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Protection of Carbon Steel Against Corrosion in Hydrochloric Acid Solution by Some Synthesized Cationic Surfactants[1]

Ismail Aiad[a], M. Abo Riya[b], Salah M. Tawfik[a], and Mahmoud A. Abousehly[c]
[a] *Egyptian Petroleum Research Institute, Nasr City, Cairo, Egypt*
[b] *Faculty of Science, Chemistry Department, Benha University,Al Qalyubiyah, Egypt*
[c] *General Petroleum Company, Cairo, Egypt*
**e-mail: salahtwfk85@yahoo.com*

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Abstract—A series of some cationic surfactants was synthesized namely: N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(dodecanoyloxy)ethoxy)ethoxy)ethanaminium chloride (DDAC); N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(tetradecanoyloxy) ethoxy) ethoxy) ethanaminium chloride (TDAC) and N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(hexadecanoyloxy)ethoxy)ethoxy)ethanaminium chloride (HDAC). Their chemical structures were characterized using FTIR and ^{1}HNMR spectroscopy. Corrosion inhibition performance of these compounds on carbon steel in 0.5 M HCl was studied using weight loss and potentiodynamic polarization methods. It was seen that the three synthesized cationic surfactants decreased the corrosion rate of mild steel in acidic medium due to the adsorption on the metal surface. And it was found that the inhibition efficiency increased with increasing the inhibitor concentration. The adsorption of inhibitors on the carbon steel surface obeys modified Langmuir equation which named Villamil isotherm adsorption. Polarization curves show that the synthesized inhibitors are mixed-type inhibitors in 0.5 M HCl. ΔG^0_{ads} were ranged from –31.65 to –33.40 kJ mol^{-1} which indicate that the adsorption process is mixture between physical and chemical adsorption.

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1. INTRODUCTION

In most oil production wells, chloride salts are found either dissolved in water or emulsified in crude. Salts also originate from brines injected for secondary recovery or from sea water ballast in marine tankers. Typically, salts in crude oil consist of 75% NaCl, 15% $MgCl_2$ and 10% $CaCl_2$ [1]. When crude oils are loaded into distillation units and heated up to about 120°C, hydrogen chloride gas is evolved as a product of $MgCl_2$ and $CaCl_2$ hydrolysis, while NaCl is essentially stable. Dry hydrogen chloride, especially in the presence of large amounts of hydrocarbon vapour or liquid is not corrosive to carbon steel, but when steam is settled down to the bottom of the crude tower and in the overhead condensing system, severe aqueous chloride corrosion of carbon steel occurs. To counteract this, corrosion inhibitors must be injected continuously through the system [2]. The inhibition of steel corrosion in acidic media using surface active agents (surfactants) has been achieved by many workers [3–10].

Different surfactant types have been reported to present corrosion inhibitory potential which depends on the classification of surfactants, substrate type, inhibitor concentration [11], time of immersion in inhibitor solution [12], type of acid, pH [13], presence of salts [14–16], co-surfactant [17, 18], temperature [19–22] and corrosion inhibitor structure [23–25]. Surfactant corrosion inhibitors have many advantages such as high inhibition efficiency, low price, low toxicity, and easy production. In general, the inhibitory action of surfactant in aqueous solutions is due to a physical (electrostatic) adsorption or chemisorption of surfactant molecules onto the metallic surface, depending on the charge of the solid surface and the free energy change of transferring a hydrocarbon chain from water to the solid surface. The adsorption of a surfactant markedly changes the corrosion resisting property of a metal and for this reason, the study of the correlation between the adsorption and corrosion inhibition is of a considerable importance [26].

The present work aimed to synthesis, study the adsorption properties and the inhibitive effects of cationic surfactants on the corrosion rate of carbon steel in 0.5 M hydrochloric acid solution by both chemical and electrochemical techniques.

2. MATERIALS AND METHODS

2.1. Materials

Di-ethylene glycol (purity >99), triethanol amine (purity >99) and chloroacetic acid (purity >99) were purchased from Sigma-Aldrich chemical company.

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Dodecanoic (purity >98), tetradecanoic (purity >99) and hexdecanoic acids (purity >99)were analytical grade chemicals were obtained from Aldrich chemical company (Germany). All the reagents were analytical grade and used as received without further purification.

Tests were performed on carbon steel (CS) of the following composition: 0.11% C, 0.45% Mn, 0.04% P, 0.05% S, 0.25% Si, and the reminder is Fe.

