Chemical Inhibition for Steel Corrosion in Succinic acid at Different Temperature

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Abstract. The steel infrastructure is continuously under corrosive attack in most environmental and industrial conditions. There is an ongoing search for environmentally friendly, highly effective inhibitor compounds that can provide a protective action in situations ranging from the marine environment to oil and gas pipelines. The corrosion inhibition of transmission steel in 1M HCl cell in the presence of succinic acid at temperatures (20,30,40,50 and 60) °C at concentrations within the range (10^{-6}-10^{-4}) M for two hours using the weight loss method (WLM). The results showed that the inhibition efficiency increases with increasing inhibitor concentration and increases with temperature up to 60°C. The activation significance of the corrosion rates was calculated as the activation energy Ea, the change of the activation entropy ΔH, and the change in the activation entropy ΔS. Also, results show that the inhibition efficiency was increased with the increase of inhibitor concentration and increased with the increase of temperature up to 60°C. Activation parameters of the corrosion process include activation energies (Ea), activation enthalpies (ΔH), and activation entropies (ΔS). The results also showed that the adsorption of the inhibitor is subjected to the Langmuir law, and the maximum efficiency reached approximately 97% at 60°C in the 10^{-4} M inhibitor concentration.

Keywords. Inhibitor, Steel, Weight loss method (WLM), Succinic acid (SA), Corrosion rate(CR).

1. Introduction
The problem of steel corrosion is considered one of the most civil problems locally and internationally in facilities such as bridges and buildings, aircraft and ship manufacturing, and equipment, and many others. Since this phenomenon and its negative impact in various fields cannot be overlooked, there is no sudden demolition of a bridge or an unexpected crash of a building or plant unless the corrosion of the metals involved in its building foundations and the steel corrosion in particular - were involved in those accidents [1]. To understand these facts, a precise and simplified definition of this process is necessary. Corrosion is mechanical damage that occurs in metals and alloys due to chemical, biological or electrochemical reactions between metals and alloys on the one hand and the surrounding environment on the other hand. Some people are mistaken; they use the term "rust" instead of "corrosion." Rust is the material resulting from corrosion of iron formed from aqueous iron oxides. This applies to iron only, so the term rust cannot be used on corrosion of other metals, nor their outputs [2]. Abdul Amir et al. (2014) [3] studied the effect of corrosion inhibition on mild steel was examined in 1.0 M HCl using potentials of corrosion (ECORR), dynamic polarization, electrochemical impedance spectroscopy (EIS), and electrochemical frequency modulation (EFM) measurements. The obtained results indicated that PMBH had promising inhibitory effects on mild steel corrosion in 1.0
M HCl under all conditions examined. Galai et al. (2016) [4] investigated the inhibitive action against the corrosion of carbon steel in 1 M HCl solution were investigated at room temperature by various corrosion monitoring techniques, such as weight loss, potentiodynamic polarization curves, and electrochemical impedance spectroscopy (EIS) methods. Polarization studies showed that both studied inhibitors were of anodic type inhibitor in 1 M HCl. The adsorption of inhibitors on the carbon steel surface obeys Langmuir adsorption isotherm. Muthar & Farah (2018) [5] considered five fixed weights (0.5 g) from polyacrylamide with five different volumes of thiophene-2-carboxaldehyde (0.5, 1, 1.5, 2, and 2.5) ml to obtain five inhibitor concentrations in (50) ml of 15% hydrochloric acid. (C-Steel L80) rods were immersed in the prepared solution, and the lost weights were calculated at different temperatures (40, 60, 80, 90) at different times (3, 4, 5, 6) hours. It is observed that less corrosion is obtained by increasing the concentration of the inhibitor. Reda (2018) [6] has investigated the use of ammonium salt (QA-Zn+2) as a corrosion inhibitor for carbon steel in a 2.0 M sodium chloride solution by different techniques such as weight loss, open circuit potential, potentiodynamic polarization, and electrochemical impedance spectroscopic techniques. The inhibition efficiency of the used system (QA-Zn+2) increases with increasing mixed inhibitor concentrations and rising temperatures. Foda et al. (2019) [7] have conducted research considering the corrosion of carbon steel in 1M HCl solution using weight loss, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS). The extraction's inhibitive property is attributed to cinnamic aldehyde as a significant constituent in the extraction. Measurements showed that this extraction act as a mixed-type inhibitor. The inhibition efficiency was found to increase with inhibitor concentration. Wang et al. (2019) [8] have characterized and tested an extract of Solanum lasiocarum (SL) for its potential anticorrosion effect on A3 steel in a 1 M HCl solution using weight loss analysis, potentiodynamic polarization measurements, and electrochemical impedance spectroscopy. The electrochemical and weight loss results revealed that the SL extract was an efficient corrosion inhibitor with an inhibition efficiency of up to 93.31% at a concentration of 1 g/L, further confirmed by SEM observations. The aim of this research study the corrosion of transmission steel in an acidic medium that is 1M HCl in the presence of (SA) at different temperatures (20–60) degrees Celsius at concentrations within the range (10⁻⁶– 10⁻⁴) M for two hours, and then the effect Succinic acid (SA) on the corrosion process of steel in an acidic medium during the same period.

