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Corrosion Inhibition of Mild Steel in HCl Medium by 2-(3, 4, 5-Trimethoxybenzylidene) Hydrazinecarbothioamide

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ABSTRACT

The inhibitive effect and adsorption behavior of 2-(3, 4, 5-trimethoxybenzylidene) hydrazine carbothioamide (TMBHC) on the corrosion behaviour of mild steel in 0.5 M hydrochloric acid solution has been studied by potentiodynamic polarization, electrochemical impedance spectroscopy (EIS) in the temperature range 30^{o} *C –* 60^{o}*C. The study reveals that the inhibition efficiency increases with increase in inhibitor concentration and with increase in temperature. TMBHC showed maximum inhibition efficiency in the range 90-95 % at optimum concentration of TMBHC at all the studied temperatures. The Tafel polarization results indicate that TMBHC acted as a mixed type of inhibitor. The adsorption of TMBHC on the metal surface takes place predominantly through Chemisorption and follows Langmuir's adsorption isotherm. The thermodynamic parameters and activation parameters were evaluated and discussed. The surface morphology was studied by Scanning electron microscopy (SEM).*

Keywords: Mild steel, corrosion, Tafel polarization, Electrochemical impedance, Chemisorption.

INTRODUCTION

Mild steels are extensive used as constructional material in many chemical and petrochemical industries due to its low-cost, easy availability and excellent mechanical properties. Acid solutions are widely used in industry, and some of the most important fields of application are acid pickling, chemical cleaning and processing, ore production, and oil well acidification [1-2]. Corrosion problems arise as a result of the interaction between the aqueous solutions and steel, especially during the pickling process in which the alloy is brought in contact with highly concentrated acids. This process can lead to economic losses due to the corrosion of the alloy [3]. The use of organic inhibitors is one of the most effective and reasonably inexpensive methods to control the corrosive attack on metals and alloys. Literature survey showed that organic compounds containing hetero atoms (such as nitrogen, sulfur, and oxygen), unsaturated bonds (such as double or triple bonds) and aromatic or heterocyclic rings functioned as effective corrosion inhibitors for many metals and alloys [3,4]. Several acid hydrazide derivatives, aromatic hydrazide derivatives, thiosemicarbazide derivatives displayed remarkable ability to inhibit corrosion of mild steel in acidic solutions [5-7].

The present work deals with the inhibitive action of TMBHC on the corrosion behaviour of mild steel in 0.5 M hydrochloric acid medium containing different concentrations of TMBHC and at different temperatures (30 – 60 ^{o}C) using Tafel polarization and EIS methods. Further the study also focuses on the inhibition mechanism by studying the adsorption isotherms, activation and thermodynamic parameters.

MATERIALS AND METHODS

Material: Mild steel in rod form with composition (% wt) C (0.159), Si (0.157), Mn (0.496), P (0.060), S (0.062), Cr (0.047), Ni (0.06), Mo (0.029), Al (0.0043), Cu (0.116) and remaining Fe was used for the corrosion study. The working electrodes were prepared from the extruded rod and embedded using epoxy resin. The specimen had an exposed surface area of 0.95 cm^{2}. Polishing of the exposed surface was done using emery papers of different grades (400-1500) and subsequently on polishing wheel using levigated alumina. The polished specimen was washed and cleaned with double distilled water and finally rinsed with acetone and dried.

Synthesis of TMBHC: 2-(3, 4, 5-trimethoxybenzylidene) hydrazinecarbothioamide (TMBHC) was synthesized as per the reported literature [8]. An equimolar mixture of ethanolic solution of 3, 4, 5-tri methoxy benzaldehyde and thiosemicarbazide was refluxed on a hot water bath for about 2h. The precipitated product was purified by recrystallization from ethanol. The characterization was done by IR (Schinadzu FTIR 8400S Spectrophotometer) and NMR spectroscopy techniques. Fig.1 represents the chemical structure of the inhibitor molecule.

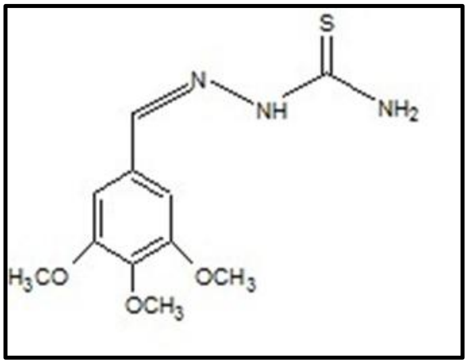


Fig.1 Chemical structure of TMBHC molecule

Medium: The stock solution of 2M hydrochloric acid was prepared by using analar grade hydrochloric acid and double distilled water and standardized by volumetric method. From the stock solution, 0.5 M hydrochloric acid solution was prepared and used as the medium.