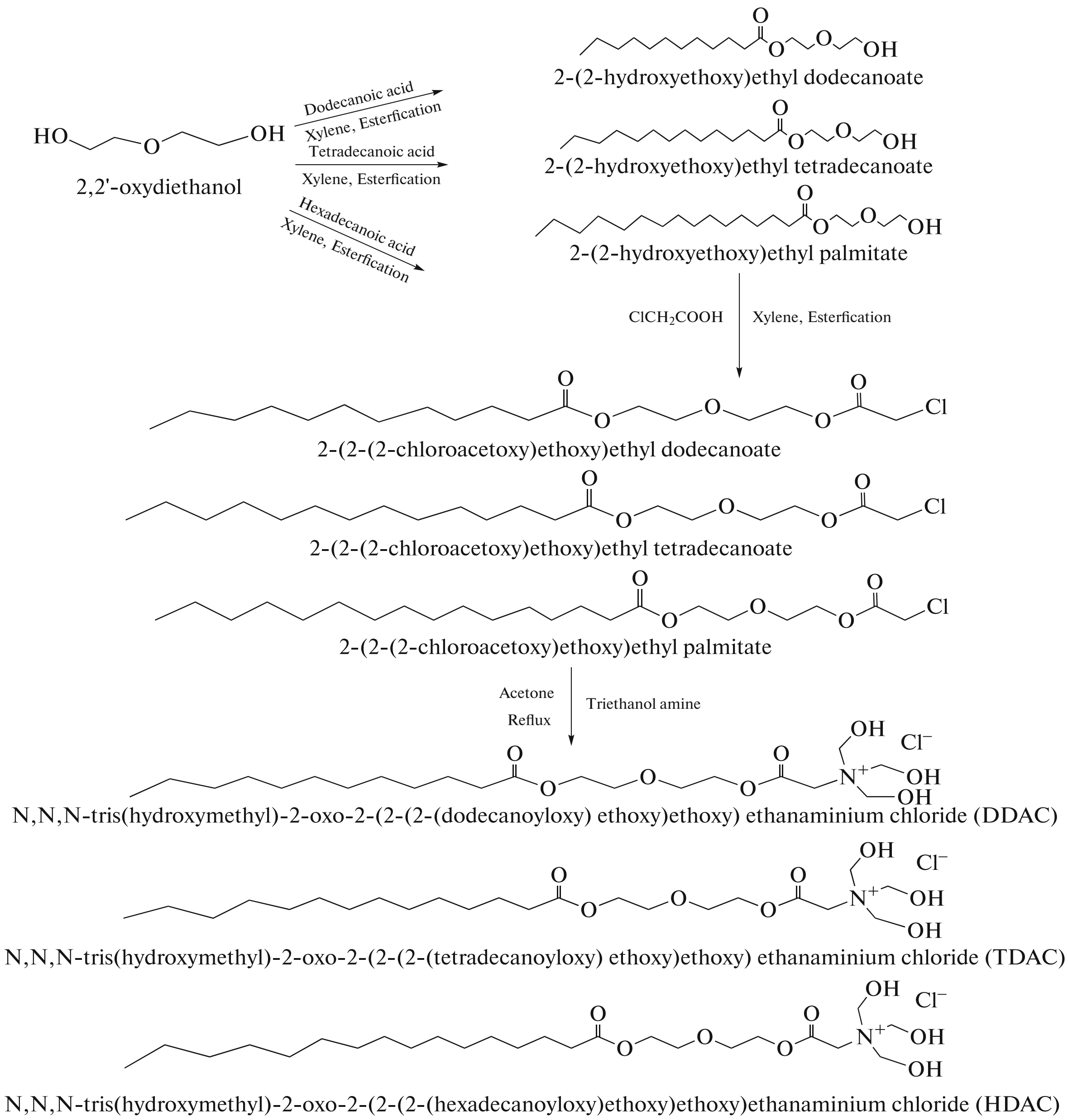
2.2. Synthesis

The used inhibitors were prepared through three steps:

I- Synthesis of 2-(2-hydroxyethoxy)ethyl alkanoate

Different fatty acids namely; Dodecanoic, tetradecanoic, and hexdecanoic acids (0.1 mol) were esterified separately by di-ethylene glycol (0.1 mol) in xylene as a solvent and 0.01% *p*-toluene sulphonic acid as a catalyst, until the azeotropic amount of water (0.1 mol, 1.8 mL) was removed. Vacuum rotary evaporator used to remove the solvent. Excess residual materials were removed by means of vacuum distillation [27].

II-Synthesis of 2-(2-(2-chloroacetoxy)ethoxy)ethyl alkanoate



Scheme 1. Synthesis of cationic surfactants.

2-(2-hydroxyethoxy)ethyl alkanoate (0.1 mol) and chloroacetic acid (0.1 mol) were esterified individually in xylene (250 mL) as the solvent under reflux conditions at 140°C, vacuum rotary evaporator used to remove the solvent. The synthesized chloroacetic acid esters were showed in Scheme 1 [28].

