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Evaluation of Corrosion Inhibition of Carbon Steel in Crude Oil by Using Different Green Corrosion Inhibitors and Various Rotation Speeds

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Abstract

Corrosion is a major problem in the petroleum industry, which often occurs to crude oil production equipment and to petroleum product transportation pipelines as well. In order to protect these parts from corrosion, much small quantities of inhibitors are constantly injected, which gradually formulate a fluffy layer of inhibitor over the metal surface so as to protect it from corrosion. Recently, the impact of corrosion inhibitors on the environment has been raising more attention and concern. New regulations related to environment have been designated, imposing a change in the use of toxic chemicals to the utilization of the so-called “green chemicals”. Experiments on carbon steel corrosion protection have been conducted in a medium of crude oil has an API gravity of 30.6 by using different concentrations, ranging between 100 – 400 ppm of different green inhibitors such as corn oil, sunflower oil, flaxseed oil and castor oil with a different rotation speeds, namely, 0, 500, 1250 and 2000 rpm. The weight loss outcomes have showed that the rate of carbon steel corrosion in the crude oil decreases with the rise of inhibitors’ concentration, while corresponds with the increase of the rotational speed. In addition, it was found that the maximum inhibition efficiency achieved for the inhibitors corn oil, sunflower oil, flaxseed oil and castor oil in crude oil was using a concentration of 400 ppm, a rotation speed of 0 rpm and an ambient temperature (25 °C) is 41.85%, 50.76%, 63.55% and 92.63%, respectively.

Keywords: Corrosion rate; Green inhibitors; Dissolution current density; Rotational speed.

تقييم تثبيط تآكل الكربون الصلب في النفط الخام باستخدام مثبطات تآكل خضراء مختلفة وسرع دوران مختلفة

الخلاصة

يعتبر التآكل مشكلة رئيسية في الصناعة البترولية، والتي تحدث غالبًا في معدات إنتاج النفط الخام وفي أنابيب نقل المنتجات البترولية ايضاً. من أجل حماية هذه الأجزاء من التآكل، يتم حقن كميات صغيرة جدا من المانع باستمرار، والذي يشكل تدريجياً

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طبقة رقيقة من المانع على سطح المعدن لحمايته من التآكل. في الآونة الأخيرة، أثار تأثير مثبطات التآكل على البيئة مزيدا من الاهتمام والقلق. تم وضع لوائح جديدة تتعلق بالبيئة، وفرض تغييراً في استخدام المواد الكيميائية السامة الى استخدام بما يسمى "المواد الكيميائية الخضراء. تم أجراء تجارب لحماية الصلب الكربوني من التآكل في وسط من النفط الخام له API يبلغ 30.6 باستخدام تراكيز مختلفة تتراوح بين 100-400 جزء في المليون من مثبطات خضراء مختلفة مثل زيت الذرة وزيت عباد الشمس وزيت بذور الكتان وزيت الخروع مع سرع دوران مختلفة وهي 0، 500، 1250 و 2000 دورة في الدقيقة. أظهرت نتائج فقدان الوزن أن معدل تآكل الفولاذ الكربوني في الزيت الخام يتناقص مع زيادة تركيز المثبطات الخضراء، بينما يرتفع مع زيادة سرعة الدوران. بالاضافة الى ذلك، وجد ان أقصى كفاءة ثبيط تم تحقيقها لمثبطات زيت الذرة وزيت عباد الشمس وزيت بذور الكتان وزيت الخروع في النفط الخام كانت باستخدام تركيز 400 جزء في المليون وسرعة دوران صفر دورة في الدقيقة وعند درجة حرارة 25 م° وهي 41.85٪، 50.76٪، 63.55٪ و 92.63٪ على التوالي.

1. Introduction

Corrosion of carbon steel (c-steel) with the existence of produced oilfield water is somehow normal in the industries of petroleum [1, 2]. Produced oilfield water, also named formation water, subsists in oil reservoirs and natural gas as well as in pipelines of petroleum product. This formation water is rich with massive amounts of dissolved salts, such as sulfate and chloride in addition to corrosive dissolved gases like H_2S and CO_2 [3, 4]. Numerous artificial organic corrosion inhibitors are utilized to protect metals, but almost all of them are quite toxic to both environment and human beings. In fact, they are non-biodegradable and often costly. The poisoning may take place either through the combination of the organic compound or through its implementation [5].

Inhibitors of corrosion are materials which are utilized in few quantities in the environment to avert or retard corrosion. The idea of corrosion protection with Inhibitors of corrosion is to create a fluffy film on the material surface to prevent corrosion. This is attained by stimulating it to evolve a thick anticorrosive component or by amending the properties of environmental resulting in the stoppage or decrease of attacked behavior [6]. The inhibitors of organic film forming are used in the systems of gas and crude oil production, transportation and storage [7]. A lot of these formulations consist of chemicals, which are considered in many countries as “priority pollutants”. For instance, amine-based inhibitors are utilized in pipelines of petroleum product [8], but because of the water contamination in the petroleum product pipelines as well as the tanks of crude oil, these inhibitors confront biodegradation. Thus, identification of ecofriendly and non-degradable inhibitors is a prerequisite issue [6, 9]. The modern generations of ecological regulations demand the surrogate to be what is known nowadays as “green chemicals”. During the last three decades, a lot of research work has been conducted on “green corrosion inhibitors”

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so as to come up solutions with which metals could be protected from corrosion, and meanwhile utilizing cheap and efficient molecules at a minimum or at a “zero” environmental impact, such as iron, carbon steel and mild steel [10, 11].

The altitude in cost and the unfriendly impact related to inorganic and organic inhibitors shall be taken into consideration when reducing their use as a corrosion preventer. Additionally, it seems that engineers and specialized scientists, who work in the area of corrosion are inclined to utilize green inhibitors. These green inhibitors shall be renewable, plausible, environmentally friendly and non-toxic [12].