2. Materials used
This paper uses cylindrical transmission steel (Stainless Steel type ASTM-A240 201); see Tables (1). The dimensions are the length is 8 cm, and the radius is 0.25 cm, the surface area common to all steel parts was used 12.95 cm², and their density 7.86 g/cm³. Succinic acid is in different concentrations, hydrochloric at a concentration of 1 M, Bashar, pipettes, etc. The physical properties of succinic acid: M = 118.09 g.mol⁻¹, ρ = 1.56 g/cm³, Pk₁ = 4.2, Pk₂ = 5.6, solubility =58 g/L (at 20 °C).

| Grade     | %  | C   | Mn | Si | P   | S   | Cr | Ni | N   | Fe   |
|-----------|----|-----|----|----|-----|-----|----|----|-----|------|
| Stainless | 0.15 max | 0.15 max | 1 max | 0.06 max | 0.03 max | 16-18 | 0.3-0.5 | 0.25 max | Bal   |

Steel 201

3. Weight loss method (WLM)
Experiments were conducted with steel specimens with a cylindrical transmission, each about 12.95 cm². After polishing and cleaning, they were accurately weighed up to 4 decimal places before use. The sample was wholly immersed in a rust solution of 250 ml contained in 500 ml cups. Subjected to 2 hours, depending on the test, at the inhibitor's desired temperature and concentration. After each test, the sample was washed with running tap water, cleaned with a brush to remove the corrosive products, then washed with tap water followed by distilled water, dried with a clean tissue dipped in acetone for one minute, dried, and then immersed in benzene for 1 minute. Dried a minute and left in a desiccator.
over a gel Silica for an hour. Pre-weighting, based on a fourth decimal point, then re-weight. The weight loss was then determined, and the rate of corrosion was expressed in (g/m².hr).

4. Corrosion rate (CR)
CR calculations from WLM data was performed according to the following equation [10]:

\[ CR = \frac{K \cdot \Delta W}{\rho \cdot A \cdot t} \quad (1) \]

Where: \( \Delta W \) = decrease in weight (g), \( \rho \) = density of the metal subjected to corrosion (g/cm³), \( A \) = Surface area subject to erosion (cm²), \( t \) = Corrosion time (hr), CR= Corrosion Rate (mils per year) (mpy) and K=Constant equal to 3.45 x 10⁶ until the corrosion rate becomes mpy [10].

5. The effect of temperature on steel corrosion in an acidic media
The effect of temperature (T) on steel corrosion was studied by placing steel pieces in hydrochloric acid with a concentration of 1M. This medium was chosen because the corrosion percentage is high compared to the rest of the studied media at laboratory temperature. For this study, the following temperatures were suggested (20, 30, 40, 50 & 60) °C [3], where the vessels containing the pieces immersed in acid were immersed entirely for two hours. They were then removed and cleaned from the corrosion products by following the method above according to each temperature's corrosion rate.