III-Synthesis of N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(alkyloyloxy) ethoxy)ethoxy) ethanaminium chloride

The synthesized cationic surfactants were obtained by coupling reaction between triethanol amine (0.1 mol) and the synthesized 2-(2-hydroxyethoxy)ethyl alkanoate (0.1 mol) in 50 mL acetone. The reaction mixture was refluxed for 12 h and left for complete precipitation of the cationic compounds. The produced quaternary ammonium salts were filtered off and recrystallized three times from acetone to produce the desired cationic surfactants: N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(dodecanoyloxy) ethoxy)ethoxy) ethanaminium chloride (DDAC); N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(tetradecanoyloxy) ethoxy)ethoxy) ethanaminium chloride (TDAC) and N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(hexadecanoyloxy)ethoxy)ethoxy)ethanaminium chloride (HDAC) [29, 30]. Scheme 1 show the synthetic route of the cationic compounds.

2.3. Instrumentation

Chemical structure of the synthesized inhibitors (Scheme 1) was confirmed by FTIR and ^{1}H NMR spectroscopy. FTIR analysis was carried out using ATI Mattson infinity series TM, Bench top 961 controlled by Win First TM V2.01 software. ^{1}H NMR analysis was measured in DMSO-d6 using Jeol ECA 500 MHZ NMR spectrometer.

2.4. Solutions

The aggressive solution, 0.5 M HCl was prepared by dilution of analytical grade HCl (37% wt) with distilled water. Concentration range of used synthesized inhibitor varied from 50 to 800 ppm for corrosion measurements. Double distilled water was used for preparing test solutions in all measurements.

2.5. Weight Loss Measurements

An analytical balance, (Model: HR 200, readability: 0.1 mg and standard deviation: ±0.2 mg), was used for the gravimetric analysis. The carbon steel sheets of 7 × 3 × 0.5 cm were abraded with a series of emery paper (grade 320–400–600–800–1000–1200) and then cleaned successively with distilled water, ethanol and acetone, and finally dried in dry air. After accurately weighting, the samples were immersed in 100 mL of 0.5 M HCl solution with and without the addition of different concentrations of cationic surfactant at 25°C. The steel specimens were taken out after 24 h and then rinsed with distilled water twice and degreased with acetone. Then specimens were immersed in 1 M HCl solution for 10 s, (chemical method for cleaning rust products), rinsed twice with distilled water, ethanol, and acetone and finally dried in dry air and accurately weighted. The experiments were carried out in triplicates in order to give a good reproducibility and the average weight loss of three carbon steel sheets was obtained. All tests in this paper were done under aerated conditions [31].

2.6. Potentiodynamic Polarization Measurements

Polarization experiments were carried out using a conventional three-electrode cell with a platinum counter electrode and a saturated calomel electrode (SCE) as a reference electrode. The working electrode was a rod of carbon steel embedded in PVC holder using epoxy resin so that the flat surface was only surface in electrode. Before each measurement, the electrode was immersed in a test solution at open circuit potential (OCP) for 30 min, until a steady state was reached. All polarization curves were recorded by a Voltalab 40 Potentiostat PGZ 301 and a personal computer was used with Voltamaster 4 software at 25°C. Each experiment was repeated at least three times to check the reproducibility. Potentiodynamic polarization measurements were obtained by changing the electrode potential automatically from –1000 to –200 mV vs. SCE at open circuit potential with a scan rate 2 mV s^{-1} at 25°C [32, 33].

3. RESULTS AND DISCUSSION

3.1. Structure

The structures of the synthesized quaternary ammonium salts (DDAC, TDAC and HDAC) were characterized using FT-IR and ^{1}H-NMR spectroscopy as follows:

N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(dodecanoyloxy)ethoxy)ethoxy)ethanaminium chloride (DDAC) FTIR (KBr): ν = 3357 cm^{-1} (OH), 2931 cm^{-1} (CH_3), 2845 cm^{-1} (CH_2), 2612 cm^{-1}($-N^+$), 1737 cm^{-1} (C=O), 1403 cm^{-1} $(CH_2)_n$, 1084 cm^{-1} (C-O) Fig. 1, ^{1}H NMR (300 MHz, CDCl3): δ = 1.00 ppm (t, 3H, $C\underline{H}_3$), 1.21 ppm (m, 2H, $C\underline{H}_2CH_3$), 2.49 ppm (m, 2H, $C\underline{H}_2CH_2CO$), 3.18 ppm (t, 2H, $CH_2C\underline{H}_2CO$), 3.48 ppm (m, nH, $C\underline{H}_2$), 3.69 ppm (t, 1H, $CH_2O\underline{H}$), 3.87 ppm (s, 2H, N-$C\underline{H}_2COO$), 4.01 ppm (t, 2H, $OC\underline{H}_2CH_2O$), 5.45 ppm (d, 2H, N-$C\underline{H}_2OH$) Fig. 2.