The current study aims to examine the efficiency of green inhibitors, such as corn oil, sunflower oil, flaxseed oil, and castor oil in preserving c-steel from corrosion, in addition to selecting the most efficient for use in protecting pipelines transporting petroleum products as well as the tanks of crude oil due to being cheap, and non-toxic to the environment and to people if compared to organic or chemical inhibitors.

2. Materials used

2.1 The corrosion medium

Crude oil is the medium where the experiments of weight loss are utilized. Analysis tests of the crude oil characterizations have been conducted in the laboratories of Midland Refineries Company, Baghdad, Iraq. The outcomes are shown in Table (1).

Table (1) Characterizations of the crude oil used in weight loss experiments.

Crude oil properties at temp. 25 ˚C	
Density (ρ)	911 kg/m^3
Kinematic viscosity (ν)	55.42 (m^2/s) × 10^{-6}
Dynamic viscosity (μ)	53.43 (kg/m.s) × 10^{-3}
Diffusivity (D)	1.679 (m^2/s) × 10^{-4}
Conc. of O_2	44 (g/l) × 10^{-3}
M.W of O_2	331.58 (g/gmol)
Crude oil constituents at temp. 25 ˚C	
Water content vol.%	0.15
Sulfur content wt.%	3.11
Sediment vol.%	0.05
Salt content wt.%	0.0072
Ram. carbon residue wt.%	5.4

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Asphaltenes content wt.%	**2.03**
Ash content wt.%	**0.0140**
Vanadium, ppm	**62.19**
Nickel, ppm	**19.69**

2.2 Castor oil

Castor oil is a vegetable oil obtained from castor beans. It is a pale yellow or colorless liquid, with a distinctive taste and smell. It has a density of 0.961 g/cm^3 and a boiling point of 595 °F (313 °C). Its formula of molecular is C57H104O9, carbon-12th has an active group of hydroxyl, which makes oil of castor further polar when contrasted to other oils [13].

2.3 Sunflower oil

Sunflower oil is an oil of vegetable pressed from the seeds of sunflower. It has a pale-yellow color, density of 0.918 g/cm^3 and a viscosity of 0.049 kg/m.s at 25 °C. It is mainly composed of polyunsaturated fat, a linoleic acid and monounsaturated fat, an oleic acid. As of 2017, hybrid sunflowers were developed to increase oil production to meet growing consumer demand for sunflower oil and its commercial varieties [14, 15].

2.4 Flaxseed oil

Flaxseed oil, also known as linseed oil or flax oil, is made from flax seeds that are squeezed to release their natural oil. It is a colorless to yellowish oil, boiling point is 316 °C and density is 0.93 g/cm^3 at 25 °C. It is primarily composed of alpha-linolenic fatty acid, monounsaturated fatty acids (mainly oleic acid), saturated fatty acids (palmitic and stearic) and protein [16, 17].

2.5 Corn oil

Corn or maize oil is extracted from the corn/maize kernels. It is generally less expensive than most other types of vegetable oils. It mainly consists of saturated, monounsaturated and polyunsaturated fatty acids (α-linolenic and linolenic acids). It has a pale yellow color, density of 0.917-0.925 g/cm^3 at 25 °C and a smoke point is 450 °F (232 °C) [18].

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3. The Experimental Work

3.1 Equipment used in the experiment

3.1.1 Balance: An electronic digital scale with amazing accuracy, having four decimal points per gram, with a maximum weight of 120 g. It is a Model of M214Ai made by BEL Engineering Company-Italy, applied to weigh the inhibitors as well as samples before and after the experiments of weight loss.

3.1.2 Thermometer: A laboratory thermometer used for measuring the temperature of different liquids ranging between (0 - 100) ˚C. Its body is made of glass, with gross length of 15.5 cm, full of red spirit, and manufactured by ELEMENTAL EUROPE LTD.

3.1.3 Water bath: A Digital Thermostatic Lab Water Bath, Model HH-1. It has been utilized to regulate the temperature of the cell with high veracity at a maximum of 120 °C. It is manufactured by MONIPA Company-USA.

3.1.4 Rotating cylinder electrode: A Modulated Speed Rotator (MSR), manufactured by the Company of Pine Research-UK. MSR incorporated an electrode rotator and a control unit with an amenable rotational speed ranging from (50 - 10000) rpm, and a reading display accuracy of 1%.

3.1.5 Drying oven: A lab drying oven with temperature ranging between (10 - 300) °C, shows an accuracy of 0.1 °C and a capacity of 80 liters, being utilized for drying carbon steel electrode. The Model Number is DHG-9075A. It is manufactured by SERICO Company-China.

3.2 Design of the working electrode

The c-steel sample utilized in weight loss experiments has a cylindrical shape, with dimensions of 3 cm in length (L), outer diameter (dout) of 3 mm and 2 cm in thickness (th). Hence, the overall surface area of a c-steel sample = 4.09 x 10^{-3} m^2 as it has been calculated by applying the following formula:

$$Sample\ area\ (A) = 2 \times \pi \times d \times L + 2 \times \pi (R^2 - r^2) \dots \dots \dots eq.1$$

where R is the outside radius of the sample (cm) and r is the outside radius of the sample (cm).

Figure 1 shows a sample of carbon steel polished using silicon carbide sheets.

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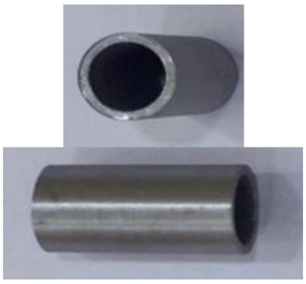

Fig. (1): Working electrode sample.

In order to assess the chemical composition (wt %) of the fundamental metals that industrialize the sample, this test was carried out at the laboratory of the State Company for Inspection and Engineering Rehabilitation (SIER) laboratory. Table (2) shows the results of the test.

Table (2) Chemical composition, wt %, of the fundamental metals of the sample.