Electrochemical measurements: Electrochemical measurements were carried out using a electrochemical work station (CH Instrument USA Model 604D series with beta software).The electrochemical cell consisted of a conventional three-electrode Pyrex glass cell with platinum counter electrode, and saturated calomel electrode (SCE) as reference electrode and mild steel as working electrode.

Finely polished mild steel specimen was exposed to the corrosion medium of 0.5 M HCl solution in the absence and presence of the TMBHC at different temperatures (30-60 °C) and allowed to establish a steady state open circuit potential (OCP). The potentiodynamic current vs potential curves were recorded by polarizing the specimen to -250 mV cathodically and +250 mV anodically with respect to the OCP at a scan rate of 0.5 mV s^{-}1. The impedance experiments were carried out in the frequency range of 100 kHz to 0.01 Hz, at the OCP by applying small amplitude AC signal of 10 mV.

Scanning electron microscopy (SEM): The SEM images of the test specimen were recorded to study the surface morphology of the same by immersing in 0.5 M HCl solution both in the presence and absence of the TMBHC using EVO 18-5-57 model.

RESULTS AND DISCUSSION

Characterization of TMBHC: Amorphous yellow solid (95 %) m.p.262-268 °C; IR (KBr) [cm$^{-1]}$]; 3556, 3394 (NH_2 str.), 3263 (NH str.), 3163 (Ar. C-H str.), 2939 (CH_3 asym str.), 2823 (CH_3 sym str.), 1620 (C=N), 1573 (Ar. C=C str), 1234 (C=S); ^{1}H NMR $CDCl_3$, 400 MHz, 11.43 (1H, NH), 8.24 (1H, CH=N), 7.95-8.10 (2H, Ar. H), 7.09 (2H, NH_2) 3.83 (6H, OCH_3), 3.68 (3H, OCH_3); Anal. Calcd. for $C_{11}H_{15}N_3O_3S$; C, 49.07; H, 5.58; N, 15.61. Elemental analysis: Found: C, 49.17; H, 5.61; N, 15.63%.

Tafel polarization measurements: Potentiodynamic polarization curves for mild steel in 0.5 M HCl solution at 30 °C without and with various concentrations of TMBHC were shown in fig. 2. The values of corrosion current density (i_{corr}), corrosion potential (E_{corr}), corrosion rate (*CR*), anodic Tafel slope (b_a), and cathodic Tafel slope (b_c) were recorded in table 1.

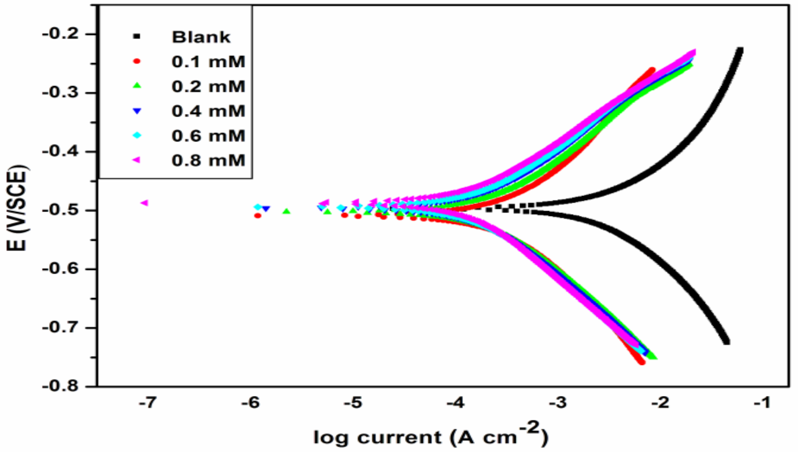


Fig. 2 Tafel polarization curves for the mild steel specimen in 0.5 M HCl with various concentrations of TMBHC at 30 °C

It can be seen from Table 1 that the i_{corr} values decreased with increasing TMBHC concentration. Further the inhibition efficiency increased with increase in inhibitor concentration as well as with temperature and attained maximum inhibition efficiency more than 90% at all the studied temperatures. A compound can be classified as an anodic- or a cathodic-type inhibitor when the change in the E_{corr} value is larger than 85 mV with respect to corrosion potential of the uninhibited solution [9]. In the present case there is no shift in the E_{corr}. This indicates that TMBHC inhibits both metal dissolution and hydrogen evolution reaction, thereby acting as a mixed-type inhibitor. Further there is no significant change in values of anodic slope (b_a) or cathodic slope (b_c), which indicated the inhibition mechanism does not alter with increase in TMBHC concentration [10].

