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Effect of Heat and Mass Transfer on Corrosion of Carbon Steel in A Crude Oil Medium Using Corrosion Inhibitors Sodium Nitrate and Castor Oil under Different Circumstances

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Abstract

In the petroleum industry, corrosion is a fundamental problem that causes many operational and commercial problems, which require careful consideration and comprehensive studies in order to discover suitable solutions. Among these problems is the occurrence of corrosion in the crude oil production equipment as well as in the transportation pipelines of petroleum products, which leads to their failure; thus, increasing the cost as a result of maintenance or replacement. To protect them from corrosion, different types of inhibitors are commonly used, in which small amounts of inhibitor are continuously injected, slowly forming a thin layer of inhibitor between them and the corrosive materials to protect them from corrosion.

In this study, the performance of the corrosion process was examined under varying temperatures, namely 20, 30, 40, 50 and 60 °C, at rotational speeds of 0, 500, 1250 and 2000 rpm. The concentrations of sodium nitrate ($NaNO_3$) inhibitor were 0, 0.5, 1.0 and 1.5 g/l of crude oil, whereas the concentrations of castor oil inhibitor were 0, 0.5, 1.0 and 1.5 ml/l of crude oil. The results demonstrated that the corrosion rate of carbon steel in the crude oil decreases with the increase in the concentration of both types of inhibitors ($NaNO_3$ and castor oil), while it increases with the rise in temperature and rotational speed. It was determined that the maximum efficiency of the green inhibitor (castor oil) in the crude oil was 93.7% at a concentration of 1.5 ml/l, temperature of 20 °C and a rotational speed of 0 rpm, while the maximum efficiency of the chemical inhibitor ($NaNO_3$) in the crude oil was 98.6% at a concentration of 1.5 g/l, temperature of 20 °C and rotational speed of 0 rpm.

Keywords: Corrosion rate; Weight loss; Inhibitors; Mass transfer coefficient; Dissolution current density.

تأثير انتقال الحرارة والكتلة على تآكل الفولاذ الكربوني في وسط من النفط الخام باستخدام مثبطات التآكل نترات الصوديوم وزيت الخروع تحت ظروف مختلفة

الخلاصة

يعتبر التآكل مشكلة أساسية في الصناعة النفطية تسبب العديد من المشاكل التشغيلية والتجارية والتي تتطلب اهتمام ودراسات شاملة من أجل إيجاد الحلول المناسبة لها. من بين هذه المشاكل حدوث التآكل في معدات إنتاج النفط الخام وكذلك في أنابيب نقل المنتجات النفطية مما يؤدي إلى فشلها. وبالتالي زيادة التكلفة نتيجة لصيانتها أو استبدالها. ومن أجل حمايتها من التآكل، عادة ما يتم استخدام أنواع مختلفة من المثبطات ، حيث يتم حقن كميات صغيرة من المانع باستمرار، مما يؤدي وببطء إلى تكوين طبقة رقيقة من المانع بينها وبين المواد المسببة للتآكل لحمايتها من التآكل.

في هذه الدراسة، تم فحص أداء عملية التآكل عند درجات حرارة مختلفة وهي 20، 30، 40، 50 و 60 درجة مئوية، وبسرعات دوران مختلفة وهي 0، 500، 1250 و 2000 دورة في الدقيقة. بينما كانت تراكيز المثبط نترات الصوديوم المستخدمة هي 0، 0.5، 1.0، و 1.5 غم \ لتر من النفط الخام، وكانت تراكيز المثبط زيت الخروع المستخدمة هي 0، 0.5، 1.0، و 1.5 مل \ لتر من النفط الخام. أظهرت النتائج أن معدل تآكل الفولاذ الكاربوني في النفط الخام يتناقص مع زيادة تركيز كلا النوعين من المثبطات (نترات الصوديوم وزيت الخروع)، بينما يزداد مع زيادة درجة الحرارة وسرعة الدوران. وجد أن أقصى كفاءة للمثبط زيت الخروع في النفط الخام كانت 93.7 % عند تركيز 1.5 مل \ لتر ودرجة حرارة 20 درجة مئوية وسرعة دوران 0 دورة في الدقيقة، بينما كانت أقصى كفاءة للمثبط نترات الصوديوم هي 98.6 % عند تركيز 1.5 غم \ لتر ودرجة حرارة 20 درجة مئوية وسرعة دوران 0 دورة في الدقيقة.

1. Introduction

Corrosion is a chemical reaction that naturally occurs between metals and surrounding environment, which may cause the dissolution of a metal and change its properties resulting in many serious problems. Generally, metals tend to revert to their complicated conditions before extraction. Thus, the most substantial chemical property of a metal or alloy is the interaction with atmospheric air (oxygen), due to which it is neglected and inhibitors are not added to protect it, which leads to its dissolution and return to its natural state. The chemical process by which a metal seeks to return to its natural, stable state as ore is known as wear [1, 2]. The chemical process by which the metal seeks to return to its natural, steady state as an ore is known as corrosion [1, 2]. In the corrosion cycle, the oxidation process that occurs for all or many of the particles on the same metal surface produces the destruction of the entire surface of the metal. Furthermore, given that most metals tend to lose electrons in air or water to oxygen (and other substances), they are easy to oxidise and produce oxide with the metal [3].

