

การยับยั้งการกัดกร่อนของเหล็กกล้าในสารละลายกรดไฮโดรคลอริกโดยใช้ 1,8-ไดอะไซโคล[5.4.0]อันเดค-7-ีน เป็นตัวยับยั้งอินทรีย์ชนิดใหม่

Corrosion Inhibition of Galvanized Steel in Hydrochloric Acid Solution using

1,8-Diazabicyclo[5.4.0]undec-7-ene as New Organic Inhibitor

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บทคัดย่อ

ในงานวิจัยนี้ 1,8-ไดอะไซโคล[5.4.0]อันเดค-7-ีน (DBU) ได้ถูกใช้งานเป็นตัวยับยั้งการกัดกร่อนอินทรีย์ของเหล็กกล้าในสารละลายกรดไฮโดรคลอริกเข้มข้น 1.0 M เป็นครั้งแรก ปฏิบัติการกัดกร่อนของเหล็กกล้าในสารละลายกรดไฮโดรคลอริกเข้มข้น 1.0 M ที่มี DBU เข้มข้น 3.0 6.0 9.0 และ 50.0 mM และที่ปราศจาก DBU ได้ติดตามโดยการวัดปริมาตรของแก๊ส และน้ำหนักที่หายไป จากทั้งสองเทคนิคพบว่า DBU เป็นตัวยับยั้งการกัดกร่อนของเหล็กกล้าในสารละลายกรดที่มีประสิทธิภาพสูง โดยประสิทธิภาพการยับยั้งการกัดกร่อนของ DBU สูงถึง 88% ณ อุณหภูมิ 30°C จากการศึกษาทางจลนศาสตร์ พบว่าอัตราการกัดกร่อนของแผ่นเหล็กลดลงเมื่ออุณหภูมิลดต่ำลงและความเข้มข้นของ DBU สูงขึ้น นอกจากนี้ค่าพลังงานก่อกัมมันต์ (E_a) จะเพิ่มขึ้นตามความเข้มข้นของ DBU จากการวิเคราะห์ทางอุณหพลศาสตร์ พบว่าการดูดซับของ DBU บนพื้นผิวของเหล็กเป็นกระบวนการที่เกิดขึ้นเองได้ และเป็นกระบวนการดูดซับทางกายภาพ เนื่องจากการเปลี่ยนแปลงพลังงานอิสระของระบบมีค่าเป็นลบ (ΔG อยู่ระหว่าง -14 ถึง -27 kJ/mol) จากผลการทดลองแสดงให้เห็นว่า DBU สามารถลดความเสียหายของแผ่นเหล็กในสารละลายกรดไฮโดรคลอริกได้อย่างมีนัยสำคัญ

คำสำคัญ : เหล็กกล้าในสารละลาย, การกัดกร่อน, 1,8-ไดอะไซโคล[5.4.0]อันเดค-7-ีน, การดูดซับ, อุณหพลศาสตร์

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Abstract

In this work, 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) was, for the first time, utilized as the organic corrosion inhibitor for galvanized steel in 1.0 M HCl, at 30 °C and 40°C. The corrosion reactions of galvanized steel in 1.0 M HCl with DBU concentrations: 3.0, 6.0, 9.0 and 50.0 mM and without DBU had been investigated by gasometrical and weight loss measurements. The results from both techniques showed that DBU was found to be the highly effective corrosion inhibitor for galvanized steel in an acidic media. The highly inhibiting efficiency of DBU was up to 88% at 30°C. The result from kinetics study showed that the corrosion rate of steel was decreased with decreasing of temperature and increasing of DBU concentration. Moreover, the activation energy (E_a) was increased with increasing of DBU concentration. From thermodynamic analysis, the adsorption of DBU on steel surface was physical adsorption and spontaneous process, due to the free energy changes of adsorption are negative (ΔG values are -14 to -27 kJ/mol). Overall results suggested that, in significant, the presence of DBU can effectively prevent the damage of steel sheet in HCl solution.

Keywords : galvanized steel, corrosion, 1,8-diazabicyclo[5.4.0]undec-7-ene, adsorption, kinetics

