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Validation of experimental and model for Temperature on wax deposition on Corrosion of Pipeline

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Abstract

This research was carried out to simulate the wax physical properties on pipeline corrosion. Wax is one of the most common components in crude oil and generates corrosion inhibition by wax deposition or formation on the internal surface of the pipeline, reducing the corrosion. Waxy crudes characteristics vary from location to location. Waxy crudes in Niger Delta oil fields in Agbada I Flow Station in Port Harcourt Rivers State have not received sufficient research attention compared to other crudes globally. A designed flow loop was fabricated for crude oil pipeline to simulate the model using the wax physical properties on pipeline corrosion. In order to measure the rate of corrosion, a linear polarization resistance method was utilized the corrosion rate in mils per year (mpy) against time (minutes) using MS1000 Corrosion Meter. A mathematical model was developed to predict wax deposition on temperature for corrosion for a cylindrical crude oil pipeline based on principle of mass, heat and material balance of mass. The models developed are temperature distribution model. MATLAB software was used for simulation with the experimental results and the input parameter from the wax physical properties and operating conditions. Based on the analysis, it has been found that as the deposition of the paraffin wax increases the corrosion rate decrease. This proves that paraffin wax deposition on the steel pipe act as a protective layer to inhibit corrosion. Comparing the results of experimental and model results for Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35^{o}C and Flow Rate at 10.21 L/min. It was observed at time 18 minutes, the experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline. From the profile plot, the values of the corrosion rate (mpy) against time (min) of the experimental and model results are 3 (0.68 mpy, 0.7467 mpy), 6 (0.75 mpy, 0.6327 mpy), 9(0.57 mpy, 0.5187 mpy), 12 (0.25 mpy, 0.4047 mpy), 15 (0.31 mpy, 0.2907 mpy), 18 (0.21 mpy, 0.1767 mpy). But the variation of the experimental and model results in terms of deviation is (0.007%) indicating that both results are insignificant in variation, showing positive agreement between the experimental and model results. This proves that paraffin wax deposition on the steel pipe act as a protective layer to inhibit corrosion.

Keywords: Simulation; Deposition; Properties; Corrosion; Wax; Temperature

1. Introduction

Waxy crude oil is a crucial petroleum resource (Zhu et al., 2024). The dissolved paraffin molecules within it are the primary factors affecting the effective functioning of oil and gas production, transportation, and storage systems (Chen, et al., 2024; Mahir et al., 2019; Zhang et al., 2024). When the oil temperature drops below the wax appearance temperature (WAT) of crude oil, paraffin molecules gradually aggregate and crystallize through collision and clustering, precipitating from the oil flow. The phenomenon of wax deposition increases the operational resistance of pipelines, reduces efficiency, and may even lead to blockages, thereby negatively impacting the economic performance of oil pipelines (Ala and Daraboina, 2024). Therefore, studying the wax

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deposition patterns in crude oil pipelines and developing wax deposition prediction models are essential for forecasting the extent of wax deposition by simulation. This work helps implement wax prevention measures promptly to ensure pipelines' safe and efficient operation (Santis et al., 2024; Alnaimat and Zianddin, 2020). Wax deposits, on the other hand, can help to prevent corrosion by forming wax layers on the interior pipeline surface, which prevent corrosive water from reaching the surface and thereby minimizing metal loss due to corrosion. Waxy crudes have different properties depending on where they're found. Corrosion in steel pipes is another problem in flow assurance in oil and gas industry. Moreover, CO_2 corrosion can cause damage in the pipeline material by deteriorating the pipelines material. Many experiments have been conducted individually on finding the factors that cause corrosion and factors causing wax precipitation. Though paraffin wax restricts the flow in the pipeline, it acts as a corrosion inhibitor by covering the inner wall of pipeline. Paraffin wax and CO_2 corrosion have caused many problems in oil and gas industry (Gjermundsen, 2006). These problems mainly caused in the transportation and utilities where the pipelines are severely corroded. The paraffin wax on the surface provides excellent corrosion protection, while others provided only moderate or negligible protection in the crude oil pipeline. Figure 1 shows wax deposition in a retrieved pipeline.

Source: (Hernandez *et al.,* 2004)

Figure 1 (a) Wax deposit in a retrieved pipeline (b). Oil pipeline corrosion

2. Materials and Methods

2.1. Materials

The following equipment were used to investigate the wax physical properties and operating condition, they are as follows- flow loop system, waxy crude oil, MS1000 LPR corrosion meter, Flow meter with temperature probe, handheld infrared thermometer, 0.5 horsepower pump.