Cr	C	P	S	Si	Mo	Mn	Ni	Co	Al	Cu	Fe
0.005	0.179	0.011	0.012	0.009	0.025	0.387	0.023	0.006	0.059	0.017	bal.

3.3 The weight loss experiment procedure

As maintained by the following procedures, the process of corrosion rate calculation has been conducted at rotational speeds (0, 500, 1250 and 2000) rpm and at different inhibitor concentrations of the neem seed oil, lemongrass extract, castor oil and bonga oil, namely, 100, 200, 300 and 400 ppm.

First of all, before each experiment, the specimen c-steel (working electrode) has been shinnied with paper of silicon carbide grit and cleaned by using gauze paper. Then, the c-steel specimen shall be immersed in crude oil for 20 minutes at 25 ℃ and at a rotational velocity of (0 rpm). After that the specimen is removed from the crude oil, cleaned and dried with gauze paper, then immersed in hydrochloric acid (HCl) for three minutes. After being removed from HCl, it is soaked in a solution of acetone for five minutes. The following step is to dry and place the c-steel in the oven at 150°C for twenty minutes. After that, the specimen is weighed by using a sensitive balance, and the first weight (W1) is registered. Once more, the c-steel is immersed in crude oil, but for three hours this time and in HCl acid for three minutes. Thereafter, it is washed with distilled water, soaked in a solution of acetone for five minutes and dried with gauze paper before being placed again in the oven at 150 ℃. For the second time, the sample is weighed and

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the weight (W2) is recorded. The final two steps are measuring the weight loss (ΔW), where ΔW= W1-W2 and calculating the corrosion rate (CR) through the use of the following formula:

$$CR = \frac{\Delta W}{A \times t} \ldots \ldots \ldots eq.2$$

where A is the c-steel specimen surface area (m^2), t is the exposure time (s) and ΔW is the loss of weight (g).

Subsequently, by using the same procedure above, the corrosion rate is measured at 25 °C, rotational velocities of (500, 1250 and 2000) rpm and at various concentrations of inhibitors of sunflower oil, flaxseed oil, castor oil and corn oil. Figure (2) displays the weight loss experiment with the devices.

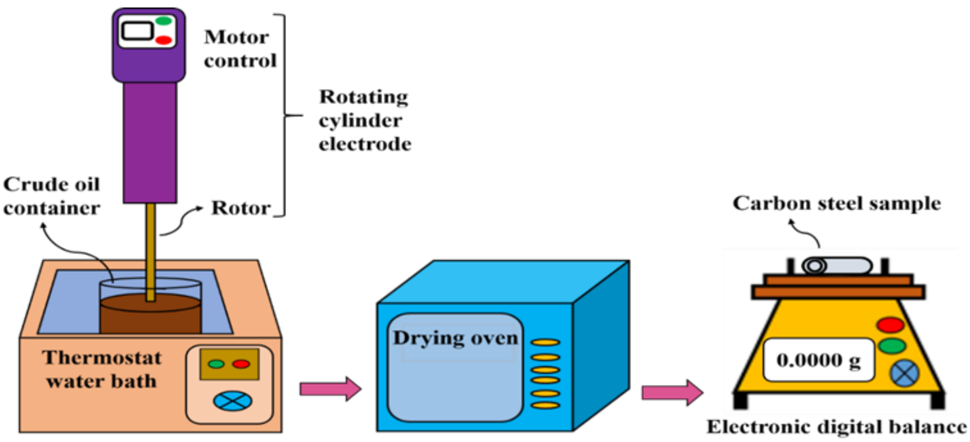

Fig. (2) Schematic diagram of weight loss experiment and the devices used in the experiment.

3.4 Calculation of the dissolution current density (I_d)

The dissolution current density of the c-steel sample in crude oil, which is mentioned in Tables (3) and (4) was determined using the following equations.

$$I_d = Z \times K \times F \times C_b \ldots \ldots \ldots eq.3$$

where

I_d: is the limiting current density (A/m^2).

Z: is the number of electrons transferred through the crude oil as a result of corrosion.

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K: is the mass transfer coefficient, which is utilised with a value of 3.27×10^{-3} m/s.

F: is the Faraday's constant, which is equal to 96487 $A.s.mol^{-1}$.

C_b: is the oxygen concentration bulk in the crude oil (mol/m^3).

The value of C_b was calculated utilising the equation below

$$C_b = \frac{C_{O_2}}{MW_t} \dots \dots \dots eq. 4$$

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

The dissolution current density values "I_d" were acquired by compensation the values of C_b (which have been obtained from equation 4) in equation 3.

4. Results and Discussion

The experimental outcomes as well as the discussions related to evaluating the concentrations of inhibitors and rotational speeds so as to comprehend and clarify the influence of these adaptable factors on the c-steel corrosion in a medium of crude oil.

The experiments of weight loss have been carried out at different rotational speeds so as to examine the influence of inhibitors concentrations (sunflower oil, corn oil, castor oil and flaxseed oil) on the weight loss, rate of corrosion in gmd (g/m^2 per day), the efficiency of the inhibitors (η) in (%) and dissolution current density (I_d) in A/m^2. Their values have been registered in Tables (3) to (5).

4.1 Effect of rotational speed on corrosion rate of c-steel and dissolution current density in a medium of crude oil

Both Table (3) and Figure (3) confirm that the corrosion rate of c-steel increases with the increasing of rotational speed, and this occurs because of the removal of the protective surface films due to the high flow of velocity, leading to an increase in the diffusion of oxygen on the metal surface, causing meanwhile a decrease in the boundary and diffusion layers [19]. Therefore, the corrosion increases with the rise of oxygen diffusion, since oxygen is the main factor for the occurrence of corrosion. This is in agreement with several previous studies [20].

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Figure (4) and Table (3) show that the dissolution current density rises with the increase of rotational speed by raising the diffusion of oxygen. In addition, it is proportionate to the increase in the corrosion rate of c-steels as shown in Table (3). This is caused by the rise of the oxygen transferred on the surface of c-steel, being a main factor for corrosion. These results are almost similar to conclusions of previous students [19].