Crude oil or “black gold” is a naturally occurring liquid, which is a mixture of compounds rich in hydrocarbons. Crude oil which is commonly found in the form of layers of sediment underground over time is created from the remains of plants and animals that died millions of years ago. Due to the high pressure and heat, it evolved into “fossil fuels” over time. It exists in four types; specifically very light crude oils, light crude oils, medium crude oils and heavy crude oils. It can be treated to produce different products, like kerosene, gasoline, diesel and petrochemicals. The physical and chemical properties of crude oil vary greatly, often in the same crude oil research area and from plant to plant. Terms such as “sweet”, “sour”, “naphthenic”, “paraffinic”, “aromatic”, “light” and “heavy”, are used to identify crude oil depending on its composition, sulphur content and boiling range. These are valuable properties as a result of their significant impact on a refinery. The determinant as regards the price of crude oil is its quality and because of the various forms of crude oil, like Brent crude, were utilized as an international price index of crude oil. The quality of crude oil depends on its weight, the heavier it is, the lower its market value, and vice versa [4, 5].

The more significant corrosion in a crude oil refining system is the overhead corrosion, which is a common problem globally. The proportion of components damaged in the refining process units varies due to the change in the chemical composition of the fluids and the limitations of processes such as acidity (pH), moisture, pressure, temperature, etc. [6]. Dissolved oxygen, carbon dioxide, nitrogen compounds, organic acids and water, in addition to hydrogen sulphide, organic sulphur compounds, mercaptans, hydrogen chloride along with inorganic and organic chlorides, are the main reasons for declination in the crude oil refining system [6, 7]. When refinery units are set up, the most common material in the construction is carbon-steel, which is subject to corrosion primarily because of the availability of water and oxygen on the surface of the carbon steel. Corrosion can be lessened by decreasing the adhesive water on the surface of the steel by creating a protective layer for the steel wall, such as a barrier or coating [7].

Corrosion inhibitors are substances which are utilised in small amounts in the environment to prevent or delay corrosion. The idea of corrosion protection with corrosion inhibitors is to produce a thin film on the surface of the material to protect it from corrosion. This is achieved by stimulating it to develop a thick anticorrosive component or by modifying the environmental properties resulting in the prevention or reduction of aggressive behaviour [8].

The high cost and adverse effect associated with inorganic and organic commercial inhibitors are reasons to consider reducing their use in corrosion prevention. Furthermore, it appears that the engineers and scientists specialising in the field of corrosion are inclined to use green inhibitors to prevent corrosion. It must be renewable, reasonable, environmentally friendly and non-toxic due to environmental concerns [9].

In the previous three decades, a lot of research work in the area of “green” inhibitors of corrosion has been performed to protect different metals from corrosion. The goal of these researches was to utilize cheap and efficient inhibitors at a minimum or “zero” environmental influence. For instance, iron and mild steel could be protected using lemongrass extract [10] and carbon steel using neem oil and punga oil [11].

The aim of this study is to design and establish a system for evaluating the various factors on carbon steel corrosion in a medium of crude oil, for instance temperature, the flow (electrode rotation) velocity, type and concentration of inhibitors, in addition to evaluating the performance of available and cheap inhibitors as an alternative to imported and expensive inhibitors.

2. Inhibitors Preparation

2.1 Castor oil

Castor oil is a vegetable oil pressed from colourless castor and bean to a very faint liquid that has a yellow colour with a special smell and taste. It is made in the United Arab Emirates (UAE), (Figure 1 (a)).

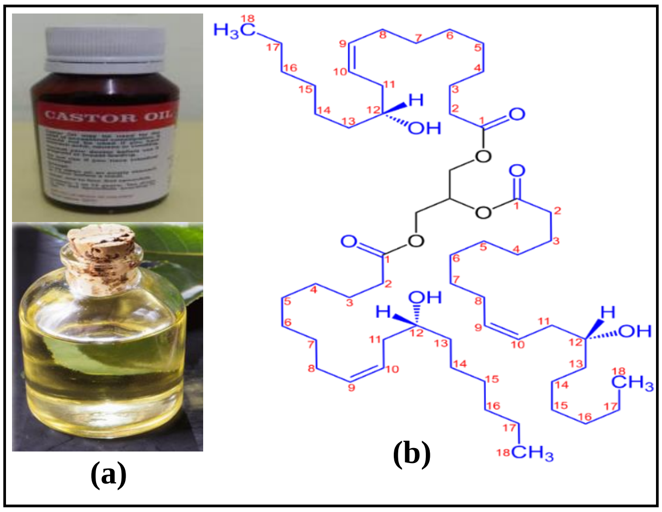

Fig. (1): (a) Castor oil inhibitor. (b) Structure of main castor oil component; ricinoleic acid and triester of glycerol [12].