2.2. Methods

Waxy crude oil laboratory flow loop system was design and fabricated to carry out series of experiment to validate the model simulated results. The experimental flow loop can give a better scenario of crude oil pipeline and accurate result to investigate the effect of temperature on wax deposit on corrosion rate in mils per year (mpy) against time in minutes on crude oil pipeline. The crude oil used in this study is one of the oilfields pipelines with waxing problems of Shell Petroleum Development Company in Niger Delta and was procured from Agbada 1 flow station in Ikwerre Local Government Area Rivers State. The characterization of the waxy crude was investigated to determine the Wax Physical Properties and Operating Conditions. Characterizations of waxy crude were performed in consonance with the requirement of ASTM D5442-17(2021). The ASTM is a standard testing method for petroleum waxes. The experimental program included variables that affect wax deposition process. The variables studied experimentally were effect of temperature between mixture and pipe wall. The corrosion rate in mil per year (mpy) against time (min) of the wax deposit on crude oil pipeline were tested using MS1000 Corrosion Meter. Then mathematical models were developed to predict the effect of wax deposition on corrosion of crude oil pipeline. The models were simulated using MATLAB software, and the results were recorded and analyzed

2.2.1. Experimental procedure

In order to simulate of wax deposition physical properties for temperature on pipeline corrosion, the crude oil sample is pumped into the flow-loop set up under different operating conditions. The range of the inlet temperature of the waxy crude oil was (10-40°C). The experiment was conducted 5 times, at time interval of 3-18 minutes, temperature was varied between 15-35°C and flow rate were also varied between 10.21-50.70 L/min. The experiment was carried out at varying flow rate with time while temperature is kept constant. At flow rate of 10.21, 20.37, 30.45, 40.28 and 50.70 L/min and time at 3, 6, 9, 12, 15 and 18 min while keeping temperature constant for each of the experimental run at 35 °C to determine the corrosion rate against time. After testing the corrosion rate of the waxy crude oil to simulate of wax deposition physical properties for temperature on pipeline corrosion at varying flow rate and time of the paraffin wax deposited on the crude oil pipeline. The results were recorded, the graph of corrosion rate (mpy) against time (min) was plotted and the result were analyzed. Figure 2 shows the experimental set-up of the flow loop.

Figure 2 Complete experimental flow loop set-up

2.2.2. Model formulation for temperature

$Q_r(\text{heat conducted in at radius r}) = -k2\pi r l \frac{dT}{dr}$ (1)

$Q_g(\text{heat generated in the element}) = -k2\pi r dr l q_g$ (2)

$Q_{g+dr}(\text{heat conducted out at radius r + dr}) = Q_r + \frac{d}{dr}(Q_r)dr$ (3)

For steady state conduction of heat flow

$Q_r - Q_g = Q_{r+dr}$ (4)

Since there will be no accumulation of heat $\frac{dT}{dr} = 0$

$\therefore Q_r = 0$

$Q_g = Q_{r+dr}$ (5)

Using equations (2) and (3) into (5)

$$2\pi r dr l q_g = d/dr\left(-k2\pi r dr l\frac{dT}{dr}\right)dr$$

As a result, the acceptable version of the heat equation is written as:

$\frac{d}{dr}\left(r\frac{dT}{dr}\right) = \frac{q_g}{k}r$ (6)

Upon integration

$$\int \frac{d}{dr}\left(r\frac{dT}{dr}\right) = -\int \frac{q_g}{k} r dr$$

$$r\frac{dT}{dr} = \frac{-q_g}{k}\int r dr$$

$$r\frac{dT}{dr} = \frac{-q_g}{k}\frac{r^2}{2} + C_1 \tag{7}$$

where
C_1 = Constant of integration

Dividing althrough of equation (7) by r

$$\frac{r\frac{dT}{dr}}{r} = -\frac{q_g}{k}\frac{r^2}{2}/r + \frac{C_1}{r}$$

$$\frac{dT}{dr} = \frac{-q_{gr^2}}{2kr} + \frac{C_1}{r}$$

$$\frac{dT}{dr} = \frac{-q_{gr^2}}{2k} + \frac{C_1}{r}$$

$$\frac{dT}{dr} = \frac{-q_g r}{2k} + \frac{C_1}{r} \tag{8}$$

Another integration offers a solution for a generic temperature distribution

$$\int\frac{dT}{dr} = \frac{-q_g}{2k}\int r dr + C_1\int\frac{1}{r}dr + C_2$$

$$T = \frac{-q_g}{2k}\left(\frac{r^2}{2}\right) + C_1 \ln r + C_2$$

$$T = \frac{-q_g}{2k}\left(\frac{r^2}{2}\right) + C_1 \log_e r + C_2 \tag{9}$$

Hollow cylinder with outside surface insulated (adiabatic)

The general solution for temperature distribution is

$$T = \frac{-q_g}{4k}r^2 + C_1 \log_e r + C_2 \tag{10}$$

$$\frac{dT}{dr} = \frac{-q_g r}{2k} + \frac{C_1}{r} \tag{8}$$

The relevant boundary conditions are used to determine the integration constant.