Table (3) Effect of rotational speed on the corrosion rate and density of dissolution current without adding corrosion inhibitors.

Rotational speeds, rpm	Corrosion rate (CR), gmd	Dissolution current density (I_d), A/m^2
0	0.4963	11.1734
500	1.1640	11.6749
1250	2.3027	12.9820
2000	2.8351	14.5412

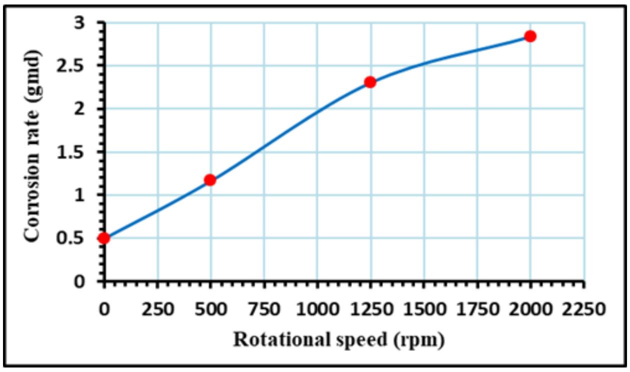

Fig. (3): Corrosion rate versus rotational speed without using a corrosion inhibitor.

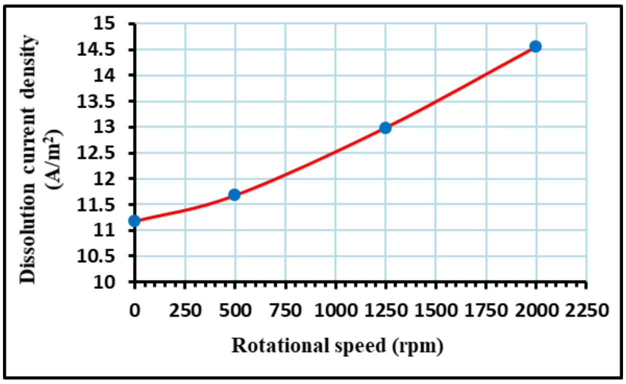

Fig. (4): Dissolution current density versus rotational speed without using a corrosion inhibitor.

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4.2 Effect of inhibitor concentration and rotational speed on corrosion rate of c-steel and dissolution current density in a medium of crude oil

From Figures (5) to (8) and Table (4), it can be observed that the inhibitors concentration of castor oil, flaxseed oil, sunflower oil and corn oil is inversely proportional to the corrosion rate of c-steel, where the corrosion rate of metal increases as concentration of the inhibitor decreases and vice versa. This is due to the reality that the inhibitors compose films surrounding the c-steel in different ways: (*i*) huge sediments are formed by adsorption; (*ii*) and/or formulate a passive layer on the c-steel surface. This signalizes that a few inhibitors delay corrosion by adsorption, composing a thin, sightless film with a light thickness of molecules, while others shape enormous sediments which coat the c-steel and protect it from oxygen attack which is considered the main reason for corrosion; (*iii*) they compose a coalescence of corrosion and absorption product, and thus creating a passive layer, which surrounds and protects the c-steel [21, 22]. Besides, corrosion rate of c-steel can be graded from largest to smallest according to the type of inhibitor used and as follows: corn oil, sunflower oil, flaxseed oil and castor oil. Accordingly, we may conclude that castor oil is the most efficient in preventing corrosion while corn oil is the least efficient.

Table (4) Effect of Inhibitors concentration on the corrosion rate and the density of dissolution current under different rotational speeds.

Inhibitor type		Rotational speeds, rpm	Inhibitor concentration (ppm)				
			0	100	200	300	0
Castor oil	CR (gmd)	0	0.4963	0.2950	0.1832	0.1467	0.1210
		500	1.1640	0.3201	0.2906	0.2674	0.2056
		1250	2.3027	0.6108	0.5508	0.5042	0.4167
		2000	2.8351	0.7590	0.7195	0.6684	0.6040
	I_d (A/m^2)	0	11.1734	9.8698	6.6450	4.8632	4.3965
		500	11.6749	10.9339	7.8543	6.3843	4.6863
		1250	12.9820	10.6749	8.8653	6.6139	5.5239
		2000	14.5412	11.9046	10.6749	7.1798	6.2097
Flaxseed oil	CR (gmd)	0	0.4963	0.2804	0.2563	0.2290	0.1987
		500	1.1640	0.6529	0.3382	0.3443	0.3162
		1250	2.3027	0.8956	0.7743	0.6579	0.5329
		2000	2.8351	1.2423	1.1377	1.0173	0.8090
	I_d	0	11.1734	11.8437	9.6714	8.3958	6.0936
		500	11.6749	12.9439	10.3974	8.4409	6.9778

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	(A/m^2)	1250	12.9820	13.9301	11.0109	9.3755	8.1184
		2000	14.5412	15.0041	12.8193	10.3239	8.7607
Sunflower oil	CR (gmd)	0	0.4963	0.3342	0.2998	0.2754	0.2488
		500	1.1640	0.7285	0.5979	0.3860	0.3517
		1250	2.3027	1.2661	0.9812	0.8103	0.6223
		2000	2.8351	1.4962	1.1558	1.0540	0.9128
	I_d (A/m^2)	0	11.1734	12.584	10.5982	9.7493	8.8149
		500	11.6749	13.4180	12.5120	10.3672	9.5143
		1250	12.9820	14.5768	13.1647	12.3247	10.2646
		2000	14.5412	15.6651	14.6880	13.0464	11.6278
Corn oil	CR (gmd)	0	0.4963	0.4665	0.4258	0.4088	0.3407
		500	1.1640	1.1605	0.9357	0.7234	0.5905
		1250	2.3027	2.1308	1.1874	1.4675	1.1431
		2000	2.8351	2.6272	2.4032	2.1562	1.9327
	I_d (A/m^2)	0	11.1734	14.8197	12.2643	11.3860	9.6972
		500	11.6749	15.7431	14.5230	12.0769	10.7632
		1250	12.9820	17.6194	15.1736	13.0657	12.1851
		2000	14.5412	18.3805	16.0568	14.8015	13.2319

