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Correlation for Predicting Wax Deposition

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Abstract

The deposition of wax from the transportation of waxy/paraffinic crude oils at temperature below the Wax Appearance Temperature (WAT) in crude oil production pipeline poses flow assurance problems and could lead to the drop in production and entire flow line blockage if not properly handled. In this paper an experimental wax flow loop was used to study the impact of wax content, flow rate and time on the deposition of wax in flow lines at different ambient temperatures. Seven waxy crude oil samples with unique compositional properties from different oilfields in the Niger Delta region of Nigeria were used in the analysis. The waxy crude oil API ranged from 32- 40 degrees while that of pour-point was 20-27°C. The samples were characterized in line with ASTM 3328 method using gas chromatographic analyses. The WAT was determined by Mettler Toledo Differential Scanning Calorimeter (DSC) 823. It was observed that in sample A at a flow rate of 0.093 litres/seconds the deposition of wax at 27°C, 24°C, 19°C and 11°C wall temperatures were 23.3 grams, 84.9 grams, 98.2 grams and 142.5 grams respectively. This shows how fast wax can deposit at lower pipe wall temperatures below the WAT. The deposition rate was found to increase with reduction in flow rate and increase in flow time. A similar trend was obtained for other samples. Also the rate of deposition was found to increase with wax content of the samples. Empirical models were generated relating deposition with rate and time. A quadratic model gave the best fit with the least root mean square error (RMSE) for both the effect of time and flow rate on mass of wax deposited at pipe wall temperatures of 27°C, 24°C, 19°C and 11°C. In the production of waxy crude oil, low pipe wall temperatures below the WAT which could result from coating failure should be avoided to prevent the crystallization and deposition of wax in production pipe line.

Keywords: *Wax deposition; flow assurance; Wax Appearance Temperature; Waxy crude oil; Wax flow loop; Molecular Diffusion.*

1. Introduction

Wax precipitation occurs when the wax molecules contained in the crude oil reach their solubility limit due to change in equilibrium conditions resulting in loss of paraffin solubility. It is worthy of note that the solubility limit has a direct dependency on temperature [1]. [2] reported that temperature and the number of light constituents are the two most important factors affecting wax precipitation and deposition. Paraffin solubility increases with increasing temperature and decreases with decreasing temperature. Waxy crude oils can be classified generally into two major categories: the paraffinic and the asphaltene wax deposits. Whereas the paraffinic wax can easily be dissolved at the onset of deposition with organic solvents and temperature control above the wax appearance temperature (WAT), the asphaltene wax deposits are more difficult to handle as they are known to be insoluble in low molecular weight organic solvents and increase in temperature has little effect in dissolving an already formed asphaltene wax [3]. Whether it is of paraffinic or asphaltenic origin, care must be taken to prevent gelling. Gelling results in serious restart problems and even complete loss of a production string or flow line if not properly managed [4-5].

In order to avoid unexpected blockage of production string or flow line resulting from wax deposition in the production of paraffinic crude oils, it is expected that operators operate within a safe region during production. To operate within a safe region requires the knowledge of the WAT, the pour-point, and other PVT properties. The WAT (cloud point) is the temperature at which the first wax crystal is formed from the crude oil as a result of a drop in temperature [6]. Villazon *et al.* [7] identified the WAT as a critical wax crystallization temperature, which depends on the composition of the wax containing fluid. The pour-point is the temperature below which a waxy crude oil will cease to flow. Hence, the critical operating region is somewhat between the WAT and the pour-point while the safe operating region is the region where the temperature is above the WAT [4,8]. To operate within the safe region requires good production practices such as insulation, heating or commingling to prevent gelling. To achieve this, operators must have an idea of the mass of wax being deposited over time on cold pipelines. The amount of wax being deposited will give an insight into how fast the internal diameter of the flowline is being reduced in order to prevent complete blockage and also determine the frequency of pigging the line [7].

Burger *et al.* [9] identified the pipe wall wax deposition as a total immobile deposit, which is equivalent to 14 to 17% solid phase, together with 83 to 86% whole oil crude.

Many researchers have developed models to predict wax deposition in production pipe lines. Burger *et al.* [9] developed models that incorporated molecule diffusion, shear dispersion, and Brownian motion in the prediction of wax deposition rate. Azevedo *et al.* [10] developed a model that showed that shear dispersion plays a major effect in the wax deposition. Martzain [11] developed an empirical model for wax deposition considering shear stripping effect. Singh *et al.* [12] developed a model that proposed the concept of wax aging. Wenda *et al.* [13] developed a model that predicted wax deposition considering sloughing in a different season.

The purpose of this study is to determine the effect of flow rate and time on the deposition of wax and develop empirical models that would correlate the amount of wax deposited with respect to flow rate and time.

2. Material and methods

2.1. Crude oil sample

For this study, seven waxy crude oil samples were obtained from different oil fields in the Niger Delta region in Nigeria. The WAT of the seven crude oil samples were obtained in the laboratory with a Mettler Toledo differential scanning calorimeter (DSC) 823, while the pour point was obtained with a pour point determination equipment. The result of the experiments is shown in Table 1, and it can be observed the WAT ranged from 25.2°C – 31°C with sample C and F having the highest WAT and wax content. It implies that samples C and F would have more constituents with a higher number of carbon atoms and would have a greater tendency of forming wax at a relatively higher temperature than the rest samples.

