

available online *(A)* www.pccc.icrc.ac.ir Prog. Color Colorants Coat. 15 (2022), 97-109



Electrochemical Evaluation of 5-aminosalicylic Acid as an Inhibitor for Under Deposit Corrosion of X60 Pipeline Steel in Marine Environments

H. Movahedinia, M. Kazemipour, M. Shahidi Zandi*

Department of Chemistry, Kerman Branch, Islamic Azad University, P.O. Box: 7635131167, Kerman, Iran.

ARTICLE INFO

Article history: Received: 22 Oct 2020 Final Revised: 08 Apr 2021 Accepted: 10 Apr 2021 Available online: 30 Jun 2021 Keywords: 5-aminosalicylic acid (5-ASA) Under deposit corrosion (UDC) Density functional theory (DFT) Electrochemical impedance spectroscopy Potentiodynamic polarization.

ABSTRACT

nhibition effects of 5-aminosalicylic acid (5-ASA) on the under deposit corrosion of X60 steel in 3.5 % NaCl solution saturated with CO_2 have been investigated by the techniques of potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). The sand-covered electrode was prepared by covering the X60 steel electrode with a layer of silica sand. The increase of 5-ASA concentration up to 600 ppm led to increasing the inhibition efficiency of X60 steel against under deposit corrosion in the brine solution. The Langmuir isotherm can describe the adsorption behavior of 5-ASA on the surface of the steel. Measurements of potentiodynamic polarization indicated that 5-ASA is an anodic inhibitor. The effects of temperature on the under deposit corrosion behavior of carbon steel were studied both in the absence and presence of 600 ppm 5-ASA. The enthalpy of the 5-ASA adsorption was obtained from the temperature dependence of the corrosion inhibition process. A reasonable agreement was observed between the IE values resulted from the Tafel and the EIS techniques. The electronic properties of 5-ASA were calculated in both the gas phase and the aqueous phase by a density functional theory (DFT) approach to establish the relationship between the inhibitive effect and molecular structure of 5-ASA. Prog. Color Colorants Coat. 15 (2022), 97-109© Institute for Color Science and Technology.

1. Introduction

The materials used for constructing pipelines are usually metallic materials such as carbon steel, which are easily susceptible to corrosion due to the interaction with corrosive environments [1]. The corrosion of steel pipelines of oil increases by settling of deposits such as sand in them. It is very important to consider this type of corrosion, namely as the under deposit corrosion (UDC), because of the pipeline leaking effect of it [2].

Because of the presence of carbon dioxide gas in the oil wells, it is worth considering the CO_2 corrosion as a major challenge in the natural gas and oil industries [3-5]. The literature survey reveals a lot of papers on the CO_2 corrosion of steel alloys [6-10]. The CO_2 corrosion

of the steel alloys has shown more severe corrosion in comparison with the same pH acidic solutions [11].

The main cathodic reactions in the CO_2 corrosion can be the reduction of H⁺, H₂CO₃, HCO₃⁻ and H₂O [12]. Despite some debate in the literature, the hydrogen reduction reaction (HER) has been agreed as the predominant cathodic reaction at the pH range of 3 to 5.5 [13]. The Fe dissolution as the main anodic reaction involves an adsorbed intermediate as the ratedetermining step [14].

The corrosion inhibitors, as the most common protecting materials for CO_2 corrosion of carbon steel [15], are substances whose small concentrations prevent the corrosion of the alloys by the corrosive

media. The molecular structure of the most popular corrosion inhibitors contains S, N, O, P atoms and aromatic rings [16]. The experiments of the sand adsorption have shown that the tendency of the corrosion inhibitors to adsorb on a sand substrate depends on their chemical nature [17].

In this paper, 5-aminosalicylic acid (5-ASA) was investigated as an inhibitor against under deposit corrosion of X60 carbon steel in 3.5% NaCl solution saturated with CO₂ by the techniques of Tafel polarization and impedance spectroscopy. Also, the relationship between inhibitive effect and molecular structure of 5-ASA was established upon the electronic properties of 5-ASA which were calculated by the DFT approach

2. Experimental

2.1. Materials

5-aminosalicylic acid was supplied from Sigma Aldrich. The working electrode used here is made of carbon steel with a surface area of 1.0 cm^2 .