6. The effect of succinic acid inhibitor concentration on steel corrosion in hydrochloric acid solution
Succinic acid was proposed as a chemical inhibitor in 1M hydrochloric acid and studied its concentration (within the M field \(10^{-4}-10^{-6}\)) on steel corrosion at different temperatures where the corrosion time was considered two hours. The corrosion rate corresponding to each concentration at each temperature is denoted by the inhibitor's presence with the symbol CRI to distinguish it from the corrosion rate without the presence of the inhibitor CR, Figure 1.

![Chemical formula for Succinic Acid (SA)](image)

7. Results and discussion
The result of calculating the corrosion rate CR according to the relationship (1) the following results were obtained and shown in Table (2). Figure (2) shows the corrosion rate as a function of temperature in the presence of hydrochloric acid as the corrosion media.

| T °C | Weight Loss (WL) (g)*10⁻³ | CR(mpy)*10⁻³ |
|------|--------------------------|--------------|
| 20   | 8.8                      | 149296.1     |
| 30   | 12.5                     | 212068.3     |
| 40   | 58.7                     | 995873       |
| 50   | 145.7                    | 2471868.7    |
| 60   | 285                      | 4835158.4    |
Figure 2. Shows the corrosion rate as a function of temperature in the presence of hydrochloric acid as the corrosion media.

7.1. Inhibitor efficiency (IE)

The surface coverage (θ) and inhibition efficiency (IE%) were calculated from the weight loss measurements using the following equations, respectively [10].

\[
\theta = \frac{CR - CRI}{CR}
\]

\[
IE = \frac{CR - CRI}{CR} \times 100
\]

CR = Corrosion Rate without inhibitor (mpy) and CRI = Corrosion Rate with inhibitor (mpy).

Tables (3-7) shows the weight loss corresponding to each temperature at a concentration of \(10^{-6}\) M, \(5 \times 10^{-6}\) M, \(10^{-5}\) M, \(5 \times 10^{-5}\) M & \(10^{-4}\) M of succinic acid, as well as the corrosion rate and the inhibition efficiency corresponding to each temperature, respectively. Figure (3) compares the corrosion rates with the inhibitor at different concentrations and the corrosion rate without using the inhibitor.

**Table 3.** The weight loss at a concentration of \(10^{-6}\) M.

| T (°C) | 20   | 30   | 40   | 50   | 60   |
|-------|------|------|------|------|------|
| ΔW(g) | 0.0028 | 0.0029 | 0.0135 | 0.0334 | 0.0645 |
| CRI (mpy) | 47.503 | 49.200 | 229.034 | 566.647 | 1094.273 |
| CR (mpy) | 149.296 | 212.068 | 995.873 | 2471.869 | 4835.158 |
| θ    | 0.6818 | 0.7680 | 0.7700 | 0.7708 | 0.7737 |
| IE % | 68.182 | 76.800 | 77.002 | 77.076 | 77.368 |

**Table 4.** The weight loss at a concentration of \(5 \times 10^{-6}\) M.

| T (°C) | 20   | 30   | 40   | 50   | 60   |
|-------|------|------|------|------|------|
| ΔW(g) | 0.0025 | 0.0028 | 0.0101 | 0.0248 | 0.0484 |
| CRI (mpy) | 42.414 | 47.503 | 171.351 | 420.744 | 821.129 |
| CR (mpy) | 149.296 | 212.068 | 995.873 | 2471.869 | 4835.158 |
| θ    | 0.7159 | 0.7680 | 0.8279 | 0.8298 | 0.8302 |
| IE % | 71.5909 | 77.6000 | 82.7939 | 82.9787 | 83.0175 |
Table 5. The weight loss at a concentration of $10^{-5}$ M

| T (°C) | 20  | 30  | 40  | 50  | 60  |
|-------|-----|-----|-----|-----|-----|
| ΔW(g) | 0.0022 | 0.0023 | 0.0062 | 0.0145 | 0.0255 |
| CRI (mpy) | 37.324 | 39.021 | 105.186 | 245.999 | 432.619 |
| CR (mpy) | 149.296 | 212.068 | 995.873 | 2471.869 | 4835.158 |
| θ | 0.7500 | 0.8160 | 0.8944 | 0.9005 | 0.9105 |
| IE % | 75.000 | 81.600 | 89.438 | 90.048 | 91.053 |