Introduction

The metal-free inhibitors for the corrosion of metal in corrosive media have been interested by many researchers. In the industries, the pickling or cleaning process by acid causes the corrosion of metal and the economic losses (Roberge, 1999). Generally, the introduction of inhibitors into the cleaning solution is an effective process to reduce the damage of metal from the corrosion. The conventional corrosion inhibitors are highly toxic to environment due to their heavy metal component such as Cr, Pb and As (Rudresh & Mayanna, 1980; Armstrong & Peggs, 1994). Therefore, it is a challenge for ones to create the metal-free corrosion inhibitors for metal in acidic solution. Recently, the researchers have successfully developed the metal-free corrosion inhibitors which are less toxic than heavy-metal containing compounds. Many organic compounds have been utilized as corrosion inhibitors for metals (Limwanich & Witthayaprapakorn, 2016; Vashi *et al.*, 2010; Abiola & James, 2010; Obot & Obi-Egbedi, 2010; Salarvand *et al.*, 2017; Zhang *et al.*, 2015; Kosari *et al.*, 2014; Ansari *et al.*, 2014). These organic compounds with heteroatom (O, N and S) can be adsorbed onto the metal surfaces, hence reducing the free corrosion sites (Obot & Obi-Egbedi, 2010). Among these inhibitors, the N-containing compounds such as imidazoline (Salarvand *et al.*, 2017), benzothiazole (Zhang *et al.*, 2015), pyridine (Kosari *et al.*, 2014) and Schiff base compounds (Ansari *et al.*, 2014) show high efficiency in inhibiting the corrosion of metals in acidic media.

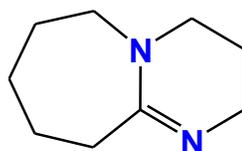
Recently, 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), which is an alkaloid compound, has been widely used as a reactive organic catalyst for the synthesis of biodegradable polyesters (Dove, 2012). Such a

compound, which has two nitrogen atoms, has caught our attention as it has a potential for use as corrosion inhibitor. To our best knowledge, there are no reports on the inhibitive effect of DBU on the corrosion of steel in acidic media before. Therefore, in this work, we have investigated the effect of DBU on the corrosion behavior of galvanized steel in 1.0 M hydrochloric acid. The corrosion reaction of galvanized steel in acidic media can be monitored by means of gasometrical (Oguzie, 2007; Okafor *et al.*, 2008; Kwolek *et al.*, 2016) and weight loss measurements (Liu *et al.*, 2016; Mourya *et al.*, 2014). The effects of DBU concentration and temperature on the corrosion of steel have also been studied. The kinetic and thermodynamic parameters for the corrosion of galvanized steel in the presence and absence of DBU inhibitor in acidic media have been determined and discussed.

Methods

Material preparation

Galvanized steel sheets (SGCC grade) with 0.038 cm in thickness were used in this study. The steel sheet was cut in size $2 \times 2 \times 0.038$ cm³ and polished by emery paper number 200 800 and up to 1200. The prepared steel sheets were rinsed with deionized water, immersed in acetone and stored in desiccators before used. 1.0 M Hydrochloric acid (HCl) was prepared by diluting the concentrated HCl (37%, RCI LABSCAN). 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) (98%, Sigma-Aldrich) with the following chemical structure was used as received.



1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU)

Gasometrical measurements

The prepared steel sheets were immersed in 30.0 mL of 1.0 M HCl in round bottom flask connected with gas inlet. The corrosion reactions of the steel sheets in 1.0 M HCl with 3.0, 6.0, 9.0 and 50.0 mM of DBU inhibitor and without DBU, at 30°C and 40°C, were investigated by careful measurement of the permeated hydrogen gas at fixed time intervals in the glass burette.

Weight loss measurements

The pre-weighed steel sheets were immersed in 30.0 mL of 1.0 M HCl with 3.0, 6.0, 9.0 and 50.0 mM of DBU inhibitor and without DBU, at 30°C and 40°C. The steel sheets were taken out of the HCl solutions at 2, 3 and 4 hours. Then, they were rinsed with deionized water and acetone, respectively. The dried steel sheets were reweighed to determine the weight loss.

Results and Discussion

Gasometrical measurements

The corrosion of galvanized steel can be simply determined by the hydrogen permeation technique (Oguzie, 2007; Okafor *et al.*, 2008; Kwolek *et al.*, 2016). The reaction of steel with HCl solution results in the formation of hydrogen gas that can permeate from the solution as the gas bubbles. The plots of hydrogen gas volume (V_{Hydrogen}) against time for the corrosion of galvanized steel in 1.0 M of HCl with 3.0, 6.0, 9.0 and 50.0 mM of DBU initiator and without DBU are illustrated in Figure 1. The results indicate that the volume of hydrogen gas was increased with increasing of corrosion time and decreasing of DBU concentration. This indicates that DBU can reduce the corrosion reaction of galvanized steel. Furthermore, the Figure 1(b) shows the increase of hydrogen gas volume with temperature under a constant concentration of DBU. From the obtained results, the corrosion rate (C_R) can be determined from Eq. (1) (Okafor *et al.*, 2008).