2.2. Methods

10 g of the acid-washed silica sand (SiO_2) was used in all experiments. The working electrode (WE) was located at the bottom of the test cell containing the brine solution and suspended silica sand to provide the sand-covered electrode (Figure 1). The corrosive solution was CO₂ saturated 3.5 % NaCl solution. The solutions under stagnant conditions were employed for the measurements.

The potentiodynamic polarization and impedance measurements were used to investigate the corrosion rate of carbon steel in the CO_2 saturated 3.5 % sodium chloride solutions both in the absence and presence of different amounts of 5-ASA. Before performing the tests, the surface of the sample was rubbed with wet sandpapers through different grades then washed with distilled water and at last dried in air. The sample, as the working electrode, was sealed by epoxy resin at one side after connecting a copper wire to it.

An Autolab 302N potentiostat equipped with Nova 1.9 software was used for potentiodynamic polarization and EIS tests. The counter electrode (CE) was prepared from a platinum rod and the reference electrode was a saturated (KCl) Ag/AgCl electrode. The electrochemical test order was EIS and afterward the polarization technique. Before performing the tests, the specimens were soaked in the solution for about 30 min to stabilize the open circuit potential (OCP).

For the EIS tests, a sinusoidal potential signal of 10 mV (vs OCP) was used in the frequency range of 100 kHz-10 mHz. Nova 1.9 software was employed for both analyzing the Nyquist plots of EIS data and determining the polarization parameters arising from Tafel curves.

3. Results and Discussion

3.1. Polarization measurements

Figure 2 shows the Tafel plots of carbon steel exposed to CO_2 saturated NaCl solutions containing different amounts of 5-ASA. Table 1 lists the current density (i_{corr}), the Tafel slopes (β_a , β_c) and corrosion potential (E_{corr}).



Figure 1: Schematic diagram of the set up of the experiment.



Figure 2: Polarization curves of carbon steel in CO₂ saturated brine solution with different concentrations of 5-ASA at 25 °C.

As it is clear from Figure 2, the anodic current density was found to decrease significantly after the addition of inhibitor, while the cathodic current density changed slightly after the inhibitor addition. Besides, it can be seen that the potential of corrosion changed to more positive values in the presence of inhibitor. Generally, the corrosion inhibitor will be considered as the cathodic or anodic type if the change in the absolute value of E_{corr} is more than 85 mV with respect to E_{corr} of the blank solution, and if the shift is less than 85 mV, the inhibitor can be classified as a mixed type [18-20]. In the present work, the maximum change in equilibrium corrosion potential was +98 mV, suggesting that the 5-ASA can be known as an anodic inhibitor. This result is consistent with the above result that the anodic current density of the steel electrode in CO₂ saturated brine solution is significantly reduced by the addition of the inhibitor.

Table 1 shows the inhibition efficiency (IE) values expressed by the following equation (Eq. 1) [21]:

$$IE_P(\%) = \frac{i_{corr} - i_{corr}}{i_{corr}} \times 100 \tag{1}$$

where i_{corr} and i_{corr} are current densities of corrosion in the blank and the inhibited solutions, respectively. The IE_P values increased with increasing the 5-ASA concentration and reached the maximum value for 600 ppm of 5-ASA. These values indicate that the 5-ASA acts as an effective inhibitor for preventing the under deposit corrosion of carbon steel at relatively low concentrations.

The surface coverage, θ , can be calculated by $\theta = IE(\%)/100$. As shown in Figure 3, an attempt was

made to test the Langmuir, Temkin and Frumkin isotherms having the following relationships (Eq. 2-4):

$$\frac{C}{\theta} = C + \frac{1}{K} \text{(Langmuir)}$$
(2)

$$\ln C = -\ln K + a\theta \quad (\text{Temkin}) \tag{3}$$

$$\ln \frac{\theta}{C(1-\theta)} = \ln K + a\theta \text{ (Frumkin)}$$
(4)

where θ is the surface coverage, C is the inhibitor concentration, K is the adsorption equilibrium constant and *a* is the molecular interaction constant, a constant expressing the interaction between adsorbed and adsorbing molecules.