It has a boiling point of 313 °C (595 °F) and a density of 0.961 g/cm^3. Its molecular formula is $C_{57}H_{104}O_9$. It is a source of ricinoleic acid, an 18-carbon polyunsaturated fatty acid, as shown Figure (1b). Between ricinoleic and fatty acids, the carbon-twelfth has an active set of hydroxyl, which makes castor oil and oleic acid more polar compared to other fats [13]. Numerous researchers have reported that the punga oil, castor oil and neem oils, which work as a mixture of retardants, may be employed as a retardant for corrosion in petrol producing pipelines. Among these three oils, castor oil provided the greatest efficacy as a corrosion inhibitor. The weight loss analysis revealed castor oil to have a robust performance of 89% compared to neem oil and punga oil [14, 15]. Therefore, it was utilized to prepare a novel green corrosion inhibitor for carbon steel in a crude oil medium. In addition, it is environmentally friendly and an inexpensive source. It was used with a concentration of 0, 0.5, 1.0 and 1.5 ml/l of crude oil solution. The experimental weight loss procedures were performed (as shown in section 4.3).

2.2 Sodium Nitrate ($NaNO_3$)

Sodium nitrate is an inorganic nitrate salt of an alkali metal with the chemical formula $NaNO_3$, comprising a sodium cation (Na^+) of 26 % and a nitrate anion (NO_3^-) of 16%. At room temperature, it exists as a white, non-flammable crystalline solid that is highly soluble in water of 880 g/l [16]. It was used as a powder (see Figure 2) with a concentration of 0, 0.5, 1.0 and 1.5 g/l, which was added to the crude oil. Experimental weight loss procedures were carried out (as shown in section 4.3).

Fig. (2): Sodium nitrate powder.

3. Working Electrode Design

The shape of the carbon steel sample used in the weight loss experiments was cylindrical, with dimensions of length (L) 4 cm, 2 cm outer diameter (d_{out}) and 3 mm thickness (th). Hence, the total surface area of the carbon steel specimen = 2.832×10^{-3} m^2. It was polished using silicon carbide sheets as shown in Figure (3).

To evaluate the chemical composition, wt% of the basic metals that make up the specimen. This test was conducted at the laboratory of the State Company for Inspection and Engineering Rehabilitation (SIER). The outcomes are as shown in Table (2).

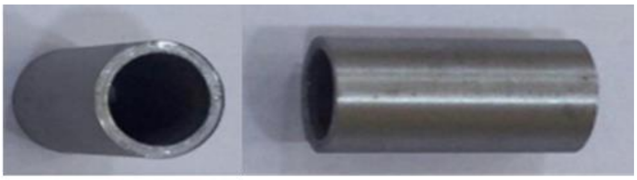

Fig. (3) The working electrode after polishing by Silicon Carbide sheets.

Table (1) The chemical composition, wt %, of the base metals of the specimen

C	Cr	P	Si	S	Mo	Mn	Co	Ni	Cu	Al	Fe
0.181	0.005	0.012	0.008	0.011	0.026	0.396	0.005	0.024	0.018	0.062	bal.

4. Experiments

The experiments were conducted to determine the average corrosion rate of a carbon steel specimen in crude oil utilising the weight loss method. Weight loss experiments were completed under various rotational velocities of 0, 500, 1250 and 2000 rpm and different temperatures of 20, 30, 40, 50 and 60 °C, as well as under various inhibitor concentrations.

4.1 The corrosion medium

The medium used in the weight loss experiments is crude oil. Analysis tests for its properties were performed in laboratories belonging to Midland Refineries in Baghdad, Iraq. The results are shown in Table (1).

Table (2) Properties of crude oil used in experiments of weight loss.

Crude oil properties	Temperature (˚C)				
	20	30	40	50	60
Density (ρ), kg/m^3	913	907	901	897	892
Kinematic viscosity (ν), (m^2/s) × 10^{-6}	66.1	50.2	29.4	19.98	14.35
Dynamic viscosity (μ), (kg/m.s) × 10^{-3}	60.43	45.851	26.872	17.929	12.798
Diffusivity (D), (m^2/s) × 10^{-4}	1.119	2.075	3.236	4.556	6.018
Conc. of O_2, (g/l) × 10^{-3}	46	42	39	35	31
M.W of O_2, (g/gmol)	337.53	326.85	308.39	290.77	281.71

4.2 Equipment used in the experiment

4.2.1 **Water bath:** Laboratory digital thermostatic water bath (HH-1 model). This was used to adjust cell temperature with high accuracy and a max of 110°C. Made by MONIPA-USA.

4.2.2 Balance: An electronic digital scale with exceptional accuracy of 4 decimal points per gram, with a farthest weight of 110 g. M214Ai model made by BEL Engineering, Italy utilised to weigh the $NaNO_3$ inhibitor and the specimen before and after the weight loss experiments.

4.2.3 Thermometer: A laboratory thermometer for measuring the temperature of various liquids ranging from 0 ˚C to 100 ˚C. The body is made of glass, total length 15.5 cm and filled with red spirit. Made by ELEMENTAL, Europe.

4.2.4 Drying oven: Laboratory dry electric oven, temperature ranging from 10 to 300 °C, displays accuracy of 0.1°C, temperature stability ± 1.0 C˚ and a capacity of 80 liters. The model number is DHG-9075A, made by SERICO, China, and it was used to dry the carbon steel specimen.

4.2.5 Rotating cylinder electrode: A Modulated Speed Rotator (MSR), made by Pine Research, UK. Included an electrode rotator and a control unit with an adjustable rotational speed ranging from 50 to 10000 rpm, with accuracy within 1% of the reading display.

4.3 The weight loss experiment procedure

According to the following steps, the corrosion rate calculation process was performed at 20 °C, static velocity (0 rpm) and without inhibitors.