The *% IE* values listed in Table 2 were calculated according to equation (1).

$$\% IE = \frac{i_{corr} - i_{corr(inh)}}{i_{corr}} \qquad (1)$$

In the above equation i_{corr} and $i_{corr(inh)}$ represents the corrosion current densities in the presence of uninhibited and inhibited solution respectively.

Table1. Tafel polarization results for the corrosion of mild steel in 0.5 M HCl in the absence and presence of TMBHC at different temperatures

Temp. (°C)	Conc. of Inhibitor (mM)	E_{corr} (mV)	$-b_c$ (mV dec^{-1})	b_a dec^{-1})	i_{corr} (mAcm^{-2})	*CR* (mpy)	*IE* (%)
30	0	-480	84.21	86.06	1.405	343	-
	0.1	-485	72.00	73.49	0.1936	47.25	86.2
	0.2	-479	71.26	70.16	0.1680	40.99	88.0
	0.4	-477	73.25	66.39	0.1436	35.04	89.7
	0.6	-476	75.33	62.48	0.1429	34.88	90.0
	0.8	-477	84.25	61.25	0.0998	24.36	92.8
40	0	-484	69.89	68.76	3.001	732.4	-
	0.1	-509	68.28	69.33	0.3007	73.39	89.9
	0.2	-499	75.22	79.12	0.2199	53.67	92.6
	0.4	-491	73.45	83.63	0.1785	43.56	94.0
	0.6	-489	70.38	84.78	0.1649	40.68	94.5
	0.8	-478	70.40	90.25	0.1440	35.15	95.2
50	0	-486	61.38	67.32	5.887	1437	-
	0.1	-516	78.09	78.81	0.3724	90.90	93.6
	0.2	-518	73.67	83.79	0.3211	78.35	94.5
	0.4	-514	67.53	86.93	0.3018	73.65	94.8
	0.6	-512	68.71	88.74	0.2706	66.05	95.4
	0.8	-518	78.45	80.80	0.1997	48.73	96.6
60	0	-486	54.84	52.38	11.35	2771	-
	0.1	-528	71.46	65.94	0.7414	180.9	93.4
	0.2	-530	68.29	72.95	0.5558	135.6	95.1
	0.4	-534	75.65	72.12	0.4781	116.7	95.7
	0.6	-519	77.02	76.82	0.4114	100.4	96.3
	0.8	-529	73.24	87.11	0.4006	98.98	96.6

Effect of temperature: The effect of temperature on corrosion rate was studied in the temperature range 30 to 60 °C at different concentrations of TMBHC. It was found that the inhibition efficiency increases with increase in temperature. The high inhibition efficiency of TMBHC was mainly due to the interactions of the adsorbed inhibitors with the surface metal atoms. The strong bonding was generally attributed to higher electron densities at active functional groups, imine group and π electrons present in the adsorbate molecules [11].

Arrhenius equation (equation 3) was used to calculate the activation energy (E_a) for the corrosion process in the presence and absence of TMBHC [12].

$$\ln(CR) = B - \frac{E_a}{RT} \tag{2}$$

where B is the Arrhenius pre-exponential constant, and R is the universal gas constant. The slope ($-E_a/R$) obtained from the plot of ln (CR) against $1/T$ used to calculate the activation energy for the corrosion process. Fig. 3 shows the Arrhenius plots for the mild steel specimen studied.

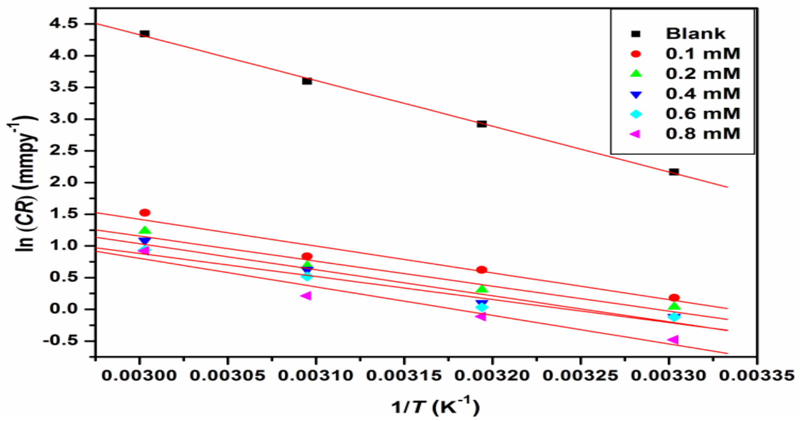


Fig. 3 Arrhenius plots of ln (CR) vs. 1/T for mild steel in 0.5 M HCl with different concentrations of TMBHC

