R} \left[\left(\frac{1}{T_1} \right) - \left(\frac{1}{T_2} \right) \right] \quad (6)$$

Where p_1 and p_2 are the corrosion rate at temperature T_1 and T_2 respectively.

The enthalpy of adsorption (H_{ads}^0) and entropy of adsorption (S_{ads}^0) were calculated using the following equation (7) and (8).

$$\Delta H^0_{ads} = Ea - RT \quad (7)$$

$$\Delta S^0_{ads} = \frac{\Delta H^0_{ads} - \Delta G^0_{ads}}{T} \quad (8)$$

The enthalpy changes (H_a^0) are positive, indicating the endothermic nature of the reaction suggesting that higher temperature favors the corrosion process. The entropy (S_a^0) values are positive, confirming that the corrosion process is entropically favorable.

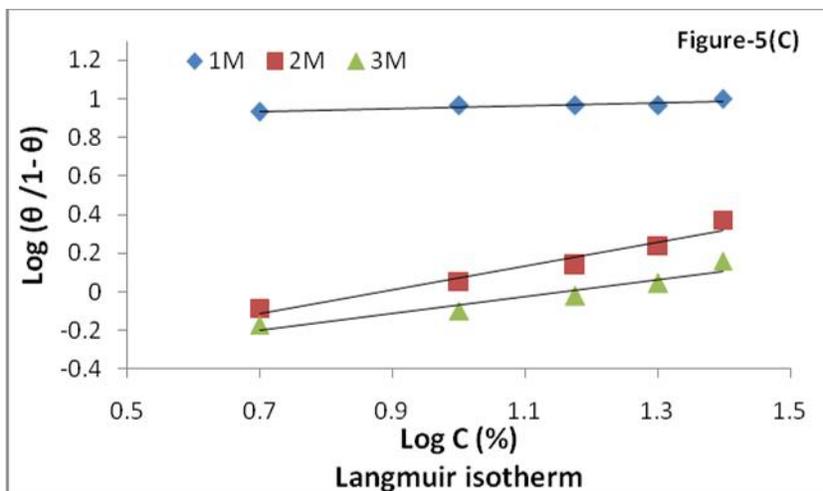
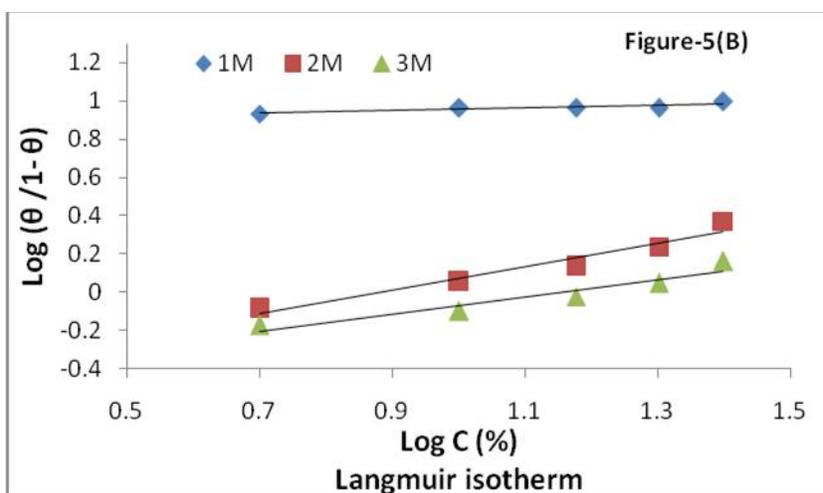
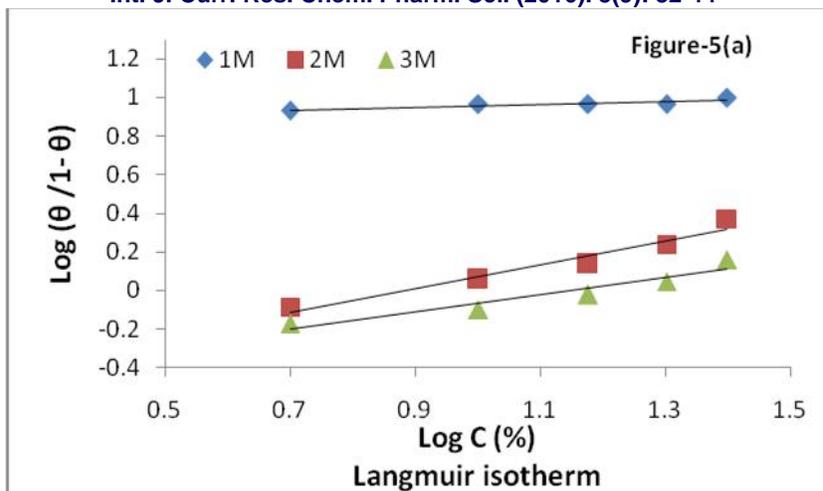