$T = T_1$ at $r = r_1$

At $r = r_2$, the conductive region is perfectly insulated and hence heat flow is zero from Fourier's Law, $Q = -kA\frac{dt}{dr}$ and accordingly the temperature derivative must be zero at $r = r_2$

Hence using equation (8), we get

$$0 = \frac{-q_g}{2k}r_2 + \frac{C_1}{r_2} \tag{11}$$

Using C_1 as subject of the formula

$$\frac{-C_1}{r_2} = \frac{-q_g}{2k}r_2 \tag{12}$$

Cross multiplying

$$-C_1 = \frac{-q_g}{2k}r_2 . r_2$$

$$-C_1 = \frac{-q_g}{2k}{r_2}^2 \tag{13}$$

Diving both sides of (13) by -1

$$\frac{-C_1}{-1} = \frac{\frac{-q_g}{2k}{r_2}^2}{-1}$$

$$C_1 = \frac{q_g {r_2}^2}{2k} \tag{14}$$

Applying the boundary condition $T = T_1$ at $r = r_1$ to equation (10) and noting that $C_1 = \frac{q_g}{2k} {r_2}^2$

$$T_1 = \frac{-q_g}{4k} {r_1}^2 + \frac{q_g}{2k} {r_2}^2 log_e r_1 + C_2 \qquad (15)$$

$$C_2 = T_1 + \frac{q_g}{4k}\left[\frac{1}{2}{r_1}^2 - {r_2}^2 log_e r_1\right] \qquad (16)$$

The generic solution for temperature distribution with these values of integration constants.

$$T = \frac{-q_g}{4k} r^2 + \frac{q_g}{2k} {r_2}^2 log_e r_1 + T_1 \frac{q_g}{2k}\left[\frac{1}{2}{r_1}^2 - {r_2}^2 log_e r_1\right.$$

$$T = T_1 + \frac{q_g}{2k}\left[\frac{{r_1}^2 - r^2}{2} + {r_2}^2 log_e\left(\frac{r}{r_1}\right)\right] \qquad (17)$$

Where k = thermal conductivity of material (metal) $(W/m - deg)$

ρ = resistivity

$q_g = I^2 \frac{\rho l}{A} \div AL = \rho\left(\frac{I}{A}\right)^2$

Temperatures are set on the interior and outer surfaces of a hollow cylinder.
The general solution for temperature distribution is

$$T = \frac{-q_g}{4k} r^2 + C_1 log_e + C_2 \qquad (18)$$

The relevant boundary conditions are used to determine the integration constants.
$T = T_1 atr = \mathrm{r}_1$ and $T = T_2 atr = \mathrm{r}_2$ that gives

$$T_1 = \frac{-q_g}{4k} r_1^2 + C_1 \mathrm{log_e r_1} + C_2 \qquad (9)$$

$$T_2 = \frac{-q_g}{4k} r_2^2 + C_1 \mathrm{log_e r_2} + C_2 \qquad (10)$$

Subtract (18) from (10)

$$T_1 - T_2 = \frac{-q_g r_1^2}{4k} + \frac{q_g r_2^2}{4k} + C_1 \mathrm{log_e r_1} - C_1 \mathrm{log_e r_2} + C_2 - C_2$$

$$T_1 - T_2 = \frac{-q_g r_1^2}{4k} + \frac{q_g r_2^2}{4k} + C_1(\mathrm{log_e r_1} - C_1 \mathrm{log_e r_2}) \qquad (19)$$

$$T_1 - T_2 - \frac{q_g r_2^2}{4k} + \frac{q_g r_1^2}{4k} = C_1(\mathrm{log_e r_1} - C_1 \mathrm{log_e r_2}) \qquad (20)$$

$$(T_1 - T_2)\left(-\frac{q_g}{4k}\right)(r_2^2 - r_1^2) = C_1\left(\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)\right) \qquad (21)$$