Table 1. Properties of waxy crude oil samples used for the study

Sample	API [°API]	WAT [°C]	Pour Point [°C]	Wax content [mg/L]
A	38.0	28.2	23.3	2.44E+05
B	34.0	27.0	21.1	1.54E+05
C	30.5	31.0	27.0	2.48E+05
D	33.0	30.0	26.0	2.48E+05
E	40.0	25.2	20.0	1.31E+05
F	30.0	31.0	26.6	3.84E+05
G	32.0	26.0	22.0	2.15E+05

Nenniger *et al.* [14] reported that the solubility of a specific n-paraffin in crude oil is a strong function of its carbon number and system temperature. Noting that the solubility decreases with a reduction in the system temperature as the carbon number distribution of paraffin decreases. They showed that the solubility of C40 in crude oil decreases by more than 2 orders of magnitude as the crude oil temperature decreases from 50 to 20°C. This is also supported by [15] that corroborates the fact that as the carbon number in waxy/paraffinic crude oil increases, the solidification temperature increases. The pour point ranged from 20.0°C – 27.0°C, with sample E having the lowest pour point. This signifies that sample E will have the least tendency of forming wax among seven samples and also have the least carbon number among the seven waxy crude oil samples. This can be confirmed in Table 1, as the wax content of sample E was the least among the samples. The experiment also showed that the pour point is strongly correlated with the WAT. An increase in the WAT also leads to an increase in the pour point and vice versa. Table 1 shows the rheological properties and wax content of the seven waxy crude oil samples used for investigating the wax deposition tendency.

2.2. Laboratory experiment in determining wax deposition

The experimental wax flow loop, as shown in Figure 1, was set up to simulate wax deposition in a horizontal pipeline in an offshore environment. The loop consists of a 20ft long 316 stainless steel tubing of ½" internal diameter with a maximum allowable working pressure of 300psia. The wax deposition experiment was performed under different uniform flow rate at variable pipe ambient temperature below the wax appearance temperature (WAT).

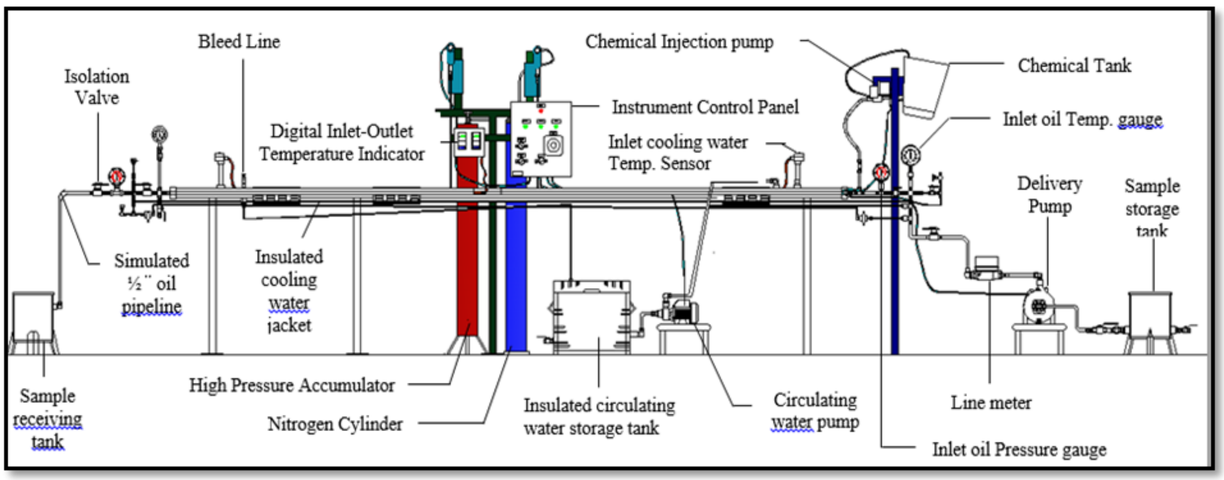

Figure 1. Locally fabricated and tested model wax flow loop [18]

2.2.1. Procedure of wax deposition in the wax flow loop

At the start of each experiment 8 litres of the waxy crude oil, the sample was preheated to 45°C above the wax appearance temperature before pouring into a storage tank to ensure that the wax was in solution before the commencement of the deposition experiment.

The waxy crude oil sample in the storage tank was pumped with the aid of a 1.5hp variable voltage electric motor speed delivery pump to the receiving tank through a ½" diameter 316 stainless steel tubing 20ft long representing the simulated pipeline. The time it took to pump 8 litres of waxy crude oil at a particular pump speed, and cooling water ambient temperature was recorded. The ½" stainless steel tubing is enclosed in a 2" insulated schedule 80 galvanized pipe. The 2" insulated galvanize pipe contains circulating cooling water, and the insulation is to prevent heat loss and maintain constant cooling water temperature. The ½" stainless steel tubing is constantly submerged in cooling water, mimicking a subsea pipeline condition. Water at a controlled temperature below the WAT was circulated in the water jacket with the aid of a 0.8 hp circulating water pump connected to an insulated circulating water storage tank.