Figure 5(a), 5(b) & 5(c): Plot of $\log(\theta / (1-\theta))$ versus $\log C$ for EPBFC, TBECBFPPC & TBCBFPPC respectively for 24h at 301 K.

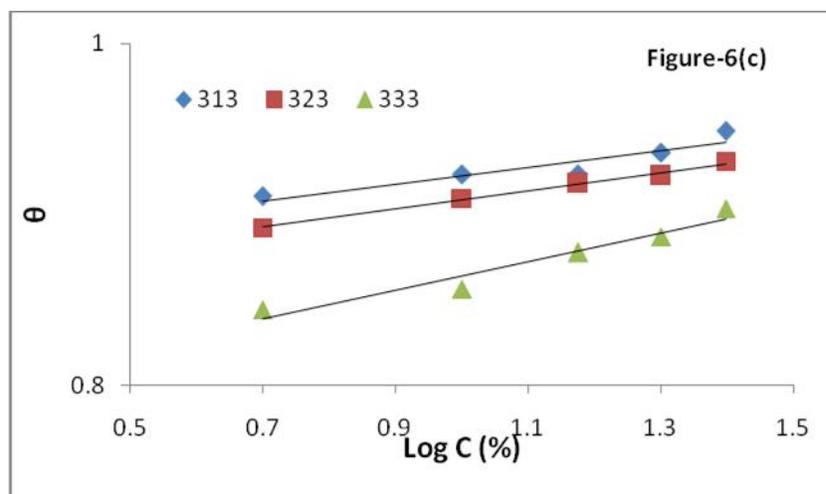
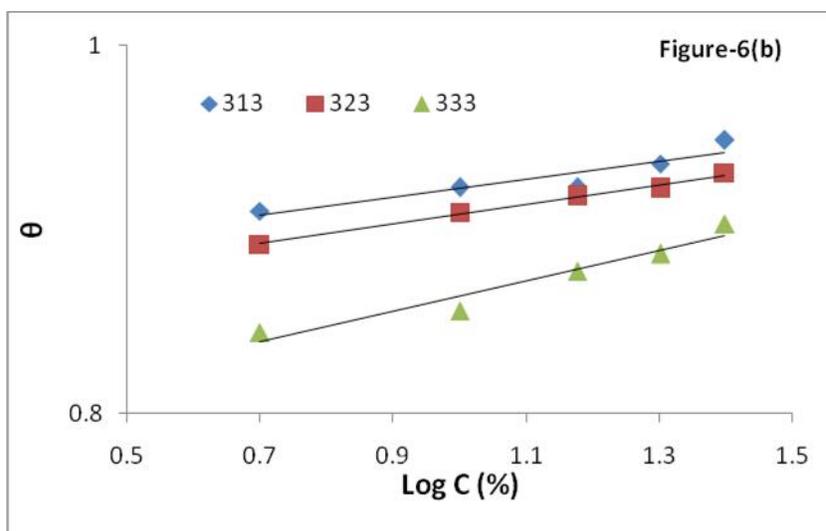
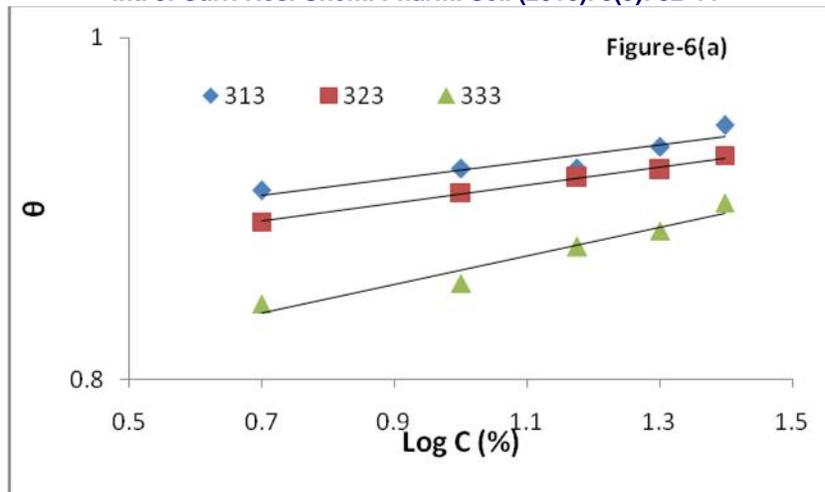