Dividing both sides of equation (3.21) by $\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)$

$$\frac{(T_1 - T_2)\left(-\frac{q_g}{4k}\right)(r_2^2 - r_1^2)}{\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)} = \frac{C_1\left(\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)\right)}{\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)}$$

$$C_1 = \frac{(T_1 - T_2) - \left(\frac{q_g}{4k}\right)(r_2^2 - r_1^2)}{\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)} \qquad (22)$$

$$\boldsymbol{C_2 = T_1 + \frac{q_g}{4k} r_1^2 - \frac{(T_1 - T_2) - \left(\frac{q_g}{4k}\right)(r_2^2 - r_1^2)}{\mathrm{log_e}\left(\frac{\mathrm{r_1}}{\mathrm{r_2}}\right)} \mathrm{log_e r_1}} \qquad \mathbf{(23)}$$

2.2.3. Simulation of the Model

A computer program was designed to solve numerically the governing equations of the developed models using the input parameter from the wax physical properties and operating conditions and the experimental data of wax physical properties on temperature for pipeline corrosion against time on pipeline corrosion. The model was simulated using MATLAB software, solved analytically and the model were developed based on principle of mass, heat and material balance of mass, the material balance of mass is also known as the law of conservation of mass. Based on the model developed, **equation (3.23)** is the Temperature distribution model used for simulate the wax physical properties of temperature on wax deposit on corrosion rate (mpy) against time (min) in crude oil pipeline. The results from computer simulation of the model were recorded, graph plotted and analyzed to compare the experimental and model data of temperature on wax deposit on corrosion rate (mpy) against time (min).

3. Results and Discussion

Table 1 Wax Physical Properties and Operating Conditions

Parameter	**Value**
Inside diameter	1.049 inch (0.0267m)
Inner pipe radius	0.0133(m)
Outside diameter	1.315 inch (0.0334 (m)
Outer pipe radius	0.0167 (m)
Pipe thickness	0.0034 (m)
Pipe length	2.007 (m)
Inlet temperature	15 (^oC)
Wall temperature	7.2 (^oC)
WAT	13.9 (^oC)
Flow velocity	0.387(kg/m^3)
Density of wax	838.5 (kg/m^3)
Density of oil	838.5 (kg/m^3)
Heat capacity of oil	2259 (J/kg^-K)
Thermal conductivity of oil	0.1466 (W/m^-K)
Thermal conductivity of wax	0.25 (W/m^-K)
Viscosity of oil	4.012cp

- **Matlab Program**

%This computer program was developed to calculate C (Θ, X, t) with respect to %0, X and t using the following parameters of the effect of temperature on wax deposit on corrosion of crude oil pipeline

%This computer program was developed to calculate C(Θ,x,t) with respect to %Θ,x and t using the following parameters for temperature at 35^{o}C while adjusting the flow rate at 10.21, 20.37,30.45,40.28 and 50.70 L/min.

clc

formatlonge

%Data Obtained

rc = 0.013325.;

D = 4.48*10^{-7};

t = [0 3 6 9 12 15, 18];

Θ = [35^0];

P = 1;

```
π = 3.142;

f = [10.21 20.37 30.45 40.28 50.70];

ρw = 838.5;

X = ?;

C0 = [0.8607 0.8913 0.778 0.8907 0.8813];

r = [1 2 3 4 5 6]

L = [0.3345 0.669 1.0035 1.338 1.6725 2.007];

c = (L + r*pi)/L;

d = (L - r*pi)/L;

%Model to be solved

Integral = sin((d.*Θ))./d - sin((c.*Θ))./c

ExpSin = exp(-r.*x).*sin(r.*Θ)

%Constant = exp(-D.*P.^2.*t)./(1 + (ρw.*Ks)./ϕ)

Constant = (D.*P.^2.*t)./(1 + (ρb.*Ks)./ϕ)

C = ((2.*C0)./L).*(rc./2).*Integral.*ExpSin.*Constant

%Export Results to MS Excel Sheet

Table = [t' Θ' X' C'];

xlswrite('obinichi4.xls', Table,'Sheet5','A5')
```

Table 2 MAT LAB Simulation of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) versus Time (min) at constant Temperature of 35^{o}C while adjusting the Flow Rate (10.21, 20.37, 30.45, 40.28 and 50.70 L/min)