Prior to each experiment, the carbon steel (working electrode) specimen was polished with silicon carbide grit papers.

1. Cleaning the specimen with clean, dry gauze paper after polishing it with silicon carbide grit papers.
2. Soaking the specimen in crude oil for 20 minutes at 20 °C and static velocity 0 rpm.
3. Drying the specimen with clean and dry gauze paper after removing it from the crude oil.
4. Soaking the specimen in hydrochloric acid (HCl) for 3 minutes.

5. The specimen is washed with distilled water and soaked in acetone solution for 5 minutes and then dried with the gauze paper.
6. Drying the specimen by utilising the oven at 160 °C for 20 minutes.
7. Specimen weighting utilising a sensitive balance and registering the first weight (W_1).
8. Immersing the specimen in crude oil for 3 hours.
9. Immersing the specimen in HCl acid for 3 minutes.
10. Washing the specimen with distilled water, soaking it in acetone solution for 5 minutes and then drying it with gauze paper.
11. Drying the specimen utilising the oven at 160 °C for 20 minutes.
12. Weighting the specimen utilising a sensitive balance and registering the second weight (W_2).
13. Measuring the weight loss (ΔW), where: $\Delta W = W_1 - W_2$.
14. Calculating the corrosion rate (CR) by using the following formula

$$CR = \frac{\Delta W}{A \times t} \cdots\cdots\cdots\cdots\cdots\cdots Eq\ 1$$

where Δw is the loss of weight (g), A is the surface area of the carbon steel specimen (m^2) and t is the exposure time (s). Then, using the same steps mentioned above, the corrosion rate was measured at temperatures (30, 40, 50 and 60) minutes, rotational speeds (500, 1250 and 2000) rpm and at different inhibitor concentrations of castor oil and sodium nitrate. Figure (4) shows the weight loss experiment with a rotational speed electrode.

Fig. (4) The weight loss experiment with a rotational speed electrode.

4.4 Calculation of the mass transfer coefficient (K)

The mass transfer coefficient of the carbon steel specimen in crude oil was determined by the following equations.

$$I_l = z \times F \times K \times C_b \cdots\cdots\cdots\cdots Eq.2$$

where I_l is the limiting current density (ampere per m^2), z is the number of electrons transferred through the crude oil as a result of corrosion, F is the Faraday's constant which is equal to 96487 C.mol^{-1}, K is the mass transfer coefficient (m/s) and C_b is the concentration bulk of oxygen in the crude oil (mol/l).

From equation 1, following relation was obtained to determine the value of K.

$$K = \frac{I_l}{z \times F \times C_b} \cdots\cdots\cdots\cdots\cdots\cdots Eq.3$$

The value of C_b was found using the formula below

$$C_b = \frac{C_{O_2}}{MW_t} \cdots\cdots\cdots\cdots\cdots\cdots\cdots Eq.4$$

where C_{O_2} is the concentration of oxygen in the crude oil (g/l) and MW_t is the molecular weight of the crude oil (g/mol).

The values of the mass transfer coefficient "K" have been obtained by compensation the values of Cb which were acquired from equation 4 in equation 3. The values of mass transfer coefficient are illustrated in Tables (4) and (5).

5. Results and discussion

This section exhibits the outcomes of experimental and the discussions of all the ranges evaluated for rotational speeds and concentrations of inhibitor to comprehend and explicate the influence of these adaptables on the carbon steel corrosion in a medium of crude oil.

The weight loss experiments were conducted at different rotational speeds to determine the effect of temperature and inhibitor concentrations (castor oil and sodium nitrate) on the corrosion rate in gmd (gram per m^2 per day), dissolution current density, mass transfer coefficient and the efficiency of the inhibitors (η) in (%). The corrosion rate values, current dissolution density and mass transfer coefficient as well as the efficiency of the inhibitors were recorded in Tables (3 to 5) are a sample of them.

5.1 Effect of temperature and rotational velocity on corrosion rate of carbon steel in crude oil

From Table (3) and Figure (5), it can be seen that the corrosion rate of carbon steel increases with increasing temperature. This is due to the increase in the solubility of oxygen and its diffusion on the surface of the metal due to the decrease in the viscosity of the crude oil at high temperature, where the viscosity is inversely proportional to the diffusion of oxygen. Therefore, the corrosion increases with the increase in the diffusion of oxygen because oxygen is the main factor for the occurrence of corrosion. This is consistent with several preceding studies [17, 18].

From Table (3) and Figure (6), it can be observed that the corrosion rate of carbon steel increases with increasing rotational speed at various temperatures 40, 50 and 60 °C. This is due to increase in the solubility of the oxygen and its diffusion on the surface of metal caused by the decrease in the viscosity of the crude oil at high temperature. While at temperatures of 20 and 30 °C, it is observed that initially the rate of corrosion decreases slightly and then is almost constant with increasing rotational speed. This is due to low solubility of oxygen and its diffusion on the metal surface due to the fact that the viscosity of crude oil remains high at low temperatures. Thus, the corrosion decreases with the decrease in the diffusion of oxygen at low temperatures. This is in agreement with earlier studies [17, 18].

