

Electrochemical studies of Carum Carvi plant as corrosion inhibitor for mild steel in 1M HCl solution

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Abstract

The application of Carum Carvi's essential oil in a corrosion inhibitor for mild steel (MS) protection was investigated in 1 M HCl solution. Essential oil from Carum Carvi was obtained by Clevenger type water distillation. The major compounds in these essential oils was identified using gas chromatography-mass Spectrometry: Apiol dill (15,6%), Limonene (15,3%), Carvone (13,3 %) and p-Cymene (11,3%). The electrochemical impedance spectroscopy and potentiodynamic measurements were used at various concentrations and temperatures. The oil acted as an efficient inhibitor against the carbon steel corrosion in 1 M HCl, and its inhibition efficiency increased with the inhibitor concentration reaching a value of up to 88% at 3 g/L. Polarization studies showed that the oil was a mixed-type inhibitor. Adsorption of oil on the steel surface in 1 M HCl solution followed Langmuir's isotherm and the thermodynamic parameters were determined and discussed.

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1. Introduction

One of the main problems in the industrial process is corrosion of metals leading to increase in manufacturing costs, thereby production costs. Metallic materials are often exposed to conditions that facilitate corrosive processes. Acid solutions, especially hydrochloric acid, that are widely used in a range of industries for acid pickling, acid cleaning, acid descaling and oil refinery equipment cleaning [1,2] several studies were conducted to investigate the effect of organic inhibitors on the corrosion of steel in hydrochloric and sulphuric acid solutions [3-8]. The inhibition efficiency of the used inhibitors was found to reduce the steel corrosion more effectively in hydrochloric acid solutions. Today, these kinds of corrosion inhibitors are slowly forsaken because of their toxicity against users and environment. Recent research has been directed towards the use of plant extracts to protect the environment and limit the risks associated with the use of chemical products. Most of the natural products are nontoxic, biodegradable and readily available in plenty, *Artemisia Mestlantica* [9], *Euphorbia falcata* [10], Argan oil [11], Jojoba oil [12], *Artemisia* oil [13,14], *Eucalyptus* oil [15,16], *Thymus* oil [17], pennyroyal oil from *Mentha pulegium* [18], extrait de Nipah [19], l'extrait de l'amande d'Argan (*Argania Spinosa*) [20], *Emblica Officinalis* [21], *Salvia officinalis* [22]. We chose Carvi a species of the family Apiacées, is a plant endemic to the region of Agouray of Morocco, it is known locally as the vernacular name "Karwya". Local people used the leaves and grains in decoction to treat, digestive disorders, diarrhea and relieve cough. The aim of this paper is to extract and to test Carum Carvi oil as corrosion inhibitor for steel in 1 M HCl solution. The study is conducted by electrochemical polarization methods. Polarization curves and the electrochemical impedance spectroscopy were carried out to study the mechanism of corrosion inhibition. The effect of temperature on the values of the electrochemical parameters characterizing the systems has been recorded by polarization curves.

2. Experimental

2.1. Plant material

The plant of *Carum Carvi* harvested in May 2013 in the south-east of Agouray (Morocco). A voucher specimen was deposited in the Herbarium of Faculty of Sciences and Techniques, Rabat, Morocco. The dried plant material is stored in the laboratory at room temperature (298 K) and in the shade before the extraction.

2.2. Hydrodistillation apparatus and procedure

The extraction of essential oil of *Carum Carvi* was conducted by hydrodistillation using a Clevenger type apparatus (Clevenger, 1928), and the essential oil yield was 1.15 %. The essential oil obtained was dried under anhydrous sodium sulfate and stored at 277 K in the dark before analysis.

2.3. Gas chromatography–mass spectrometry (GC-MS)

Samples were analyzed with a Perkin-Elmer turbo mass detector (quadrupole) coupled to a Perkin-Elmer Autosystem XL equipped with the fused-silica capillary columns Rtx-1 and Rtx-wax. Carrier gas: helium (1 mL/min), ion source temperature: 150 °C, oven temperature programmed from 60 °C to 230 °C at 2 °C/min and then held isothermally at 230 °C (35 min), injector temperature: 280 °C, energy ionization: 70 eV, electron ionization mass spectra were acquired over the mass range 35–350 Da, split: 1/80, injection volume: 0.2 µL of pure oil.

