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Organic Thin-Film Inhibitor Use to Control Corrosion of Mild Steel in Polluted Water

Rajesh Kumar Singh[1,*], Deepmala Kumari[2], Shabana Latif[3]

Abstract

Carbon steel is an important construction material used in the petroleum industry and refineries because of its low cost, good mechanical strength, and easy fabrication. Large quantities of carbon steel are used in crude oil transportation, storage, and purification units. Crude oil often contains corrosive gases such as carbon dioxide (CO_2) and sulfur dioxide (SO_2), which create aggressive environments for metallic structures. These acidic gases dissolve in water and form carbonic acid and sulfuric acid, leading to severe electrochemical corrosion reactions on the metal surface. As a result, carbon steel undergoes various forms of corrosion, including galvanic corrosion, pitting corrosion, stress corrosion, crevice corrosion, and intergranular corrosion. Temperature variations during crude oil processing further accelerate metal deterioration and crack formation. In the present investigation, the heterocyclic organic compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea was synthesized and used as an inhibitor to mitigate corrosion of steel in a carbon dioxide medium. The corrosion behavior of carbon steel was evaluated using gravimetric (weight loss) and potentiostatic techniques. Electrochemical parameters, such as electrode potential, corrosion current, and corrosion current density, were determined using a potentiostat. Immersion tests of uncoated and inhibitor-coated carbon steel specimens were carried out at varying temperatures and carbonic acid concentrations. The adsorption behavior of the inhibitor on the outer surface of the metal was analyzed using Langmuir, Freundlich, and Temkin adsorption isotherms. Thermodynamic parameters, including activation energy, heat of adsorption, Gibbs free energy, enthalpy, and entropy, were calculated to understand the adsorption mechanism, thin-film formation, and nature of the corrosion inhibition process. The synthesized compound exhibited excellent surface coverage, enhanced coating efficiency, improved stability, and increased durability of carbon steel in carbon dioxide environments.

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Keywords: Corrosion, carbon steel, crude oil, carbon dioxide, corrosion inhibitor, thin-film coating, adsorption isotherm, potentiostat

INTRODUCTION

Corrosion is a major problem in petroleum refinery and crude oil production industries [1, 2] because of the availability of corrosive gases, such as carbon dioxide [3] and sulfur compounds [4], in oil reservoirs and processing systems. These corrosive species create aggressive acidic environments that significantly deteriorate metallic equipment, pipelines, storage tanks, and refinery units [5]. The petroleum industry spends enormous amounts of money annually on the maintenance, repair, and replacement of corroded metallic components [6].

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Several corrosion protection techniques have been developed to minimize metal degradation in hostile environments [7]. Metallic and non-metallic coatings [8] are commonly applied to protect carbon steel surfaces [9]; however, many conventional coatings [10] fail to provide long-term protection under severe operating conditions. Different protective methods, such as electroplating, flame spraying, cladding, hot dipping, and vapor deposition [11], have also been employed for corrosion control. Similarly, polymeric materials, rubbers, thermoplastics, and thermosetting plastics are used as surface laminates to isolate metals from corrosive media [4], but these coatings often suffer from poor adhesion, porosity, thermal instability, and limited durability [12].

Corrosion inhibitors [13] are among the most effective and economical methods for controlling metallic corrosion in acidic media [14]. Organic and inorganic inhibitors [15, 16] are generally classified as anodic, cathodic, or mixed-type inhibitors [17] depending on their mechanism of action. These compounds reduce the corrosion current, shift the electrode potential, and form protective barriers on the metal surface [18, 19]. Recently, nanotechnology-based coatings have gained attention because of their high surface activity, improved mechanical strength, and superior protective efficiency. Nanocoatings [20] can be produced through top-layer coating, chemical conversion coating, thermal barrier coating, and incorporation of nanocrystals into the metallic matrix [21].

Despite these advances, many nano-coating systems contain micro-pores and defects [22] that permit the penetration of corrosive ions through osmotic processes, resulting in gradual metal deterioration [23]. Therefore, the development of highly adsorptive organic compounds capable of forming compact and stable protective films on carbon steel surfaces remains an important area of corrosion research.

In the present study, a heterocyclic thiourea derivative, 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea, was synthesized and evaluated as a protective inhibitor for metals in carbon dioxide environments. The compound possesses heteroatoms such as nitrogen and sulfur, which enhance adsorption onto the metal surface through coordinate bonding and electron donation mechanisms. The inhibitor forms a thin protective film over the carbon steel surface, thereby reducing the attack of corrosive species and improving the mechanical stability and durability of the metal in petroleum processing environments.

METHODOLOGY AND SYNTHESIS

Materials

Carbon steel specimens were used for corrosion studies. Analytical grade chemicals such as phosphorus pentachloride (PCl_5), benzene, potassium tert-butoxide (t-BuOK), tert-butyl alcohol, cyclohexene, sodium periodate ($NaIO_4$), thiourea, ethanol, and alkali were used without further purification. Double-distilled water was used for the preparation of all solutions.

Preparation of Carbon Steel Specimens

Carbon steel sheets were cut into dimensions of 3×5 cm². The surfaces of the specimens were polished successively with different grades of Emery paper to obtain smooth surfaces. The polished samples were washed thoroughly with distilled water, followed by acetone, to remove grease, dust, and other impurities. After cleaning, the specimens were dried and preserved in a desiccator to avoid atmospheric moisture contamination before experimental use.