Time (min)	**Corrosion Rate @10.21 L/min**	**Corrosion Rate @20.37 L/min**	**Corrosion Rate @30.45 L/min**	**Corrosion Rate @40.28 L/min**	**Corrosion Rate @50.70 L/min**
0	0.8607	0.8913	0.778	0.8907	0.8813
1	0.8227	0.8558	0.7506	0.8617	0.8586
2	0.7847	0.8203	0.7232	0.8327	0.8359
3	0.7467	0.7848	0.6958	0.8037	0.8132
4	0.7087	0.7493	0.6684	0.7747	0.7905
5	0.6707	0.7138	0.641	0.7457	0.7678
6	0.6327	0.6783	0.6136	0.7167	0.7451
7	0.5947	0.6428	0.5862	0.6877	0.7224
8	0.5567	0.6073	0.5588	0.6587	0.6997
9	0.5187	0.5718	0.5314	0.6297	0.677

10	0.4807	0.5363	0.504	0.6007	0.6543
11	0.4427	0.5008	0.4766	0.5717	0.6316
12	0.4047	0.4653	0.4492	0.5427	0.6089
13	0.3667	0.4298	0.4218	0.5137	0.5862
14	0.3287	0.3943	0.3944	0.4847	0.5635
15	0.2907	0.3588	0.367	0.4557	0.5408
16	0.2527	0.3233	0.3396	0.4267	0.5181
17	0.2147	0.2878	0.3122	0.3977	0.4954
18	0.1767	0.2523	0.2848	0.3687	0.4727

Table 3 Experimental results for Temperature at 35 °C on Corrosion Rate (mpy) against Time (min) on Wax Deposition

Time (min)	**Corrosion Rate (mpy) @10.21 L/min**	**Corrosion Rate (mpy) @ 20.37 L/min**	**Corrosion Rate (mpy) @ 30.45 L/min**	**Corrosion Rate (mpy) @ 40.28 L/min**	**Corrosion Rate (mpy) @ 50.70 L/min**
3	0.68	0.76	0.54	0.67	0.75
6	0.75	0.67	0.72	0.93	0.89
9	0.57	0.71	0.66	0.74	0.64
12	0.25	0.38	0.45	0.68	0.59
15	0.31	0.27	0.33	0.52	0.43
18	0.21	0.32	0.24	0.49	0.56

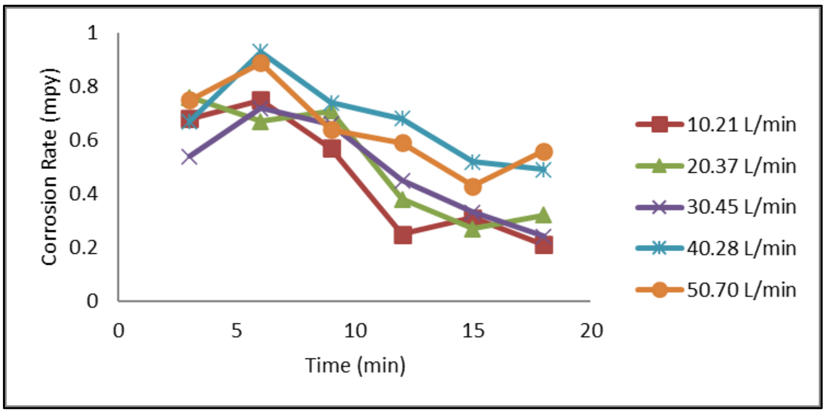

Figure 3 Graph of the Effect of Temperature at 35 °C on Corrosion Rate (mpy) against Time (min) on Wax Deposition

Figure 3 shows the graph of effect of temperature on corrosion rate against time at different flow rate of wax deposition during the corrosion inhibition.

A significant reduction in corrosion rates and excellent corrosion protection was achieved at a flow rate of 10.21 L/min for 18 minutes at a constant temperature of 35 ⍰, while others gave only moderate or negligible protection to the crude oil pipeline. It was observed that at time 3 min and at flow rate of 10.21 L/min, the corrosion rate is 0.68mpy and 0.76 mpy at 20.37 L/min at the same time, 0.54 mpy at the same time and flow rate of 30.45 L/min, 0.67 mpy at flow rate of 40.28 L/min, and 0.75 mpy at flow rate of 50.70 L/min. At time 6 min and flow rate of 10.21 L/min, 20.37 L/min, 30.45 L/min, 40.28 L/min, 50.70 L/min the corrosion rate were 0.75 mpy, 0.67 mpy, 0.72 mpy, 0.93 mpy, and 0.89 mpy respectively. At time 9 min corrosion rate were 0.57 mpy, 0.71 mpy, 0.66 mpy, 0.74 mpy, and 0.64 mpy in the order of the flow rates respectively. At time 12 min in the order of the flow rates were 0.25 mpy, 0.38 mpy, 0.45 mpy, 0.68 mpy, and 0.59 mpy respectively. At time 15 min corrosion rate were 0.31 mpy, 0.27 mpy, 0.33 mpy, 0.52 mpy, and 0.43 mpy in the order of the flow rates respectively and at 18 min the corrosion rate were 0.21 mpy, 0.32 mpy, 0.24 mpy, 0.49 mpy, and finally ending at 0.56 mpy respectively.