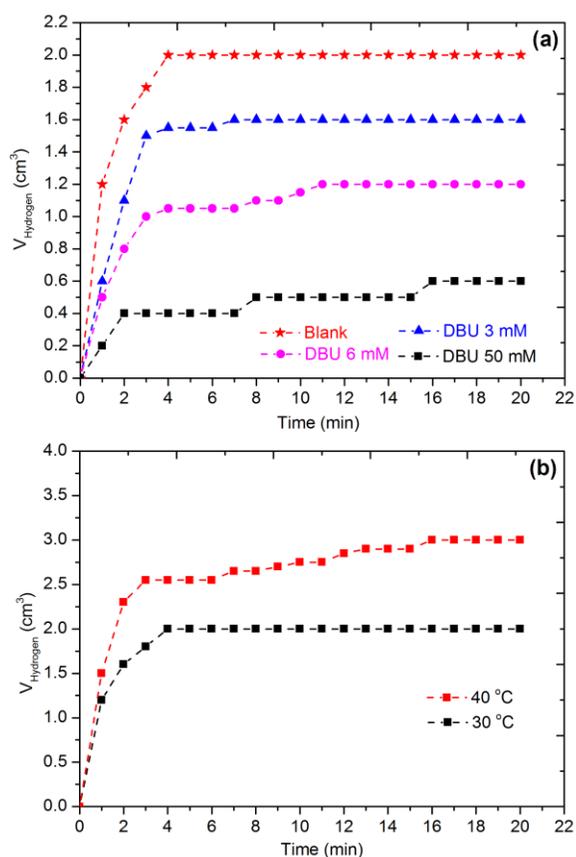


Figure 1 (a) Plots of hydrogen gas volume vs. corrosion time of galvanized steel in 1.0 M HCl at 30°C in the presence and absence of DBU corrosion inhibitor. (b) Plots of hydrogen gas volume vs. corrosion time of galvanized steel in 1.0 M HCl at 30°C and 40°C, in the presence of 3.0 mM of DBU.

$$C_R = \frac{\Delta V}{\Delta t} = \frac{V_t - V_i}{t_f - t_i} \quad (1)$$

where V_t is the volume of hydrogen gas at the time t and V_i is the initial volume of hydrogen gas, respectively. From the obtained values of C_R , the degree of surface coverage (θ) and %inhibition ($\%I$) can be determined from Eqs. (2) and (3), respectively (Okafor *et al.*, 2008).

$$\theta = \frac{C_{R,blank} - C_{R,DBU}}{C_{R,blank}} \quad (2)$$

$$\%I = \left(\frac{C_{R,blank} - C_{R,DBU}}{C_{R,blank}} \right) \times 100 \quad (3)$$

where $C_{R,blank}$ is the corrosion rate of steel in acidic media without DBU inhibitor and $C_{R,DBU}$ is the corrosion rate of steel in acidic media in the presence of DBU inhibitor. The determined values of C_R , θ and $\%I$ for the corrosion of galvanized steel in 1.0 M HCl, at 30°C and 40°C, with and without DBU inhibitor are summarized in Table 1.

Table 1 The corrosion rate, degree of surface coverage and %inhibition for the corrosion of galvanized steel in 1.0 M HCl, at 30°C and 40°C, in the presence and absence of DBU inhibitor using gasometrical measurements.

Temperature (°C)	DBU concentration (mM)	Corrosion rate (cm ³ /min)	Degree of surface coverage (θ)	%Inhibition (%)
30	0.0	0.260	0.000	0.0
	3.0	0.100	0.615	61.5
	6.0	0.080	0.692	69.2
	9.0	0.065	0.750	75.0
	50.0	0.030	0.885	88.5
40	0.0	0.380	0.000	0.0
	3.0	0.150	0.605	60.5
	6.0	0.135	0.645	64.5
	9.0	0.110	0.711	71.1
	50.0	0.090	0.763	76.3

The results from Table 1 indicate that the corrosion rate of galvanized steel is decreased with increasing of DBU concentration. Moreover, the degree of surface coverage of DBU on the steel surface is increased with increasing of DBU concentration indicating to the more absorption of DBU molecules on steel surface. The increase of DBU concentration also increases the values of %*I*. From gasometrical measurement, the maximum value of %*I* of DBU for the corrosion of galvanized steel in 1.0 M HCl is 88.5% at 30°C. When the temperature increases from 30°C to 40°C, it is found that the degree of surface coverage of DBU on steel surface is decreased due to desorption of DBU molecules from steel surface. This indicates that the adsorption of DBU on steel surface is the physical adsorption, in agreement with the literatures (Abiola & James, 2010; Oguzie, 2007; Okafor *et al.*, 2008). After obtaining the values of corrosion rate, the activation energy (E_a) for the corrosion of galvanized steel is also determined by using the Arrhenius equation as shown in Eq. (4) (Bentiss *et al.*, 2007),

$$\log \frac{R_2}{R_1} = \frac{E_a}{2.303R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \quad (4)$$