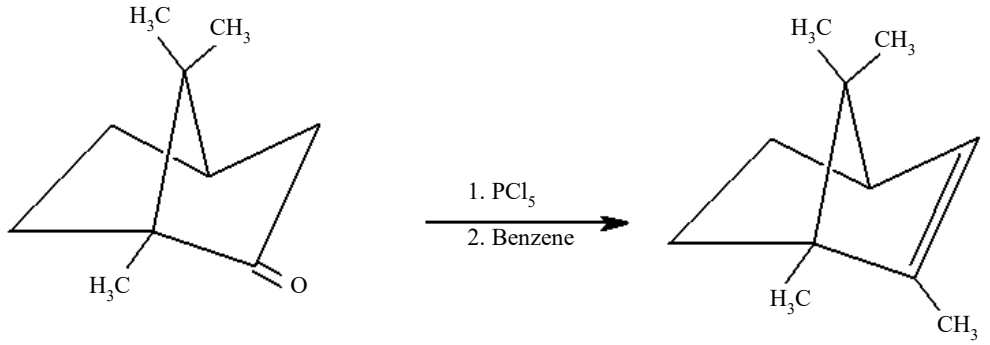
Synthesis of 6,11,11-Trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10 diylidenebisthiourea

The corrosion inhibitor 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea was synthesized through a multistep reaction sequence.

Step 1: Synthesis of 2-Chloro-1,7,7-trimethylbicyclo[2.2.1]hept-2-ene

Phosphorus pentachloride solution in dry benzene was slowly added to 1,7,7-trimethylbicyclo[2.2.1]heptan-2-one at 0°C under constant stirring. The reaction mixture was maintained at a low temperature to control the reaction rate. The product obtained after the completion of the reaction was 2-chloro-1,7,7-trimethylbicyclo[2.2.1]hept-2-ene.

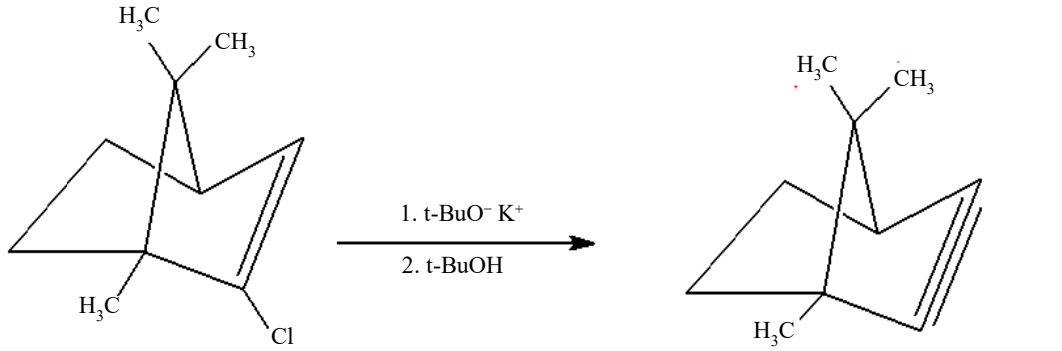
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1,7,7-trimethylbicyclo[2.2.1]heptan-2-one 2-chloro-1,7,7-trimethylbicyclo[2.2.1]hept-2-ene

Step 2: Synthesis of 1,7,7-Trimethylbicyclo[2.2.1]hep-2-yne

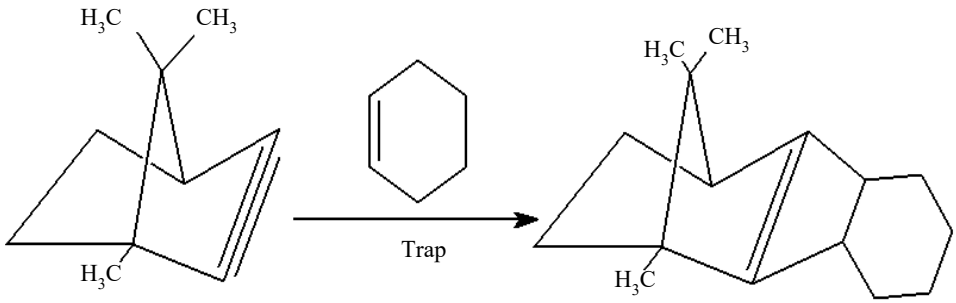
The chlorinated compound obtained in Step 1 was treated with potassium tert-butoxide (t-BuOK) in tert-butyl alcohol. The reaction mixture was refluxed with a strong base to achieve dehydrohalogenation, resulting in the preparation of 1,7,7-trimethylbicyclo[2.2.1]hep-2-yne.



2-chloro-1,7,7-trimethylbicyclo[2.2.1]hept-2-ene 1,7,7-trimethylbicyclo[2.2.1]heptan-2-yne

Step 3: Synthesis of 1,9,9-Trimethyl-1,2,3,4,4b,5,6,7,8-decahydro-1,4-methanobiphenylene

The alkyne intermediate synthesized in Step 2 was reacted with cyclohexene, which acted as a trapping agent. The cycloaddition reaction produced 1,9,9-trimethyl-1,2,3,4,4b,5,6,7,8-decahydro-1,4-methanobiphenylene.

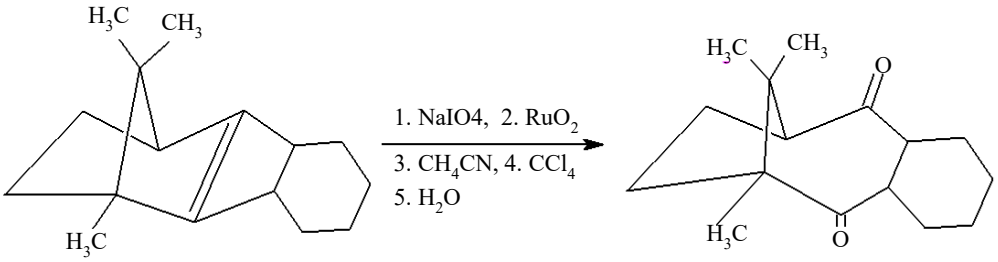


1,9,9-trimethyl-1,2,3,4,4b,5,6,7,8-decahydro-1,4-methanobiphenylene.