The best results were found for Langmuir isotherm (Figure 4). As can be seen in Figure 4, the plot of C/θ vs. C for the inhibitor is a linear plot with the correlation coefficient and slope close to 1, confirming the best fit of the polarization data to the Langmuir isotherm.

3.2. Impedance measurements

The results of EIS measurements for carbon steel exposed to CO_2 saturated brine solutions containing different amounts of 5-ASA are shown in Figure 5. The investigated electrochemical system has resistive and capacitive elements since the Nyquist plots are in the form of semi-circles. According to the Nyquist plots, the charge transfer resistance (R_{cl}) increased with 5-ASA amount and reached its maximum value for 600 ppm of 5-ASA in the carbon dioxide saturated NaCl solution.

C /ppm	i _{corr} /µA.cm ⁻²	$-E_{corr}/mV$	$\beta_a/mV.decade^{-1}$	$\beta_c/mV.decade^{-1}$	$IE_P(\%)$
0	45	744	103	956	-
100	18.2	752	68	514	59.6
200	12.9	648	51	335	71.3
300	6.7	686	72	215	85.1
400	5.1	656	70	174	88.7
500	3.8	652	71	329	91.6
600	2.9	646	61	253	93.6

Table 1: Polarization parameters and the corresponding inhibition efficiencies for carbon steel in 3.5% NaCl solution saturated with CO₂ in the absence and presence of different concentrations of 5-ASA at 25 °C.



Figure 3: Adsorption isotherms of the inhibitor calculated by Tafel polarization data for carbon steel in 3.5 % NaCl solution saturated with CO₂ (a) Langmuir (b) Temkin and (c) Frumkin.



Figure 4: Langmuir adsorption isotherm of the inhibitor calculated by Tafel polarization data for carbon steel in 3.5 % NaCl solution saturated with CO₂; (a) concentration in ppm and (b) concentration in mM.



Figure 5: Nyquist plots for carbon steel in 3.5% NaCl solution saturated with CO₂ in the absence and presence of different concentrations of 5-ASA at 25 °C.

For investigating the details of electrochemical reactions occurring at the electrode/solution interface, Randless equivalent circuit was employed to fit the EIS results. A resistance of charge transfer (R_{ct}) and a constant phase element (Q_{dl}) were used in parallel to represent the corrosion process. The impedance value (Z_Q) of Q_{dl} element can be determined by the following equation (Eq. 5) [22]:

$$Z_{\rm Q} = \frac{1}{Y_0 \left(2\pi f j\right)^n} \tag{5}$$

where Y_0 is the Q constant, n is the exponent of Q element and f is frequency. Table 2 lists the parameters resulted from fitting of Nyquist spectra to the proposed equivalent circuit.

It is evident from Table 2 that the increase of the 5-ASA concentration up to 600 ppm led to an increase in the R_{ct} values. This condition is due to the increased coverage of the steel surface by the 5-ASA, which can lead to decrease the aggressiveness of the CO_2 saturated brine solution. The IE % values in Table 2 were computed using the equation 6:

$$IE_{EIS}(\%) = \frac{\dot{R_{ct}} - R_{ct}}{\dot{R_{ct}}} \times 100$$
(6)

Where R_{et} and R'_{ct} are the resistances of charge transfer for carbon steel in the CO₂ saturated brine solution before and after the addition of the 5-ASA, respectively. The increase of the 5-ASA concentration up to 600 ppm led to an increase in the IE values. The impedance IE % values (Table 2) are completely consistent with the polarization IE % values and confirm each other (Table 1). The isotherms of Langmuir, Frumkin, and Temkin were used for fitting data (Figure 6).