It was evident from the table 2 that the values of E_a for the corrosion of mild steel in the presence of TMBHC lower than those in the absence of inhibitor, which indicates chemical adsorption of inhibitor molecules on the metal surface [13]. The enthalpy and entropy of activation for the metal dissolution process were determined using the transition state equation (3) and recorded in the table 2 [14].

$$CR = \frac{RT}{Nh} exp\left(\frac{\Delta S^{\#}}{R}\right) exp\left(\frac{-\Delta H^{\#}}{RT}\right) \qquad (3)$$

Where *h* is Plank's constant and *N* is Avagadro's number. A plot of ln (*CR/T*) versus 1/*T* for mild steel specimen in 0.5 M HCl led to a straight line with slope = $-\Delta H^{\#}/T$ and intercept = ln(*R/Nh)* + $\Delta S^{\#}/R$ as shown in fig. 4. The negative values of $\Delta S^{\neq}$ indicate that a decrease in disordering takes place on going from reactant to the activated complex and the positive sign of the $\Delta H^{\neq}$ showed the endothermic nature of steel dissolution process [15].

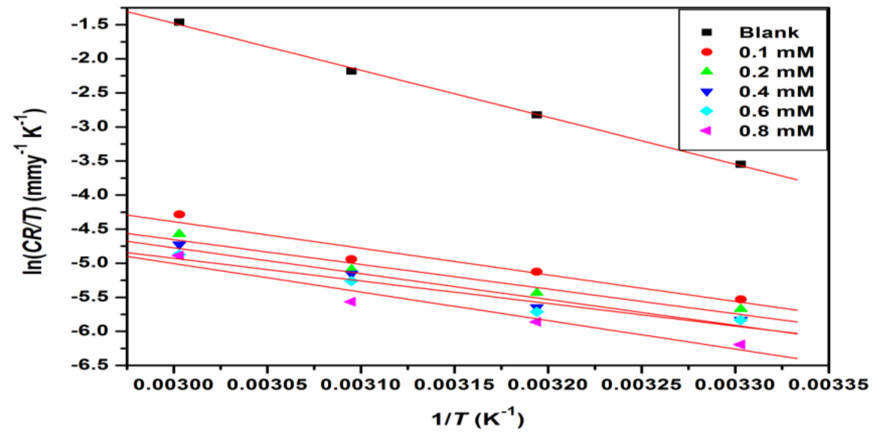


Fig. 4 Plot of ln (*CR*)/*T* versus 1/*T* for mild steel specimen in 0.5 M HCl containing various concentrations of TMBHC

Table 2. Activation parameters for the corrosion of mild steel in 0.5 M HCl acid containing different concentrations of TMBHC

Conc. of inhibitor (mM)	E_a (kJmol^{-1})	$\Delta H^{\neq}$ (kJmol^{-1})	$\Delta S^{\neq}$ (Jmol^{-1}K^{-1})
0	59.94	57.30	-37.91

0.1	35.08	32.45	-136.66
0.2	32.77	30.13	-142.59
0.4	34.17	31.54	-145.81
0.6	30.18	27.55	-155.84
0.8	37.43	34.79	-134.73

Adsorption isotherm: The study of adsorption isotherms provides basic information regarding the interaction between the inhibitor molecule and the metal surface. The values of surface coverage (Θ) at different concentrations of TMBHC were calculated from equation (4) and have been used to explain the isotherm to fit the adsorption process.

$$\Theta = \frac{i_{corr} - i_{corr(inh)}}{i_{corr}} \qquad (4)$$

where i_{corr} and $i_{corr(inh)}$ represent the corrosion current densities in the presence of uninhibited and inhibited solution respectively. In the present study, various adsorption isotherms are tested and it was found that the adsorption of TMBHC on the mild steel surface in hydrochloric acid medium follows the Langmuir adsorption isotherm which is given by the expression (5) [16].

$$\frac{C_{inh}}{} = \frac{1}{K_{ads}} + C_{inh} \qquad (5)$$

where C_{inh} is inhibitor concentration, Θ is the degree of surface coverage and K_{ads} is the adsorption equilibrium constant. The value of K_{ads}, determined from the plot of C_{inh}/Θ vs. C_{inh} (Fig. 5) at constant temperature is used to calculate the value of the standard free energy of adsorption (ΔG^o_{ads}) using the expression (6) [17].

$$K = \frac{1}{55.5} exp\left(\frac{-\Delta G^o_{ads}}{RT}\right) \qquad (6)$$

where K is the equilibrium constant, R is the universal gas constant and T is absolute temperature and 55.5 is the concentration of water in solution in mol/dm^3.