2.4. Components identification

The identification of the essential oil constituents was based on: (i) comparison with the mass spectra of authentic reference compounds where possible and by reference to WILEY275, NIST 02 and Adams mass

spectral libraries [23-26] (ii) comparison of their retention index (RI), calculated relative to the retention times of a series of C-5 to C-30 n-alkanes, with linear interpolation, with those of our own library of authentic compounds or literature data [26,27].

2.4. Specimen preparation and solution

2.4.1. Corrosion tests

Corrosion tests have been carried out on electrodes cut from sheets of C38 steel. The steel strips contained 0.36 wt% C, 0.66 wt% Mn, 0.27 wt% Si, 0.02 wt% S, 0.015 wt% P, 0.21 wt% Cr, 0.02 wt% Mo, 0.22 wt% Cu, 0.06 wt% Al and the remainder in iron. The specimens were embedded in epoxy resin, leaving a working area of 1 cm². The working surface was subsequently ground with 120 and 1200 grit grinding papers, cleaned by distilled water and ethanol. The solutions (1 M HCl) were prepared by dilution of an analytical reagent grade 37% HCl with doubly distilled water.

2.4.2. Electrolytic solution

The corrosive solution, 1 M HCl was prepared by dilution of analytical grade 37 % HCl with distilled water. The concentration range of Carum Carvi essential oil employed was 0.6 to 3 g/L and the volume of the electrolyte used was 25 mL in each experiment

2.5. Electrochemical measurements

The electrochemical study was carried out using a potentiostat PGZ301 piloted by Voltamaster software. Electrochemical measurements, including potentiodynamic polarization curves and electrochemical impedance spectroscopy (EIS), were performed in a three-electrode cell. The C38 steel specimen was used as the working electrode, a platinum wire as the counter electrode and a saturated calomel electrode (SCE) as the reference electrode. The working electrode is in the form of a disc from mild steel of the surface 1 cm².

2.5.1. Electrochemical impedance spectroscopy (EIS)

The impedance measurements were carried out using ac signals of 10 mV amplitude for the frequency spectrum from 100 kHz to 10 Hz. The electrode was kept for hour in the test solution before starting the impedance measurements. The charge transfer resistance (R_{ct}) was obtained from the diameter of the semicircle of the Nyquist plot. The percentage inhibition efficiency (IE%) was calculated using the polarization resistance as follows. where ($R_{ct b}$) and ($R_{ct inh}$) are respectively charge transfer resistances in the absence and presence of inhibitor.

$$IE = \left(1 - \frac{R_{ct b}}{R_{ct inh}}\right) * 100 \quad (1)$$

2.5.2. Potentiodynamic polarization

Polarization measurements were carried out in a conventional three electrode within the electrolytic cell. Saturated calomel electrode (SCE) and platinum electrode were used as reference and auxiliary electrodes respectively. The working electrode is in the form of a rectangular disk from carbon steel of the surface 1cm², these electrodes are connected to Voltalab PGZ 301 piloted by computer associated to “Volta Master 4” software. Before recording each curve, a stabilization time of 60 min was allowed, which was proved to be satisfactory to attain a stable value for E_{corr} . Corrosion current densities were obtained from the polarization curves by linear extrapolation of the Tafel curves. Measurements were performed in the 1 M HCl solution containing different concentrations of the tested inhibitor by changing the electrode potential automatically from -800 to -300 mV versus corrosion potential at a scan rate of 1 mV.s⁻¹. The linear Tafel segments of anodic and cathodic curves were extrapolated to corrosion potential to obtain the

current densities (I_{corr}) [28, 29]. The IE% was calculated using the following equation 2; where (i_{corr}°) and (i_{corr}°)_{inh} are respectively the corrosion current densities ($\mu\text{A}/\text{cm}^2$) in the absence and presence of the inhibitor.

$$\text{IE\%} = \left(1 - \frac{i_{\text{corr}}^{\circ}}{i_{\text{corr}}^{\circ}}\right) * 100 \quad (2)$$

3. Results and discussion

3.1. Carvi oil analysis

Rendement of Oil extraction the Caraway was 1.15 %, and analyzed by Gas chromatography (GC) and Gas chromatography mass spectrometry (GC-MS) techniques [30]. The obtained constituent percentages of the Carvi Carum essential oil (C.C) are summarized in Table 1.