Table (3) Effect of temperature on the weight loss, corrosion rate and the density of dissolution current of a specimen of carbon steel in crude oil under rotational speed of (0, 500, 1250 and 2000) rpm without adding inhibitors.

	Rotational speeds, rpm	Temperature (˚C)				
		20	30	40	50	60
Weight loss (ΔW), g	0	0.0361	0.0429	0.0482	0.0548	0.0635
	500	0.0148	0.0207	0.0516	0.0902	0.1374
	1250	0.0175	0.0258	0.0894	0.1276	0.1982
	2000	0.0271	0.0482	0.1326	0.1478	0.2579
Corrosion rate (CR), gmd	0	0.5311	0.6312	0.7092	0.8067	0.9343
	500	0.2177	0.3046	0.7592	1.3271	2.0215
	1250	0.2575	0.3796	1.3153	1.8774	2.9161
	2000	0.3987	0.7092	1.9509	2.1746	3.7944
Dissolution current density (I_d), A/m^2	0	5.386	6.591	7.347	8.085	9.508
	500	3.490	4.968	9.475	13.824	14.106
	1250	2.421	3.763	13.190	19.764	20.148
	2000	4.239	7.477	20.763	22.508	38.761

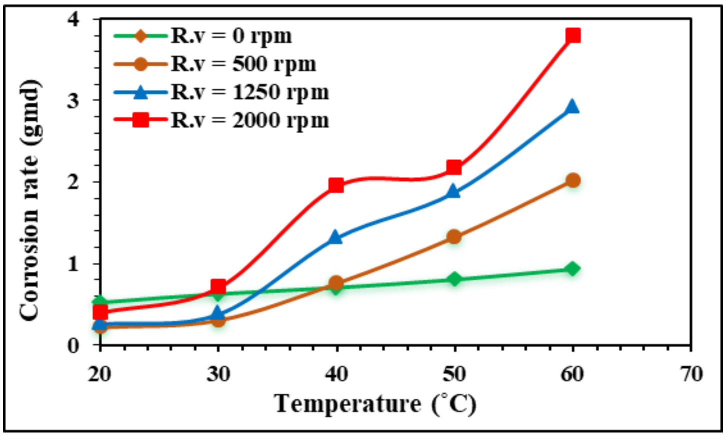

Fig. (5): Temperature versus corrosion rate of carbon steel in crude oil at different rotational velocities.

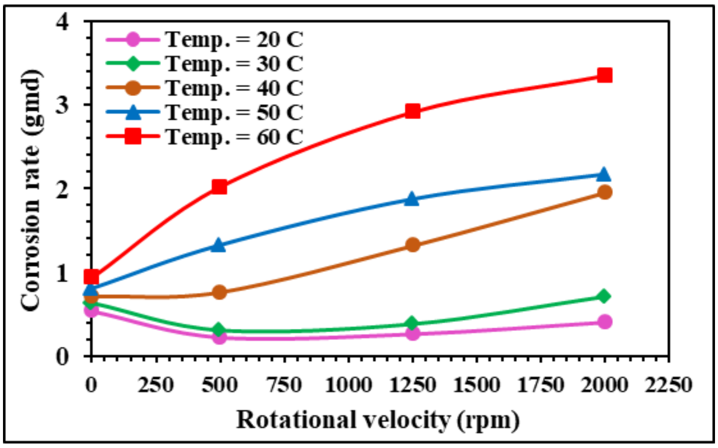

Fig. (6): Rotational velocity versus corrosion rate of carbon steel specimen in crude oil at different temperature.

5.2 Effect of temperature and rotational velocity on dissolution current density of carbon steel in crude oil

Figure (7) and Table (3) illustrate that the current dissolution density rises with increasing temperature by increasing the oxygen diffusivity. Moreover, it is also directly proportional to the increase in the carbon steel corrosion rate as shown in Table (3). It can be noticed that the current dissolution density increases with increasing rotational speed as a result of the increase in the oxygen imparted onto the carbon steel surface. It is also directly proportional to the increase in the carbon steel corrosion rate, as illustrated in Table 3. This is in accordance with what numerous researchers have observed [19, 20].

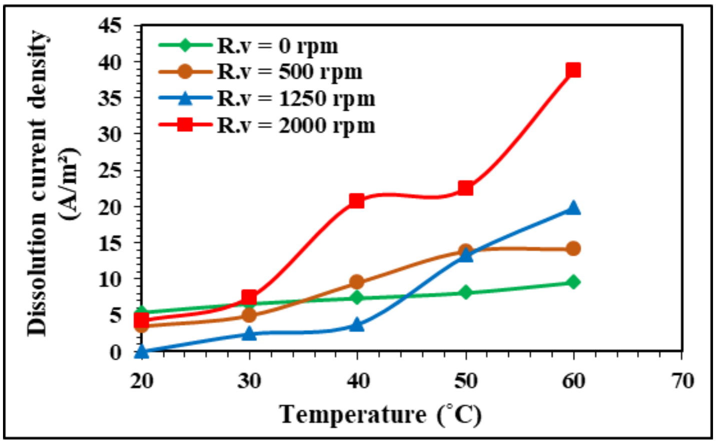

Fig. (7): Temperature versus density of dissolution current of carbon steel specimen in crude oil at different rotational velocity.