where R_1 and R_2 are the corrosion rates of galvanized steel at temperature T_1 and T_2 , respectively. E_a is the activation energy of corrosion and R is the universal gas constant ($8.3142 \text{ J mol}^{-1} \text{ K}^{-1}$). After obtaining the kinetics information, the heat of adsorption of DBU on steel surface can be determined by using Eq. (5) (Oguzie, 2007; Okafor *et al.*, 2008; Bhajiwala & Vashi, 2001),

$$Q_{ads} = 2.303R \left[\log \left(\frac{\theta_2}{1-\theta_2} \right) - \log \left(\frac{\theta_1}{1-\theta_1} \right) \times \frac{T_1 T_2}{T_2 - T_1} \right] \quad (5)$$

where Q_{ads} is the heat of adsorption, θ_1 and θ_2 are the degrees of surface coverage of DBU on steel surface at T_1 and T_2 , respectively. The obtained values of E_a and Q_{ads} are summarized in Table 2. These results indicate that the values of E_a are increased with increasing of DBU concentration, indicating to the lower corrosion rate at higher DBU concentration. Furthermore, the positive values of Q_{ads} reveal to the adsorption of DBU on steel surface is the endothermic process.

Table 2 The values of activation energy (E_a) and heat of adsorption (Q_{ads}) for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence and absence of DBU inhibitor using gasometrical measurements.

DBU concentration (mM)	Activation energy (E_a) (kJ/mol)	Heat of adsorption (Q_{ads}) (kJ/mol)
0.0	29.9	-
3.0	32.0	22.4
6.0	41.3	30.0
9.0	41.5	53.8
50.0	86.6	67.0

For thermodynamics consideration, the Langmuir adsorption isotherm is used to determine the equilibrium constant of the adsorption/desorption process as shown in Eq. (6). This isotherm assumes that one substrate site is covered by one adsorbate. Moreover, the free energies of all active sites are equal and the adsorbed molecules do not interact with each other throughout the covered area of steel surface (El-Etre, 2006).

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \quad (6)$$

where K_{ads} is the equilibrium constant of adsorption/desorption process and C is the concentration of DBU inhibitor. Plots of Langmuir adsorption isotherm are depicted in Figure 2, which show a good fit with Langmuir adsorption isotherm with $R^2 > 0.999$. This indicates that the adsorption of DBU molecules on steel surface obeys the Langmuir adsorption isotherm. From Figure 2, it is found that the values of K_{ads} for the adsorption of DBU on steel surface at 30°C and 40°C are 5.12×10^2 and 7.87×10^2 L/mol, respectively. From the obtained K_{ads} values, the Gibbs free energy change (ΔG) for the adsorption of DBU on steel surface can be determined from Eq. (7) (O'MBockris & Swinkles, 1964; Bayol *et al.*, 2007),

$$\ln K_{ads} = \ln \left(\frac{1}{55.5} \right) - \frac{\Delta G}{RT} \quad (7)$$

where constant value of 55.5 is the concentration of water. The determined ΔG values for the corrosion of galvanized steel at 30°C and 40°C in the presence of DBU inhibitor are -25.8 and -26.9 kJ/mol, respectively. The

negative value of ΔG suggests that the adsorption of DBU on steel surface is the spontaneous process (Singh & Quraishi, 2010). The obtained values of ΔG are lower than -20 kJ/mol suggesting that the adsorption of DBU on steel surface is the physical adsorption (Donahue & Nobe, 1965; Kamis *et al.*, 1991). To support the results obtained from the gasometrical measurement, hence the weight loss measurement is utilized.

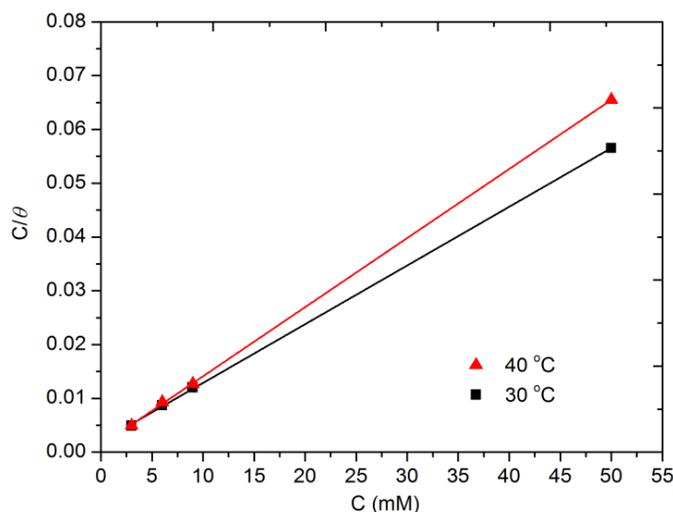


Figure 2 Plots of Langmuir adsorption isotherm for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C, in the presence of DBU inhibitor obtained from the gasometrical measurements.