Table 6. The weight loss at a concentration of $5 \times 10^{-5}$ M.

| T (°C) | 20  | 30  | 40  | 50  | 60  |
|-------|-----|-----|-----|-----|-----|
| ΔW(g) | 0.0021 | 0.0022 | 0.0037 | 0.0063 | 0.0111 |
| CRI (mpy) | 35.627 | 37.324 | 62.772 | 106.882 | 188.317 |
| CR (mpy) | 149.296 | 212.068 | 995.873 | 2471.869 | 4835.158 |
| θ | 0.7614 | 0.8240 | 0.9370 | 0.9568 | 0.9611 |
| IE % | 76.136 | 82.400 | 93.697 | 95.676 | 96.105 |

Table 7. The weight loss at a concentration of $10^{-4}$ M.

| T (°C) | 20  | 30  | 40  | 50  | 60  |
|-------|-----|-----|-----|-----|-----|
| ΔW(g) | 0.0012 | 0.0013 | 0.0026 | 0.0058 | 0.0105 |
| CRI (mpy) | 20.359 | 22.055 | 44.110 | 98.399 | 178.137 |
| CR (mpy) | 149.296 | 212.068 | 995.873 | 2471.869 | 4835.158 |
| θ | 0.8636 | 0.896 | 0.9557 | 0.9602 | 0.9631 |
| IE % | 86.364 | 89.6 | 95.571 | 96.019 | 96.316 |

**Figure 3.** Shows a comparison between the corrosion rates with the inhibitor at different concentrations and the corrosion rate without using the inhibitor.

7.2. *Calculation of thermodynamic magnitudes*

7.2.1. *Calculate the activation energy* ($E_a$). The activation energy of steel corrosion in 1M hydrochloric acid in the presence and absence of the inhibitor (succinic acid) is calculated from the Arrhenius relationship as there is a relationship between corrosion rate (CR) and temperature (T), expressed by the following mathematical equation [11]:
\[ \log CR = \log A - \frac{Ea}{2.303RT} \]  

Where: \( Ea \) is the apparent effective activation energy, \( R \) = the general gas constant and \( A \) = the Arrhenius preexponential factor.

A plot of \( \log \) of corrosion rate obtained by weight loss measurement vs. 1/T gave straight lines, as shown in Figure (4). The Activation energies in the presence of inhibitor are lower than uninhibited acid since only small differences are observed between the values of activation energy calculated. The \( Ea \) is graphically calculated when drawing the line representing the variations of \( \log CR \) in terms of 1/T, where the line's slope is expressed in \( (Ea / 2.303R) \). Some authors have reported \( Ea < 80 \text{ kJ/mol} \) values as an indicator of physical adsorption, while the value of \( Ea > 80 \text{ kJ/mol} \) is related to chemical adsorption [11]. Tables (8), (9), (10), (11), and (12) show the logarithm of the corrosion rate and the temperature inverse corresponding to each concentration of the inhibitor. Where \( T(K)=T(C)+273.15 \).

**Table 8. The Log CR at inhibitor concentration of \( 10^{-6} \text{ M} \).**

| C(M) | T (°C) | T (K) | 1/T (K\(^{-1}\)) | CR (mpy) | Log CR |
|------|--------|-------|-----------------|--------|-------|
| 20   | 293.15 | 0.003411 | 47.5033 | 1.6767 |
| 30   | 303.15 | 0.003299 | 49.1999 | 1.6920 |
| 40   | 313.15 | 0.003193 | 229.0338 | 2.3599 |
| 50   | 323.15 | 0.003095 | 566.6466 | 2.7533 |
| 60   | 333.15 | 0.003002 | 1094.2727 | 3.0391 |