5.3 Effect of temperature, rotational speed and inhibitor concentration on corrosion rate, efficiency of the inhibitors, and mass transfer coefficient of carbon steel in crude oil

From Figures (8) and (9) and Tables (4) and (5), it can be seen that the inhibitor concentration of both the sodium nitrate and castor oil is inversely proportional to the carbon steel corrosion rate, given that the higher the inhibitor concentration, the lower the corrosion rate and vice versa.

This is attributed to the fact that the inhibitors form films around the carbon steel in several ways: (1) by adsorption, massive precipitates are formed; (2) and/or a passive layer is formed on the surface of the carbon steel. That indicates that some inhibitors retard corrosion by adsorption to form a fluffy, invisible film with only a few molecules thickness, while others form massive precipitates that cover the carbon steel and save it from attack; (3) formed by causing the carbon steel to corrode in such a way that an amalgamation of adsorption and corrosion product form a passive layer [21, 22]. It was also found that the corrosion rate in the presence of the $NaNO_3$ inhibitor is lower than the corrosion rate in the presence of the castor oil inhibitor for the same temperature and rotational speed conditions employed.

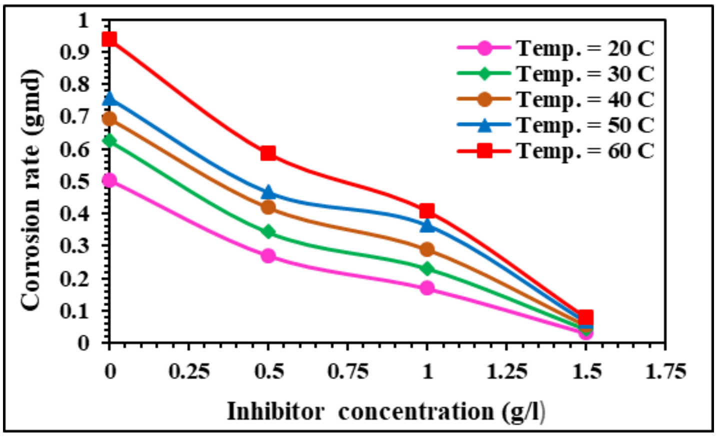

Fig. (8): The NaNO3 inhibitor concentrations versus corrosion rate of carbon steel in crude oil at different temperature and 0 rpm.

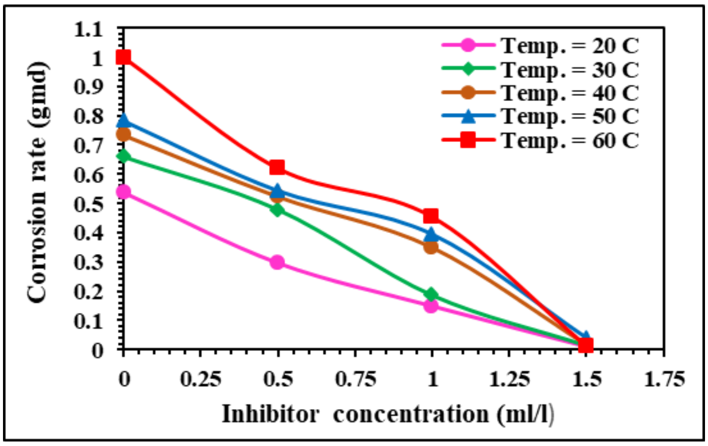

Fig. (9): The castor oil inhibitor concentrations versus corrosion rate of carbon steel in crude oil at different temperature and 0 rpm.

Table (4) The values of the corrosion rate, dissolution current density, mass transfer coefficient, and inhibitor efficiency for a specimen of carbon steel in crude oil at 0 rpm, different temperature and various NaNO3 inhibitor concentration.

	$NaNO_3$ concentration (g/l)	Temperature (˚C)				
		20	30	40	50	60
CR (gmd)	0	0.5032	0.6238	0.6930	0.7562	0.9372
	0.5	0.2692	0.3413	0.4178	0.4649	0.5856
	1.0	0.1677	0.2295	0.2884	0.3634	0.4075
	1.5	0.0294	0.0412	0.0530	0.0647	0.0779
I_d (A/m^2)	0	5.284	6.510	7.286	7.896	9.421
	0.5	3.148	4.817	5.327	5.911	6.938
	1.0	2.017	3.174	4.203	4.665	5.420
	1.5	0.318	0.439	0.501	0.623	0.759
K (m/s)	0	1.167×10^{-4}	3.632×10^{-4}	3.773×10^{-4}	4.348×10^{-4}	5.709×10^{-4}
	0.5	1.590×10^{-4}	3.686×10^{-4}	3.799×10^{-4}	5.465×10^{-4}	6.462×10^{-4}
	1.0	1.848×10^{-4}	3.711×10^{-4}	3.843×10^{-4}	8.704×10^{-4}	7.893×10^{-4}
	1.5	2.041×10^{-4}	5.431×10^{-4}	8.847×10^{-4}	1.890×10^{-3}	2.168×10^{-3}
η (%)	0	---	---	---	---	---
	0.5	50.5	49.3	47.4	46.8	44.2
	1.0	66.3	65.8	63.9	61.0	55.4
	1.5	98.6	98.1	97.3	96.8	96.1

Table (5) The values of the corrosion rate, dissolution current density, mass transfer coefficient, and inhibitor efficiency for a specimen of carbon steel in crude oil at 0 rpm, different temperature and various castor oil inhibitor concentration.