N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(tetradecanoyloxy) ethoxy) ethoxy) ethanaminium chloride (TDAC) FTIR (KBr): ν = 3351 cm^{-1} (OH), 2931 cm^{-1} (CH_3), 2843 cm^{-1} (CH_2), 2612 cm^{-1}($-N^+$),1733 cm^{-1}

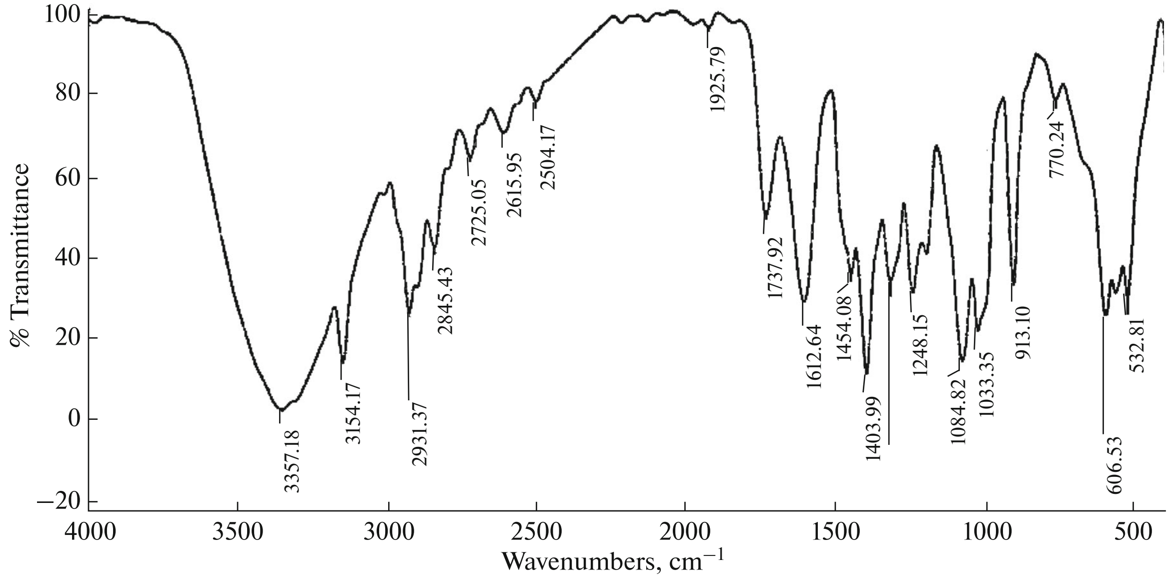


Fig. 1. FTIR Spectrum of the synthesized cationic surfactant (DDAC).

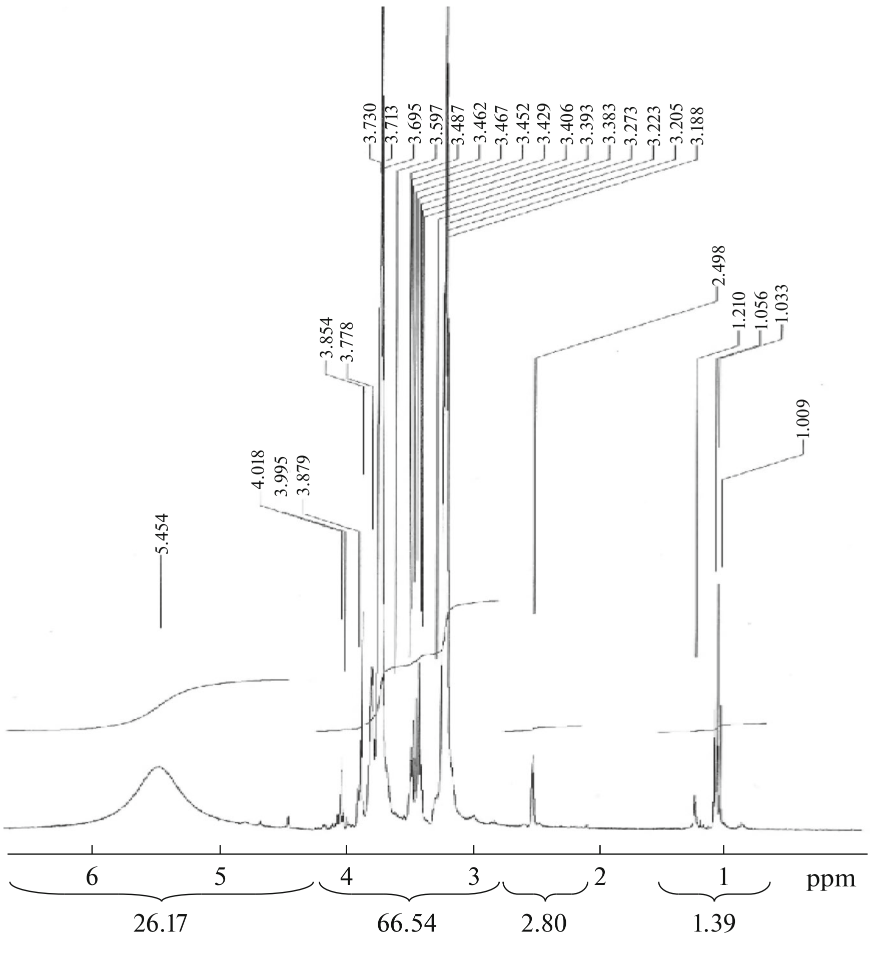


Fig. 2. ^{1}H-NMR Spectrum of the synthesized cationic surfactant (DDAC).