Table 1: Chemical composition of Carum Carvi (entire plante) essential oil from Morocco

N°	compounds	Ir apol	Ir pol	HE% apol	Ir Lit
1	α -Thujene	922	1022	0,3	932
2	α -Pinene	930	1022	1,8	936
3	Sabinene	964	1119	0,2	973
4	β -Pinene	970	1109	0,1	978
5	Myrcene	980	1165	0,7	987
6	α -Phellandrene	999	1165	19,5	1002
7	p-Cymene	1014	1268	11,3	1015
8	\square -Phellandrene	1023	1209	4,6	1023
9	Cineole 1,8	1023	1209		1024
10	Limonene	1023	1201	15,3	1025
11	Terpinolene	1078	1279	0,1	1082
12	undecane	1098	1098	0,1	1100
13	cis-p-Menth-2-en-1-ol	1106	1550	0,1	1108
14	Camphor	1120	1507	0,2	1123
15	Borneol	1148	1693	0,3	1150
16	Cryptone	1155	1651	0,3	1160
17	p-Cymen-8-ol	1162	1829	0,4	1169
18	Dillether	1169	1507	7,1	1170
19	Z-Dihydrocarvone	1171	1593	0,4	1172
20	E-Dihydrocarvone	1178	1612	0,8	1176
21	Carvone	1219	1719	13,3	1214
22	Piperitone	1227	1709	1,2	1226
23	Carvacrol	1278	2189	0,9	1278
24	Apiol dill	1598	2336	15,6	
TOTAL				94,3	

Ir apol = retention indices on the apolar column (Rtx-1)

Ir pol = retention indices on the polar column (Rtx-Wax)

HE%= Relative percentages of components (%) are calculated on GC peak areas on the apolar column

Ir lit = retention indices on the apolar column of literature [31, 32]

The main components of Carvi Carum essential oil (C.C), shown in Fig. 1, are α -Phellandrene (19.5 %) followed by Carvacrol (15.6 %), Limonene (15.3 %), Carvone (13.3 %) and p-Cymene (11,3 %)

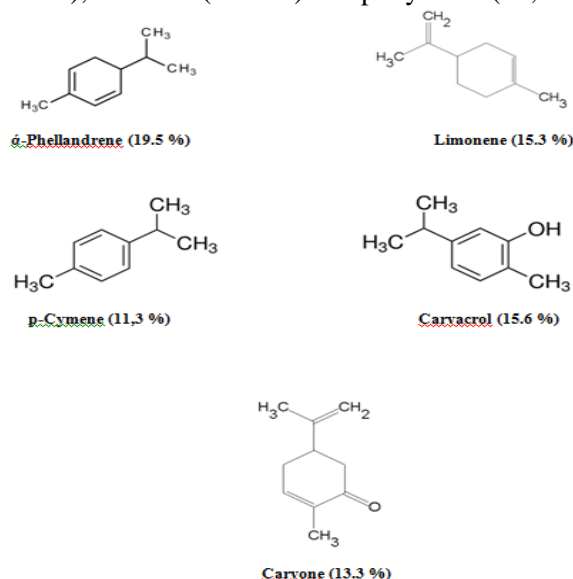


Figure 1: Chemical structures of majority components of essential oil the carvi carum

3.2. Effect of concentration

3.2.1. Potentiodynamic polarization measurement

Potentiodynamic polarization curves for mild steel in 1 M hydrochloric acid solution in the absence and presence of various concentrations of C.C at 303°C are shown in Fig. 2 Potentiodynamic polarization experiments were undertaken to distinguish the effect of C.C on the anodic dissolution of Mild steel and cathodic hydrogen ion reduction, respectively.

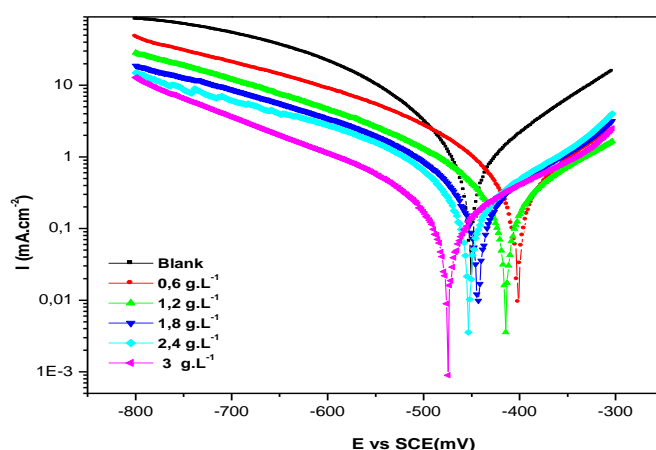


Figure 2: Polarization curves of C38 steel in 1M HCl solution (1) at different concentrations of Carum Carvi oil at 303 °C