	Castor oil concentration (ml/l)	Temperature (˚C)				
		20	30	40	50	60
CR (gmd)	0	0.5370	0.6591	0.7327	0.7816	0.9987
	0.5	0.2957	0.4782	0.5223	0.5429	0.6194
	1.0	0.1486	0.1854	0.3487	0.3943	0.4532
	1.5	0.0103	0.0132	0.0162	0.0398	0.0118
I_d (A/m^2)	0	5.301	6.627	7.316	8.136	9.618
	0.5	3.827	4.217	4.921	5.745	5.984
	1.0	2.172	2.358	2.810	3.541	3.626
	1.5	0.090	0.120	0.158	0.136	0.134
K (m/s)	0	1.979×10^{-6}	2.529×10^{-6}	2.872×10^{-6}	3.113×10^{-6}	4.623×10^{-6}
	0.5	1.170×10^{-6}	2.581×10^{-5}	2.854×10^{-5}	4.481×10^{-5}	5.378×10^{-5}
	1.0	1.634×10^{-5}	2.623×10^{-5}	2.837×10^{-5}	7.624×10^{-5}	9.842×10^{-5}
	1.5	1.452×10^{-4}	2.674×10^{-4}	4.781×10^{-4}	6.564×10^{-4}	9.785×10^{-4}
η (%)	0	---	---	---	---	---
	0.5	50.3	34.3	40.4	39.6	43.1
	1.0	63.5	61.8	57.6	58.1	60.4
	1.5	93.7	93.1	92.8	92.0	91.5

Figures (10) and (11) and Tables (4) and (5) reveal that the mass transfer coefficient is directly proportional to temperature, rotational velocities and the inhibitor concentration (castor oil or $NaNO_3$). This suggests that an increase in the mass transfer coefficient leads to an increase in the corrosion rate because the temperature and rotational speeds are directly proportional to the rate of corrosion. This is in agreement with the observation of several previous researches [23, 24].

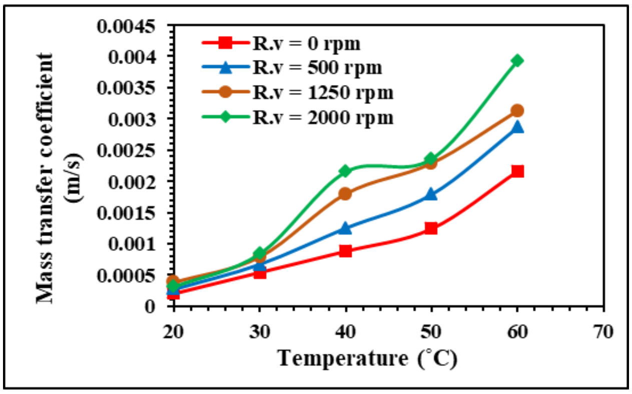

Fig. (10) Temperature versus mass transfer coefficient of carbon steel in crude oil at 1.5 g/l of NaNO3 inhibitor concentration and different rotational velocities.

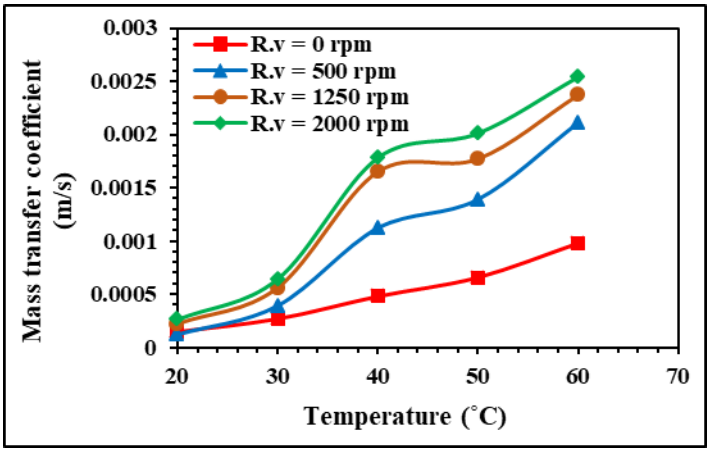

Fig. (11): Temperature versus mass transfer coefficient of carbon steel in crude oil at 1.5 ml/l of castor oil inhibitor concentration and different rotational velocities.

Tables (4) and (5) and Figures (12) and (13) reveal that the efficiency of both the $NaNO_3$ inhibitors and the castor oil is inversely proportional to the rotational speed. This indicates that the efficiency of the inhibitor is reduced by increasing the rotational speed due to the removal of the inhibitor layer at a high speed. In addition, it was established that the efficiency increases with decreasing temperature, increasing the concentration of the inhibitor and decreasing the corrosion rate. Moreover, the above figures and tables reveal that the efficiency of the $NaNO_3$ inhibitor is more than that of castor oil, with their efficiency being 98.6% and 93.7%, respectively. This is because the $NaNO_3$ inhibitor creates a thicker and stronger contiguous layer on the surface of the carbon steel than the castor oil inhibitor, which in turn isolates the arrival of the dissolved oxygen onto the surface of the carbon steel. This is in agreement with the observations of several previous papers [25, 26].