(C=O), 1404 cm^{-1} $(\mathrm{CH_2})_n$, 1030 cm^{-1} (C–O); ^{1}H NMR (300 MHz, CDCl3): δ = 0.83 ppm (t, 3H, $\mathrm{C\underline{H}_3}$), 1.22 ppm (m, 2H, $\mathrm{C\underline{H}_2CH_3}$), 2.50 ppm (m, 2H, $\mathrm{C\underline{H}_2CH_2CO}$), 3.17 ppm (t, 2H, $\mathrm{CH_2C\underline{H}_2CO}$), 3.49 ppm (m, nH, $\mathrm{C\underline{H}_2}$), 3.69 ppm (t, 1H, $\mathrm{CH_2O\underline{H}}$), 3.78 ppm (s, 2H, N-$\mathrm{C\underline{H}_2COO}$), 3.87 ppm (t, 2H, $\mathrm{OC\underline{H}_2CH_2O}$), 4.10 ppm (d, 2H, N-$\mathrm{C\underline{H}_2OH}$).

N,N,N-tris(hydroxymethyl)-2-oxo-2-(2-(2-(hexadecanoyloxy) ethoxy)ethoxy)ethanaminium chloride (HDAC) FTIR (KBr): ν = 3331 cm^{-1} (OH), 2933 cm^{-1} ($\mathrm{CH_3}$), 2840 cm^{-1} ($\mathrm{CH_2}$), 2613 cm^{-1}(–N$^+$), 17378 cm^{-1} (C=O), 1403 cm^{-1} $(\mathrm{CH_2})_n$, 1034 cm^{-1} (C–O); ^{1}H NMR (300 MHz, CDCl3): δ = 1.01 ppm (t, 3H, $\mathrm{C\underline{H}_3}$),1.21 ppm (m, 2H, $\mathrm{C\underline{H}_2CH_3}$), 2.49 ppm (m, 2H, $\mathrm{C\underline{H}_2CH_2CO}$), 3.22 ppm (t, 2H, $\mathrm{CH_2C\underline{H}_2CO}$), 3.45 ppm (m, nH, $\mathrm{C\underline{H}_2}$), 3.68 ppm (t, 1H, $\mathrm{CH_2O\underline{H}}$), 3.74 ppm (s, 2H, N-$\mathrm{C\underline{H}_2COO}$), 3.76 ppm (t, 2H, $\mathrm{OC\underline{H}_2CH_2O}$), 5.32 ppm (d, 2H, N-$\mathrm{C\underline{H}_2OH}$).

3.2. Weight Loss Measurements

The corrosion rate (k) was calculated from the following equation [34]:

$$k = (\Delta W/St), \tag{1}$$

where ΔW is the average weight loss of three parallel carbon steel sheets, S is the total area of one specimen, and t is immersion time.

The inhibition efficiency (η_w) of the prepared cationic surfactant inhibitors on the corrosion of CS are calculated from the following equation [35]:

$$\eta_w\,\% = ((W - W_0)/W_0) \times 100, \tag{2}$$

where W and W_0 are the weight loss of carbon steel in the absence and presence of the inhibitors, respectively.

Figure 3 shows the inhibition efficiency of surfactant inhibitors at different concentrations in 0.5 M HCl at 25°C. Inhibition efficiency increased with increasing inhibitors doses.

Weight loss data of carbon steel in 0.5 M HCl in the absence and presence of various concentrations of inhibitors are represented in Table 1. The obtained results showed the efficiency increased gradually by increasing inhibitor concentration while corrosion rate decrease. The efficiency is attributed to increasing inhibitors adsorption on the metal surface, which leads to increasing coverage metal area (θ). This inhibitors adsorption forms a protective layer on the metal surface, which decreases the contact between the metal surface and the aggressive medium decreasing the fatal effect of aggressive medium on the metal surface. This adsorption can be explained by an electrostatic interaction between polar groups in surfactants and sites on the metallic surface. In addition to the interaction between lone pairs of oxygen and nitrogen atoms with positively charged steel surfaces.

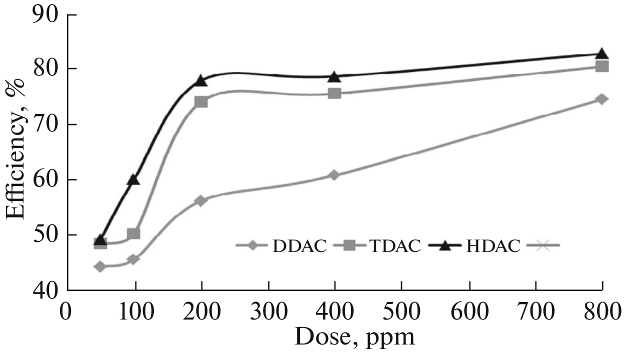


Fig. 3. Variation of the inhibition efficiency with different concentrations of the synthesized inhibitors in 0.5 M HCl at 25°C.