Weight loss measurements

The corrosion reaction of galvanized steel in 1.0 M HCl in the presence and absence of DBU inhibitor is investigated by measuring of the weight loss of steel sheet. Plots of the weight loss against DBU concentration at different reaction time are displayed in Figure 3(a). From the results, it is found that the weight loss of steel sheets is increased with increasing reaction time. Moreover, the addition of DBU into HCl solution can effectively decreases the weight loss of steel sheet. When the temperature is raised, the corrosion reaction is occurred and proceeded rapidly due to the increasing energy of system, causing to desorption of DBU molecules from steel surface as shown in Figure 3(b). Furthermore, the %*I* of the corrosion of galvanized steel is found to increase with increasing of DBU concentration and decreasing of temperature similar to the results obtained from gasometrical analysis.

From the obtained values of weight loss, the corrosion rate (C_R) can be determined by using Eq. (8) (Okafor *et al.*, 2008). The determined values of C_R , θ and %*I* for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence and absence of DBU using the weight loss technique are summarized in Table 3.

$$C_R = \frac{W_f - W_i}{(t_f - t_i)A} \tag{8}$$

where W_i , W_f and A are the initial weight, the final weight and the surface area of steel sheet, respectively. The results shown in Table 3 reveal that the corrosion rate is decreased with increasing of DBU concentration while the degree of surface coverage and %inhibition are increased. Moreover, the corrosion rate is increased with increasing of temperature similar to the results obtained from gasometrical measurements.

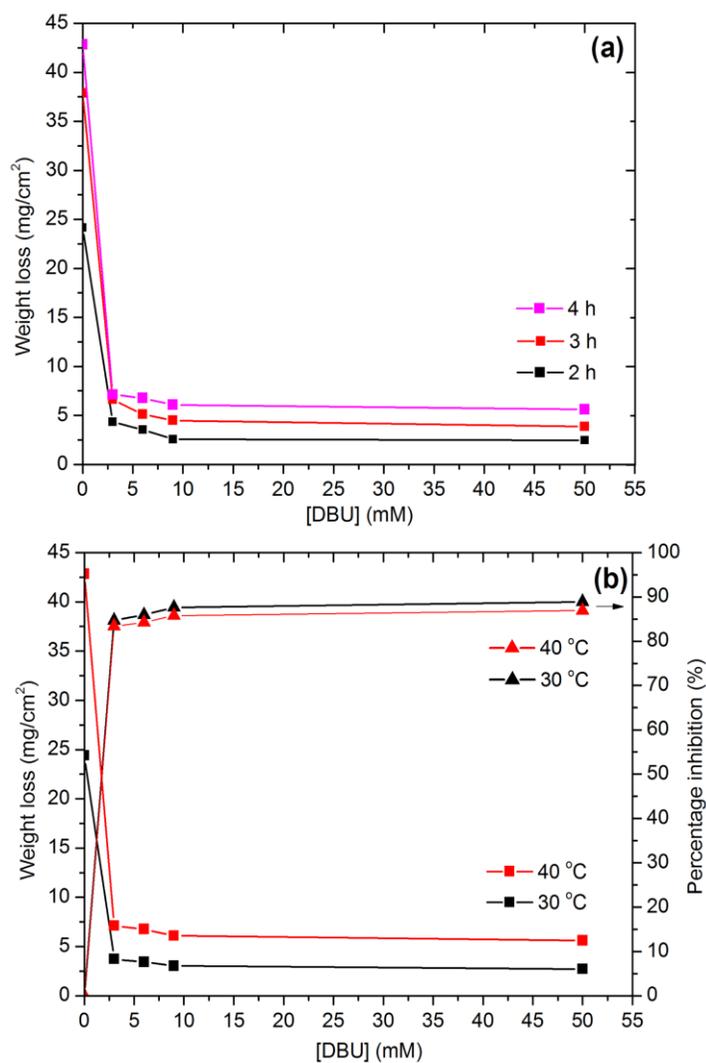


Figure 3 (a) Plots of the weight loss vs. DBU concentration for the corrosion of galvanized steel in 1.0 M HCl at 40°C for 2, 3 and 4 h. (b) Plots of the weight loss and %inhibition vs. DBU concentration for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 4 °C for 4 h.

Table 3 The obtained corrosion rate, degree of surface coverage and %inhibition for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence and absence of DBU inhibitor using the weight loss measurements.