Figure 6(a), 6(b) & 6(c): Plot of θ versus $\log C$ for EPBFC, TBECBFPPC & TBCBFPPC respectively for 3h.

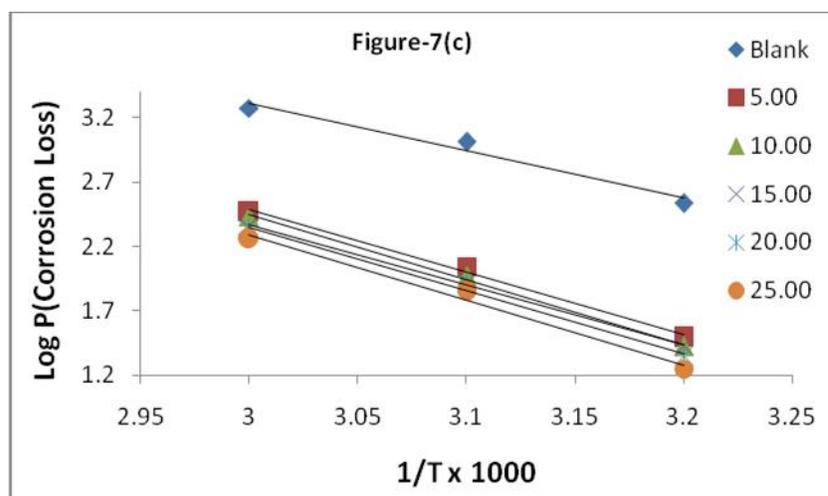
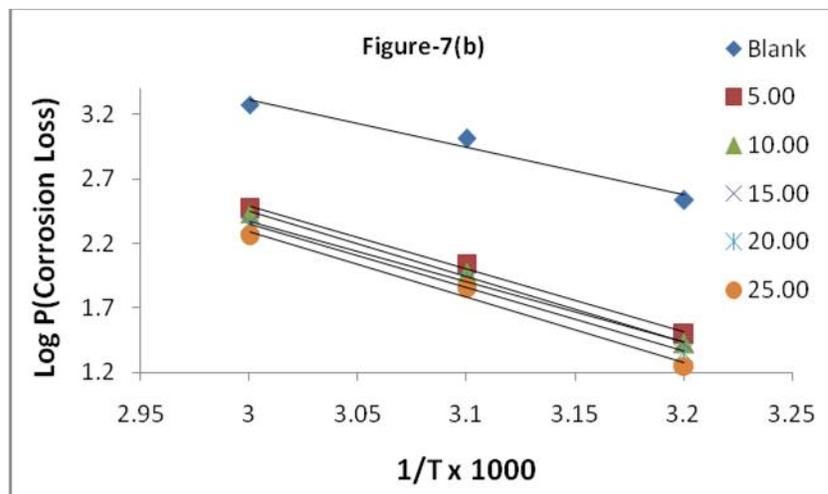
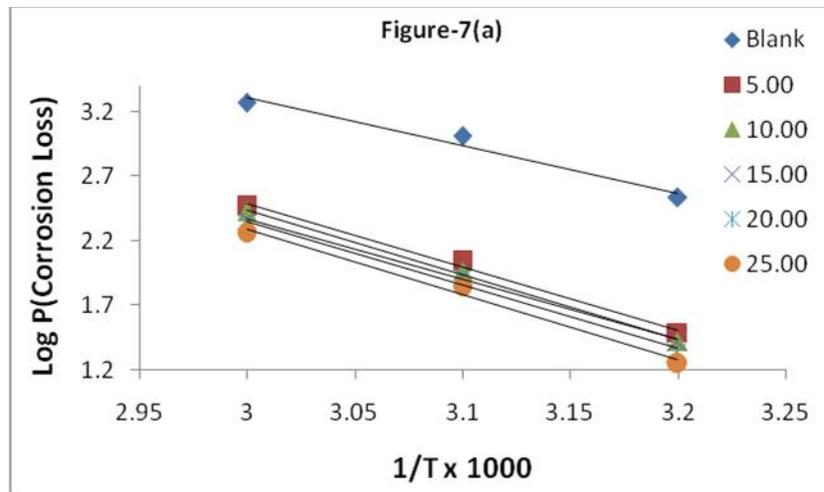