**Table 9. The Log CR at inhibitor concentration of \( 5 \times 10^{-6} \text{ M} \).**

| C(M) | T (°C) | T (K) | 1/T (K\(^{-1}\)) | CR (mpy) | Log CR |
|------|--------|-------|-----------------|--------|-------|
| 20   | 293.15 | 0.003411 | 42.4137 | 1.6275 |
| 30   | 303.15 | 0.003299 | 47.5033 | 1.6767 |
| 40   | 313.15 | 0.003193 | 171.3512 | 2.2339 |
| 50   | 323.15 | 0.003095 | 420.7436 | 2.6240 |
| 60   | 333.15 | 0.003002 | 821.1286 | 2.9144 |

**Table 10. The Log CR at inhibitor concentration of \( 10^{-5} \text{ M} \).**

| C(M) | T (°C) | T (K) | 1/T (K\(^{-1}\)) | CR (mpy) | Log CR |
|------|--------|-------|-----------------|--------|-------|
| 20   | 293.15 | 0.003411 | 37.3240 | 1.5720 |
| 30   | 303.15 | 0.003299 | 39.0206 | 1.5913 |
| 40   | 313.15 | 0.003193 | 105.1859 | 2.0220 |
| 50   | 323.15 | 0.003095 | 245.9993 | 2.3909 |
| 60   | 333.15 | 0.003002 | 432.6194 | 2.6361 |

**Table 11. The Log CR at inhibitor concentration of \( 5 \times 10^{-5} \text{ M} \).**

| C(M) | T (°C) | T (K) | 1/T (K\(^{-1}\)) | CR (mpy) | Log CR |
|------|--------|-------|-----------------|--------|-------|
| 20   | 293.15 | 0.003411 | 35.6275 | 1.5518 |
| 30   | 303.15 | 0.003299 | 37.3240 | 1.5720 |
| 40   | 313.15 | 0.003193 | 106.8824 | 2.0289 |
| 50   | 323.15 | 0.003095 | 188.3167 | 2.2749 |
Table 12. The Log CR at inhibitor concentration of 5x10^{-6} M.

| C(M)   | T (°C) | T (k)  | 1/T (K^{-1}) | CR (mpy) | Log CR |
|--------|--------|--------|--------------|-----------|--------|
| 5x10^{-6} M | 20     | 293.15 | 0.003411    | 20.3586   | 1.3087 |
|         | 30     | 303.15 | 0.003299    | 22.0551   | 1.3435 |
|         | 40     | 313.15 | 0.003193    | 44.1102   | 1.6445 |
|         | 50     | 323.15 | 0.003095    | 98.3997   | 1.9930 |
|         | 60     | 333.15 | 0.003002    | 178.1374  | 2.2508 |

Figure (4) shows a comparison between the changes in the logarithm of the corrosion rate as a function of the temperature is inverted at each concentration of with and without the inhibitor. Table (13) shows the graphically calculated activation energy corresponding to the different concentrations of succinic acid. It is noted that the adsorption in this study is physical adsorption because of $E_a < 80$ kJ/mol [11].

Figure 4. Shows a comparison between log CR and (1/T) at each concentration of the with and without the inhibitor.

Table 13. The activation energy corresponding to the different concentrations of succinic acid.

| C(SA)   | $E_a$(kJ/mol) |
|---------|---------------|
| ----    | 76.3531       |
| 10^{-6}M | 72.8509       |
| 5x10^{-6}M | 67.7118       |
| 10^{-5}M | 56.225        |
| 5x10^{-5}M | 46.341        |
| 10^{-4}M | 48.5609       |

7.2.2. Calculate the adsorbed constant (K). The CR data can be used to analyze the adsorption mechanism. The Langmuir isotherm was expressed as:

$$
\theta = \frac{K.C}{1 + K.C}
$$

Where: K is the equilibrium constant for the adsorption isotherm representing the degree of adsorption (i.e., the higher the value of K indicates that the inhibitor is strongly adsorbed on the metal surface. C is inhibitor concentration (cm$^3$/L), and $\theta$ is the surface coverage. Equation rearranging will give:
A curve can be drawn, representing the changes in surface coverage in terms of $C$ at each temperature, Figure 5.