Step 4: Synthesis of 6,11,11-Trimethyldecahydro-6,9-methanobenzo[8]annulene-5,10-dione

The bicyclic compound obtained in Step 3 was oxidized using sodium periodate ($NaIO_4$). The oxidation reaction converted the intermediate into 6,11,11-trimethyldecahydro-6,9-methanobenzo[8]annulene-5,10-dione.

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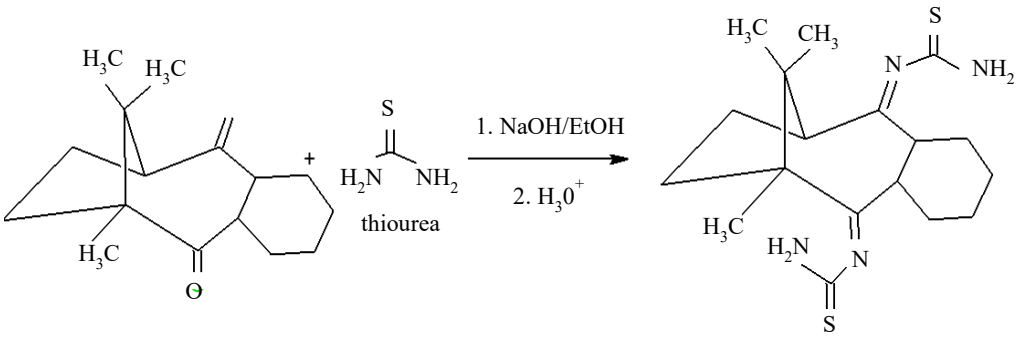


1,9,9-Trimethyl-1,2,3,4,4b,5,6,7,8,8a-decahydro-1, 4-methanobiphenylene

6,11,11-Trimethyldecahydro-6,9-methano-benzo[8]annulene=5,10-dione

Step 5: Synthesis of 6,11,11-Trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea

The diketone compound synthesized in Step IV was refluxed with thiourea in an ethanolic alkaline medium. The condensation reaction yielded the final inhibitor compound, 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea.



6,11,11-trimethyldecahydro-6, 9-methano-benzo[8]annulene-5,10-dione

6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5, 10-diylidene)bis(thiourea)

Corrosion Measurements

The corrosion behavior of uncoated and inhibitor-coated carbon steel specimens was evaluated by the gravimetric (weight loss) method at temperatures of 298 K, 303 K, 308 K, and 313 K for immersion periods of 3, 6, 9, and 12 months.

The metal corrosion rate was determined by the equation:

$$K = 13.56\ M / dAt$$

Where K, corrosion rate; M, mass loss of the specimen; d, density of the metal; A, surface area of the specimen; t, immersion time.

Surface Coverage Area and Coating Inhibition Efficiency of Compound

Both parameters were calculated using the following equations:

$$\theta = (1 - K/K_0)$$

$$\%IE = (1 - K/K_0) \times 100$$

Where K_o, corrosion rate without inhibitor; K, corrosion rate with inhibitor.

Thermodynamic Parameters

The energy of activation during the corrosion process was evaluated using the Arrhenius equation:

$$K = A\ e^{-Ea/RT}$$

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The heat of adsorption was calculated from:

$$\log(\theta/1-\theta) = \log A - e^{-q_a/2.303RT} + \log C$$

The free energy change was determined using:

$$K_r = kT/h\ e^{-\Delta G\#/RT}$$

The transition state equation used for determination of enthalpy and entropy was:

$$K^{\#} = e^{\Delta S\#/R}\ e^{-\Delta H\#/RT}$$

Adsorption Isotherms

The adsorption behavior of the inhibitor on the carbon steel surface was analyzed using Langmuir, Freundlich, and Temkin adsorption isotherms.

Langmuir Isotherm

$$(\theta/1-\theta) = A\ C\ e^{-q_a/RT}$$

Freundlich Isotherm

$$C/\theta = K\ C$$

Temkin Isotherm

$$C/\theta = K \log C$$

Electrochemical Measurements

Electrochemical studies were done by applying Potentiostat/Galvanostat Model 173. The electrode potential, corrosion current, and current density of corrosion were measured to calculate the inhibition performance of the synthesized inhibitor.

RESULTS AND DISCUSSION

Corrosion Rate of Uncoated and Coated Metal in Carbon Dioxide Medium

The corrosion rates of uncoated and coated carbon steel in a carbon dioxide medium at temperatures of 298, 303, 308, and 313 K for immersion periods of 3, 6, 9, and 12 months were determined by the gravimetric method using the synthesized organic inhibitor 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea, and the results are recorded in Table 1.

The experimental results revealed that the corrosion rate values of uncoated carbon steel increased progressively with increasing temperature and immersion period owing to accelerated electrochemical reactions in the carbon dioxide environment. However, after coating with 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea, the metal corrosion rate declined significantly at all experimental temperatures. The reduction in corrosion rate confirmed that the synthesized organic compound acted as an efficient corrosion inhibitor for carbon steel in a CO_2 medium.

Inhibitor molecules adsorbed strongly on the steel interface through heteroatoms such as nitrogen and sulfur present in the thiourea group, resulting in the formation of a protective barrier film between the metal surface and corrosive medium. This protective film restricted the osmotic process of corrosive ions and minimized the oxidation and reduction reactions responsible for corrosion.