Figure 7(a), 7(b) & 7(c): Arrhenius plots in absence and presence of EPBFC, TBECBFPPC & TBCBFPPC respectively.

Table 1: Energy of activation (E_a), heat of adsorption (Q_{ads}) and free energy of adsorption (UG^0_{ads}) for mild steel in 1.0 M HCl Containing inhibitors.

System	Mean E_a from Eq.(6) (kJ. mol ⁻¹)	E_a from Arrhenius plot (kJ. mol ⁻¹)	Q_{ads} (kJ. mol ⁻¹)		Mean value (kJ. mol ⁻¹)		
			313-323 (K)	323-333 (K)	G^0_{ads}	H^0_{ads}	S^0_{ads}
Blank	72.79	70.38	-	-	-	-	-
EPBFC	102.83	98.93	-22.21	-44.03	-8.38	100.19	0.3434
TBECBFPPC	114.49	110.46	-46.82	-44.59	-8.48	111.85	0.3814
TBCBFPPC	100.35	96.76	-26.49	-32.93	-9.04	97.71	0.3377

Anodic and Cathodic polarization curves for mild steel in 1M HCl at 25mM inhibitor concentration of the presence and absence of inhibitors are shown in Figure 8 to 11. The value of the corrosion potential with inhibitors were found become more positive than the without inhibitors. Polarization study reveals that the inhibitors function as little anodic, but significant cathodic inhibitors, inhibitor functions as a mixed

inhibitor. It is evident from the figure that cathodic tafel slopes (c) remain almost unchanged with increasing inhibitor concentration. This indicates that hydrogen evolution is activation controlled and the addition of inhibitor did not change the mechanism of cathodic hydrogen evolution reaction²⁹⁻³⁰. The values for the Tafel parameters obtained from this plot with and without inhibitors are given in Table-2.