 Table 2: Impedance parameters and the corresponding inhibition efficiencies for carbon steel in 3.5% NaCl solution saturated with CO₂ in the absence and presence of different concentrations of 5-ASA at 25°C.

C /ppm	$R_s/\Omega.cm^2$	$R_{ct}/k\Omega.cm^2$	n	$10^{6} \text{ Y/}\Omega^{-1}.\text{cm}^{-2}$	IE _{EIS} (%)
0	10.0	0.48	0.839	206	-
100	11.0	1.10	0.875	84	56.4
200	11.3	2.02	0.815	89	76.2
300	13.1	2.77	0.893	66	82.7
400	9.0	3.24	0.917	56	85.2
500	13.1	4.72	0.870	95	89.8
600	10.9	5.65	0.831	90	91.5



Figure 6: Adsorption isotherms of the inhibitor calculated by EIS data for carbon steel in 3.5 % NaCl solution saturated with CO₂ (a) Langmuir (b) Temkin and (c) Frumkin.



Figure 7: Langmuir adsorption isotherm of the inhibitor calculated by EIS data for carbon steel in 3.5 % NaCl solution saturated with CO₂; (a) concentration in ppm and (b) concentration in mM.

As can be seen from Figure 7, the EIS results confirmed that the adsorption of 5-ASA molecules can be fitted well to the Langmuir isotherm because both the regression parameter and the slope values are notably close to 1.

3.3. The effect of temperature

Polarization measurements in the range of 25 to 55° C were used to determine the activation energy (E_a) and some thermodynamic quantities for the carbon steel corrosion in the brine CO₂ saturated solution

containing 600 ppm 5-ASA. The Tafel curves for carbon steel exposed to the carbon dioxide saturated brine solutions in the blank solution and 600 ppm 5-ASA concentration are demonstrated in Figure 8.

Table 3 lists the corrosion factors obtained at various temperatures. It is evident from the polarization results that with an increase in temperature, a decrease in IE % has happened. A slight change in the IE values (less than 10%) with the rise of temperature from 25 to 55 °C proves the strong adsorption bonding of 5-ASA on the steel surface. It means that besides physisorption, the chemisorption of 5-ASA should also be involved.

Arrhenius equation can express the temperature

influence on the corrosion rate according to equation 7:

$$i_{corr} = A \exp\left(\frac{-E_a}{RT}\right) \tag{7}$$

where i_{corr} is the corrosion current, A is the Arrhenius pre-exponential factor, E_a is the energy of activation, T is temperature (K), and R is the molar gas constant (8.314 J K⁻¹mol⁻¹). E_a values can be obtained from the slope (- E_a/R) of the Arrhenius plot [lni_{corr}vs 1/T]. Figure 9 shows the Arrhenius plots for carbon steel electrode in 3.5 % NaCl solutions saturated with CO₂ in the absence (blank) and the presence of 5-ASA.

 Table 3: Effect of temperature on the corrosion parameters of carbon steel in 3.5 % NaCl solution saturated with CO2 containing 600 ppm 5-ASA at 25 °C.

C/ppm	T/ºC	i _{corr} /µA.cm ⁻²	IE%	
0	25	45	-	
	35	63	-	
	45	91	-	
	55	121	-	
	25	2.9	93.6	
C 00	35	5.3	91.6	
000	45	10.7	88.2	
	55	19.2	84.1	



Figure 8: Effect of temperature on the polarization curves in 3.5 % NaCl solutions saturated with CO₂ (a) without inhibitor and (b) in the presence of 600 ppm 5-ASA.



Figure 9: Arrhenius plots for carbon steel in 3.5 % NaCl solution saturated with CO₂ in the absence and presence of 600 ppm 5-ASA.

According to the slopes of the Arrhenius plots, it was revealed that the calculated E_a value in the presence of 5-ASA was larger than that in the absence of 5-ASA (51.8 kJ/mol vs 27.1 kJ/mol). Therefore, the rate of under deposit corrosion of carbon steel in the brine CO₂ saturated solutions decreased by 5-ASA.