The circulating water temperature below the WAT was varied for the series of experiments to create different pipeline temperature sea bed conditions (27°C, 24°C, 19°C, 11°C). The crude oil entering the loop was metered with the aid of a high accuracy inline meter. This meter displays the litres of crude oil pumped from the sample delivery tank into the loop.

At the end of every experiment, the mass of wax deposited was extracted by disconnecting the ½ inch diameter 20 ft long wax flow loop and inserting a ¼″ tubing (head blogged) into the ½″ pipe to push out the wax. The wax deposited on the pipe wall (total immobile deposit) of the 1/2″ stainless steel pipe was weighed using a digital weighing scale.

After extracting the total immobile wax deposit, the ½″ pipe was cleaned of any trace of waxy crude oil remaining with a release of a mixture of nitrogen gas from nitrogen cylinder tank and diesel from a high-pressure accumulator tank into the 1/2″ stainless steel tubing line. Also, any trapped air in the cooling water jacket was bled off at the end of the experiment to avoid cavitation through the vent line. Temperatures at the inlet and outlet alongside the pressures of the 1/2″ tubing simulated pipeline were recorded continuously using Aschcroft temperature and MPC pressure gauge.

The loop is equipped with two temperature sensors to measure the inlet and the outlet temperatures of the cooling water contained in the insulated 2″ galvanized pipe water jacket. A H340 digital inlet/outlet temperature Panel transmits the inlet and outlet temperature of the cooling water jacket in real time as the experiment goes on.

½ inch Swagelok isolation ball valves with a maximum working pressure of 2500 psia are installed at the inlet and outlet of the wax flow loop. This is used to isolate the 20″ simulated ½″ pipeline wax flow loop from other sections for maintenance and wax extraction purposes. The loop is fitted and equipped with a Fisher Rosemount Differential Pressure Transmitter with a maximum working pressure of 3626 psia. This was used to obtain the differential pressure between the inlet and outlet pressure of the wax flow loop.

The time it took to pump 8 litres of waxy crude oil at a particular pump speed, and cooling water ambient temperature was recorded. Pump speed and cooling water pipe ambient temperatures were varied to determine the effect of temperature, flow time, and flow rate on the wax deposition.

3. Results and discussion

3.1. Effects of time on the mass of wax deposited

Figure 2 shows the effect of flow time on the mass of wax deposited for the individual samples at different temperatures. From Figure 2, it was observed that the mass of wax deposited increased with time through the wax flow loop at a given flow rate and temperature. This is in agreement with the effect of time on the deposition of wax, as reported by [16]. In their study, it was reported that the weight of the mass of wax deposited (wax thickness) increased with an increase in the flow time. Tao *et al.* [1] also reported an increase in the mass of wax deposited as the flow time of the waxy crude oil sample increase in a cold finger experiment.

In the wax flow loop experiment conducted (Figure 2), it was observed that at lower pipe wall temperatures below the WAT, it took a longer time to pump a given volume of waxy crude oil because of increased viscosity. For instance, at 27°C cooling water ambient temperature, it took 86 seconds to pump 8 litres of waxy crude oil sample A (WAT=28.2°C) through the wax flow loop at delivery pump variable voltage speed of 125 volts with wax deposition of 23.3 grams. At 24°C ambient temperature, it took 88 Seconds to pump the same quantity of waxy crude oil at the same pump speed with wax deposition of 83.3 grams. At 19°C, it took 92 seconds to pump the same quantity of waxy crude oil sample through the wax flow loop at the same variable speed pump voltage with a wax deposition of 112 grams. While at 11°C, it took 102 Seconds to pump the same quantity of waxy crude oil through the wax flow loop at the same variable speed pump voltage with wax deposition of 146.8grams. A similar trend was obtained in the other samples B, C, D, E, F & G (Figure 2).

This is in agreement with [5]. It was observed from the close up images of the deposition process that the wax thickness increased with an increase in flow time of the waxy crude oil in the wax flow loop.