Although the inhibiting efficiency of green inhibitors is lower than chemical inhibitor, it is necessary to continue research for high efficiency green inhibitors as an alternative to chemical inhibitors. The green inhibitors possess the advantages of cheapness, availability, environmental friendliness and they do not form complex compounds when added to crude oil. These are the benefits that cannot be achieved by using the chemical inhibitors.

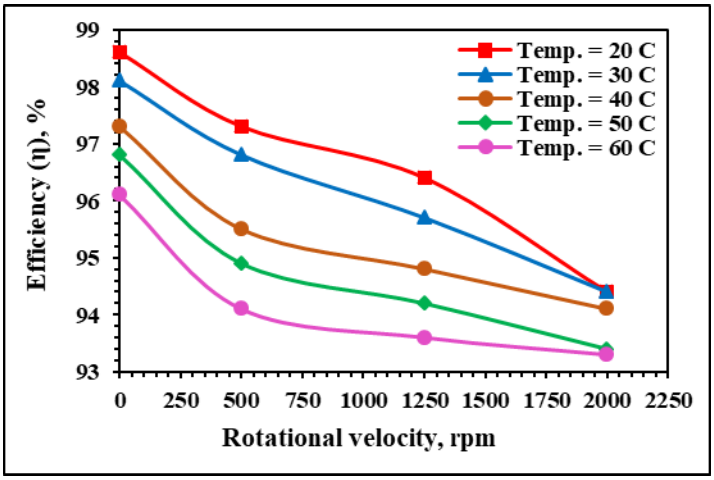

Fig. (12): The rotational velocity versus NaNO3 inhibitor efficiency at 1.5 g/l concentration and different temperatures.

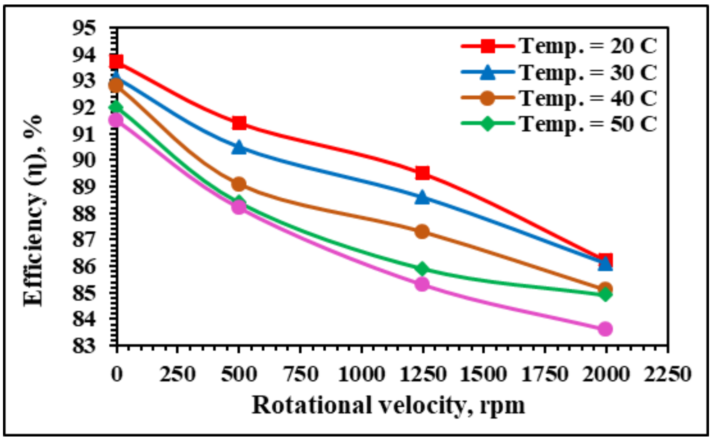

Fig. (13): The rotational velocity versus castor oil inhibitor efficiency at 1.5 ml/l concentration and different temperatures.

6. Conclusion

The following points represent the conclusion of this research:

1. The corrosion rate is directly proportional to the temperature and rotational speeds. This signifies an increase in the corrosion rate with increasing temperature and rotational speeds. This is due in turn to the removal of the protective surface films because of the high velocity flow which resulted in the diffusion of the dissolved oxygen (the main cause of corrosion) on the carbon steel surface due to the decreasing boundary and diffusion layers.

2. An increase in the molecular diffusion coefficient due to an increase in temperature, as this causes an increase in the diffusion rate of the oxygen and the reaction speed. This explains the effect of temperature on the corrosion rate by changing two main factors, namely, the solubility and diffusion of oxygen.

3. The mass transfer coefficient increases with increasing temperature, rotation speed and inhibitor concentration ($NaNO_3$ or castor oil). It was established that the mass transfer coefficient when using sodium nitride inhibitor is greater than when using the castor oil inhibitor.

4. The efficiency of the inhibitor is inversely proportional to the rotational speed and temperature of both inhibitors ($NaNO_3$ and castor oil). This indicates that the efficiency of the inhibitor is reduced by increasing the rotation speed and temperature, as they help to remove the layer of inhibitor that protects the carbon steel from corrosion at high speed.

5. The efficiency of the $NaNO_3$ inhibitor is better than that of the castor oil inhibitor, where the maximum efficiency of the $NaNO_3$ inhibitor was 98.6% at 20 °C, a 1.5 g/l concentration and rotational velocity of 0 rpm, while the maximum efficiency of castor oil was 93.7% at a temperature of 20 °C, a concentration of 1.5 ml/l and a rotation velocity of 0 rpm. The reason for this, is that the $NaNO_3$ inhibitor creates an adjacent layer on the surface of the carbon steel that is thicker and stronger than that produced by the castor oil inhibitor, which in turn is more efficient at protecting the surface from corrosion. This suggests that using the chemical inhibitor sodium nitrate to prevent corrosion of the carbon steel in the crude oil medium is better than using the green inhibitor (castor oil), because of its great ability to prevent the arrival of dissolved oxygen onto the surface of the carbon steel and thus protect it from corrosion.

6. The comparison of the inhibiting efficiency of various green inhibitors demonstrates that the castor oil possesses highest value of 93.7%. This is the higher value than the one presented for lemongrass extract, which is 58.19% [10], as well as better than the inhibiting efficiency achieved by neem oil (81%) and punga oil (83%) [11].

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