The values of i_{corr} , E_{corr} , b_c cathodic and b_a anodic (b_c and b_a Tafel slopes) were obtained by the extrapolation of linear Tafel segments of the cathodic curve and the calculated anodic Tafel lines as described in Fig.3 (tafel mesure). As it is shown in Table 2, the I_{corr} decreases with the rise of inhibitor concentrations without change in the

mechanism of the hydrogen reaction. It is illustrated from the data listed in Table 2, that both anodic metal dissolution of iron and cathodic hydrogen evolution reaction were inhibited after the addition of the oil in 1 M HCl solution. The inhibition of these reactions was more pronounced on increasing carvi oil concentration. However, the visual examination of polarization curves depicted in Fig. 2 reveals that the cathodic curves are shifted towards lower current density side with increase in inhibitor concentration. According to Yan et al [33] an inhibitor can be classified as cathodic, anodic or mixed-type. From the table 2, we can deduced that, the presence of oil in the acidic solution results in a slight shift of corrosion potential toward more negative in comparison to that in its absence, and the values of corrosion potential nearly remain constant with the addition of a few concentrations of oil. These results indicate that oil acts as a mixed-type inhibitor with predominant cathodic effectiveness.

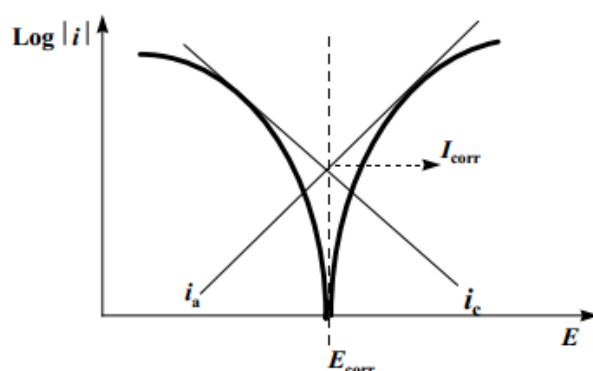


Figure 3: Determination of electrochemical parameters by extrapolation from Tafel straight

Table 2: Potentiodynamic polarization parameters for C38 steel in 1 M HCl at various concentrations of C.C at 303 K

Inhibitor	Concentration (g.L ⁻¹)	E _{corr} (mV/SCE)	I _{corr} (μA cm ⁻²)	ba (mV dec ⁻¹)	bc (mV dec ⁻¹)	IE%
Blanc	--	-450,3	728,00	105,1	-75,5	--
	0,6	-401,3	300,00	106,4	-96,8	58,8
	1,2	-417,1	224,94	125,3	-111,1	69,1
H.C p	1,8	-443,4	200,91	126,7	-99,5	72,4
	2,4	-453,4	159,53	110,1	-77,8	78,1
	3	-474,3	87,60	130,3	-110,5	88,0

The dependence of the inhibition efficiency versus the inhibitor concentration of oil is also showed in Table above. Inhibition efficiency (IE%) increased with inhibitor concentration, reaching 88 % at 3 g/L Carvi oil. The inhibition efficiency obtained indicates that oil the C.C acts as effective inhibitor.

3.2.2. Electrochemical impedance spectroscopy measurements (EIS)

The corrosion behavior of steel in acidic solution 1M HCl in the absence and presence various concentrations of the Carvi oil was also investigated by EIS method at 303 K after 60 min of immersion (Figure 4). The Nyquist plots generally comprise of only one depressed capacitive semicircle in the high frequency region, and reveal that the impedance response of C38 changed significantly on addition of Carvi oil to the corrosive media, is observed steady enhancement in the impedance when the oil concentration is increased. The Nyquist plots exhibit single depressed semicircles across the frequency range studied, which denotes that the dissolution

process is controlled by charge transfer reaction [34]. The depression of the Nyquist semicircle for solid electrodes is often termed as frequency dispersion which can be ascribed to different physical phenomena such as surface roughness, active sites, and non homogeneity of the solids [35]. The EIS spectra were examined via fitting to the equivalent circuit model see Fig. 5, where R_s represents the solution resistance, R_{ct} represents the charge transfer resistance and CPE represents the constant phase element to used in place of the double layer capacitance (C_{dl}).