Table 4 Comparison of Experimental and Model Result of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 10.21 L/min

Time (min)	CR EXP(mpy)	CR MODEL(mpy)	ERROR
3	0.68	0.7467	-0.0667
6	0.75	0.6327	0.1173
9	0.57	0.5187	0.0513
12	0.25	0.4047	-0.1547
15	0.31	0.2907	0.0193
18	0.21	0.1767	0.0333

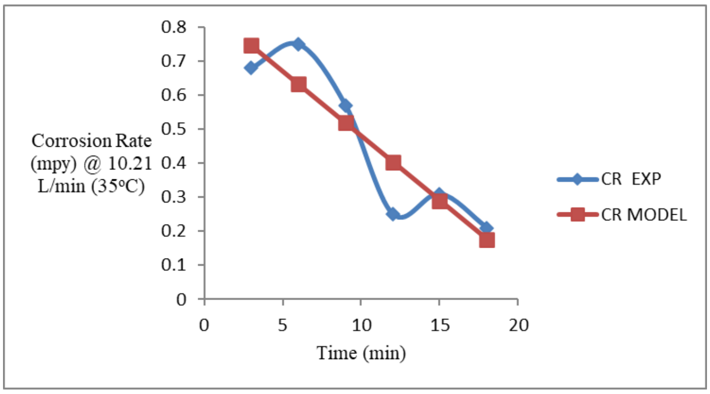

Figure 4 Comparison of Experimental and Model Results of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 10.21 L/min

At time 18 minutes, the experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline. From the profile plot, the values of the corrosion rate (mpy) against time (min) of the experimental and model results are 3 (0.68 mpy, 0.7467 mpy), 6 (0.75 mpy, 0.6327 mpy), 9(0.57 mpy, 0.5187 mpy), 12 (0.25 mpy, 0.4047 mpy), 15 (0.31 mpy, 0.2907 mpy), 18 (0.21 mpy, 0.1767 mpy). But the variation of the experimental and model results in terms of deviation is (0.007%) indicating that both results are insignificant in variation, showing positive agreement between the experimental and model results.

Table 5 Comparison of Experimental and Model Result of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 20.37 L/min

Time (min)	CR EXP(mpy)	CR MODEL(mpy)	ERROR
3	0.76	0.7848	-0.0248
6	0.67	0.6783	-0.0083
9	0.71	0.5718	0.1382
12	0.38	0.4653	-0.0853
15	0.27	0.3588	-0.0888
18	0.32	0.2523	0.0677

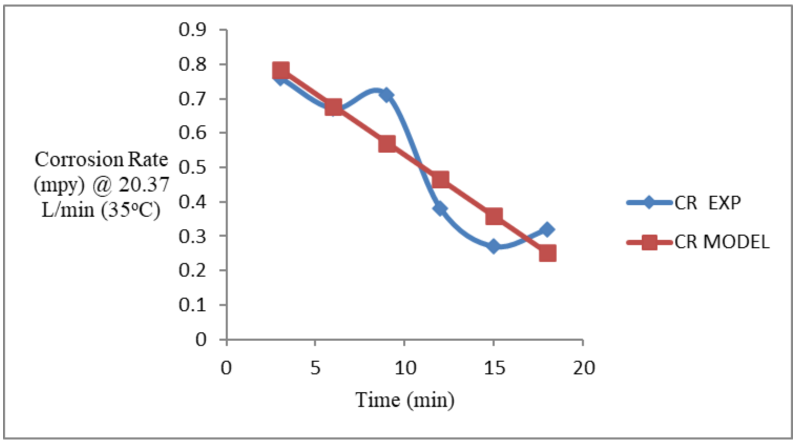

Figure 5 Comparison of Experimental and Model Results of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 20.37 L/min

At time 15 and 18 minutes, the experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline From the profile plot, the values of the corrosion rate (mpy) against time (min) of the experimental and model results are 3 (0.76 mpy, 0.7848 mpy), 6 (0.67 mpy, 0.6783 mpy), 9(0.71 mpy, 0.5718 mpy), 12 (0.38 mpy, 0.4653 mpy), 15 (0.27 mpy, 0.3588 mpy), 18 (0.32 mpy, 0.2523 mpy). But the variation of the experimental and model results in terms of deviation is (0.04%) indicating that both results are insignificant in variation, showing positive agreement between the experimental and model results.