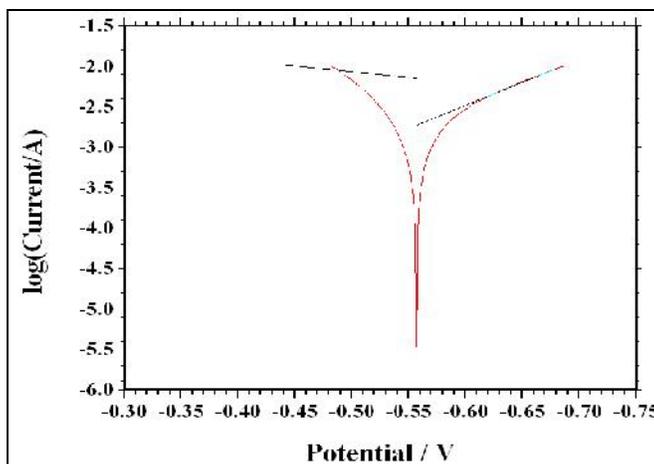


Figure 8: Polarisat ion curves for corrosion of mild steel in 1 M HCl.

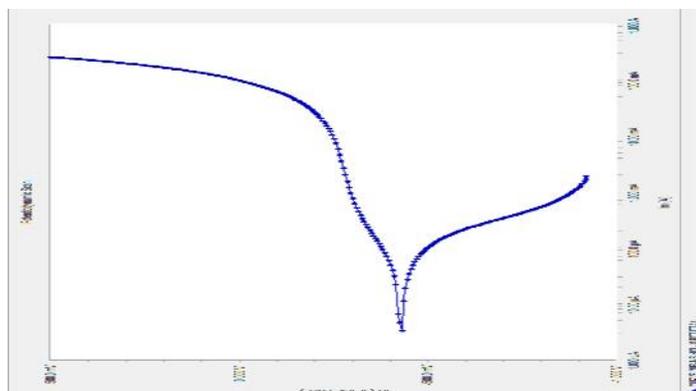


Figure 9: Polarisat ion curves for corrosion of mild steel in 1 M HCl containing 25 mm EPBFC.

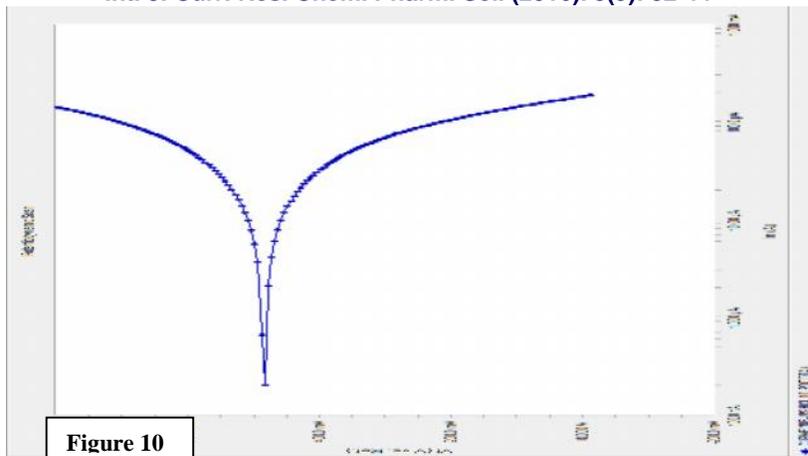


Figure 10: Polarisation curves for corrosion of mild steel in 1 M HCl containing 25 mm TBECBFPPC

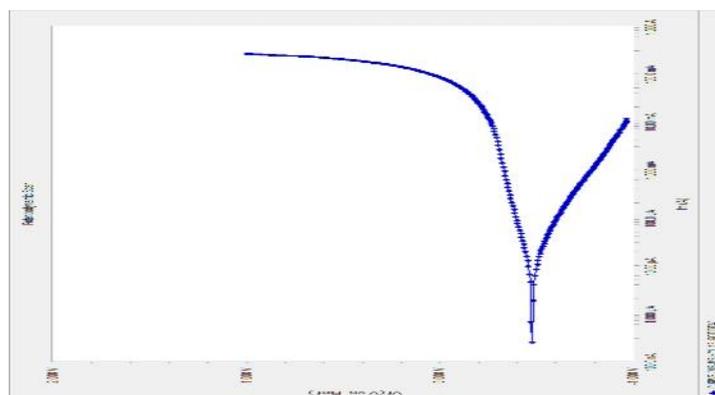


Figure 11: Polarisation curves for corrosion of mild steel in 1 M HCl containing 25 mm TBCBFPPC.