Temperature (°C)	DBU concentration (mM)	Corrosion rate (cm ³ /min)	Degree of surface coverage (θ)	%Inhibition (%)
30	0.0	6.100	0.000	0.0
	3.0	0.933	0.847	84.7
	6.0	0.856	0.860	86.0
	9.0	0.756	0.876	87.6
	50.0	0.678	0.889	88.9
40	0.0	10.711	0.000	0.0
	3.0	1.778	0.834	83.4
	6.0	1.689	0.842	84.2
	9.0	1.522	0.858	85.8
	50.0	1.400	0.869	86.9

From the obtained values of corrosion rate and degree of surface coverage, the E_a and Q_{ads} are determined by using Eqs. (4) and (5). The values of E_a and Q_{ads} determined from weight loss technique for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence and absence of DBU inhibitor are summarized in Table 4.

Table 4 The determined values of activation energy (E_a) and heat of adsorption (Q_{ads}) for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence and absence of DBU inhibitor using the weight loss measurements.

DBU concentration (mM)	Activation energy (E_a) (kJ/mol)	Heat of adsorption (Q_{ads}) (kJ/mol)
0.0	44.4	-
3.0	50.8	114.7
6.0	53.6	119.6
9.0	55.2	129.8
50.0	57.2	137.9

The results show that the values of E_a are increased with increasing of DBU concentration similar to gasometrical measurements. The obtained Q_{ads} values are positive indicating that the adsorption of DBU on steel surface is the endothermic process. To investigate the thermodynamics of the adsorption of DBU on steel surface, the Langmuir adsorption isotherm (Eq. (6)) is used to determine the equilibrium constant of adsorption/desorption process (K_{ads}). After obtaining the values of K_{ads} , the Gibbs free energy change (ΔG) for the adsorption of DBU on steel surface is determined by using Eq. (7). Plots of Langmuir adsorption isotherm for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence of DBU inhibitor obtained from the weight loss measurements are illustrated in Figure 4. The plots resemble a linear behavior with $R^2 > 0.999$ indicating that the adsorption of DBU on steel surface obeys the Langmuir adsorption isotherm.

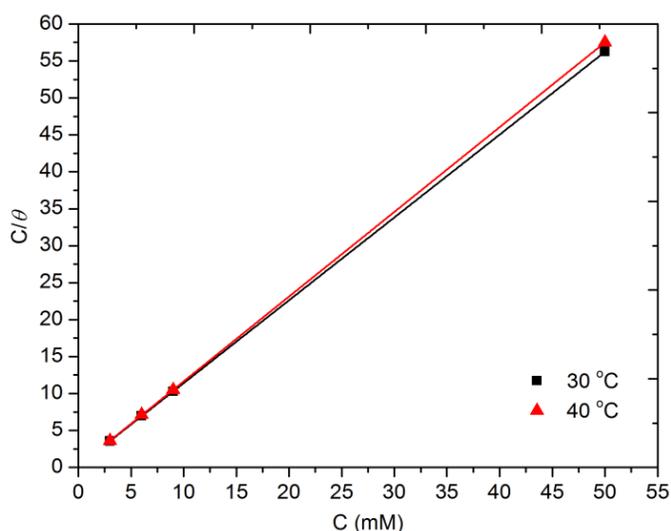


Figure 4 Plots of the Langmuir adsorption isotherm for the corrosion of galvanized steel in 1.0 M HCl at 30°C and 40°C in the presence of DBU inhibitor obtained from the weight loss measurements.

From Figure 4, the values of K_{ads} for the adsorption of DBU on steel surface at 30°C and 40°C are 4.88 and 5.24 L/mol, respectively. The determined ΔG values for the corrosion of galvanized steel at 30°C and 40°C in the presence of DBU inhibitor using the weight loss measurements are -14.1 and -14.3 kJ/mol, respectively. The obtained ΔG values indicate that the adsorption of DBU on steel surface is the physical adsorption and spontaneous process similar to gasometrical measurement (Donahue & Nobe, 1965; Kamis *et al.*, 1991).

The corrosion of galvanized steel in HCl solution with and without DBU inhibitor studied in this work can be simply described by Figure 5. In the absence of DBU in HCl solution, the galvanized steel is rapidly corroded due to many free corrosion sites on the steel surface that react with H^+ ions from HCl solution. In the presence of DBU in HCl solution, DBU molecules will be adsorbed on steel surface through nitrogen atom of high electro negativity. This results in the electrostatic attraction between DBU molecules and the molecular surface of steel.

From this, the free corrosion sites on steel surface are adsorbed by DBU molecules that prevent the H^+ ions from HCl solution. Therefore, the H^+ ions cannot accept the electron on steel surface to form hydrogen gas ($H_2(g)$) resulting in the decrease of corrosion rate.