The trends of corrosion inhibition were clearly observed in Figure 1, where the graph plotted between log K and 1/T produced straight lines corresponding to Arrhenius behavior. The coated specimens produced lower corrosion rates compared to the uncoated specimens throughout the experimental period.

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Table 1. Rate of corrosion of uncoated and coated carbon steel with 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea in CO_2 medium.

Parameters	298 K	303 K	308 K	313 K
Immersion period (months)	3	6	9	12
Corrosion rate without inhibitor, K_0	1783	2101	2589	2982
log K_0	3.251	3.322	3.413	3.474
Corrosion rate with inhibitor, K	238	372	431	693
log K	2.376	2.570	2.634	2.840
Surface Coverage (θ)	0.86	0.82	0.84	0.76
(1 − θ)	0.133	0.177	0.166	0.232
θ/(1 − θ)	6.490	4.646	5.006	3.302
log [θ/(1 − θ)]	0.81	0.67	0.69	0.51
K/T	71.044	112.727	133.024	217.241
log (K/T)	1.851	2.052	2.123	2.336
Inhibition efficiency (%IE)	86	82	83	76

Where,
M(1) = 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea

Activation Energy

The Arrhenius plots obtained from Figure 1 between log K and 1/T were linear, indicating that this graph obeyed the Arrhenius equation ($K = Ae^{-Ea/RT}$).

The activation energy values were calculated from the slopes of the Arrhenius plots, and the results are summarized in Table 2. The activation energy of the uncoated metal was higher because of the rapid destruction of the metal in the carbon dioxide environment. After coating with 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea, the activation energy values decreased considerably, indicating that the coating molecules adsorbed effectively on the metal surface and reduced the rate of the corrosion reaction.

The reduction in activation energy after coating suggested that the inhibitor formed a stable adsorbed film on the carbon steel surface through chemisorption. The adsorption of inhibitor molecules blocked the active corrosion sites and increased the resistance against attack by carbonic acid generated in the CO_2 medium.

The inhibition efficiency values obtained at different temperatures also emphasized that the synthesized inhibitor possessed excellent protective properties. A maximum inhibition efficiency of 86% was observed at 298 K, while a slight decrease in efficiency occurred with increasing temperature owing to the partial desorption of inhibitor molecules from the metal interface.

The overall results confirmed that 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea is a highly effective inhibitor for steel in a carbon dioxide environment.

Heat of Adsorption

The heat of adsorption of coating compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea was evaluated from the adsorption data. The adsorption energy values indicated that the coating compound was strongly adsorbed on the metal surface through chemical bonding (chemisorption). The higher adsorption energy values suggested the formation of a stable protective film on the base metal surface, which effectively reduced the corrosion rate, as depicted in Table 2.

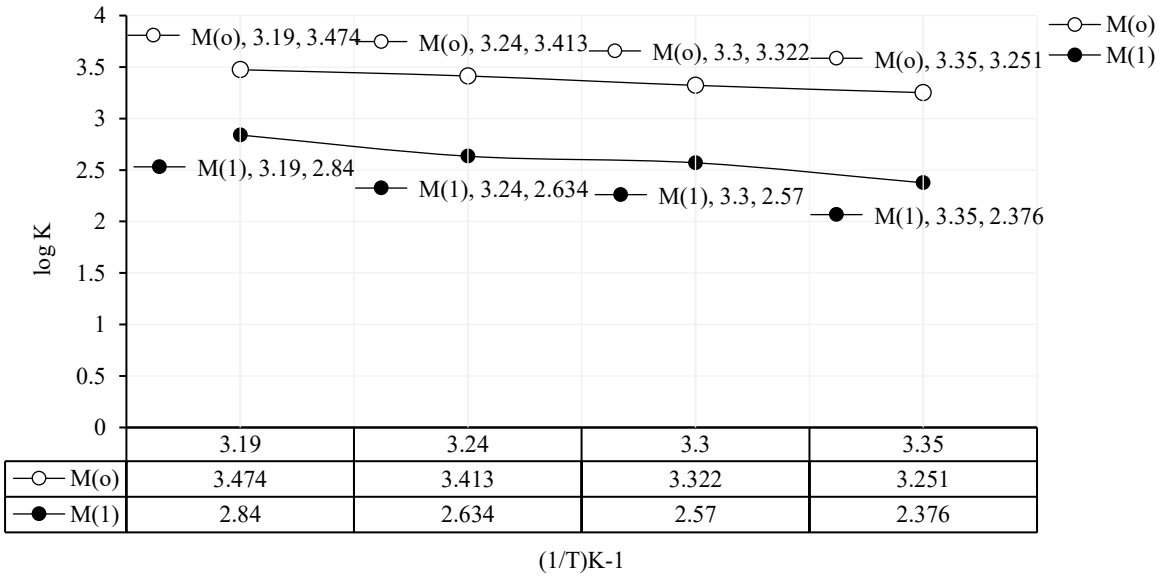
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The degree of surface coverage (θ) was calculated from the inhibition efficiency values and applied to the Langmuir adsorption isotherm equation, $\log(\theta/1-\theta) = \log A - \Delta H_{ads}/2.303RT$.

The plot of $\log(\theta/1-\theta)$ versus 1/T shown in Figure 2 gave a straight line, confirming that the adsorption process obeyed the Langmuir adsorption isotherm. The linear relationship indicated monolayer adsorption of the inhibitor substance on the outer surface of the metal without significant interaction between the adsorbed species. The negative values of heat of adsorption further confirmed that the adsorption process was spontaneous and exothermic in nature.