The following equation can be employed for calculation of the Gibbs energy of inhibitor adsorption (ΔG_{ads}) on the carbon steel (Eq. 8):

$$\Delta G_{ads} = -RT \ln(55.5K_{ads}) \tag{8}$$

where T is the temperature (K), R is the gas constant and K_{ads} is the adsorption equilibrium constant. The reciprocal of the intercept of the isotherm line is equal to the equilibrium constant of adsorption (Figure 4). The values of K_{ads} and ΔG_{ads} are summarized in Table 4. Generally, if ΔG_{ads} values are more positive than -20 kJ/mol, it can be said that physical adsorption has occurred and if ΔG_{ads} values are more negative than -40 kJ mol⁻¹, it can be said that chemical adsorption has occurred. Therefore, it can be concluded from the obtained value for ΔG_{ads} that the adsorption of 5-ASA is not solely chemisorption or physisorption but involving comprehensive adsorption (both chemical and physical).

The adsorption enthalpy, ΔH_{ads} , can be computed by the equation 9 [23]:

$$\ln\left(\frac{\theta}{1-\theta}\right) = \ln A + \ln C - \frac{\Delta H_{ads}}{RT}$$
(9)

Table 4: The values of K_{ads} and ΔG_{ads} corresponding to
polarization and EIS data in 3.5 % NaCl solution
saturated with CO2.

sample	Т	afel	EIS		
Inh	K _{ads} (M ⁻¹)	ΔG_{ads} (kJ.mol ⁻¹)	K _{ads} (M ⁻¹)	ΔG_{ads} (kJ.mol ⁻¹)	
5-ASA	1905	-28.7	2017	-28.8	

where θ is the surface coverage calculated from θ =IE(%)/100, A is a constant, C is the inhibitor concentration, R is the gas constant, and T is temperature. A straight line is obtained from the plot of ln(θ /(1- θ)) versus 1/T at the constant amount of the 5-ASA as shown in Figure 10. The line slope is equal to Δ H_{ads}/R. The calculated value of Δ H_{ads} for inhibitor adsorption is gathered in Table 5. The exothermic adsorption behavior of the 5-ASA on the steel surface can be understood from the negative value of Δ H_{ads}.

The following equation was employed to calculate the adsorption entropy (ΔS_{ads}) (Eq. 10):

$$\Delta G_{ads} = \Delta H_{ads} - T \Delta S_{ads} \tag{10}$$

The obtained values for ΔS_{ads} are shown in Table 5. For accounting the positive values of ΔS_{ads} , it should be noticed that the adsorption of the 5-ASA molecules on the carbon steel surface is accompanied by desorption of water molecules from the surface. Thus, while the adsorption process for the 5-ASA is associated with a decrease in entropy of the solute, the opposite is true for the solvent. The thermodynamic values obtained are the algebraic sum of the adsorption of organic molecules and desorption of water molecules. Hence, the gain in entropy is attributed to the increase in solvent entropy.

3.4. Theoretical study

To understand the interaction of 5-ASA with carbon steel, quantum chemical calculations were carried out using the methodology of Hartree-Fock (HF) in the gas phase and the density functional theory (DFT) method in the aqueous phase.

Generally, the adsorption of an organic inhibitor molecule on a metal surface is reported to occur based on donor-acceptor interactions between the π -electrons of the organic inhibitor and the orbital of the metal surface atom [24]. Thus, the energies of HOMO and LUMO of the inhibitor molecule are very important in discussing its interaction with a metal surface. The vacant orbital of Fe atom can interact with the HOMO of the inhibitor, while, the 4s orbital of Fe atom interacts with the LUMO of the inhibitor atom. The inhibitor molecule with more energy of HOMO (less negative) tends to be more donating and that with the lower energy of LUMO (more negative) tends to be more accepting. Therefore, the inhibition efficiency will be increased by increasing the HOMO energy (less negative) and decreasing LUMO energy (more negative). Furthermore, with decreasing the energy gap (ΔE) between HOMO and LUMO, the interactions between the inhibitor molecule and metal atom become stronger and the inhibition efficiency will be increased [25]. The quantum chemical parameters in both the gas phase and aqueous phase are presented in Table 6.