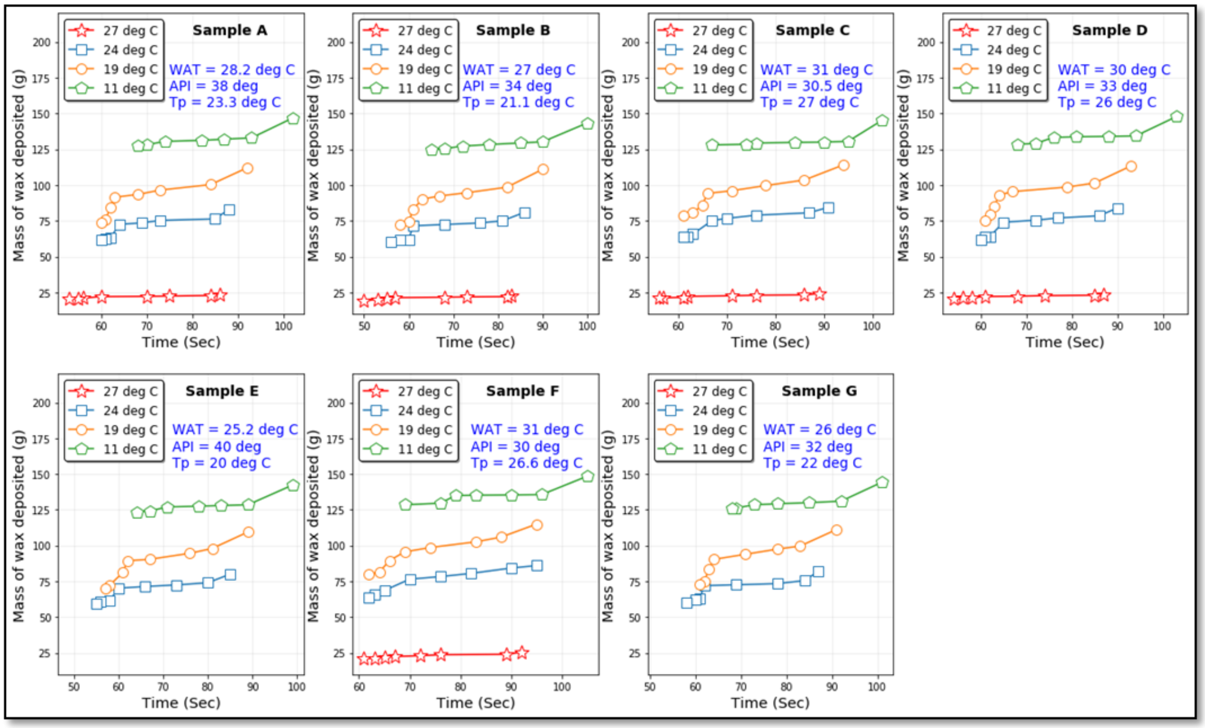

Figure 2. Effect of flow time on the mass of wax deposited for individual samples

Figure 3 shows the mass of wax deposited for all the samples at pipe wall ambient temperatures of 27°C, 24°C, 19°C, and 11°C plotted against flow time in the wax flow loop. It showed from Figure 3 that as the temperature reduces below the WAT, the mass of wax deposited increased with flow time within the loop.

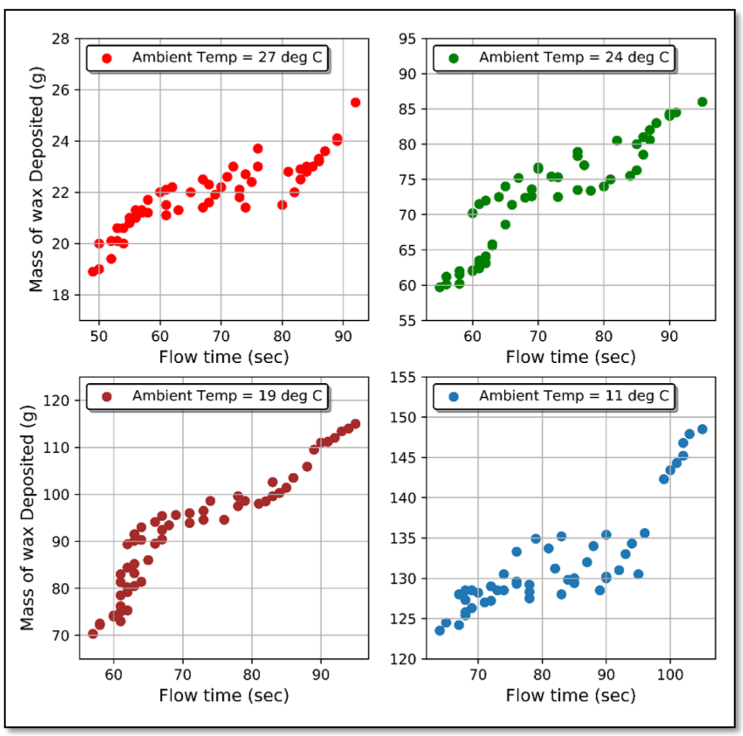

Figure 3. Effect of flow time on the mass of wax deposited for all samples at different pipe ambient temperature

3.2. Effects of flowrate on the mass of wax deposited

Figure 4 shows the plots of mass deposited against the flow rate at different temperatures for the individual samples used in this experiment. It could be observed from Figure 4 that the mass of wax deposited reduced with an increase in flow rate. This observation could be attributed to the fact that the drop in the ambient temperature of the cooling water at 27°C, 24°C, 19°C, and 11°C impeded the flow rate due to increased viscosity resulting in the longer retention time of the waxy crude oil in the loop and subsequent increase in the mass of wax deposited. Adeyanju *et al.* [17] in their work stated that reduction in flow rate could result in a reduction in shear stress at the oil deposit interface, which will lead to fewer shears stripping and consequently leading to an increase in the wax deposited.

It could also be observed from Figures 4 that the mass of wax deposited increased as the ambient temperature decreased from 27°C, 24°C, 19°C & 11°C, respectively, for a given flow rate. This is attributed to the fact that temperature drop below the WAT will accelerate the precipitation of wax due to an increase in the concentration gradient of waxy crystals in the radial direction; and subsequent deposition on the cool pipe wall. This is in alignment with works carried out on the effect of temperature on a wax deposition by [16]. They reported that wax deposition on the pipe wall increases with an increase in the differential temperature between the pipe wall temperature below the WAT and the temperature of the oil entering the pipe for the same duration of flow. They observed a remarkable wax deposition profile when the temperature differential was high.