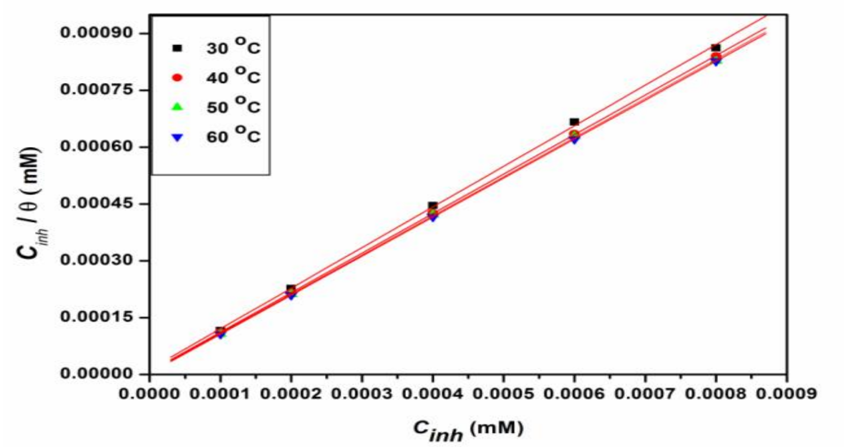


Fig. 5 Langmuir's adsorption isotherm of TMBHC on mild steel in 0.5 M HCl at different temperatures

Straight line was obtained in the plot of ΔG^o_{ads} versus T that is shown in fig. 6. The standard enthalpy of adsorption (ΔH^o_{ads}) and the standard entropy of adsorption (ΔS^o_{ads}) are computed from the slope and intercept of the straight line respectively according to the thermodynamic equation (7).

$$\Delta G^{o}_{ads}=\Delta H^{o}_{ads} - T\,\Delta S^{o}_{ads} \qquad (7)$$

The plots obtained are linear with the correlation coefficients nearly equal to one. The calculated values of ΔG^{o}_{ads}, ΔH^{o}_{ads} and ΔS^{o}_{ads} are tabulated in table 3.

Table 3. Thermodynamic parameters for the adsorption of HMBHC on mild steel surface in 0.5 M HCl at different temperatures

Temp. (°C)	ΔG^{o}_{ads} (kJ mol^{-1})	Slope	ΔH^{o}_{ads} (kJ mol^{-1})	ΔS^{o}_{ads} (J mol^{-1}K^{-1})
30	-38.37	0.999	35.35	-243.6
40	-41.10	0.999		
50	-43.17	0.999		
60	-45.80	0.999		

The negative values of ΔG^{o}_{ads} show the strong interaction and spontaneous adsorption of the inhibitor molecules onto the mild steel surface. In general, the values of ΔG^{o}_{ads} up to -20 kJ mol^{-1} or less than -20 kJ mol^{-1} imply physisorption and greater than -40 kJ mol^{-1} indicates the chemisorption [18]. It can be seen from the Table 3 the ΔG^{o}_{ads} value corresponding to lower temperature indicates the physisorption, whereas the values corresponds to higher temperature indicating chemisorptions

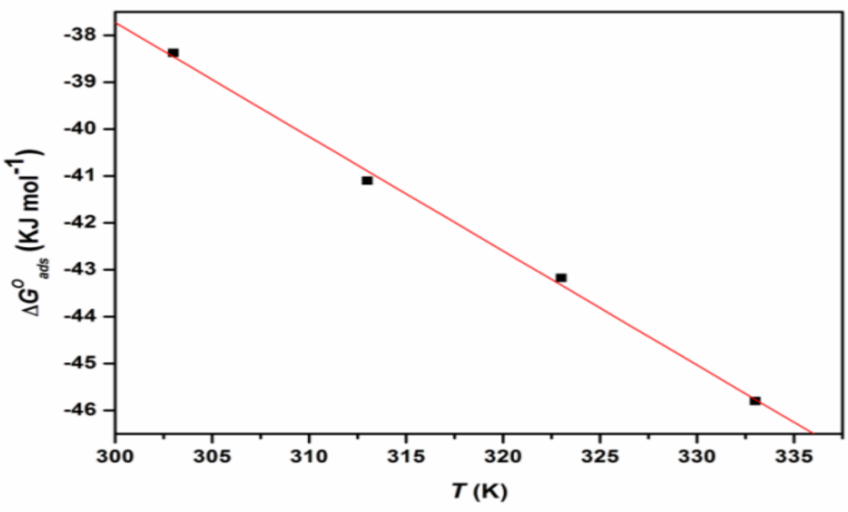


Fig. 6 Plot of ΔG^{o}_{ads} versus temperature for the adsorption of TMBHC on Mild steel in 0.5 M HCl