As it can be seen from the quantum chemical parameters given in Table 7, 5-ASA has a higher E_{HOMO} , a lower E_{HOMO} , a lower energy gap, and a higher dipole moment than some inhibitors earlier reported as good corrosion inhibitors [25-28].

It has been reported that the increasing values of dipole moment facilitate adsorption and increase the inhibition efficiency. Meanwhile, several irregularities can be observed in the case of correlation of dipole moment with inhibition efficiency in the literature [25, 29].



Figure 10: Plot of In $(\theta/1-\theta)$ vs. 1/T for carbon steel 3.5 % NaCl solution saturated with CO₂ containing 600 ppm 5-ASA.

Table 5: Activation and thermodynamic parameters of adsorption obtained by potentiodynamic polarizationmeasurements for carbon steel in 3.5 % NaCl solution saturated with CO2 in the absence and presence of 600 ppm 5-ASA at 25 °C.

Sample	E _a (kJ.mol ⁻¹)	K _{ads} (M ⁻¹)	∆G _{ads} (kJ.mol ⁻¹)	∆H _{ads} (kJ.mol ⁻¹)	ΔS _{ads} (J.K ⁻¹ . mol ⁻¹)
Blank	27.1	-	-	-	-
5-ASA	51.8	1905	-28.7	-22.0	22.5

Table 6: The calculated quantum chemical parameters for 5-ASA.

Medium	Method	E _{HOMO} (ev)	E _{LUMO} (ev)	ΔE (ev)	μ (D)
Gas phase	HF	-8.970	4.530	13.500	3.419
Aqueous phase	DFT	-7.228	-0.729	6.499	4.782

Table 7: Comparison of quantum chemical parameters of 5-ASA inhibitor with some corrosion inhibitors earlier reported.

Inhibitor	E _{HOMO} (ev)	E _{LUMO} (ev)	AE (ev)	μ(D)	Ref.
Aminotriazole	-10.395	0.438	10.833	1.2	[25]
Triazole	-9.309	0.106	9.415	2.9	[25]
Benzotriazole	-8.433	-0.571	7.862	3.8	[25]
2,3-diaminonaphthalene	-8.16	0.14	8.02	2.9	[26]
C-1 ^a	-9.645	-0.165	9.480	0.803	[27]
C-2 ^b	-9.295	0.222	9.517	1.32	[27]
Ketoprofen	-10.86	-0.21	10.65	20.75	[28]
5-ASA	-7.228	-0.729	6.499	4.782	This work

[a] dibenzo-bis-imino crown ether

[b] dibenzo-diaza crown ether

Figures 11 and 12 show the optimized structures and Frontier orbital energy distributions of the HOMO and LUMO for 5-ASA obtained in the gas phase and aqueous phase, respectively.

The reactive ability of the inhibitor is closely related to the Frontier molecular orbitals (HOMO and LUMO). As seen in Figure 11, the electronic distributions of HOMO and LUMO obtained from the gas phase are mostly located on the aromatic ring of 5ASA. It can be seen from Figure 12 that in the aqueous phase the HOMOs of 5-ASA are largely delocalized over the C5 and C6 atoms of the aromatic ring, while the electronic distributions of the LUMO are notably located on the carbonyl group. These results prove that the most active sites of 5-ASA are probably located around these regions. The above mentioned FTIR results are in agreement with the quantum chemical results obtained from the aqueous phase.







Figure 12: The optimized molecular structure, HOMO and LUMO for 5-ASA using DFT in aqueous phase.