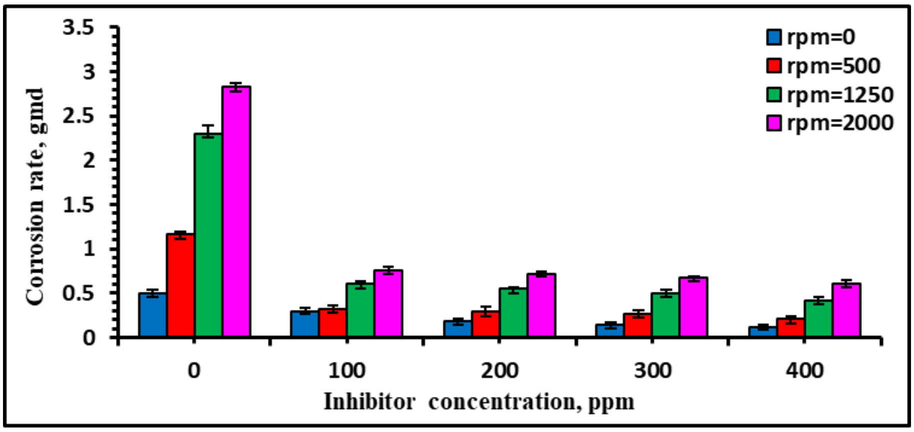

Fig. (5): Corrosion rate versus castor oil inhibitor concentration under different rotational speeds.

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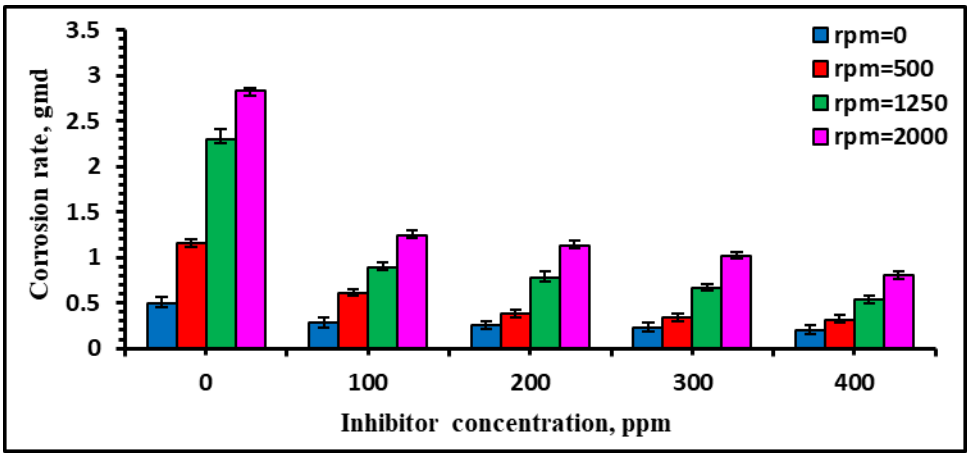

Fig. (6): Corrosion rate versus flaxseed oil inhibitor concentration under different rotational speeds.

Figures (9) to (12) and Table (4 illustrate that the density of current dissolution increases due to raising the rotational speed as an outcome of the rise in oxygen transported at the surface of carbon steel. Moreover, it can be observed that the density of current dissolution is inversely proportional to the inhibitor concentration, where the density of current dissolution increases when concentration of the inhibitor decreases and vice versa. This, in turn, is due to the fact that the protective films on the surface of c-steel increase in thickness with the increase in the concentration of the inhibitor, which results in a decrease in the diffusion of dissolved oxygen (the main corrosion reason) on the surface of c-steel, and thus causing a decline in the value of the dissolution current density. It is remarkable to note that these findings have been concluded by many researchers [23, 24]. Table 4 shows the dissolution current density values graded from low to high as per the type of inhibitor, and they are castor oil, flaxseed oil, sunflower oil and corn oil, respectively.

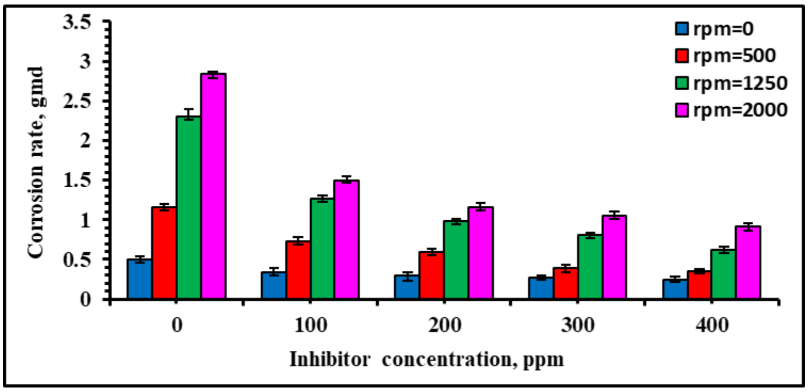

Fig. (7) Corrosion rate versus sunflower oil inhibitor concentration under different rotational speeds.

