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PREDICTING THE MASS OF WAX DEPOSITED FOR WAXY CRUDE OIL SAMPLES FROM NIGER DELTA IN NIGERIA

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Abstract

Wax deposition in production systems has constituted one of the myriads of major flow assurance problems in the oil industry. This results from the deposition of wax on the wall of production pipelines when waxy crude oils flow at a temperature below the Wax Appearance Temperature (WAT) and thus reducing the effective diameter of the pipe lines. Accurate prediction of the deposition of wax could save capital and operational investment in the production of waxy crude oil as this would inform timely decision for pigging or passing hot oil through the flow lines to clear off suspected wax accumulation. In this study, an experimental wax flow loop was used to determine wax deposition for different flow rates at temperatures below the WAT using seven waxy crude oil samples with unique compositional properties from different fields in Niger Delta. The range of API covered was 30 - 40 degrees while that of pour-point was 20-27°C. The samples were characterized in line with ASTM 3328 using Gas chromatographic type Agilent 7890A equipment. Pour point was determined in line with ASTM D97 using pour point determination equipment. In order to monitor the mass of wax deposited in the field, laboratory deposition profile of wax resulting from variation of flow rates with respect to ambient temperatures below the WAT was up-scaled from laboratory to field units to account for real life field operating condition. An up-scale equation was developed to account for all variables that influence wax deposition with the normalized mass rate $\dot{m}_n$ obtained from the laboratory wax flow loop experiment conducted. Molecular diffusion was considered as the principal mechanism for deposition. Due to the effect of temperature on wax formation, the mass of wax deposited was found to increase with increase in diameter and length of pipe as the ambient temperature reduces below the WAT. The further result shows massive wax accumulation within 24hrs of wax formation and should be avoided in production pipelines operation.

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

1. Introduction

The deposition of wax during the production of waxy or paraffinic crude oils is a serious flow assurance problem that has been a subject of numerous investigations [1-2]. These investigations are conducted in order to abate its occurrence and also ensure the flow of paraffinic crude oil to the desired destinations. During the production of waxy crude oils, the lighter components keep the heavier components in solution depending on the temperature, pressure, and the structure of the crude oil sample [3]. Temperature drop in the production system substantially reduces solubility of the heavier fractions in the crude oil. Hence, under unfavorable conditions below the Wax Appearance Temperature (WAT), waxy crude oil samples have the tendency of precipitating wax contents that can inhibit flow, increase pumping power or completely stop production if not properly managed [4-8].

Crude oil flowing in a production pipeline is cooled due to drop in the ambient temperature. Molecular diffusion starts as soon as the wall temperature of the pipe reduces to the WAT, which leads to the oil near the pipe wall being saturated with wax in solution, and precipitation of wax begins. Wax precipitation result to a concentration gradient between dissolved wax in the turbulent core and the wax remaining in the solution at the pipe wall. Due to this, dissolved wax diffuse towards the pipe wall where it is subsequently precipitated. The mass flux of dissolved wax molecules controlled by molecular diffusion only is defined by Fick's law [9].

The solubility coefficient was determined by performing centrifugation experiment on the oil [9-10]. The fraction of precipitated wax in crude oil was plotted against the temperature, and the slope of the curve was defined as the solubility coefficient. The molecular diffusion dominates at high temperature and heat flux conditions and forms the main mechanism of wax deposition. The quantity of wax deposited was determined experimentally under uniform flow rate at a given temperature with the aid of a wax flow loop [2]. This loop simulates oil field pipeline wax deposition. The test section was cooled externally by a chiller unit. Wax deposition occurred within the test section and was monitored by pressure drop measurement between the two ends of the test section. At the end of each experiment, the test section was disconnected and inspected for the thickness and weight of wax deposited. They were able to determine the mass of wax deposited with respect to test duration in the wax flow loop and observed that the mass deposited increased with flow time.