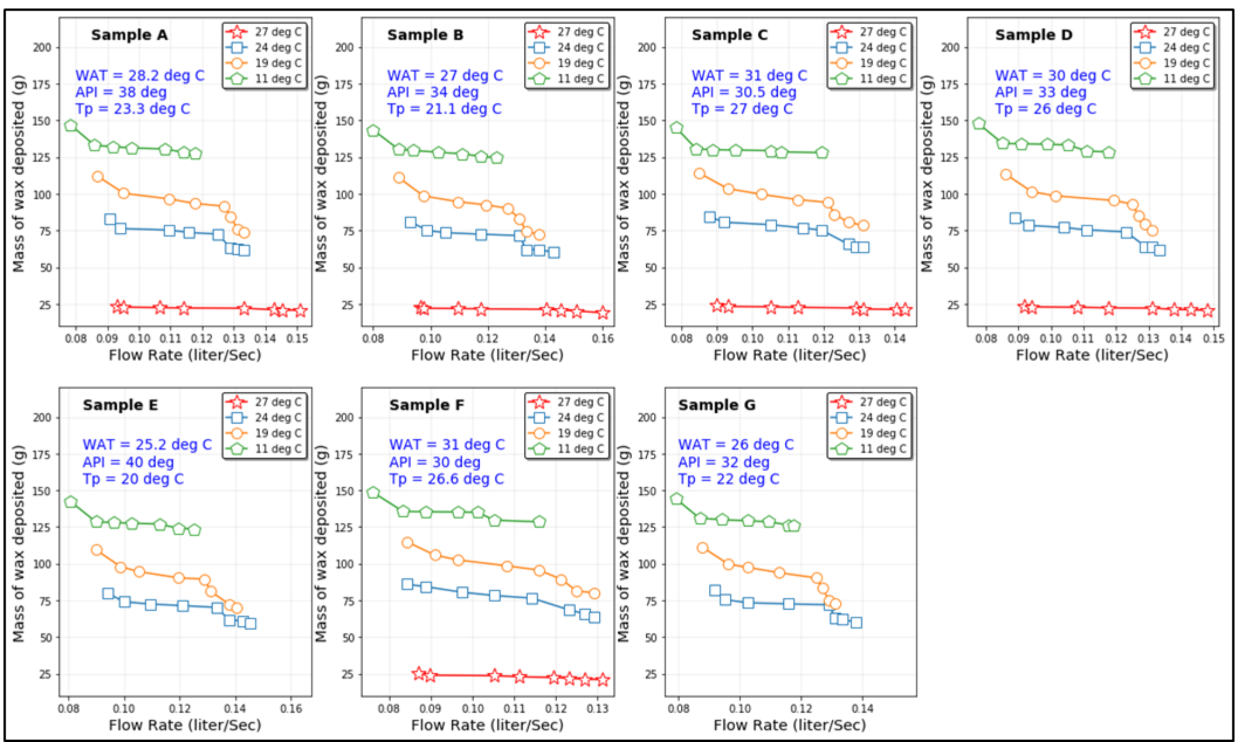

Figure 4. Effect of flow rate on the mass of wax deposited for individual samples

The effect of temperature on deposition is also in alignment with work done by [8]; they reported that both the pipe wall and crude oil temperature should be above the cloud point and critical wax production rate region to prevent wax deposition.

Figure 5 shows the plot of the mass of wax deposited and the flow rate at different temperatures for all the samples. It further shows that as the flow rate increases, the rate of deposition increases.

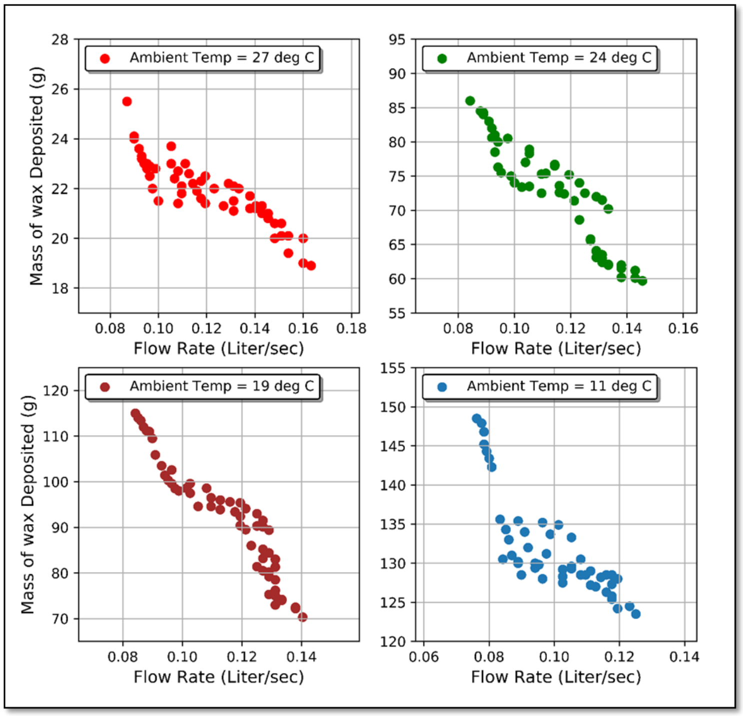

Figure 5. Effect of flow rate on the mass of wax deposited for all samples at different ambient temperatures

3.3. Empirical models

Table 2 shows the different models developed with their parameters and the best fit model that correlates the effect of time on mass deposited.