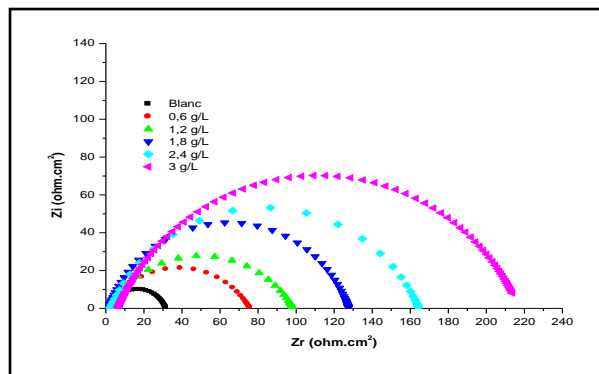


Figure 4: Nyquist plots for the corrosion of C38 steel in 1M HCl solutions in the absence and presence the various concentrations of Carvi oil at 303 K.

The impedance parameters derived from the equivalent circuit model are presented in Table 4. The impedance (Z) of CPE is given by the expression:

$$Z_{CPE} = Q^{-1}(j\omega)^{-1} \quad (3)$$

where Q is the CPE constant, ω is the angular frequency, $j^2 = -1$ is the imaginary number and n is the CPE exponent which gives details about the degree of surface inhomogeneity resulting from surface roughness, inhibitor adsorption, porous layer formation, etc. [36].

The double layer capacitance is obtained from [37]:

$$C_{dl} = ((QR_{ct}^{1-n}))^{1/n} \quad (4)$$

Where Q is the CPE constant, n is coefficient of surface inhomogeneity and R_{ct} is charge transfer resistance

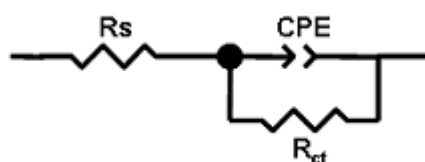


Figure 5: Electrical equivalent circuit (R_s : solution resistance, R_{ct} : charge transfer resistance, CPE: constant phase element)

The impedance parameters derived from these studies using Ec-Lab software are summarized in Table 4, the values the charge transfer of the corrosion process, and also, the diameter of the semicircle (R_{ct}) increases with increasing Carvi oil concentration. This is because, we can say that the addition of inhibitor increases the adsorption over the metal surface and results in the formation of a protective layer which may decrease the electron transfer between the metal surface and the corrosive medium [38]; [39] and [40]. This results in an increase in the protection efficiency. The inhibition efficiency got from the charge transfer resistance is calculated by relation (1). From the electrochemical impedance data (Table 3), it is clear that the R_{ct} values increase with inhibitor concentration and consequently the inhibition efficiency increases to 87 % at 3 g/L. In fact, the presence of CC oil is

accompanied by the increase of the value of R_{ct} in acidic solution confirming a charge transfer process mainly controlling the corrosion of steel. The decrease in C_{dl} may be due to the adsorption of the inhibitor (CC oil) on the metal surface [41]; [42]. We observed a good agreement between results of polarization curves and impedance results.

Table 3: Impedance data for C38 steel in 1M HCl solutions in the presence and absence of Carvi oil

$C_{oil} (g.L^{-1})$	$R_s (m\Omega.cm^{-2})$	$R_{ct} (\Omega.cm^{-2})$	n	$Q (\mu F.cm^{-2})$	$C_{dl} (\mu f.cm^{-2})$	E%
Blank	1,459	26,28	0,731	514	215	--
0,6	1,386	74,62	0,653	467	82,7	65
1,2	1,393	97,17	0,661	530	116,0	73
1,8	1,489	126,6	0,794	214	84,3	79
2,4	2,179	162,5	0,738	139	36,5	84
3	6,271	211,2	0,737	72,7	17,7	87

3.3. Effect of temperature

To investigate the mechanism of inhibition and to calculate the activation energies of the corrosion process, EIS measurements were taken at various temperatures in the absence and the presence of different concentrations of oil (Figs. 4 and 5).