7.2.3. Calculate enthalpy ($\Delta H$) and entropy ($\Delta S$). The other form of the Arrhenius equation can be used to calculate enthalpy and entropy, where:

$$ CR = \frac{RT}{h \times N_A} \exp\left(\frac{\Delta S}{R}\right) \exp\left(-\frac{\Delta H}{RT}\right) $$

(7)

Where: $R$ = general constant for gases, $T$: temperature, $\Delta S$ = entropy change, $\Delta H$ = enthalpy change, $h$: Planck's constant ($h = 6.6256 \times 10^{-34}$ Joule. Sec) and $N_A$: Avogadro's number ($N_A = 6.023 \times 10^{23}$ mole). Dividing both sides of Equation (7) by $T$ and then taking the logarithm of both sides, we get the relationship:

$$ \log\left(\frac{CR}{T}\right) = \log\left(\frac{RT}{h \times N_A}\right) + \left(\frac{\Delta S}{2.303R}\right) - \left(\frac{\Delta H}{2.303RT}\right) $$

(8)

When drawing the graph line that represents the changes of $\log(CR/T)$ in terms of $(1/T)$, we get a straight line whose slope represents the value $(-\Delta H/2.303R)$, and its intersection with the axis in order to represent the value $\log(R/h*N_A)+\Delta S/2.303R$. Thus, enthalpy and entropy values can be inferred at different inhibitor concentrations, and Table (14) shows that the values of $\Delta H$, $\Delta S$, and $E_a$ corresponding to each of the inhibitor concentrations, Figure 6.

| $K$ ($M^{-1}$)$\times10^{-6}$ | $T$ (°C) |
|-------------------------------|---------|
| 0.5                           | 20      |
| 1                             | 30      |
| 1.4                           | 40      |
| 1.6                           | 50      |
| 1.6                           | 60      |
It can be noted from **Table (15)** that the values of \( E_a \) in the presence of the inhibitor are lower than their values without the presence of the inhibitor, and this indicates the efficiency of the inhibitor. Collectivism and not disintegration.

**Figure 6.** Shows the changes of log\((CR/T)\) in terms of \((1/T)\) at each inhibitor concentration.

**Table 15.** The values of \( \Delta H \), \( \Delta S \), and \( E_a \) corresponding to each of the inhibitor concentrations.

| Inhibitor concentration (M) | \( \Delta H \) (kJ/mol) | \( -\Delta S \) (J/mol) | \( E_a \) (kJ/mol) |
|-----------------------------|-------------------------|------------------------|------------------|
| 0                           | 73.7567                 | 1.9196                 | 76.63531         |
| \( 10^{-6} \)               | 62.2837                 | 3.277984               | 72.8509         |
| \( 5 \times 10^{-6} \)      | 59.62419                | 13.98313               | 67.7118         |
| \( 10^{-5} \)               | 49.1756                 | 50.87576               | 56.225          |
| \( 5 \times 10^{-5} \)      | 32.70332                | 107.8786               | 46.341          |
| \( 10^{-4} \)               | 44.4386                 | 73.00598               | 48.5609         |

8. Conclusions
1- The corrosion process in the acidic medium is hazardous and is greatly affected by the increase in temperature, as the rate of corrosion increases with the increase in temperature.
2- Succinic acid can be used in inhibiting iron corrosion in an acidic medium at different temperatures.
3- The inhibition efficiency of succinic acid in hydrochloric acid at a specific temperature is proportional to its concentration, as the inhibition efficiency at the 50 °C degree was approximately 97% when using the inhibitor with a concentration of \( 10^{-4} \) M.
4- The calculated activation energies indicate that the succinic acid used in the damping process is physically adsorbed on the steel parts' surface.
5- The optimum concentration for using succinic acid as an inhibitor is \( 5 \times 10^{-2} \) M, where the activation energy, enthalpy, and entropy had the lowest values calculated for all concentrations, followed by the concentration \( 10^{-4} \) M.
6- Succinic acid used in minimal quantities is an environmentally friendly and non-toxic substance, so it is recommended to use it in the chemical inhibition of iron erosion.
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