The positive sign of ΔH^{o}_{ads} indicated that the adsorption of inhibitor molecule is an endothermic process. In general, an endothermic process is attributed to chemisorption while an exothermic adsorption process signifies either physisorption or chemisorption [19]. In the present case, the calculated value of ΔH^{o}_{ads} with positive sign (35.35 kJ mol^{-1}) indicates the chemisorption of inhibitor. The large and negative ΔS^{o}_{ads} value indicates that a decrease in randomness takes place when going from reactants to the activated complex [20].

Electrochemical impedance spectroscopy: The impedance responses of the corrosion behaviour of mild steel in the absence and presence of TMBHC were given in terms of Nyquist plot (Fig.7). As seen from Fig. 7, the plots obtained with depressed semicircle of which the diameter increased with increase in inhibitor concentration. This indicates that the charge transfer process mainly controlling the corrosion of mild steel. The depressed capacitive behaviour can be attributed to the contribution from roughness of the surface, active sites distribution or inhibitor adsorption [21].

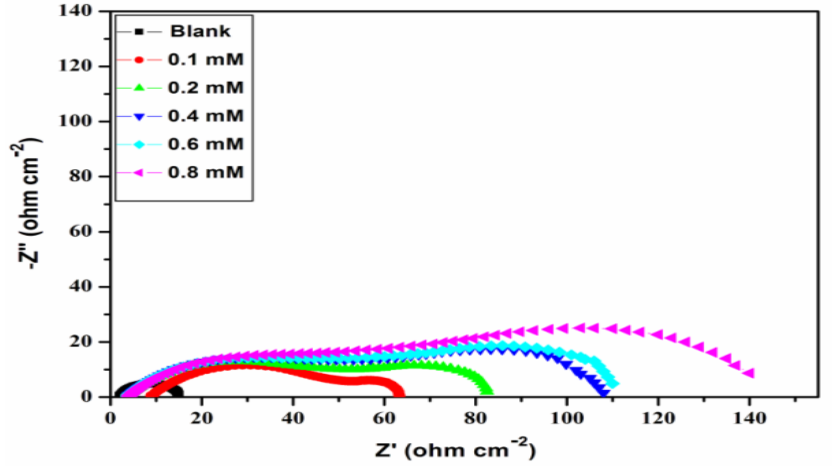


Fig.7 Nyquist plots for mild steel specimen in 0.5 M HCl acid containing different concentrations of TMBHC at 40 °C

The impedance parameters were analysed by fitting suitable equivalent circuit to the Nyquist plots using ZSimpWin software version 3.21. A simplest Randles equivalent circuit as shown in fig.8 (a) was used to fit the Nyquist plot in the absence of inhibitor in 0.5 M hydrochloric acid solution. It consists of solution resistance R_s, charge transfer resistance R_{ct} and one constant phase element (CPE). CPE was employed instead of the double-layer capacitance (C_{dl}) to describe the heterogeneity in the system. The Nyquist plots for the corrosion inhibition of mild steel in the presence of inhibitor consisted of one distorted capacitive loop at higher frequency due to charge transfer reaction and the time constant of the electric double layer [22]. The suitable equivalent circuit was used to simulate the impedance data in presence of TMBHC as shown in Fig. 8(b). Similar circuits were used to model steel acid interface in the presence of inhibitor [23]. It included the solution resistance (R_s), fast charge transfer process (R_1), time constant of the electric double layer (CPE_1), the capacitance of the surface film (CPE_2) and the surface layer resistance (R_2). The impedance parameters obtained were reported in table 4.