4. Conclusion

5-ASA was employed as an inhibitor for under deposit corrosion protection of carbon steel in CO_2 saturated NaCl solution. Tafel polarization curves showed that the 5-ASA reduced the corrosion of carbon steel. According to EIS measurements, the corrosion inhibition was caused by an increase in the charge transfer resistance at the steel-solution interface. The data acquired from the Tafel and the impedance measurements indicated that the adsorption of 5-ASA on carbon steel in brine solution saturated with CO_2 follows the Langmuir isotherm. The Tafel polarization experiments at different temperatures suggested that 5-ASA can effectively minimize the corrosion effects of solutions on the alloy surface. The reason for the inhibition of alloy by 5-ASA was due to the adsorption of 5-ASA molecules on the alloy surface which was also evidenced by Langmuir isotherm study. The IE and ΔG_{ads} values obtained from the Tafel method showed acceptable compatibility with the data acquired from the EIS technique. The relationship between inhibitive effect and molecular structure of 5-ASA was established upon the electronic properties of 5-ASA which were calculated by the DFT approach.

5. References

- Z. Mahidashti. M. Rezaei, M. P. Asfia, Internal underdeposit corrosion of X60 pipeline steel upon installation in a chloride-containing soil environment, *Colloids Surf. A Physicochem. Eng. Asp.*, 602(2020), 125120.
- D. Han. R. J. Jiang, Y. F. Cheng, Mechanism of electrochemical corrosion of carbon steel under deoxygenated water drop and sand deposit, *Electrochim. Acta*, 114(2013), 403-408.
- T. das Chagas Almeida. M. C. E. Bandeira. R. M. Moreira, O. R. Mattos, New insights on the role of CO₂ in the mechanism of carbon steel corrosion, *Corros. Sci.*, 120(2017), 239-250.
- 4. D. Dwivedi. K. Lepková, T. Becker, Carbon steel corrosion: a review of key surface properties and characterization methods, *RSC Advances*, 7(2017), 4580-4610.
- 5. R. F. Wright, E. R. Brand, M. Ziomek-Moroz, J. H. Tylczak, P. R. Ohodnicki, Effect of HCO₃⁻ on electrochemical kinetics of carbon steel corrosion in CO₂-saturated brines, *Electrochim. Acta*, 290(2018), 626-638.
- D. A. Lopez. S. N. Simison, S. R. d. Sanchez, The influence of steel microstructure on CO₂ corrosion. EIS studies on the inhibition efficiency of benzimidazole, *Electrochim. Acta*, 48(2003), 845-854.
- W. Li. B. Brown. D. Young, S. Nešic, Investigation of Pseudo-Passivation of Mild Steel in CO₂ Corrosion, *Corrosion*, 70(2014), 294-302.
- R. D. Motte. R. e. Mingant. J. Kittel. F. Ropital. P. Combrade. S. Necib. V. Deydier, D. Crusset, Near surface pH measurements in aqueous CO₂ corrosion, *Electrochim. Acta*, 290(2018), 605-615.
- A. Kahyarian. B. Brown, S. Nesic, Electrochemistry of CO₂ corrosion of mild steel: Effect of CO₂ on iron dissolution reaction, *Corros. Sci.*, 129(2017), 146-151.
- 10. S. Hatami. A. Ghaderi-Ardakani. M. Niknejad-Khomami. F. Karimi-Malekabadi. M. R. Rasaei, A. H. Mohammadi, On the prediction of CO₂ corrosion in petroleum industry, *J. Supercrit. Fluids*, 117(2016), 108-112.
- B. R. Linter, G. T. Burstein, Reactions of pipeline steels in carbon dioxide solutions, *Corros. Sci.*, 41(1999), 117-139.
- J. Han. J. Zhang, J. W. Carey, Effect of bicarbonate on corrosion of carbon steel in CO₂ saturated brines, *Int. J. Greenh. Gas Con.*, 5(2011), 1680-1683.
- R. A. D. Motte. R. Barker. D. Burkle. S. M. Vargas, A. Neville, The early stages of FeCO₃ scale formation kinetics in CO₂ corrosion, *Mater. Chem. Phys.*, 216(2018), 102-111.
- R. Feng. J. Beck. M. Ziomek-Moroz, S. N. Lvov, Electrochemical corrosion of ultra-high strength carbon steel in alkaline brines containing hydrogen sulfide, *Electrochim. Acta*, 212(2016), 998-1009.
- 15. [M. Javidi. R. Chamanfar, S. Bekhrad, Investigation on the efficiency of corrosion inhibitor in CO₂

corrosion of carbon steel in the presence of iron carbonate scale, *J. Nat. Gas. Sci. Eng.*, 61(2019), 197-205.