Table 2. Empirical models on the effect of time on mass deposition for various ambient temperatures

S/N	Model Type	Ambient temperature, (°C)	Model parameter	Goodness of fit
1	$m_d = at^b$	27	a = 6.675 b = 0.282	R^2 = 0.787 RMSE = 0.601
		24	a = 5.072 b = 0.623	R^2 = 0.848 RMSE = 3.041
		19	a = 3.326 b = 0.778	R^2 = 0.869 RMSE = 4.442
		11	a = 38.427 b = 0.280	R^2 = 0.699 RMSE = 3.525
2	m_d=a+bt	27	a = 15.711 b = 0.090	R^2 = 0.778 RMSE = 0.615
		24	a = 27.315 b = 0.627	R^2 = 0.841 RMSE = 3.103
		19	a = 20.613 b = 0.996	R^2 = 0.865 RMSE = 4.500
		11	a = 94.769 b = 0.453	R^2 = 0.722 RMSE = 3.386
3	m_d=aexp^{bt}	27	a = 16.526 b = 0.004	R^2 = 0.774 RMSE = 0.620
		24	a = 39.287 b = 0.008	R^2 = 0.830 RMSE = 3.214
		19	a = 43.663 b = 0.010	R^2 = 0.853 RMSE = 4.708
		11	a = 99.27 b = 0.004	R^2 = 0.731 RMSE = 3.329
4	m_d=a+ bt+ct^2	27	a = 11.375 b = 0.220 c = -0.001	R^2 = 0.787 RMSE = 0.608
		24	a = -32.355 b = 2.901	R^2 = 0.864 RMSE = 2.901

S/N	Model Type	Ambient temperature, (°C)	Model parameter	Goodness of fit
			c = -0.0113	
		19	a = -71.053 b = 3.494 c = -0.017	R^2 = 0.884 RMSE = 4.216
	m_d=a+ bt+ct^2	11	a = 199.174 b = -2.088 c = 0.015	R^2 = 0.813 RMSE = 2.805

From the table, the quadratic model 4 gave the best fit, with the coefficient of determination ranging from 0.787 – 0.884 and root mean squared error (RMSE) ranging from 0.608 – 4.216 for the different ambient temperature. Model 4 was considered the best because the maximum value of the RMSE was lower than other models. The RMSE indicates the absolute fit of the model to the data, which is how close the observed data points are to the models predicted values.

The cross-plot of the measured against the predicted wax deposited using the quadratic model for the effect of time on mass deposition is shown in Figure 6.

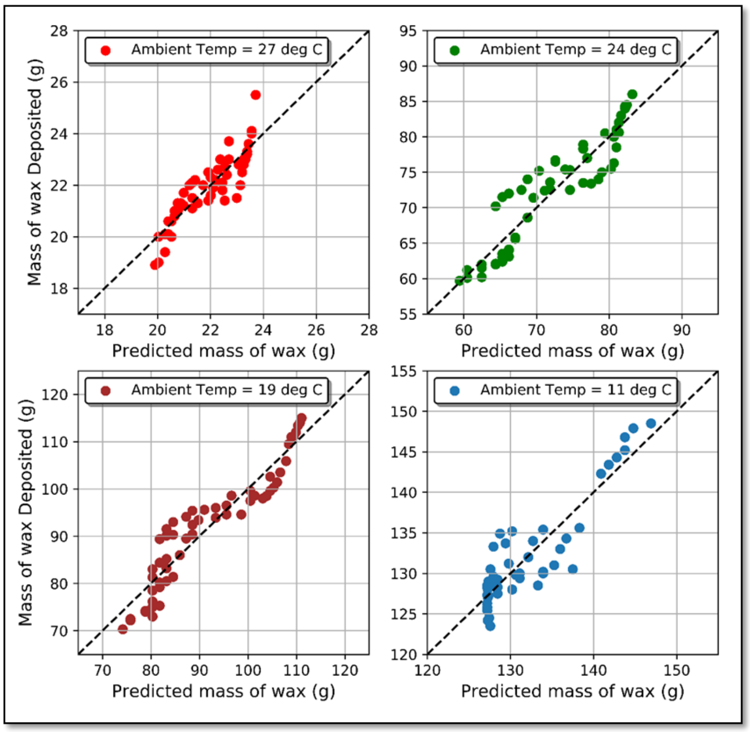

Figure 6. Cross-plot of correlated and experimental wax deposition mass for the effect of flow time on mass deposited

It can be observed from the cross-plots that there was a good correlation between the predicted and the measured wax deposited for the different ambient temperatures, as most of the data points fell close to the 45° diagonal line in the graph. At an ambient temperature of 27°C, it could be seen from the cross plot that the data points were much closer to the 45° diagonal line. This would give a better estimation of the deposition profile by the model due to the low RMSE of 0.608 compared to other temperature RMSE. Prediction of the mass of wax deposited with the model at 27°C will deviate from the observed values by approximately $\pm$ 1.216g while the prediction of the mass of wax deposited for 24°C, 19°C, and 11°C will deviate from the observed value by $\pm$5.802g, $\pm$8.452g and $\pm$5.61g respectively. As the temperature drops from 27°C to 24°C, 19°C, and 11°C the deviation from the 45° diagonal line, reducing the quality of the prediction, as seen in the increase of the RMSE. This could be attributed to the fact that as the temperature drops further below 27°C, the non-Newtonian characteristics of the waxy crude oil increased resulting in a more erratic deposition profile from the mean. This was in agreement with [18] when they reported that the non-Newtonian characteristics (the variation of shear stress to shear strain with the increase in viscosity) of waxy crude oil increases as the pipe wall temperature drops below the WAT.