Table 4. EIS results for mild steel in 0.5 M HCl acid in the absence and presence of different concentrations of TMBHC

Temp. (°C)	Conc. of inhibitor (mM)	R_{ct} (Ω cm^{-2})	C_{dl} (uFcm^{-2})	*IE* (%)
30	0	16.75	1279	
	0.1	100.73	864	83.3
	0.2	134.41	511	87.5
	0.4	155.2	311	89.2
	0.6	163.5	287	89.7
	0.8	212.24	195	92.1
40	0	10.01	2945	
	0.1	62.23	2223	83.8
	0.2	83.8	1416	87.9
	0.4	110.93	832	90.9
	0.6	113.99	751	91.2

	0.8	138.5	457	92.7
50	0	5.0	10615	
	0.1	56.68	2698	91.3
	0.2	65.5	1943	92.3
	0.4	72.54	1902	93.1
	0.6	76.2	1530	93.4
60	0.8	97.6	912	94.9
	0	2.331	45560	
	0.1	31.64	7627	92.7
	0.2	40.79	4851	94.3
	0.4	51.57	3213	95.5
	0.6	56.41	2630	95.9
	0.8	61.65	2320	96.2

The impedance of *CPE* can be given by the following expression (8) [24].

$$Z_{CPE} = \frac{1}{Y_o((jw)^n} \qquad (8)$$

Where, Y_0 is used for magnitude of *CPE*, *w* is the angular frequency for which $-Z$ reaches its maximum values, and *n* is an empirical exponent ($0 \le n \le 1$), which measures the deviation from the ideal capacitive behavior.

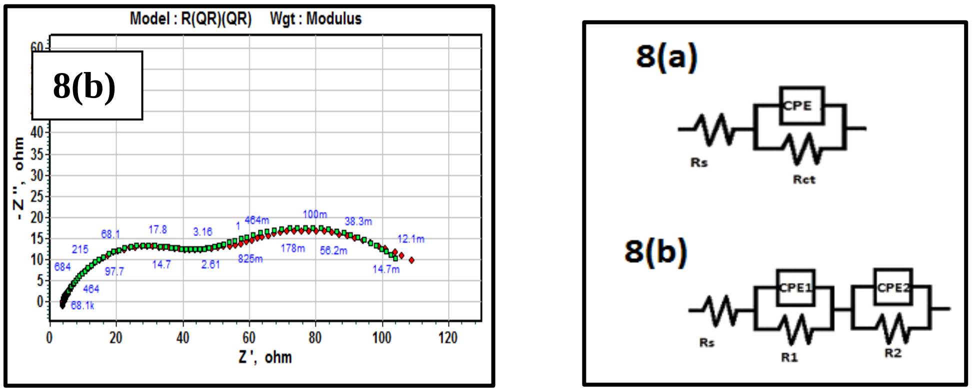


Fig. 8 Equivalent circuit used to fit experimental EIS data for the corrosion of mild steel (a) In the absence of TMBHC (b) In the presence of TMBHC in 0.5 M HCl medium in the presence of TMBHC.

The *CPE* behaves like an ideal double-layer capacitance (C_{dl}) and was calculated from the frequency (f_{max}) at which the imaginary component of impedance was maximum ($Z_{im,\ max}$) using the equation (9).

$$C_{dl} = \frac{1}{2\pi f_{max} R_{ct}} \qquad (9)$$

The increase in inhibitor concentration tends to decrease the double layer capacitance (C_{dl}), due to the replacement of the adsorbed water molecule from the metal surface by the adsorbed inhibitor molecule thereby decreasing the active surface area by protective film formation. Further decrease in C_{dl} was attributed to increase in the thickness of the electrical double layer at the metal/solution interface [25].

The charge transfer resistance R_{ct} is a measure of resistance against electron transfer across the surface and is inversely proportional to corrosion rate. The R_{ct} obtained from the summation of R_1 and R_2, which was the used to calculate the percentage inhibition (% IE) using equation (10).

$$\% \text{ IE} = \frac{R_{ct} - R^{o}{}_{ct}}{R_{ct}} \times 100 \qquad (10)$$

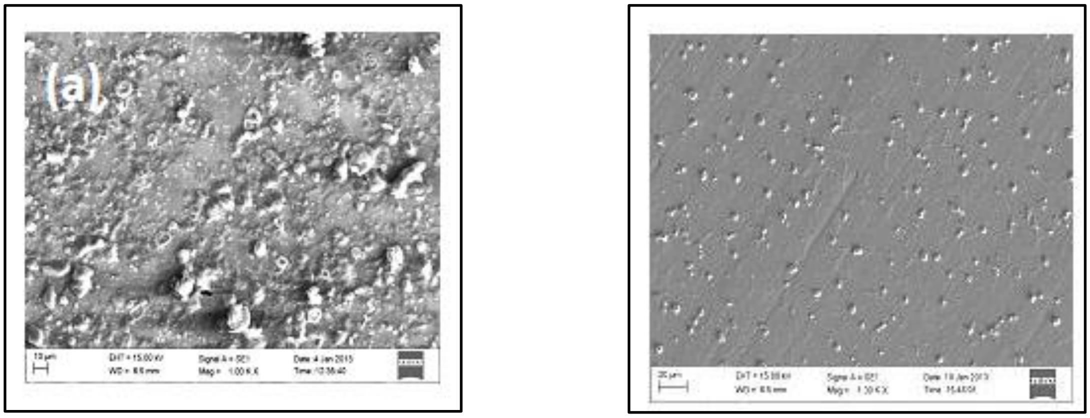
Where, R_{ct} and $R^{o}{}_{ct}$ indicate the charge transfer resistance in presence and absence of TMBHC. The increase in inhibitor concentration results in increasing the R_{ct} value, which specified that the corrosion process was mainly controlled by charge transfer process [4].