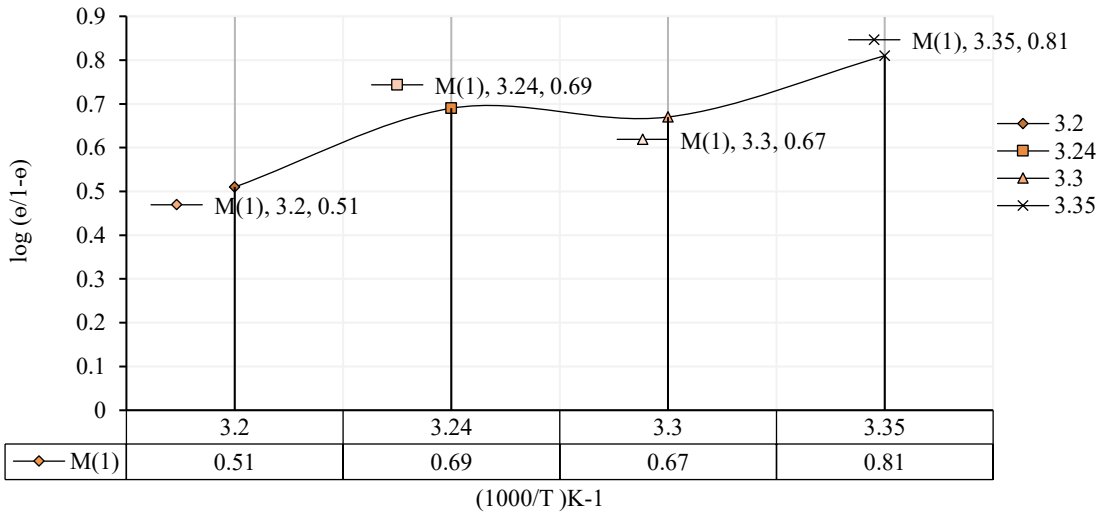
Surface Accommodation Area

The surface accommodation area (θ) of the organic coating compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea was determined from the adsorption and inhibition efficiency data. The results revealed that the coating compound covered a larger surface area of the metal at lower temperatures, indicating strong adsorption of the inhibitor on the carbon steel surface. However, the surface coverage area values decreased with increasing temperature, suggesting partial desorption of the inhibitor from the metal surface at higher temperatures (Table 1).



	3.19	3.24	3.3	3.35
M(o)	3.474	3.413	3.322	3.251
M(1)	2.84	2.634	2.57	2.376

Figure 1. log K Vs 1/T for carbon steel.



	3.2	3.24	3.3	3.35
M(1)	0.51	0.69	0.67	0.81

Figure 2. log (ɵ/1-ɵ) Vs 1/T carbon steel.

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Figure 3, which represents the plot of θ versus T, produced an approximately linear relationship confirming that the adsorption process obeyed the Langmuir adsorption isotherm. The linearity of the plot indicated monolayer adsorption of inhibitors on the metal surface without significant interaction among the adsorbed species. The decrease in surface coverage at higher temperatures further supported that adsorption was predominantly chemical in nature and affected by thermal agitation of molecules.

Coating Efficiency

The coating efficiency of 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea was determined at different temperatures, such as 298, 303, 308, and 313 K, and the obtained values are listed in Table 1. Figure 4 shows the relationship between percentage efficiency (%E) and temperature (T). The results indicate that the coating compound exhibited higher inhibition efficiency at lower temperatures, showing effective adsorption and formation of a protective film on the carbon steel surface. However, the percentage efficiency decreased gradually with increasing temperature owing to the partial desorption of inhibitor molecules from the metal surface.

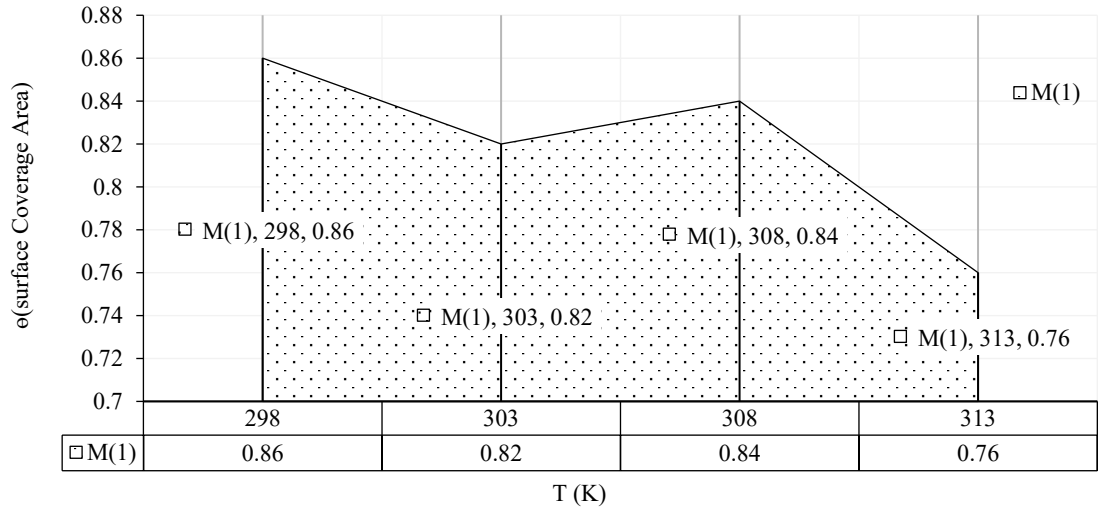


Figure 3. ɵ Vs T carbon steel.