Table 2: Polarization data and inhibition efficiency of EPBFC, TBECBFPPC & TBCBFPPC for mild Steel in 1 M HCl.

System	E_{corr} (mV)	I_{corr} (A/cm ²)	Tafel slope (V/decade)			Inhibition efficiency (%)	
			- c	+ a		Pol. Method From I_{corr}	Wt. loss method
Blank	-557	1.590×10^{-5}	5.75	1.44	2.64	-	-
EPBFC	-428	1.150×10^{-6}	58.4	50.5	62.4	99.67	93.46
TBECBFPPC	-484	2.941×10^{-4}	20.8	21.7	24.5	93.98	93.46
TBCBFPPC	-478	4.290×10^{-6}	71.7	57.3	73.4	99.91	90.85

The values of corrosion current densities in the presence and absence of inhibitor were obtained from the graph while percentage efficiency (%) was calculated using the Equation (8). The inhibition efficiency from Tafel plots agrees well (within ± 4 %) with the values obtained from weight loss data.

$$y(\%) = \left[\frac{i_{corr}(u) - i_{corr}(i)}{i_{corr}(u)} \right] \times 100 \quad (9)$$

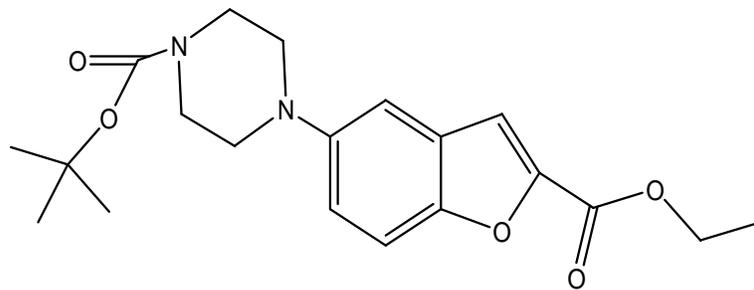
The linear polarization study was carried out from cathodic potential versus OCP to an anodic potential

of versus OCP with a sweep rate 0.01 V S^{-1} to determine the polarization resistance (R_p'). From the measured polarization resistance value, the inhibition efficiency has been calculated using the relationship:

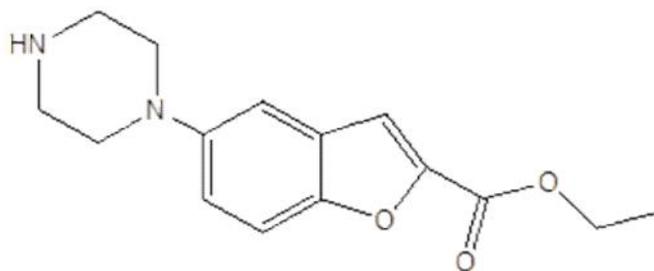
$$\eta\% = \frac{R_p - R_p^0}{R_p} \times 100 \quad (10)$$

Where R_p^0 and R_p' are the polarization resistance in the absence and in the presence of inhibitor, respectively.