Inhibition mechanism: Corrosion inhibitive action of TMBHC on mild steel in 0.5 M HCl solution can be explained on the basis of adsorption phenomenon. The presence of free electron pairs in the sulphur, oxygen and the nitrogen atoms, π-electrons on the aromatic rings, imine group, electron donating group and molecular size of TMBHC might have played a vital role in the adsorption of the inhibitor and the formation of coordinate bond with metal. The adsorbed TMBHC form a protective film on the metal surface, which acts as a barrier between metal and corrosive medium.

The kinetic and thermodynamic parameters reveal that corrosion inhibition of mild steel in hydrochloric acid medium was predominantly due to the chemical adsorption of TMBHC on the metal surface. The possible mechanism for the corrosion inhibition can be explained as follows. In a highly acidic solution, as in the present case, the TMBHC molecule can undergo protonation at its amino groups and can exist as a protonated positive species. Further, the metal surface is positively charged in the presence of acidic medium. This would cause the negatively charged chloride ions or inhibitor molecules to become adsorbed on the metal surface, via their negative centres. The positively charged protonated TMBHC molecules can interact electrostatically with the negatively charged chloride adsorbed metal surface resulting in physisorption particularly at lower temperature [26].

The higher inhibition efficiency attained at elevated temperature was due to the adsorption of TMBHC molecule on the surface of metal via chemisorption process. This was due the displacement of the initially occupied water molecules from the metal surface by the inhibitor molecules and interacts with the metal surface. The interaction was due to sharing of electrons between the hetero atoms (O, S and N) and the metal. In addition, the horizontal orientation of the entire molecule with respect to the metal surface can also lead to donor-acceptor interaction of π-electrons of the aromatic ring with those vacant d orbitals of the metal surface resulting in chemisorption [27]. The presence of imine group (–CH=N–) and electron donating groups (OCH_3) in TMBHC also participating in enhancing the inhibition efficiency and makes the inhibitor more potential towards for the corrosion inhibition of mild steel.

Scanning electron microscopy: The effect of corrosion on the surface morphology of the mild steel sample was assessed by recording the SEM images of the specimen samples subjected to corrosion in 0.5 M hydrochloric acid for 3 h in the presence and the absence of TMBHC. Fig.9 (a) shows the facets due to the corrosive action of 0.5 M HCl on the mild steel surface with cracks and rough surface. Smooth sample surface without any visible corrosion attack after immersion in 0.5 M HCl in the presence of TMBHC is shown in fig 9. (b). Thus, it can be concluded TMBHC formed a uniform protective film on the specimen surface preventing it from undergoing corrosion.



(a) **(b)**

Fig. 11 SEM images of the mild steel (a) 0.5 M HCl solution and (b) 0.5 M HCl containing 0.8 mM of TMBHC.

APPLICATIONS

The study is useful to investigate the inhibitive effect, temperature effect and adsorption behaviour of a hydrazide derivative named TMBHC on corrosion of mild steel in 0.5 M HCl using, potentiodynamic polarization and electrochemical impedance spectroscopy techniques. TMBHC shows very good inhibition efficiency of more than 90% at all the studied temperature at low concentration 8×10^{-4} M (≈ 150 ppm). TMBHC can be effectively used as potential inhibitor for the corrosion control of mild steel in hydrochloric acid medium in pickling processes.

CONCLUSIONS

- TMBHC showed reasonably good inhibition efficiency (more than 90%) at optimum concentration (0.8 mM) at all studied temperature.
- The studied inhibitor acted as mixed type of inhibitor
- The inhibition efficiency increases with increase in inhibitor concentration and with increase in temperature

  The adsorption of TMBHC obeyed Langmuir's isotherm and the adsorption takes place through chemisorption
- There is a good correlation between EIS and Tafel polarization results.

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