In 1988, Weingarten and Euchner built a diffusion deposition cell to investigate the deposition of wax at different cooling temperatures. The mass of wax deposited from crystallization was plotted against the test duration to obtain a normalized mass rate from the application of Fick's law of molecular diffusion. The Normalized mass rate was defined as the product of the diffusion constant c and the solubility coefficient, and it characterizes the composition of the waxy crude oil. Hsu *et al.* [11] reported that for a given oil and temperature, with the application of heat flux in the radial direction with known wax deposition tendency and flow velocity, the laboratory deposition parameter due to molecular diffusion can be scaled up to field unit to account for larger diameter and longer pipes.

The purpose of this paper is to develop a mathematical model that predicts wax deposition in production pipeline considering molecular diffusion as the principal mechanism of wax deposition from crude oil samples from the Niger Delta of Nigeria. This would help to predict the frequency of pigging or passing hot oil through the flow lines to clear accumulated wax and prevent production down time, which could result from complete pipeline blockage.

2. Material and methods

2.1 Crude oil sample

Seven waxy crude oil samples were collected from different oil fields across the Niger Delta in Nigeria. The rheological properties of the crude oils were determined through appropriate experimental procedures, and the results are presented in Table 1. The WAT ranged from 25.2°C–31°C, while the pour point ranged from 20°C–27°C. These values indicate that all the crude oil samples will pose challenges such as wax crystallization and gelling when it flows at sea temperature without proper heat insulation.

Table 1. Characteristics 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

2.2 Characterization of the crude oil

The samples were characterized in line with ASTM 3328 using gas chromatographic type Agilent 7890A equipment. Pour point was determined in line with ASTM D97 using pour point determination equipment. The equipment used hydrogen flame ionization detector and the temperature regulated column operated up to 430°C. The equipment had the capability to perform simulated distillation up to hydrocarbon number C_{60}. The result of the gas chromatography is presented in Figure 1; the result revealed that the samples had majority of the carbon number ranging from C_{12} to C_{40} with negligible component of carbon number from C_{44} - C_{60}. This validated report by [12] that most crude oil in the Niger Delta Region of Nigeria is paraffinic (waxy) crude oil.