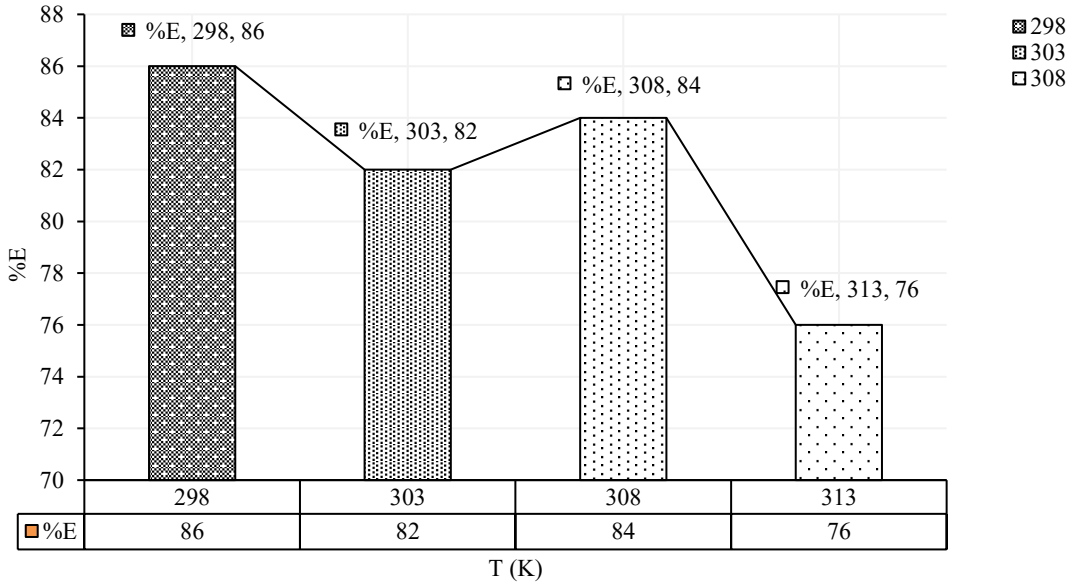


Figure 4. %E Vs T for carbon steel coating with M(1).

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Table 2. Thermal parameters of 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea.

Thermal parameters	298 K	303 K	308 K	313 K	C (ppm)
Ea(o)	233	235	237	238	—
Ea(S1)	170	181	183	194	200
q(S1)	-58	-70	-48	-35	—
ΔG(S1)	-295	-305	-304	-313	—
ΔH(S1)	-132	-145	-147	-159	—
ΔS(S1)	-127	-136	-139	-147	—
θ(S1)	0.86	0.82	0.84	0.76	—

The reduction in coating efficiency at elevated temperatures suggested weakening of the adsorbed protective layer because of increased thermal agitation of molecules. This behavior confirmed that adsorption of the coating compound on the carbon steel surface was temperature-dependent and followed the Langmuir adsorption mechanism. The percentage coating efficiency varied with temperature for 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea.

Free Energy

The free energy values (ΔG) of coating compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea are listed in Table 2. The negative values of free energy indicate that the adsorption and coating processes were spontaneous and exothermic. The coating compound strongly adhered to the carbon steel surface through chemical bonding (chemisorption), resulting in the formation of a stable protective layer over the base metal surface.
The decrease in free energy values with increasing surface coverage (θ) suggested that adsorption became more favorable as larger areas of the carbon steel surface were occupied by inhibitor molecules. The higher surface coverage values confirmed the effectiveness of the coating compound in minimizing corrosion of carbon steel.

Enthalpy

The enthalpy values (ΔH) of 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea are listed in Table 2. The enthalpy values became more negative with increasing temperature from 298 to 313 K, indicating that the coating process involved an exothermic reaction. The negative enthalpy values confirmed that heat energy was released during the adsorption of inhibitor molecules onto the carbon steel surface.
The negative sign of free energy and enthalpy further demonstrated that the coating substance was firmly attached to the base metal through chemical bonding. It was also observed that as enthalpy decreased, the surface coverage area increased, indicating enhanced adsorption and improved coating performance.

Entropy

The entropy values (ΔS) generated by 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea are listed in Table 2. The negative entropy values indicate that the inhibitor molecules were arranged in an ordered manner on the steel surface during adsorption. This orderly arrangement supported the formation of a compact and stable protective film through chemical bonding. Figure 5 illustrates the relationship between ΔG (free energy), ΔH (enthalpy), ΔS (entropy), and surface coverage (θ) at temperatures of 298, 303, 308, and 313 K. The graphical representation shows that the thermal parameter values decreased while the surface coverage area increased, confirming strong adsorption behavior and effective corrosion protection by the coating compound.

Discussion of Thermal Parameters

The thermal parameters of 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea are summarized in Table 2 at temperatures 298, 303, 308, and 313 K. The

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activation energy values of coated carbon steel, Ea(S1), were lower than the activation energy values of uncoated carbon steel, Ea(o), indicating that the coating compound effectively adsorbed on the steel surface face and formed a protective barrier through chemical bonding.

The negative values of heat of adsorption, q(S1), confirmed that the adsorption process was exothermic in nature. Similarly, the negative free energy values, ΔG(S1), indicated that adsorption of the coating compound on the carbon steel occurred spontaneously through chemisorption. The increasingly negative ΔG values suggested stronger interactions between the inhibitor molecules and the metal surface.

The enthalpy values, ΔH(S1), were also negative and became more negative with increasing temperature, confirming the release of heat during the coating process. This observation supports the accommodation of a stable adsorbed film on the steel surface.