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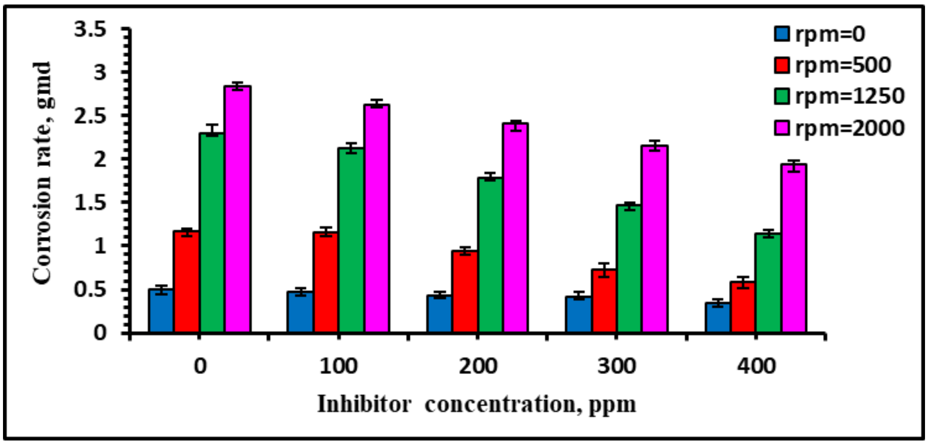

Fig. (8): Corrosion rate versus corn oil inhibitor concentration under different rotational speeds.

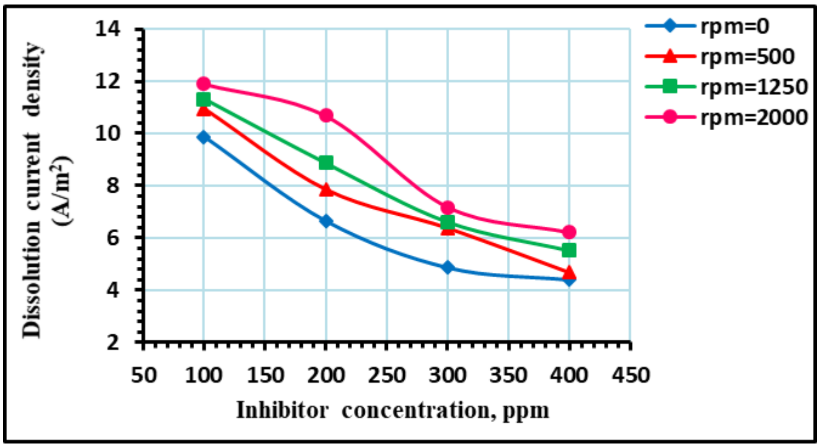

Fig. (9): Dissolution current density versus castor oil inhibitor concentration under different rotational speeds.

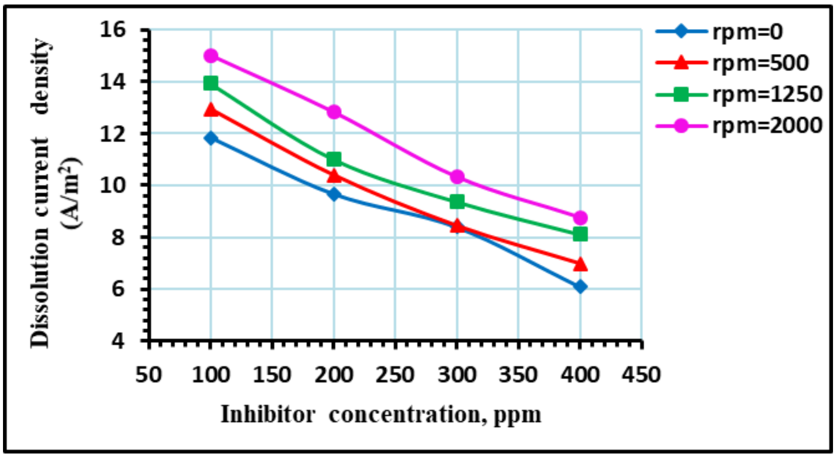

Fig. (10): Dissolution current density versus flaxseed oil inhibitor concentration under different rotational speeds.

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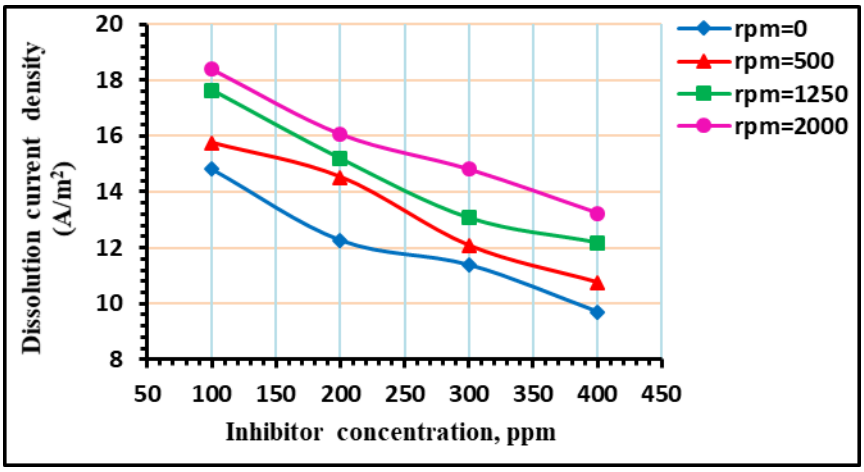

Fig. (11): Dissolution current density versus sunflower oil inhibitor concentration under different rotational speeds.

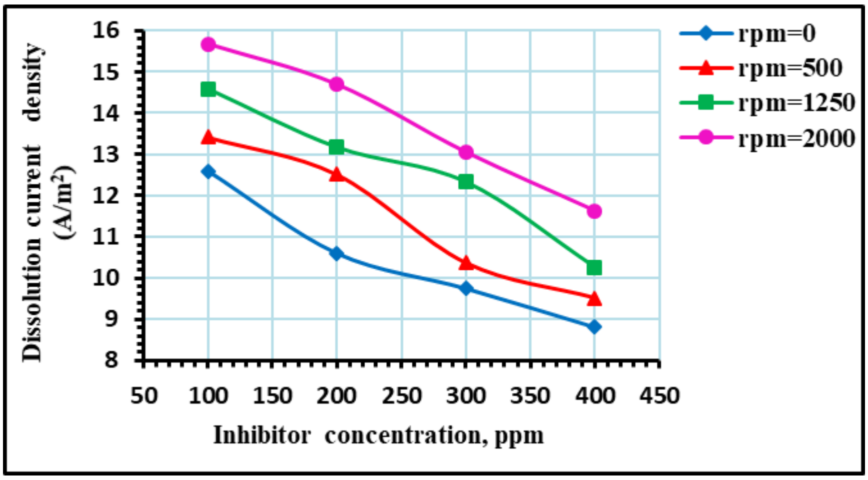

Fig. (12): Dissolution current density versus corn oil inhibitor concentration under different rotational speeds.