Increase the hydrophobicity of the synthesized cationic surfactant by increasing the hydrophobic chain length from dodecyl derivatives (DDAC) to hexadecyl derivatives (HDAC) leading to pumps the surfactant molecules to the surface which leads to the adsorption on the steel surface and increase the inhibition efficiency e.g. $\eta_{\%}$ = 74.0, 80.0 and 82.3% at 800 ppm for DDAC, TDAC and HDAC, respectively. That could be due to the increase in the hydrophobicity of these compounds with more non-polar chains and the water/surfactant molecules interactions increased, which forced them to the steel surface. And the surfactant contains a charge on the head group (positive charge) which leads to more repulsion in the bulk of aqueous solution and increasing adsorption onto the carbon steel surface [36].

Table 1. Weight loss data for carbon steel in 0.5 M HCl without and with different concentrations of the synthesized cationic surfactant at 25°C

		k, mg cm^{-2} h^{-1}	θ	η_w, %
Absence	0.00	0.042	–	–
DDAC	50	0.024	0.44	43.6
	100	0.023	0.45	44.9
	200	0.019	0.56	55.5
	400	0.017	0.60	60.2
	800	0.011	0.74	74.0
TDAC	50	0.022	0.48	47.7
	100	0.021	0.50	49.5
	200	0.011	0.73	73.5
	400	0.011	0.75	75.0
	800	0.008	0.80	80.0
HDAC	50	0.022	0.49	48.5
	100	0.017	0.59	59.4
	200	0.010	0.77	77.4
	400	0.009	0.78	78.2
	800	0.007	0.82	82.3

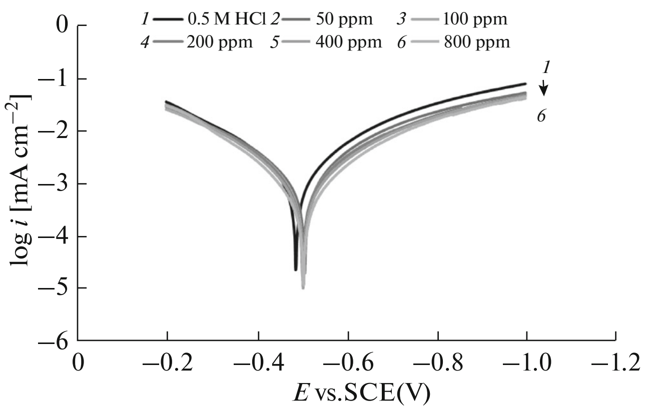


Fig. 4. Polarization curves for carbon steel in 0.5 M HCl in the absence and presence of different concentrations of inhibitor DDAC at 25°C.

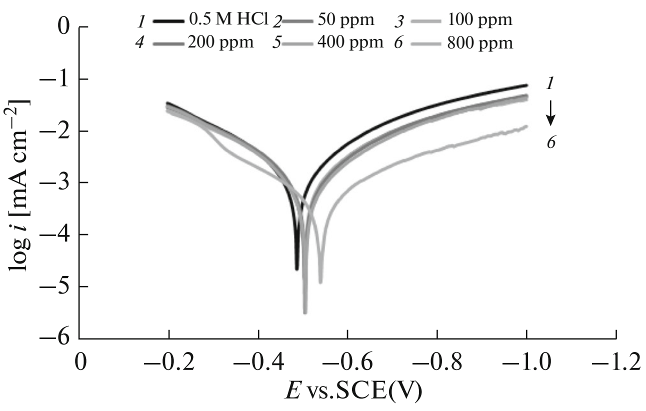


Fig. 5. Polarization curves for carbon steel in 0.5 M HCl in the absence and presence of different concentrations of inhibitor TDAC at 25°C.

3.3. Potentiodynamic Polarization Curves

Figures 4–6 represents the potentiodynamic polarization curves of carbon steel in 0.5 M HCl in the presence and absence of various concentrations of cationic surfactants inhibitor at 25°C. It was observed that, both of cathodic and anodic curves showed lower current density in the presence of cationic surfactant inhibitors than those recorded in solutions without cationic surfactant inhibitors. This behavior indicated that all used cationic surfactant inhibitors had significant effects on both cathodic and anodic reactions of corrosion process.