- 16. H. H. Zhang, Y. Chen, Experimental and theoretical studies of benzaldehyde thiosemicarbazone derivatives as corrosion inhibitors for mild steel in acid media, J. Mol. Struct., 1177(2019), 90-100.
- V. Pandarinathan. K. Lepková. S. I. Bailey, R. Gubner, Evaluation of corrosion inhibition at sand-deposited carbon steel in CO₂-saturated brine, *Corros. Sci.*, 72(2013), 108-117.
- 18. Y. Liang. C. Wang. J. Li. L. Wang, J. Fu, The penicillin derivatives as corrosion inhibitors for mild steel in hydrochloric acid solution: experimental and theoretical studies, *Int. J. Electrochem. Sci.*, 10(2015), 8072-8086.
- 19. S. Hari Kumar, S. Karthikeyan, Torsemide and furosemide as green inhibitors for the corrosion of mild steel in hydrochloric acid medium, *Ind. Eng. Chem. Res.*, 52(2013), 7457-7469.
- M. Lebrini. F. Robert. H. Vezin, C. Roos, Electrochemical and quantum chemical studies of some indole derivatives as corrosion inhibitors for C38 steel in molar hydrochloric acid, *Corros. Sci.*, 52(2010), 3367-3376.
- 21. V. S. Sastri, Green Corrosion Inhibitors; Theory and Practice, John Wiley & Sons, New Jersey, 2011.
- 22. M. G. Hosseini. M. Ehteshamzadeh, T. Shahrabi, Protection of mild steel corrosion with Schiff bases in 0.5M H₂SO₄ solution, *Electrochim. Acta*, 52(2007), 3680-3685.
- 23. G. Golestani. M. Shahidi, D. Ghazanfari, Electrochemical evaluation of antibacterial drugs as environment-friendly inhibitors for corrosion of carbon steel in HCl solution, *Appl. Surf. Sci.*, 308(2014), 347-362.
- 24. S. A. Umoren. I. B. Obot. A. Madhankumar, Z. M. Gasem, Performance evaluation of pectin as ecofriendly corrosion inhibitor for X60 pipeline steel in acid medium: Experimental and theoretical approaches, *Carbohydr. Polym.*, 124(2015), 280-291.
- 25. I. B. Obot, N. O. Obi-Egbedi, Theoretical study of benzimidazole and its derivatives and their potential activity as corrosion inhibitors, *Corros. Sci.*, 52(2010), 657-660.
- 26. K. F. Khaled, Molecular simulation, quantum chemical calculations and electrochemical studies for inhibition of mild steel by triazoles, *Electrochim. Acta*, 53(2008), 3484-3492.
- 27. I. B. Obot. N. O. Obi-Egbedi, S. A. Umoren, The synergistic inhibitive effect and some quantum chemical parameters of 2,3-diaminonaphthalene and iodide ions on the hydrochloric acid corrosion of aluminium, *Corros. Sci.*, 51(2009), 276-282.
- 28. R. Hasanov. S. Bilge. S. Bilgiç. G. Gece, Z. Kılıç, Experimental and theoretical calculations on corrosion

inhibition of steel in 1 M H₂SO₄ by crown type polyethers, *Corros. Sci.*, 52(2010), 984-990.

29. K. F. Khaled. K. Babić-Samardžija, N. Hackerman, Theoretical study of the structural effects of polymethylene amines on corrosion inhibition of iron in acid solutions, *Electrochim. Acta*, 50(2005), 2515-2520.

How to cite this article:			
H. Movahedinia, M. Kazemipour, M. Shahidi Zandi, Electrochemical Evaluation of 5-			
aminosalicylic Acid as an Inhibitor for Under Deposit Corrosion of X60 Pipeline Steel in			
Marine Environments. Prog. Color Colorants Coat., 15 (2022), 97-109.			