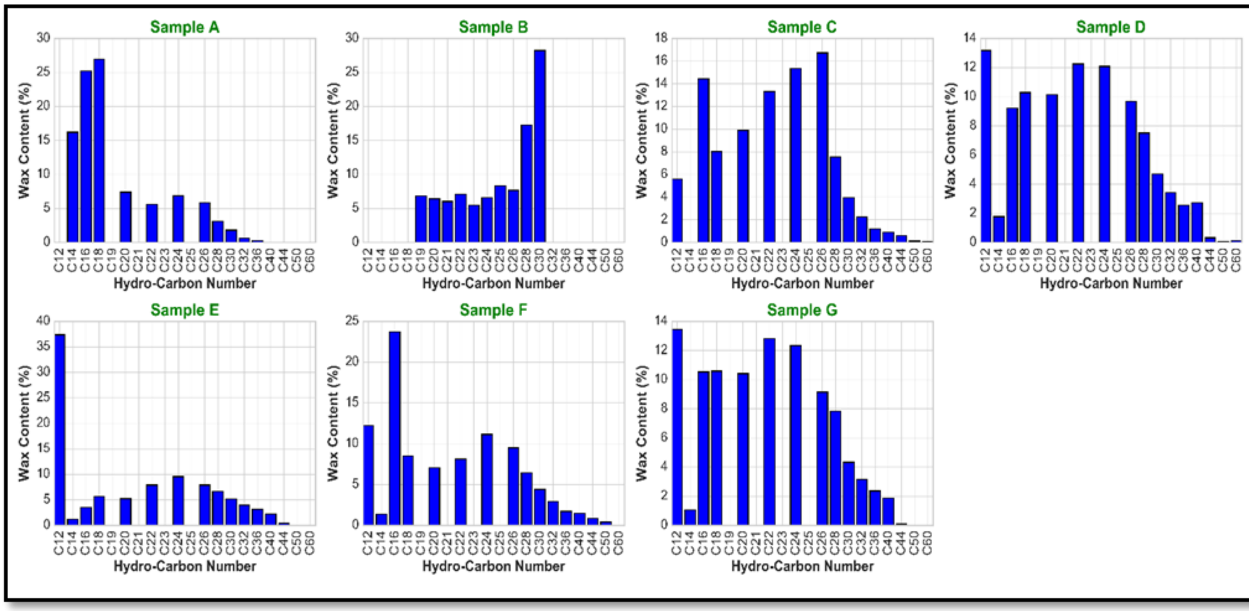

Figure 1. Percentage composition of hydrocarbon number

2.3 Laboratory experiment in determining the wax deposition

The experimental wax flow loop fabricated, as shown in Figure 2 was setup to simulate wax deposition in production pipeline. The wax deposition experiment was performed under different uniform flow rate at variable pipe ambient temperature above and below the WAT. The wax flow loop employed the same principle used by [13]. The length of the wax flow loop was 20ft long with a ½ inch diameter stainless steel pipe.

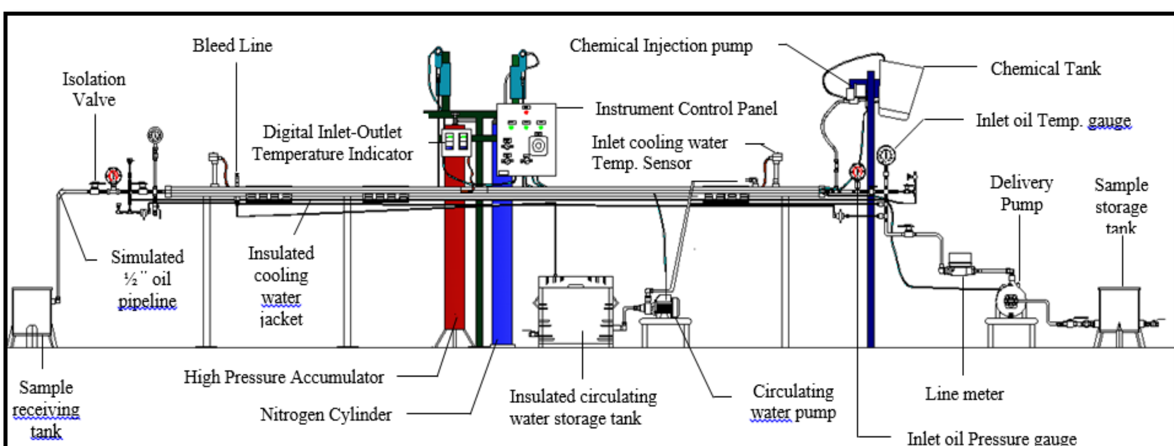

Figure 2. Locally fabricated and tested model wax flow loop

2.3.1. Experimental procedure of wax deposition in the wax flow loop

8 litre of waxy crude oil was pumped from the sample storage tank to the receiving tank through a ½" tubing representing the simulated pipeline. Water at a controlled temperature below the WAT was circulated in a water jacket with the aid of water pump 3 to cool the crude oil in the ½" pipe line. The waxy crude oil sample was heated above the WAT in a water bath set at 45°C .and then transferred into the sample storage tank, where it was pumped through the ½" tubing pipeline to the receiving storage tank.

The circulating water temperature below the WAT was varied for the series of experiments to create different pipeline temperature conditions (27°C, 24°C, 19°C, 11°C). The line meter was used to measure the quantity of crude oil pumped by the delivery pump through the wax flow loop. After performing each set of experiment, the mass of wax deposited in the loop was extracted and weighed.

A mixture of nitrogen gas and diesel from the high pressure accumulator after every experiment was released through a ¼" stainless steel tubing line to clear any stagnant liquid of waxy crude oil in the simulated ½" stainless steel tubing pipeline.

The mass deposited in the wax flow loop was determined by disconnecting the ½ inch diameter 20 ft length wax flow loop and inserting a ¼" tubing (head blogged) synonymous to mechanical pigging to push out the wax. With the aid of installed temperature and pressure gauges, continuous record of the temperature at the inlet, outlet and the pressure drop across the 1/2" tubing simulated pipeline were monitored. The trapped air in the cooling water jacket was expelled during the experiment by bleeding through the vent line in the equipment to avoid cavitation.