Values of the corrosion current densities (i_{corr}), corrosion potential (E_{corr}), cathodic Tafel slope (β_c), and anodic Tafel slope (β_a) were calculated from Figs. 4–6 and are listed in Table 2. It is clear that the presence of the inhibitors causes a markedly decrease in the corrosion rate. The E_{corr} values of all synthesized inhibitors were shifted slightly toward both cathodic and anodic directions and did not show any definite trend in 0.5 M HCl suggest that the three inhibitors act as mixed type inhibitors with predominantly anodic; i.e. meaning inhibitors reduce the anodic dissolution of mild steel and retards the cathodic hydrogen evolution

Table 2. Potentiodynamic polarization parameters for corrosion of carbon steel in 0.5 M HCl in absence and presence of different concentrations of the synthesized cationic surfactants at 25°C

Inhibitor	Conc. of inhibitor, M	$-E_{\text{corr}}$, mV (SCE)	i_{corr}, mA cm^{-2}	β_a, mV dec^{-1}	$-\beta_c$, mV dec^{-1}	η_p, %
Absence	0.00	491	2.29	238	234	–
DDAC	50	508	1.58	229	234	31.0
	100	511	1.57	222	204	31.4
	200	506	1.34	208	205	41.5
	400	508	1.28	207	224	44.1
	800	508	0.71	166	177	69.0
TDAC	50	510	1.59	219	230	30.6
	100	508	1.57	229	234	31.4
	200	509	1.39	202	221	39.3
	400	510	1.24	199	255	45.9
	800	544	0.58	239	256	74.7
HDAC	50	506	1.43	208	225	37.6
	100	506	1.40	209	217	38.9
	200	501	1.32	186	198	42.4
	400	514	1.01	209	229	55.9
	800	521	0.18	173	216	92.1

reaction, but the effect on the anodic dissolution reactions is more than on the cathodic hydrogen evolution reactions [37, 38]. Moreover, these inhibitors caused a change in the anodic and cathodic Tafel slopes indicating that, the inhibitors are affecting the anodic and cathodic reaction mechanism without blocking the reaction sites of carbon steel surface. Inhibition efficiency, (η_p, %), was obtained from the following equation [39]:

$$\eta_p(\%) = \{(i_{corr} - i^0_{corr}/i_{corr})\} \times 100, \quad (3)$$

where i_{corr} and i^0_{corr} are uninhibited and inhibited corrosion current densities, respectively, determined by extrapolation of Tafel lines to the corrosion potential. Data in Table 2 show that the inhibition efficiency increased with increasing the inhibitor concentrations.

The results obtained from the weight loss measurements were in good agreement with those obtained from the polarization.

3.4. Adsorption Isotherm

The adsorption isotherm experiments were performed to have insights into the mechanism of corrosion inhibition, since it describes the molecular interaction between inhibitor molecules them-selves and with the active sites on metal surface [40]. The degree of surface coverage (θ) which determined from the weight loss measurements were used to fit into different adsorption isotherm models and the correlation coefficient (R^2) was used to choose the best isotherm, which was Langmuir adsorption isotherm:

$$\text{Langmuir isotherm } C/\theta = C + (1/K_{ads}), \quad (4)$$

where K_{ads} is the equilibrium constant of the adsorption process and C is the inhibitor concentration. Figure 7 show the linear relationships of C/θ versus C, and suggest that the adsorption of prepared inhibitors on mild steel surface obeyed the Langmuir adsorption isotherm. The correlation (R^2) of the Langmuir adsorption nearly equal 1 for prepared inhibitors as depicted in Table 3. The slopes of the straight lines are more than unity. Therefore, it could be concluded that each inhibitor unit occupies more than one adsorption site, also there are interactions between adsorbent species on the metal surface as well as changes in the adsorption heat with increasing surface coverage [41], factors which were not taken into consideration in the derivation of the isotherm.

Therefore, the adsorption of the synthesized cationic surfactants on the mild steel surface can be represented by modified Langmuir equation which named Villamil isotherm, taking into consideration the interactions between adsorbate species as well as changes in the heat of adsorption with changing surface coverage as follows [42]:

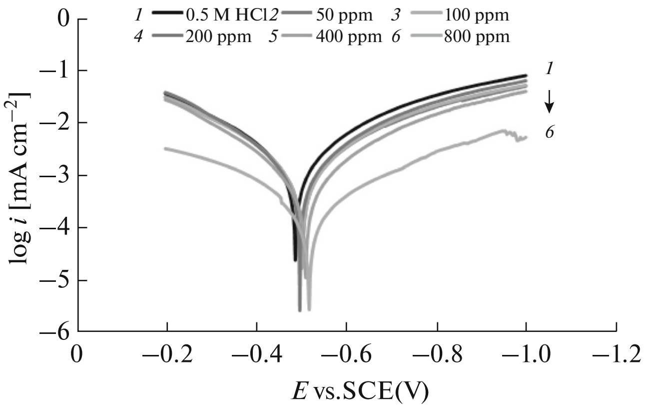


Fig. 6. Polarization curves for carbon steel in 0.5 M HCl in the absence and presence of different concentrations of inhibitor HDAC at 25°C.