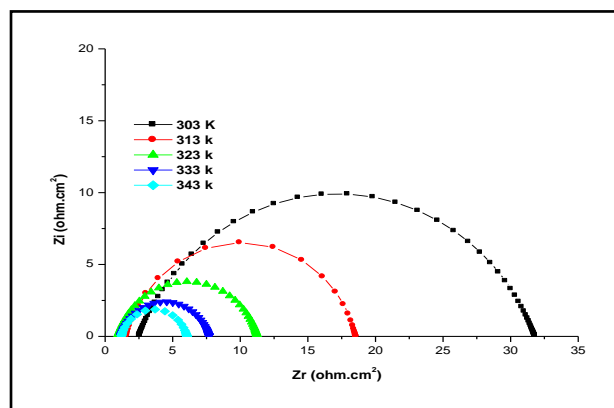


Figure 6: Nyquist plots for corrosion of steel in 1 M HCl at different temperatures

From these results, the R_{ct} values decrease with increasing temperature both in uninhibited and inhibited solutions and the values i_{corr} increase also with temperatures. In the presence of the tested inhibitor, the dissolution of carbon steel is extensively retarded. The inhibition efficiencies are found to decrease with increasing the solution temperature from 303 to 343 K. This suggests possible partial desorption of some of the adsorbed inhibitors from the metal surface at higher temperatures [43]. Similar behaviors were observed in the case of argan oil in the same medium [44], *Ervatamia coronaria* extract [45], and alkaloids extract of *Geissospermum laeve* [46]. In case of physical adsorption, the extent of adsorption decreases with rise in temperature. Some information on the mechanism of the inhibitor action can be obtained by comparing apparent activation energy (E_a), obtained in the presence of inhibitor with that in its absence. The values of E_a were calculated using Arrhenius equation [47]:

$$i_{corr} = A \exp\left(-\frac{E_a}{RT}\right) \quad (5)$$

Where E_a the apparent activation corrosion energy, R is the universal gas constant, A is the Arrhenius pre-exponential factor. The plots of $\ln(i_{corr})$ versus $1/T$ without and with inhibitor gave straight lines (Fig. 8).

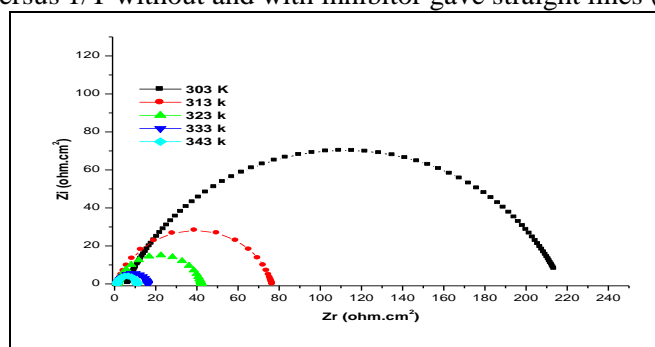


Figure 7: Nyquist plots for corrosion of steel in 1 M HCl+ 3 g/l the CC oil at different temperature

Table 4: Summarizes the electrochemical parameters deduced from the impedance spectra and polarization in the presence and absence the C.C oil at the concentration 3 g/L

Temperature (K)	Icorr	E%	R_{ct}	IE%
303	87,60	88	211,20	87
313	190.05	82	75,11	77
323	403.83	75	40,82	71
333	640.87	67	14,76	56
343	1332.65	57	9,84	51

The values of E_a calculated from the slopes of the straight lines are recorded in Table 5. Inspection of Table 5 revealed that increase in the values of E_a in presence of inhibitors indicating strong adsorption of the inhibitor molecules at the metal surface. It is further noted that the observed value of E_a in presence of the inhibitor at each concentration is greater than that in its absence. The increase in activation energy after the addition of the inhibitor to the 1 M HCl solution can indicate physical adsorption (electrostatic) [48]. The values of standard enthalpy of activation (ΔH_a) and standard entropy of activation (ΔS_a) were calculated using the following equation [49]:

$$i_{corr} = \frac{RT}{Nh} \exp\left(\frac{\Delta S_a}{R}\right) \exp\left(-\frac{\Delta H_a}{RT}\right) \quad (6)$$