Table 6 Comparison of Experimental and Model Result of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 30.45 L/min

Time (min)	**CR EXP(mpy)**	**CR MODEL(mpy)**	**ERROR**
3	0.54	0.6958	-0.1558
6	0.72	0.6136	0.1064
9	0.66	0.5314	0.1286
12	0.45	0.4492	0.0008
15	0.33	0.367	-0.037
18	0.24	0.2848	-0.0448

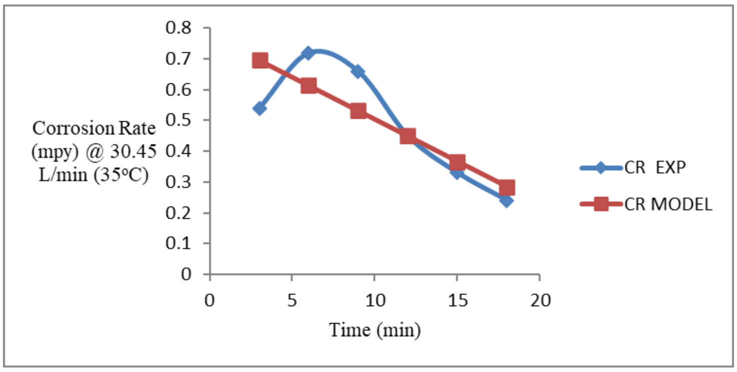

Figure 6 Comparison of Experimental and Model Results of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 30.45 L/min

Figure 6: illustrate the variation profile plot of experimental and model results of the effect of temperature on wax deposit on corrosion rate (mpy) against time (min) at temperature of 35 °C and flow rate at 30.45 L/min during the corrosion inhibition. At time 18 minutes, the experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline. From the profile plot, the values of the corrosion rate (mpy) against time (min) of the experimental and model results are 3 (0.54 mpy, 0.6958 mpy), 6 (0.72 mpy, 0.6136 mpy), 9(0.66 mpy, 0.5314 mpy), 12 (0.45 mpy, 0.4492 mpy), 15 (0.33 mpy, 0.367 mpy), 18 (0.24 mpy, 0.2848 mpy). But the variation of the experimental and model results in terms of deviation is (0.06%) indicating that both results are insignificant in variation, showing positive agreement between the experimental and model results.

Table 7 Comparison of Experimental and Model Results of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 40.28 L/min

Time (min)	CR EXP(mpy)	CR MODEL(mpy)	ERROR
3	0.67	0.828	-0.158
6	0.93	0.7653	0.1647
9	0.74	0.7026	0.0374
12	0.68	0.6399	0.0401
15	0.52	0.5772	-0.0572
18	0.49	0.5145	-0.0245

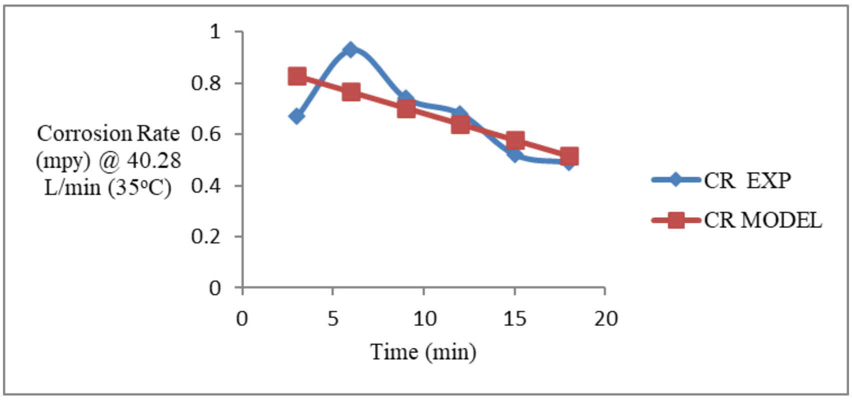

Figure 7 Comparison of Experimental and Model Results of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 40.28 L/min

Figure 7: illustrate the variation profile plot of experimental and model results of the effect of temperature on wax deposit on corrosion rate (mpy) against time (min) at temperature of 35 °C and flow rate at 40.28 L/min during the corrosion inhibition. At time 18 minutes, the experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline. From the profile plot, the values of the corrosion rate (mpy) against time (min) of the experimental and model results are 3 (0.67 mpy, 0.828 mpy), 6 (0.93 mpy, 0.7653 mpy), 9(0.74 mpy, 0.7026 mpy), 12 (0.68 mpy, 0.6399 mpy), 15 (0.52 mpy, 0.5772 mpy), 18 (0.49 mpy, 0.5145 mpy). But the variation of the experimental and model results in terms of deviation is (0.06%) indicating that both results are insignificant in variation, showing positive agreement between the experimental and model results.