Empirical models on the effect of flow rate on mass deposition for various ambient temperatures are shown in Table 3. It could be observed that model 4, which was also the quadratic model, gave the best fit. The coefficient of determination ranged from 0.763 – 0.896, and the RMSE ranged from 0.588 – 3.995. Model 4 was considered the best because the maximum value of the RMSE was lower than other models. The RMSE indicates the absolute fit of the model to the data, which is how close the observed data points are to the models predicted values. The RMSE at lower temperatures was higher than at 27°C. This can be attributed to the fact as the temperature falls below the WAT in the temperature range of 27°C, 24°C, 19°C, and 11°C, the non-Newtonian characteristic increases with an increase in viscosity below the WAT. At such low pipe wall temperatures, the variation of the shear stress to share strain is more which results in an increase in variation of deposition profile from the mean. This was in alignment with [18] when they reported that the viscosity of waxy crude oil increases with a drop in pipe wall temperature below the WAT with the increase in non-Newtonian characteristics.

Table 3. Empirical models on the effect of flow rate on mass deposition for various ambient temperatures

S/N	Model Type	Ambient temperature (°C)	Model parameter	Goodness of fit
1	$m_d = aQ^b$	27	a = 11.998 b = -0.282	R^2 = 0.787 RMSE = 0.601
		24	a = 18.509 b = -0.778	R^2 = 0.848 RMSE = 3.041
		19	a = 16.756 b = -0.778	R^2 = 0.869 RMSE = 4.442
		11	a = 68.833 b = -0.280	R^2 = 0.699 RMSE = 3.255
2	$m_d = a + bQ$	27	a = 28.135 b = -51.550	R^2 = 0.798 RMSE = 0.586
		24	a = 119.136 b = -409.74	R^2 = 0.864 RMSE = 2.848
		19	a = 169.957 b = -682.644	R^2 = 0.890 RMSE = 4.072
		11	a = 168.002 b = -362.667	R^2 = 0.656 RMSE = 3.771
3	$m_d = a\exp^{bQ}$	27	a = 29.099 b = -2.361	R^2 = 0.796 RMSE = 0.589
		24	a = 136.909 b = -5.629	R^2 = 0.860 RMSE = 2.909
		19	a = 207.958 b = -7.205	R^2 = 0.881 RMSE = 4.227
		11	a = 173.982 b = -2.790	R^2 = 0.664 RMSE = 3.721
4	$m_d = a + bQ + cQ^2$	27	a = 24.985 b = 1.147 c = -213.332	R^2 = 0.800 RMSE = 0.588
		24	a = 95.971 b = 5.940 c = -1821.072	R^2 = 0.870 RMSE = 2.833
		19	a = 132.603 b = 6.381 c = -3102.542	R^2 = 0.896 RMSE = 3.995
		11	a = 283.049 b = -2716.718 c = 11803.434	R^2 = 0.763 RMSE = 3.163

Figure 7 shows the cross-plot of the measured against the predicted wax deposited using the quadratic model. From Figure 7, it could be seen that there was a good agreement between the predicted and measured wax deposited for most of the ambient temperatures as most of the points fall close to the 45° line. It could be seen from the cross plot that the predicted against the experimental wax deposited for the 27°C plot fell much closer to the 45° degree diagonal line than any other temperature, which was reflected in the low RMSE. Predicting with the quadratic model obtained at 27°C, the predicted wax deposited will deviate from the observed by approximately ±1.176g, while the prediction of wax deposited for 24°C, 19°C, 11°C will deviate from the observed by ±5.67g, ±7.99g, and ±6.326g respectively. The cross plot showed that as the temperature decreases, the quality of predicted wax deposited obtained from the empirical quadratic model tends to drops due to the erratic deposition profile at non-Newtonian.