3. Development of wax deposition model by molecular diffusion

The wax deposition model was developed from Fick's law of molecular diffusion when oil is flowing through a pipe were the ambient temperature is lower than the oil temperature. As the oil cools in the pipe due to the exchange of heat between the pipe wall and the environment, the temperature of the oil at the pipe wall approaches the WAT. On further cooling the oil temperature fall below the WAT and solid wax crystal start to precipitate out of the waxy crude oil. The temperature gradient formed near the wall of the pipe leads to a concentration gradient of the dissolved wax, and the precipitated wax crystal start to migrate toward the pipe wall by molecular diffusion. Molecular diffusion is defined by Equation (1) and (2) as reported [9].

$$\frac{dm_d}{dt} = \rho A \mathrm{D} \frac{dC}{dr} \quad \text{(Fick's law)} \tag{1}$$

$$\frac{dm_d}{dt} = \rho A \mathrm{D} \frac{dC}{dT}\frac{dT}{dr} \tag{2}$$

where: ρ is the density of the oil; A internal surface area; D is the diffusion coefficient, $\frac{dC}{dr}$ is the concentration gradient in the radial direction; $\frac{dC}{dT}$ is defined as the solubility coefficient, which is the change in the fraction of precipitated wax in crude oil against change in temperature; $\frac{dT}{dr}$ is the temperature gradient in the radial direction.

In a study done by [14], the diffusion coefficient (D) in an equation developed by [15] was reduced to a simpler equation that just related the diffusion coefficient to the viscosity μ and a diffusion constant C shown in Equation (3). Equation (3) was substituted in Equation (2) to obtain Equation (4)

$$D = \frac{C}{\mu} \tag{3}$$

$$\frac{dm_d}{dt} = \rho A \frac{C}{\mu}\frac{dC}{dT}\frac{dT}{dr} \tag{4}$$

In 1988, Weingarten and Euchner in their study came up with the concept of normalized mass rate $\dot{m}_n$ which is the product of the diffusion constant C and the solubility coefficient $\frac{dC}{dT}$. This product characterizes the oil composition, and the independent evaluation of the two parameters was not necessary. The resultant normalized rate depends only on temperature for a given oil composition. This was done to reduce the number of experiments that will be performed in other to obtain the mass deposition rate. The normalized mass rate was then applied in Equation 4 to obtain the rate of mass deposited as described by Equation (5).

$$\frac{dm_d}{dt} = \frac{\rho A\dot{m}_n}{\mu}\frac{dT}{dr} \quad (5)$$

The temperature gradient in the radial direction was obtained by heat transfer analysis. The relationship between the radial temperature profile and longitudinal temperature profile were given by Equation (6) as reported by [9].

$$\frac{dT}{dr} = \frac{Q\rho C_p}{K_o \pi D}\frac{dT}{dx} \quad (6)$$

where: $\frac{dT}{dx}$ is the temperature gradient in the longitudinal direction; Q is the flow rate; C_p is the specific heat capacity; K_o is the thermal conductivity of oil; D is the diameter of the pipe; ρ is the density.

The longitudinal temperature profile was obtained through heat transfer analysis by [16] assuming constant surface temperature as given in Equation (7).

$$T(x) = T_a + (T_o - T_a)exp^{\left(\frac{-UPx}{\dot{m}C_p}\right)} \quad (7)$$

where: T_a is the ambient temperature of the surrounding; T_o is the oil temperature at the inlet of the pipe; P is the surface area of the pipe; x is a distance downstream from the inlet of the pipe; U is the overall heat transfer coefficient and $\dot{m}$ is the mass flow rate

The temperature change with respect to changes in the distance in the longitudinal direction was obtained by taking the derivative of Equation (7) to obtain Equation (8) which was then substituted in Equation (6) to give the change in temperature in the radial direction as given in Equation (9).

$$\frac{dT}{dx} = \frac{-UP}{\dot{m}C_p}(T_o - T_a)exp^{\left(\frac{-UPx}{\dot{m}C_p}\right)} \quad (8)$$

$$\frac{dT}{dr} = \frac{-U}{K_o}(T_o - T_a)exp^{\left(\frac{-UPx}{\dot{m}C_p}\right)} \quad (9)$$