4.3 Effect of inhibitor concentration and rotational speed on inhibition efficiency of c-steel in a medium of crude oil

Table (5) and Figures (13) to (16) reveal that the efficiency of the inhibitors used is inversely proportional to the rotational speed. This marks that the inhibitor efficiency is decreases with rising the rotational speed, as the rate of corrosion is increased because of the elimination of the inhibitor layer which occurs due to high speed. This means, as the electrode starts to rotate, stimulated convection flow increases the dissolution and diffusion of c-steel ions from the corroded surface towards the crude oil. The rise in c-steel ion transportation rate occurs

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simultaneously with the decrease in the thickness of the diffused layer (δ), which further eases ion diffusion toward the surface of the c-steel and consequently, raises the rate of corrosion. The diffused layer thickness can be specified, depending on the kinematic viscosity (v), diffusion coefficient (D), and angular rotation speed (ω) as shown in the following formula [25]:

$$\delta = \frac{D^{\frac{1}{3}}}{0.62\omega^{\frac{1}{2}}v^{\frac{-1}{6}}} \ldots\ldots\ldots eq.5$$

Moreover, it can be noticed that the inhibition efficiency increases with the rise of the inhibitor concentration, and this is due to the fact that the thickness of the protective layer, which protects c-steel from corrosion, is directly proportional to the concentration of the inhibitor and the ability of the inhibitor molecule to be adsorbed onto the surface of the metal [26]. It must be noted that castor oil molecules are adsorbed onto the c-steel surface more rapidly than other oils molecules due to the difference in their binding energies. As the binding energy of castor oil is higher than that of the other three oils, its adsorption will be greater. Thus, the adsorption capacity of inhibitor molecules on the steel surface depends on the difference in binding energies at 25 ˚C (298 ˚K); they will adhere to the following order: castor oil > flaxseed oil > sunflower oil > corn oil. In addition, the figures and efficiency table displayed below show that the efficiency of the inhibitors, from highest to lowest, corresponds with their ability to be adsorbed from the metal surface; they are noted as follows: castor oil, flaxseed oil, sunflower oil and corn oil, where their efficiency is 92.63%, 63.55%, 50.76% and 41.85%, respectively. This is because the castor oil inhibitor creates a thicker and stronger adjoining layer on the surface of the c-steel than the rest of the inhibitors, which in turn segregates the access of dissolved oxygen to the surface of the c-steel. It is considerable to that these findings are harmonious with the remarks of a number of former researches [27, 28].

The inhibiting efficiency comparison of different green inhibitors reveals that castor oil is in possession of highest value, and that is 92.93%. This value indeed is greater than the inhibiting efficiency attained by punga oil (83%) and neem oil (81%) [29]. It is better as well than the one offered by lemongrass extract, which is 58.19% [30].

In spite of the fact that the efficiency of green inhibitors is less than that of chemical inhibitors [31], it is substantial to go ahead with research to find high efficiency green inhibitors as an

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alternate to chemical inhibitors. Green inhibitors, as a matter of fact, possess the characteristics of environmental friendliness, in addition to availability and cheap prices. Besides, they do not compose complex compounds when placed in crude oil. These are the good features that cannot be attained by utilizing chemical inhibitors.

Table (5) Inhibition efficiency values of different concentrations of inhibitors under different rotational speeds.

Inhibitor type	Rotational speeds, rpm	Efficiency (η), %			
		100 ppm	200 ppm	300 ppm	400 ppm
Castor oil	0	54.32	61.84	81.65	92.63
	500	48.38	58.70	72.64	88.59
	1250	45.98	54.91	67.29	84.67
	2000	37.81	47.44	62.45	80.33
Flaxseed oil	0	41.91	49.82	59.13	63.55
	500	37.14	43.80	53.72	57.34
	1250	34.52	41.25	49.86	53.87
	2000	29.96	35.73	46.69	49.08
Sunflower oil	0	36.73	43.60	49.68	50.76
	500	33.17	37.79	42.59	46.43
	1250	31.28	34.81	39.25	42.88
	2000	29.49	30.48	33.02	40.56
Corn oil	0	30.25	36.97	39.24	41.85
	500	28.11	33.87	35.06	38.53
	1250	27.74	32.19	32.82	36.77
	2000	25.41	29.34	30.70	34.29

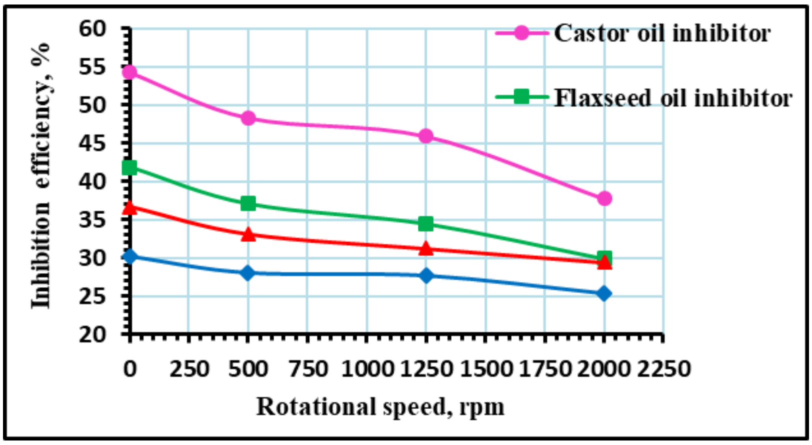

Fig. (13): Inhibition efficiency of inhibitors castor oil, flaxseed oil, sunflower oil and corn oil at concentration of 100 ppm versus different rotational speeds.