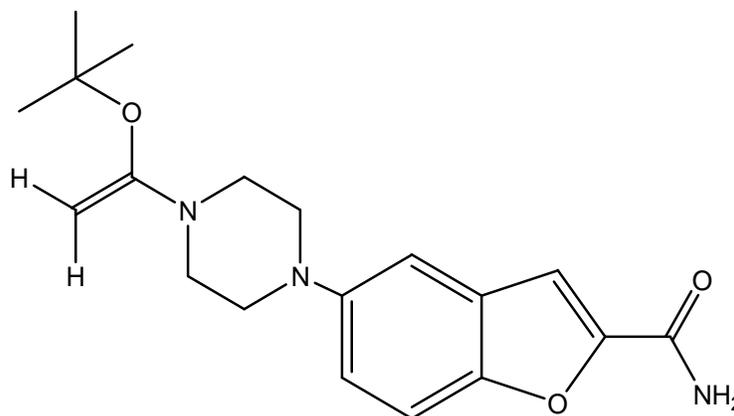
Mechanism of piperazine derivatives:



tert-butyl 4-(2-(ethoxycarbonyl)benzofuran-5-yl)piperazine-1-carboxylate



ethyl 5-(piperazin-1-yl)benzofuran-2-carboxylate



5-(4-(1-*tert*-butoxyvinyl)piperazin-1-yl)benzofuran-2-carboxamide

This is consistent with the results obtained in the present study where EPBFC and TBECBFPPC gave more inhibition than that for TBCBFPPC. However, the higher value of inhibition efficiency obtained for EPBFC and TBECBFPPC might be due to the presence of carboxylate ion which is attached at position no. 2 of benzofuran, which is absent in TBCBFPPC. On the other hand, the lower value of inhibition efficiency for EPBFC than that of TBECBFPPC might be attributed to the presence of hydrogen atom at piperazine N atom instead of ethoxy carbonyl group of TBECBFPPC.

Adsorption of the compound may be due to the interaction of between the π -electrons of benzene ring present in the compound with the positively charged mild steel surface. The interaction of the lone pairs of electrons of nitrogen atoms of the azo group with the positively charged mild steel metal surface may also play significant role on the adsorption of the compound on the mild steel surface.

The compounds are stabilized by the resonance involving the nonbonding pair of electrons on the nitrogen atom and the strong electron-withdrawing effect of the carbonyl group. The strong electron withdrawing carbonyl oxygen takes on a partial negative charge. Protonation of an amide occurs on the oxygen rather than the nitrogen. The carbonyl carbon atom competes for the nitrogen electron pair forming an N=C double bond but they are less basic than amine.

More precisely, electron withdrawal by carbonyl oxygen destabilizes a positive charge on nitrogen, whether this charge is acquired by protonation or by electrophilic attack on the ring.

Conclusion

As a constant inhibitor concentration, the inhibition efficiency of all inhibitors decreases as the concentration of acid increases. At all concentration of acid, as the inhibitor concentration increases inhibition efficiency increases and corrosion rate decreases. As the temperature increases corrosion rate increases in plain acid. Addition of inhibitors in corrosive media indicates that as the temperature increases corrosion rate increases while inhibition efficiency decreases. In all cases, the value of heat of adsorption (Q_{ads}) and the value of free energy of adsorption (G_a^0) is negative. The Value of change of enthalpy (H_a^0) and entropy of adsorption (S_a^0) is positive. A mean value of 'E_a' in inhibiting acid is higher than the value of 'E_a' in acid only. In almost all the cases, the inhibition efficiency from Tafel plots agrees well (within $\pm 4\%$) with the values obtained from weight loss data.

Acknowledgments

The authors are thankful to Department of Chemistry, and Department of Chemistry, Arts, Science and Commerce College, Kamrej Char Rasta, Surat for providing laboratory facilities.

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How to cite this article:

P S Desai and N S Indorwala. (2016). Inhibitory action of piperazine derivatives on mild steel corrosion in hydrochloric acid solutions. *Int. J. Curr. Res. Chem. Pharm. Sci.* 3(9): 32-44.

DOI: <http://dx.doi.org/10.22192/ijcrcps.2016.03.09.005>