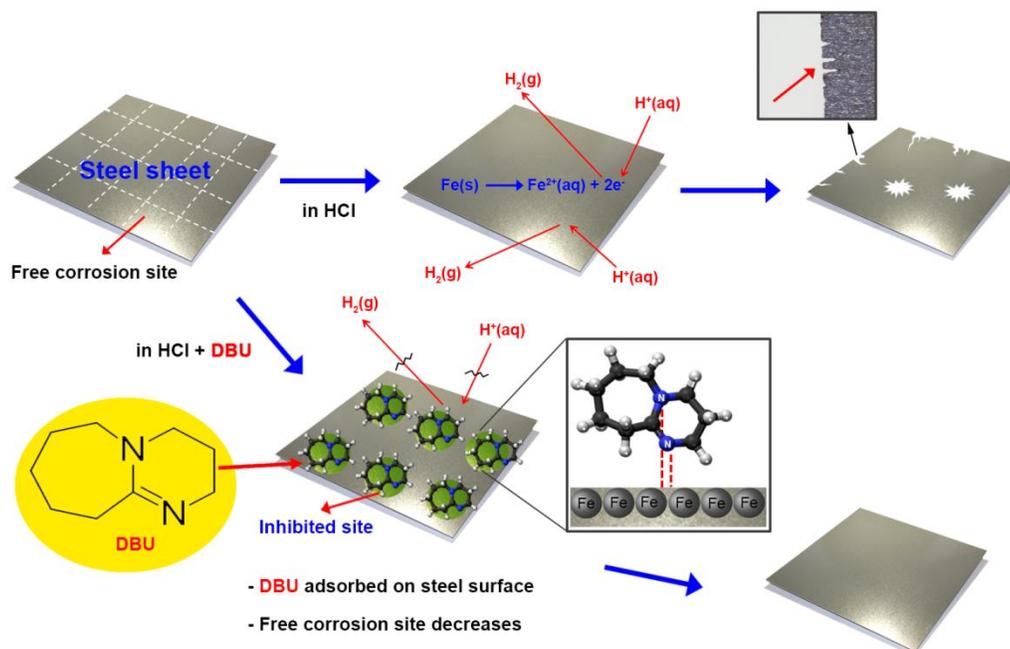


Figure 5 The simple illustration for the corrosion inhibition of galvanized steel in HCl solution by DBU.

Conclusions

The inhibitive effect of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), the new organic inhibitor, in the corrosion of galvanized steel in 1.0 M HCl was successfully investigated by using the gasometrical and weight loss measurements. From kinetic results, DBU acted as an effective corrosion inhibitor with high %inhibition (more than 80%). The corrosion of steel in HCl solution was reduced by DBU with low concentration range of 3.0 – 50.0 mM. Furthermore, the corrosion rate of steel was controlled by DBU concentration. From thermodynamic analysis, DBU was spontaneously adsorbed on steel surface and the adsorption behavior obeys the Langmuir adsorption isotherm. The resulting values of ΔG suggested that the adsorption of DBU on steel surface was the physical adsorption. From the results, it was suggested that, in significant, the presence of DBU in HCl solution can prevent the corrosion of galvanized steel. The results obtained from this work can be applied to other systems. Other compounds which are in a similar class of DBU might be effective as the corrosion inhibitors for metals.

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References

- Abiola, O.K. & James, A.O. (2010) The Effects of *Aloe vera* Extract on Corrosion and Kinetics of Corrosion Process of Zinc in HCl Solution. *Corrosion Science*, 52, 661-664.
- Ansari, K.R., Quraishi, M.A. & Singh, A. (2014). Schiff's Base of Pyridyl Substituted Triazoles As New and Effective Corrosion Inhibitors For Mild Steel in Hydrochloric Acid Solution. *Corrosion Science*, 79, 5-15.
- Armstrong, R.D. & Peggs, L. (1994). The Behaviour of Lead Silicate As a Corrosion Inhibitor for Iron and Zinc, *Corrosion Science*, 36, 749-757.
- Bayol, E., Kayakirilmaz, K. & Erbil, M. (2007). The Inhibitive Effect of Hexamethylenetetramine of The Acid Corrosion of Steel. *Materials Chemistry and Physics*, 104, 74-82.
- Bentiss, F., Bouanis, M., Mernari, B., Traisnel, M., Vein, H. & Lagrenee, M. (2007). Understanding The Adsorption of 4H-1,2,4-Triazole Derivatives on Mild Steel Surface in Molar Hydrochloric Acid. *Applied Surface Science*, 253, 3696-3704.
- Bhajiwala, H.M. & Vashi, R.T. (2001). Ethanolamine, Diethanolamine and Triethanolamine As Corrosion Inhibitors for Zinc in Binary Acid Mixture ($\text{HNO}_3 + \text{H}_3\text{PO}_4$). *Bulletin of Electrochemistry*, 17, 441-448.
- Donahue, F.M. & Nobe, K. (1965). Theory of Organic Corrosion Inhibitors: Adsorption and Linear Free Energy Relationships. *Journal of Electrochemical Society*, 112, 886-891.
- Dove, A.P. (2012). Organic Catalysis for Ring-Opening Polymerization. *ACS Macro Letters*, 1, 1409-1412.
- El-Etre, A.Y. (2006). Khillah Extract As Inhibitor for Acid Corrosion of SX 316 Steel. *Applied Surface Science*, 252, 8521-8525.
- Kamis, E., Bellucci, F., Latanision, R.M. & El-Ashry, E.S.H. (1991). Acid Corrosion Inhibition of Nickel by 2-(Triphenylphosphoranylidene) Succinic Anhydride. *Corrosion*, 47, 677-686.
- Kosari, A., Moayed, M. H., Davoodi, A., Parvizi, R., Momeni, M., Eshghi, H. & Moradi, H. (2014). Electrochemical And Quantum Chemical Assessment of Two Organic Compounds From Pyridine Derivatives As Corrosion Inhibitors for Mild Steel in HCl Solution Under Stagnant Condition and Hydrodynamic Flow. *Corrosion Science*, 78, 138-150.