The entropy values, ΔS(S1), were negative, indicating that the inhibition substance became more orderly arranged on the metal surface during adsorption. Such an orderly arrangement enhanced the compactness and stability of the protective coating film.

The surface coverage area values, θ(S1), demonstrated that a significant portion of the steel surface was covered by the inhibitor molecules. Higher surface coverage area values confirmed improved adsorption and better corrosion protection efficiency of the coating compound.

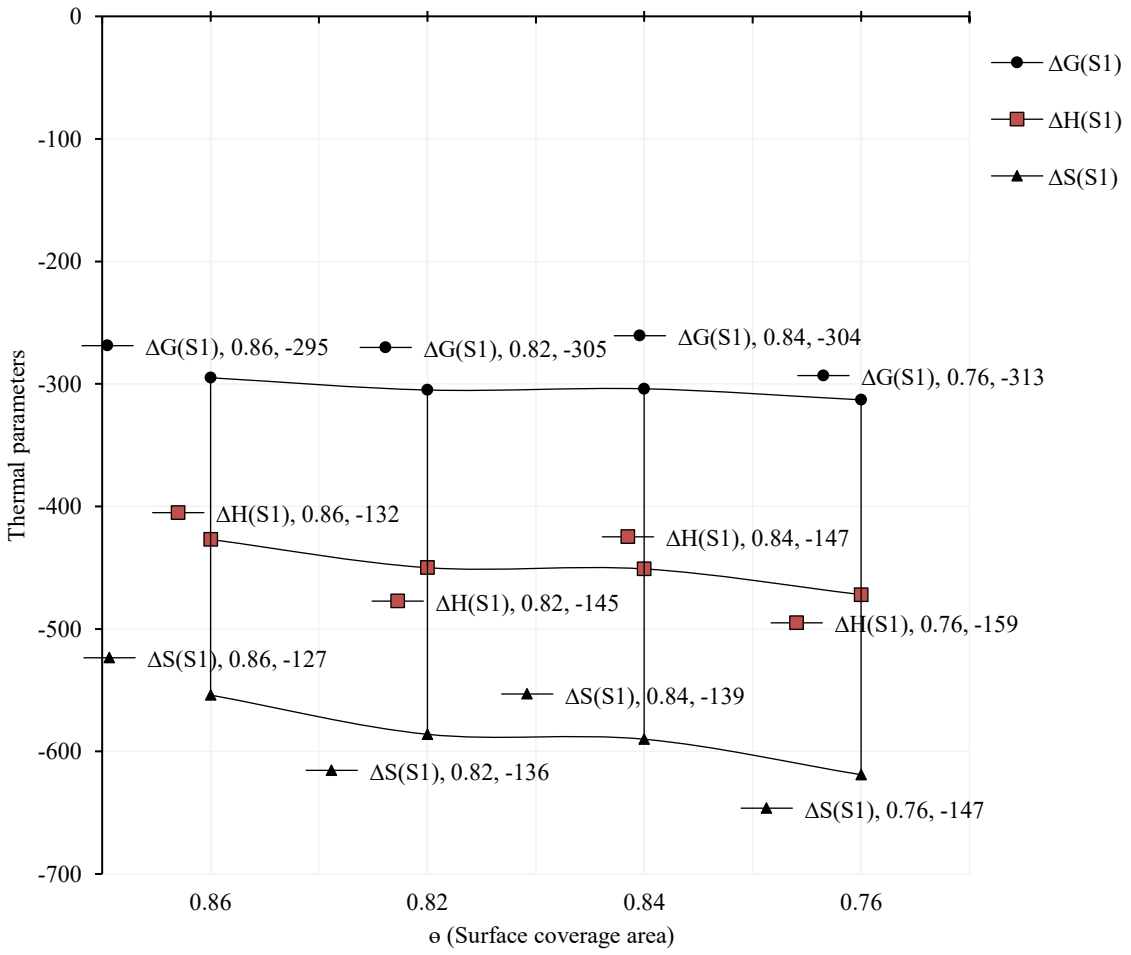


Figure 5. Thermal parameters Vs ɵ (Surface coverage area).

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Potentiostatic Polarization Study

The potentiostatic polarization parameters of uncoated and coated carbon steel with 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea are presented in Table 3. The uncoated carbon steel exhibited higher electrode potential (ΔE), corrosion current (ΔI), anodic polarization (βa), corrosion current density (Ic), and corrosion rate (Kcr). However, after coating with the organic compound, these values decreased significantly, indicating effective corrosion inhibition by the coating material.

The coating compound increased cathodic polarization (βc) and reduced the current density, thereby minimizing the dissolution of metal in an acidic medium. The mitigation in corrosion rate and increase in surface coverage (θ) confirmed the creation of a strong protective thin-film barrier on the steel surface. This thin passive barrier prevented the attack of H^+ ions on the steel surface and reduced electrochemical corrosion reactions. The potentiostatic polarization behavior can be described by the following relationship between electrode potential and current density: $E \propto Ic$.

Figure 6 illustrates the plot of electrode potential (E) versus current density (Ic). The graphical representation shows that the uncoated carbon steel possessed higher electrode potential and current density values, whereas the coated carbon steel exhibited lower values owing to the adsorption of the inhibitor molecule on the steel surface. This observation confirmed that the coating compound acted as an effective mixed-type inhibitor by suppressing both anodic and cathodic corrosion reactions.

MECHANISM OF COATING COMPOUND

The organic coating compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea is an electron-rich compound containing sulfur, nitrogen, and multiple functional groups. These active centers facilitated strong adsorption of the compound onto the steel outer face through chemical bonding. The adsorption of the coating substance resulted in the formation of a thin and stable passive film barrier between the corrosive medium and the base metal surface.