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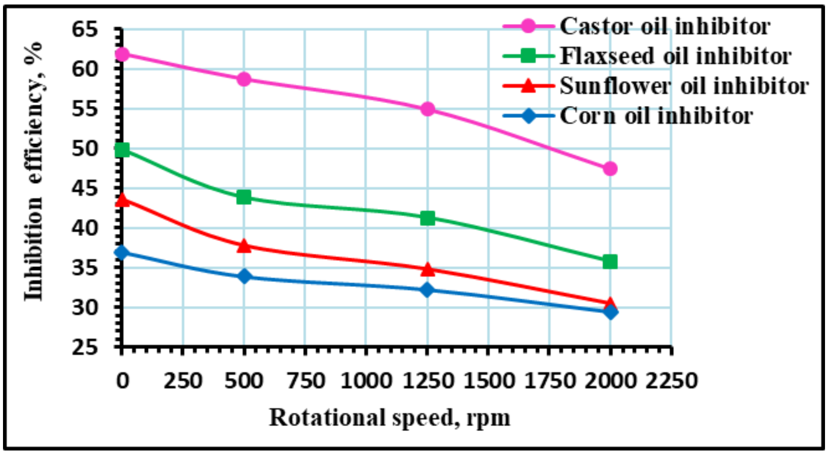

Fig. (14): Inhibition efficiency of inhibitors castor oil, flaxseed oil, sunflower oil and corn oil at concentration of 200 ppm versus different rotational speeds.

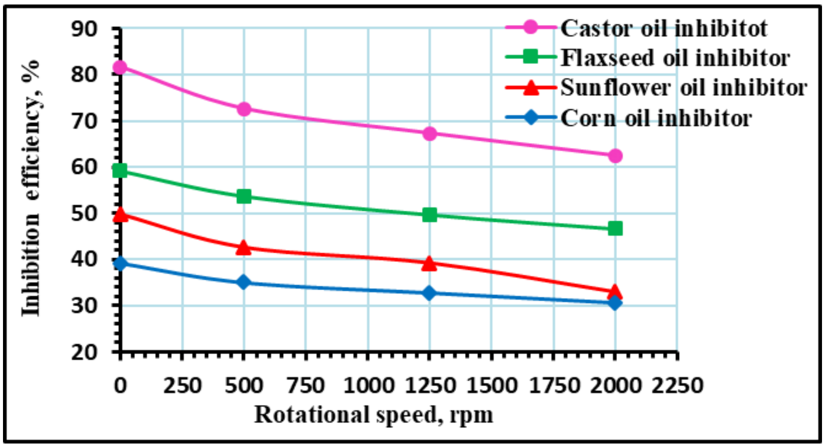

Fig. (15): Inhibition efficiency of inhibitors castor oil, flaxseed oil, sunflower oil and corn oil at concentration of 300 ppm versus different rotational speeds.

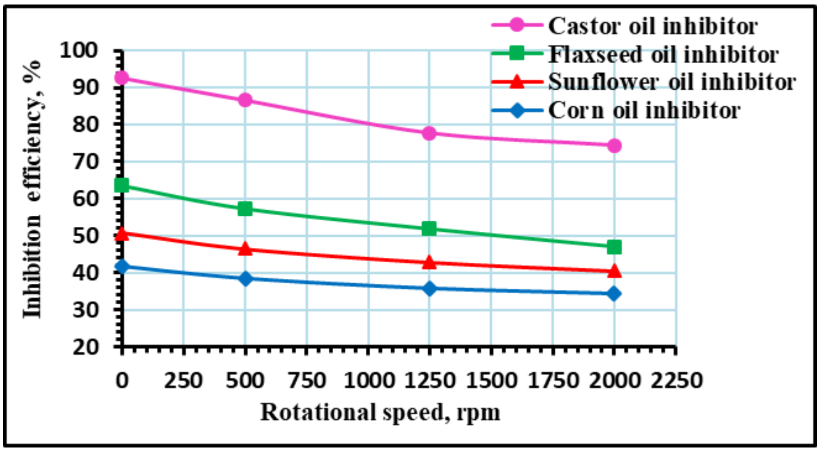

Fig. (16) Inhibition efficiency of inhibitors castor oil, flaxseed oil, sunflower oil and corn oil at concentration of 400 ppm versus different rotational speeds.

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5. Conclusions

1. The rate of corrosion of c-steel in a medium of crude oil is directly proportional to the rotational speeds. While, it is inversely proportional to the concentration of green inhibitor.

2. Increasing in the coefficient of molecular diffusion and dissolution current density as a consequence of an increase in rotational speed, as this leads to a rise in the reaction speed and the diffusion rate of the oxygen. This clarifies the impact of rotational speed on the rate of corrosion via changing two prime factors, that is, the oxygen diffusion and solubility.

3. The inhibition efficiency of the inhibitors used in this research is inversely proportional to the speed of rotation. While, it is directly proportionate to the inhibitor concentration.

4. The inhibition efficiency of the castor oil inhibitor is better than the inhibition efficiency of the other inhibitors, where the maximum efficiency of the castor oil inhibitor is 92.93% at ambient temperature (25 °C), a 400 ppm inhibitor concentration and rotational velocity of 0 rpm. Whilst, the maximum efficiency of the other inhibitors, namely, flaxseed oil, sunflower oil and corn oil at the same conditions has been 63.55%, 50.76% and 41.85%, respectively. The reason for this, is that the castor oil inhibitor generates a neighboring layer on the surface of the c-steel that is stronger and thicker than that created by the other inhibitors, being, therefore, more effective in protecting of the surface of c-steel from corrosion.

5. In general, it can be concluded that the castor oil inhibitor achieved good results in terms of the inhibition efficiency, but it is still in need of some necessary chemical modifications to achieve reliable results when utilized instead of the chemical inhibitors, that are still used more than green inhibitors due to their ability to build a thicker protective layer for the metal and in a shorter time [31].

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