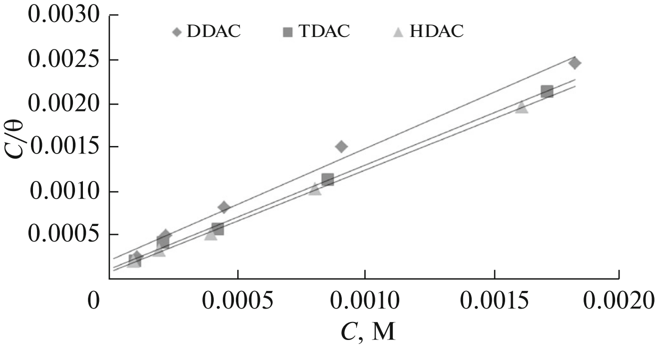


Fig. 7. Langmuir isotherm adsorption model of the synthesized inhibitor on the carbon steel surface in 0.5 M HCl at 25°C.

$$C/\theta = nC + (n/K_{ads}), \quad (5)$$

where n is the value of the slopes obtained by above plot and referee to number of displacement adsorbed water molecule from metal surface, and the intercept permit the calculation of equilibrium constant K_{ads} for all the used surfactants and listed in Table 3.

The standard adsorption free energy (ΔG^0_{ads}) obtained according to the following equation:

Table 3. Regression coefficient (r^2), adsorption constant (K_{ads}) and adsorption free energy (ΔG_{ads}) of DDAC,TDAC and HDAC inhibitors at 298°K

Inhibitors	Slope	Regression coefficient, r^2	K_{ads}, $M^{-1} \times 10^3$	ΔG_{ads}, kJ mol^{-1}
DDAC	1.2723	0.9890	6.36	−31.65
TDAC	1.1790	0.9975	11.8	−33.18
HDAC	1.1605	0.9992	12.9	−33.40

$$\Delta G^0_{\text{ads}} = -RT\ln(55.5K_{\text{ads}}). \qquad (6)$$

The value of 55.5 is the molar concentration of water in the solution expressed in molarity units (mol L^{-1}).

The negative values of ΔG^0_{ads} suggest that the adsorption of the inhibitor on the metal surface is a spontaneous process; inspection data in Table 3, ΔG^0_{ads} were ranged from –31.65 to –33.40 kJ mol^{-1} which indicate that the adsorption process is mixture between physical and chemical adsorption [43]. As the obtained ΔG^0_{ads} ranged between –20 to –40 kJ mol^{-1}, we can say that the adsorption process is mixture between chemical and physical [43]. So we can conclude that the adsorption of these surfactant on the metal surface is mixture between a physical and chemical process but physically is predominant.

3.5. Mechanism of Inhibition

The adsorption of organic molecules on solid surfaces cannot be considered only as purely physical or as purely chemical adsorption phenomenon. In physical adsorption, the inhibitor molecules can be adsorbed on the steel surface via electrostatic interaction between the charged metal surface and charged inhibitor molecule. While in the chemical adsorption arises from the donor acceptor interactions between free electron pairs of the hetero atoms and p-electrons of multiple bonds as well as phenyl group and vacant d-orbitals of iron. It has been noted that the adsorption of compounds and the orientation of molecules could be dependent on the pH and/or electrode potential. In addition to surface activity of these compounds these factors play an important role in adsorption on interface [44–47]. In the case of parallel adsorption of inhibitor molecules, the steric factors also must be taken into account. It is also necessary to consider the factors of electrochemical dissolution of metal in the electrolyte solution. The mechanism of the steel dissolution in the acidic medium is described in the literature and presented for example in [48, 49].

However, more work should be made to confirm the above arguments.

The inhibition efficiency values of the investigated inhibitors in 0.5 M HCl solution were in the following order: HDAC > TDAC > DDAC The best cationic inhibitor under this study was inhibitor (HDAC). The differences in the corrosion inhibition efficiency of three cationic can be attributed to the molecular structure effect. In addition, the hydrophobic chain length. The adsorption of the inhibitor molecules on the carbon steel surface can be explained on the basis of the donor-acceptor interaction between p electrons of donor atoms N and O of the inhibitors and the vacant *d*-orbitals of iron surface atoms.

4. CONCLUSIONS

1. The synthesized cationic surfactants act as efficient inhibitors for the corrosion of carbon steel in 0.5 M HCl.

2. The results obtained from the weight loss measurements were in good agreement with those obtained from the potentiodynamic polarization method.

3. The corrosion inhibition efficiencies increased with increasing inhibitor concentration.

4. The decrease in the corrosion rate of carbon steel in the presence of cationic inhibitors indicated that adsorbed protective layer formed on the carbon steel surface.

5. The three inhibitors act as mixed type inhibitors with predominantly anodic; i.e. meaning inhibitors reduce the anodic dissolution of mild steel and retard the cathodic hydrogen evolution reaction.

6. The adsorption of the synthesized surfactants on the mild steel surface can be represented by a modified Langmuir equation which named Villamil isotherm.

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