The protective coating film reduced the mobility and diffusion of H^+ ions toward the carbon steel surface and thereby suppressed anodic and cathodic corrosion reactions. The compound exhibited excellent thermal stability and maintained effective surface coverage even at higher temperatures. The coating material covered a large surface area even at lower concentrations and demonstrated high coating efficiency in acidic and carbon dioxide environments.

The strong interaction between the inhibitor molecules and the carbon steel surface occurred through chemisorption, leading to enhanced durability, mechanical strength, and corrosion resistance of the metal. The protective barrier minimized physical, chemical, and electrochemical degradation caused by the carbon dioxide medium.

Table 3. Potentiostatic Polarization Parameters of 6,11,11-Trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea.

Coating	ΔE	ΔI	βa	Bc	βaβc/(βa+βc)	Ic	Kcr	Θ
M(o)	-1150	815	572	421	242	74	316	—
	-1200	845	601	491	270	82	350	—
	-1300	900	657	543	297	89	379	—
	-1400	1050	734	602	330	103	441	—
M(1)	-750	379	350	445	195	42	134	0.42
	-800	400	400	455	212	46	154	0.44
	-900	450	425	460	220	47	175	0.46
	-910	480	440	470	232	53	215	0.48

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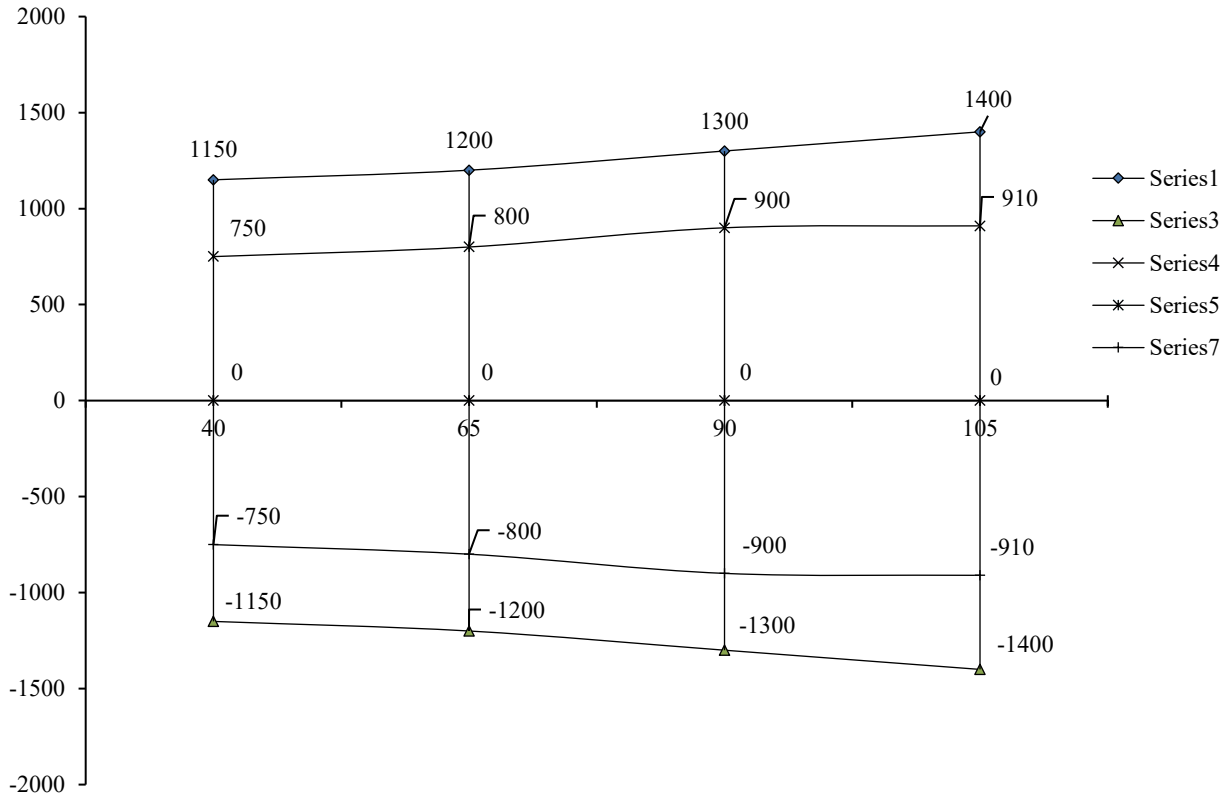


Figure 6. E Vs I uncoated and coated carbon steel with M(1).

CONCLUSION

The experimental results revealed that the corrosion rate of steel in a carbon dioxide medium was effectively decreased by the coating compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea. The surface coverage results demonstrated that the compound covered a significant portion of the metal surface at higher temperatures and concentrations.

The adsorption isotherm studies confirmed that the coating material adsorbed strongly on the metal surface following Langmuir adsorption behavior. Thermal parameter studies, such as free energy, enthalpy, and entropy, indicated that the coating compound bonded with the base metal through chemical adsorption and produced spontaneous and exothermic reactions.

Potentiostatic polarization results showed that the coating substance reduced the current density and corrosion rate while enhancing surface coverage and coating efficiency. The thin passive barrier film formed by the coating compound effectively prevented the attack of corrosive H^+ ions on the metal interface.

Therefore, the compound 6,11,11-trimethyldecahydro-6,8-methanobenzo[8]annulene-5,10-diylidenebisthiourea can be considered an efficient corrosion protective coating material for steel in acidic carbon dioxide environments because of its excellent adsorption characteristics, thermal stability, and high inhibition efficiency.

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