Where R is the universal gas constant, h is the Plank's constant; N is the Avogadro's number, ΔS_a is the entropy of activation and ΔH_a is the enthalpy of activation. The Arrhenius plots for the corrosion rate of C38 steel are given in Fig. 9. Values of entropy and enthalpy of corrosion for mild steel in 1 M HCl with the absence and presence of various concentrations of oil (C.C) were determined from the slope ($-\Delta H_a/R$) and intercept ($\ln R/Nh + \Delta S_a/R$) of the plots $\ln(i_{corr}/T)$ versus $1000/T$. These values are listed in Table 5. The values of E_a and ΔH_a should ideally be equal for a chemical reaction in electrolytic solutions. The values of these parameters recorded in Table 3 show that there small difference between the two values in all the cases. Inspection of these data reveals that the ΔH_a values for dissolution reaction of mild steel in 1.0 M HCl in the presence of oil are higher (42,44 -38,58 kJ mol⁻¹) than that of in the absence of inhibitors (25,74 kJ mol⁻¹). The positive signs of ΔH_a reflect the endothermic nature of the mild steel dissolution process what suggesting that the dissolution of mild steel is slow in the presence of inhibitor [50]. The values of ΔS in the absence and presence of inhibitor are negative. Moreover, ΔS_a values are superior in 1 M HCl solutions containing oil than that obtained in the uninhibited solution. This can be explained by the replacement process of water molecules during adsorption of oil on the steel surface [51]. This observation is in agreement with the findings of other workers [52-45]. The negative values of ΔS_a show that the activated complex in the rate determining step represents an

association rather than a dissociation step, meaning that a decrease in disordering takes place on going from reactants to the activated complex [56].

Table 5: Value of activation parameters E_a , ΔH_a and ΔS_a for C-steel in 1 M HCl in the absence and presence of oil (C.C)

Inhibitor	Concentration (g/L)	E_a (kJ/mol)	ΔH_a (kJ/mol)	ΔS_a (J/mol.K)
oil Carvi Carum	Blank	34,06	25,74	-105,09
	0,6	39,83	42,44	-70,47
	1,2	44,97	51,31	-59,55
	1,8	46,41	55,01	-33,56
	2,4	47,57	51,05	-24,33
	3	54,76	38,58	-38,47

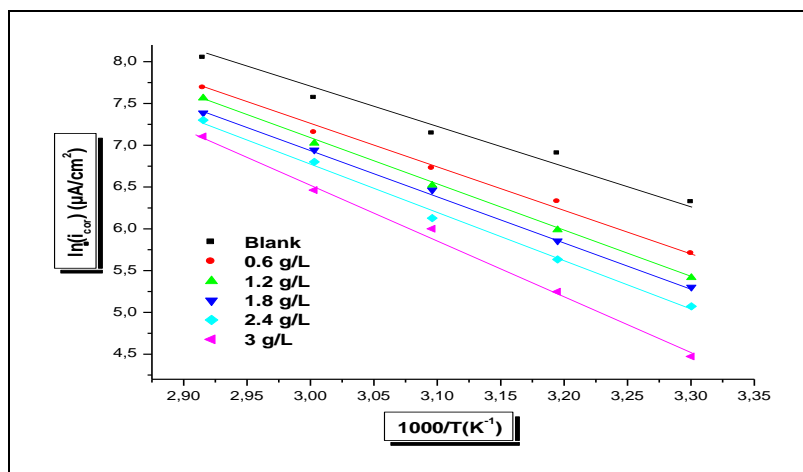


Figure 8: Arrhenius plots for mild steel corrosion rates (i_{corr}) in 1 M HCl in absence and in presence of different concentrations of oil C.C