Table 8 Comparison of Experimental and Model Result of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35°C and Flow Rate at 50.70 L/min

Time (min)	CR EXP(mpy)	CR MODEL(mpy)	ERROR
3	0.75	0.8132	-0.0632
6	0.89	0.7451	0.1449
9	0.64	0.677	-0.037
12	0.59	0.6089	-0.0189
15	0.43	0.5408	-0.1108
18	0.56	0.4727	0.0873

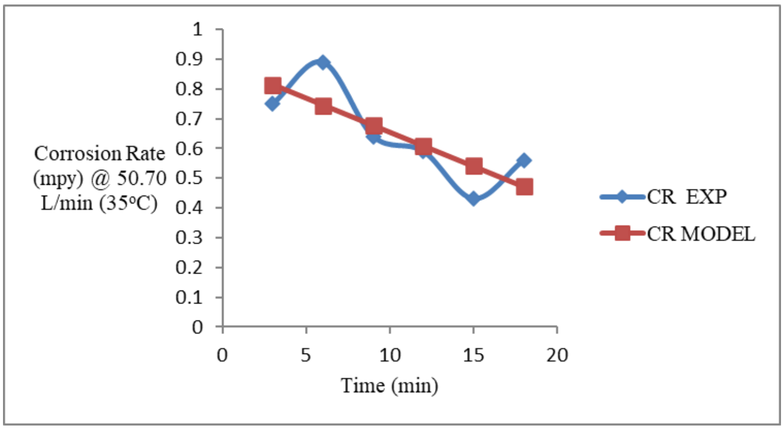

Figure 8 Comparison of Experimental and Model Results of the Effect of Temperature on Wax Deposit on Corrosion Rate (mpy) against Time (min) at Temperature of 35 °C and Flow Rate at 50.70 L/min

Figure 8: shows the variation profile plot of experimental and model results of the effect of temperature on wax deposit on corrosion rate (mpy) against time (min) at temperature of 35 °C and flow rate at 50.70 L/min during the corrosion inhibition. At time 15 and 18 minutes, the experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline.

From the profile plot, the values of the corrosion rate (mpy) against time (min) of the experimental and model results are 3 (0.75 mpy, 0.8132 mpy), 6 (0.89 mpy, 0.7451 mpy), 9(0.64 mpy, 0.677 mpy), 12 (0.59 mpy, 0.6089 mpy), 15 (0.43 mpy, 0.5408 mpy), 18 (0.56 mpy, 0.4727 mpy). But the variation of the experimental and model results in terms of deviation is (0.06%) indicating that both results are insignificant in variation, showing positive agreement between the experimental and model results.

4. Conclusion

Waxy crude oil can have anywhere from 20 to 50 percent normal paraffin in the oil fraction. Alkane compounds, often known as saturates, are hydrocarbons having just single bonds. Paraffin is a typical name for them. In their solid state, alkanes have the general formula C_nH_{2n+2} and are referred to as "wax." The term "paraffin" comes from the Latin term "lacking affinity," which refers to the paraffin's lack of reactivity, including at the steel surface. Paraffin can precipitate and form on pipe surfaces at low temperatures-below the "wax appearance temperature"- despite the lack of surface chemical activity (WAT). When the sulfur and nitrogen-containing surface-active chemicals found in crude oils were investigated independently, it was discovered that some of the sulfur and nitrogen-containing compounds provided good corrosion protection while others, on the other hand, provided just modest or negligible corrosion protection. The experimental and model results predicted a significant reduction of corrosion rates while others gave only moderate or negligible protection to the crude oil pipeline.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflicts of interest and no financial or personal conflicts of interest."

Statement of ethical approval

All participants provided written informed consent prior to enrolment in the study. This research was conducted ethically in accordance with the Engineering standard

Statement of informed consent

I have read and I understand the provided information which is correct and permitting you to publish the manuscript online.

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