- Kwolek, P., Kaminski, A., Dychton, K., Drajewicz, M. & Sieniawski, J. (2016). The Corrosion Rate of Aluminium in The Orthophosphoric Acid Solutions in The Presence of Sodium Molybdate. *Corrosion Science*, 106, 208-216.
- Limwanich, W. & Witthayaparakorn, C. (2016). Corrosion Protection of Zinc Sheet in Acidic Media Using D,L-Lactic Acid As Green Corrosion Inhibitor. *Burapha Science Journal*, 21(3), 249-256. (in Thai)
- Liu, H., Gu, T. Zhang, G., Wang, W., Dong, S., Cheng, Y. & Liu, H. (2016). Corrosion Inhibition of Carbon Steel in CO₂-Containing Oilfield Produced Water in The Presence of Iron-Oxidizing Bacteria and Inhibitors. *Corrosion Science*, 105, 149-160.
- Mourya, P., Banerjee, S., Singh, M.M. (2014). Corrosion Inhibition of Mild Steel in Acidic Solution by Tagetes erecta (Marigold flower) Extract As A Green Inhibitor. *Corrosion Science*, 85, 352-363.
- O'MBockris, I. & Swinkles, D.A. (1964). Adsorption of *n*-Decylamine on Solid Metal Electrodes. *Journal of Electrochemical Society*, 111, 736-743.
- Obot, I.B. & Obi-Egbedi, N.O. (2010) Theoretical Study of Benzimidazole and Its Derivatives and Their Potential Activity As Corrosion Inhibitors. *Corrosion Science*, 52, 657-660.
- Oguzie, E.E. (2007). Corrosion Inhibition of Aluminum in Acidic and Alkaline Media by *Sansevieria trifasciata* Extract. *Corrosion Science*, 49, 1527-1539.
- Okafor, P.C., Ikpi, M.E., Uwah, I.E., Ebensi, E.E., Ekoe, U.J. & Umoren, S.A. (2008). Inhibition Action of Phyllanthusamarus Extracts on The Corrosion of Mild Steel in Acidic Media. *Corrosion Science*, 50, 2310-2317.
- Roberge, P.R. (1999). *Handbook of Corrosion Engineering*. New York: McGraw-Hill.
- Rudresh, H.B. & Mayanna, S.M. (1980). Tertiary Arsines As Corrosion Inhibitors for Zinc in Acid Solution. *Materials and Corrosion*, 31, 286-290.
- Salarvand, Z., Amirnasr, M., Talebian, M., Raeissi, K. & Meghdadi, S. (2017). Enhanced Corrosion Resistance of Mild Steel in 1 M HCl Solution by Trace Amount of 2-Phenyl-benzothiazole Derivatives: Experimental, Quantum Chemical Calculation and Molecular Dynamics (MD) Simulation Studies. *Corrosion Science*, 114, 33-145.
- Singh, A.K. & Quraishi, M.A. (2010). The Effect of Some Bis-thiadiazole Derivatives on The Corrosion of Mild Steel in Hydrochloric Acid. *Corrosion Science*, 52, 1373-1385.
- Vashi, R.T., Bhajiwala, H.M. & Desai, S.A. (2010). Ethanolamines As Corrosion Inhibitors for Zinc in (HNO₃ + H₂SO₄) Binary Acid Mixtures, *E-Journal of Chemistry*, 7, 665-668.
- Zhang, K., Xy, B., Yang, W., Yin, X., Liu, Y. & Chen, Y. (2015). Halogen-Substituted Imidazoline Derivatives As Corrosion Inhibitors for Mild Steel in Hydrochloric Acid Solution. *Corrosion Science*, 90, 284-295.