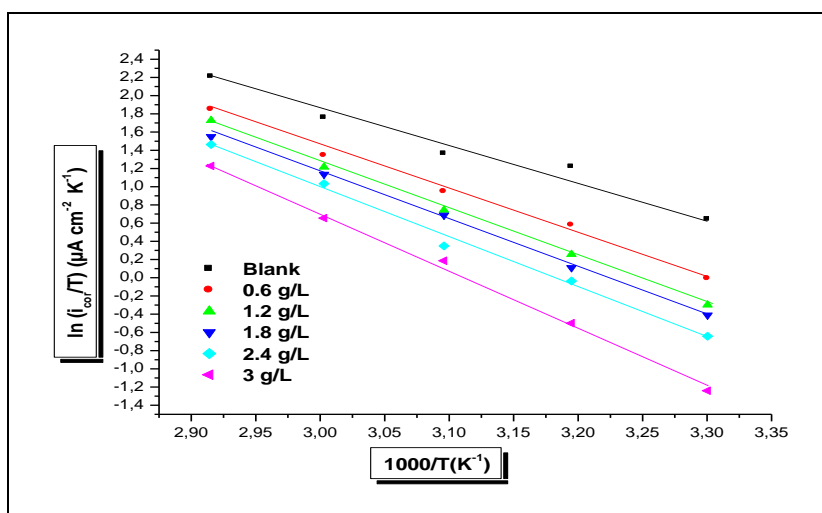


Figure 9: Transition-state plots for mild steel corrosion rates (i_{corr}) in 1 M HCl in absence and in presence of different concentrations of oil

3.4. Adsorption isotherm

The basic information on the interaction between inhibitor and mild steel can be provided by the adsorption isotherm. Two main types of interaction can describe the adsorption of the organic or inorganic compounds: physical adsorption and chemisorption. These are influenced by the chemical structure of the inhibitor, the type of the electrolyte and the charge and nature of the metal. The most frequently used isotherms are Langmuir [57], Frumkin [58] and Temkin [59]. Experimental results the graph of C/θ vs C yielded straight lines as shown in Fig. 10 which is in good agreement with Lagmuir isotherm. The strong correlation ($R^2 \approx 1$) suggests that the adsorption of inhibitors on the MS surface obeyed this isotherm. According to this isotherm, θ is related to the Concentration (C_{inh}) and equilibrium constant of adsorption K_{ads} , using Eq. (7):

$$\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh} \quad (7)$$

C_{inh} is the inhibitor concentration; θ is the degree of surface coverage values for various concentrations of the inhibitors in acidic solution; it has been evaluated from the EIS measurements; K_{ads} is the adsorption equilibrium constant. The values of K_{ads} decreased in this study with the increase in the temperature (Table 6) indicating that the binding power of the inhibitor to the metal surface decreases with the increasing of temperature and that adsorption of Carum Carvi E oil on the carbone steel surface was unfavorable at higher temperature.

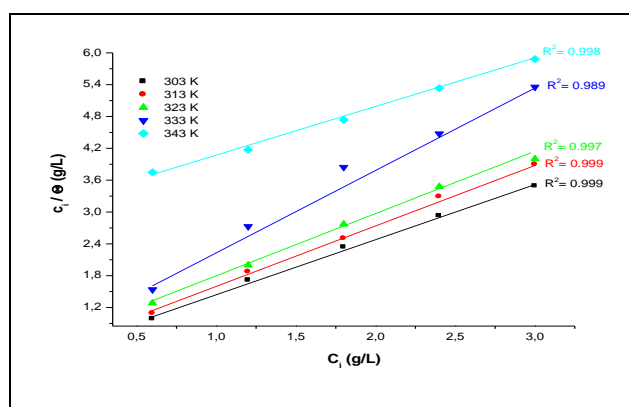


Figure 10: Langmuir's isotherm adsorption the C.C oil on steel surface in 1 M HCl at different temperatures

Table 6: Thermodynamic parameters of adsorption for MS in 1 M HCl at different temperatures from Langmuir adsorption isotherm

T (K)	K_{ads}
303	2,705115
313	2,576390
323	1,586798
333	1,042372
343	0,833689

4. Conclusion

The studied oil Carvi Carum's shows excellent inhibition properties for the corrosion of C38 steel in 1 M HCl at 303 K, the inhibition efficiency increases with increasing of this oil concentration. The values of the inhibition efficiency calculated from potentiodynamic polarization measurement and electrochemical impedance spectroscopy

measurements (EIS) were in good agreement. Based on the polarization results, the investigated oil acts predominantly as a mixed-type inhibitor with predominant cathodic effectiveness. Adsorption of oil on the C38 steel in 1 M HCl obeys the Langmuir adsorption isotherm model. The inhibition efficiency of oil is temperature dependant, and inhibition efficiency decreases slightly with the increase in the temperature. The addition of oil leads to an increase in activation corrosion energy what shows that inhibitor is strongly adsorbed on the metal surface (physisorption).

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