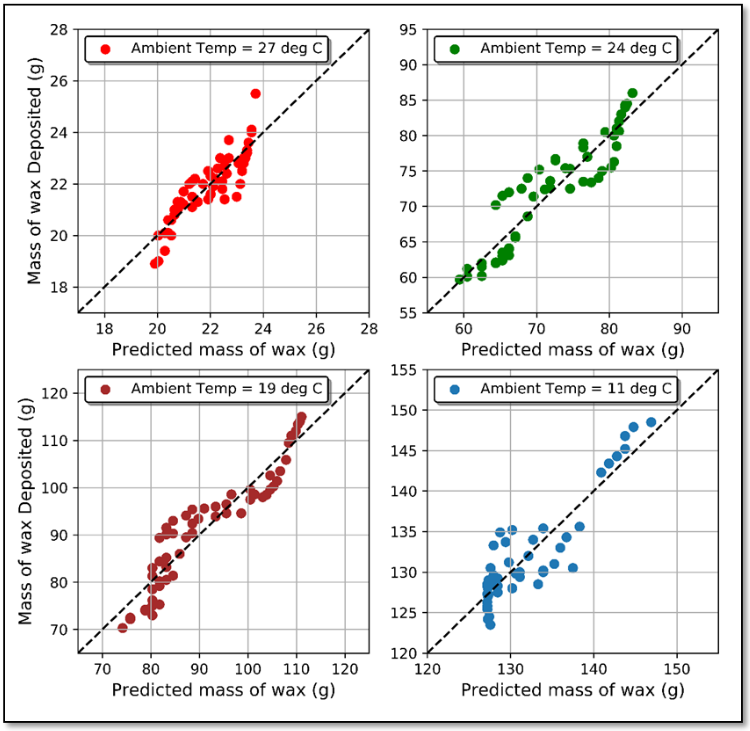

Figure 7. Cross-plot of correlated and experimental wax deposition mass for the effect of flow rate on mass deposited

3.4. Comparison of the mass of wax deposited and wax content at a specific flow rate for temperatures 27°C, 24°C, 19°C and 11°C

The comparison was made to study wax deposition at a particular flow rate with respect to temperature and wax content. From Table 4 -7, it could be observed that there was a strong correlation between the mass of wax deposited and the wax content at temperatures 27°C, 24°C, and 19°C. From the analysis samples that had high wax content deposited more wax. Sample F which had a wax content of 3.84E+05mg/L, deposited the most wax at a uniform flow rate 0.11 litres/second, followed by Sample D and C which both had wax content of 2.48E+05. The sample with the least wax content deposited the least amount of wax compared to the other samples. From Table 7, it was observed that at 11°C sample E with the least wax content had the least deposition. Samples with higher wax content at this temperature also had high wax deposition without a defined trend. This could be attributed to the highly non-Newtonian nature of the crude oil at this temperature, which could have affected the deposition pattern. The above analysis confirms the fact that the wax content of waxy crude oils is an indicator of the mass of wax that could be deposited.

Table 4. Summary of mass of wax deposited at a particular flow rate at 27°C

Samples	Flow rate (L/s)	Temperature (oC)	Mass of wax deposited (grams)	Wax content [mg/L]
A	0.11	27	22.31	2.44E+05
B	0.11	27	21.79	1.54E+05
C	0.11	27	22.74	2.48E+05
D	0.11	27	22.62	2.48E+05
F	0.11	27	23.78	3.84E+05

Table 5. Summary of mass of wax deposited at a particular flow rate at 24°C

Samples	Flow rate (L/s)	Temperature (oC)	Mass of wax deposited (grams)	Wax content [mg/L]
A	0.11	24	75.19	2.44E+05
B	0.11	24	73.08	1.54E+05
C	0.11	24	77.75	2.48E+05
D	0.11	24	75.65	2.48E+05
E	0.11	24	72.46	1.31E+05
F	0.11	24	77.08	3.84E+05
G	0.11	24	72.96	2.15E+05

Table 6. Summary of mass of wax deposited at a particular flow rate at 19°C

Samples	Flow rate (L/s)	Temperature (oC)	Mass of wax deposited (grams)	Wax content [mg/L]
A	0.11	19	96.34	2.44E+05
B	0.11	19	94.51	1.54E+05
C	0.11	19	96.95	2.48E+05
D	0.11	19	97.06	2.48E+05
E	0.11	19	93.19	1.31E+05
F	0.11	19	97.88	3.84E+05
G	0.11	19	94.85	2.15E+05

Table 7. Summary of mass of wax deposited at a particular flow rate at 11°C

Samples	Flow rate (L/s)	Temperature (oC)	Mass of wax deposited (grams)	Wax content [mg/L]
A	0.11	11	129.80	2.44E+05
B	0.11	11	127.34	1.54E+05
C	0.11	11	128.42	2.48E+05
D	0.11	11	127.27	2.48E+05
E	0.11	11	127.13	1.31E+05
F	0.11	11	129.11	3.84E+05
G	0.11	11	128.35	2.15E+05

4. Conclusion

In this work, an experiment to determine the amount of wax deposited was conducted with a wax flow loop and empirical models were developed that showed the relationship between mass of wax deposited against time and flow rate at different ambient pipe wall temperatures. In the study it was observed that at pipe wall temperature below the WAT, the mass of wax deposited increased as the resident time of the oil in the pipe increased and decreased with increased flow rate. It was observed that in sample A at a flow rate of 0.093 litres/seconds the deposition of wax at 27°C, 24°C, 19°C and 11°C pipe wall temperatures were respectively 23.3 grams, 84.9 grams, 98.2 grams and 142.5 grams. Similar trend was obtained for other samples at pipe wall temperatures below the WAT. This shows how critical the drop in temperature below the WAT is on wax crystallization and deposition. It was further observed that the mass of wax deposited increased with the wax content of the samples. A quadratic model proved to be the best correlating model for both the effect of time and flow rate with a relative lower Root mean square error (RMSE) when compared to other models generated. In the production of waxy crude oil, the production pipe line should be well insulated to prevent heat loss that could result in pipe wall temperature dropping below the WAT to prevent wax crystallization and deposition.

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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