Substituting Equation (9) into Equation (5) and then integrate to obtain the predicted mass deposited as given in Equation (10).

$$m_d = \frac{\dot{m}_n \rho AUt}{\mu K_o}(T_o - T_a)exp^{\left(\frac{-UPx}{\dot{m}C_p}\right)} \quad (10)$$

The wax deposition measured in the experiment conducted was the total immobile wax deposit, which is made up of oil filled in the interstitial space and the solid wax crystal. In 1981, Burger *et al.* [9] reported that the solid wax crystal is about 14–17% of the total immobile deposit; therefore Equation (10) was divided by 0.17 to predict Total immobile deposit given by Equation (11)

$$m_d = \frac{\dot{m}_n \rho AUt}{0.17\mu K_o}(T_o - T_a)exp^{\left(\frac{-UPx}{\dot{m}C_p}\right)} \quad (11)$$

where: m_d = total mass deposited (lbm); $\dot{m}_n$ = normalized mass rate (lbm ft/hr^2.°F); t = time (hr); L = length of pipe (ft); U = overall heat coefficient (Btu/hr. ft^2.°F); ρ = density (lbm/ft^3), d = internal pipe diameter (ft); μ = viscosity (lbm/ft.hr); Q = flowrate (litre/sec); K_o = thermal conductivity of oil (Btu/hr.ft.°F), and A = surface area of the pipe(ft^2).

The normalized mass rate $\dot{m}_n$ was obtained by comparing the wax deposited from the experiment to the wax predicted using Equation (11). Microsoft Excel Solver was used by adopting the least square criteria which minimize the difference between the sum of square of the wax deposited in the experiment to the wax predicted using the model to obtain the normalized mass rate.

The mass of wax deposited in the laboratory was limited to a simulated stainless ½" tubing diameter and 20ft length. The wax deposition model was up-scaled from experimental laboratory scale to field scale to account for larger pipeline diameter and longer pipe length to address real life field situation. It also considers other variables that influence wax deposition in crude oil production pipelines, as shown in Equation (12).

$$m_d = \frac{1.7053E^6 \dot{m}_n \rho dLUt}{\mu K_o}(T_o - T_a)exp^{\left(\frac{-3670.61E^{-5}U dx}{Q\rho C_p}\right)} \quad (12)$$

where: m_d = total mass deposited (g); $\dot{m}_n$ = normalized mass rate (g ft/hr^2.°F); t = time (hr); L = length of pipe (Km); U = overall heat coefficient (Btu/hr. ft^2.°F); ρ = density (lbm/ft^3); d = internal pipe diameter (inches); μ = viscosity (centipose); Q = flowrate (Barrel/day), and K_o = thermal conductivity of oil (Btu/hr.ft.°F).

4. Results and discussion

4.1 Normalized mass rate

Results for the normalized mass rate $\dot{m}_n$using Microsoft Excel Solver for all samples are presented in Figure 3. It can be observed that there was a correlation between the normalized mass rate and the wax content of the samples as presented in Table 1. Samples C, D, and F which had high normalized mass rate, also had high wax content while Sample E which had the lowest normalized mass rate also had least wax content. From Figure 3, it can be observed that the normalized mass rate increased as the temperature increased to about 24°C before a steep reduction in the normalized mass rate beyond 24°C. The normalized mass rates in this study gave similar trend as reported by [4].

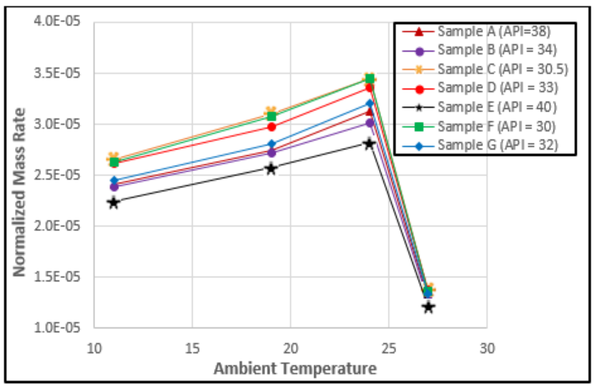

Figure 3. Normalized mass rate and ambient temperature for individual sample

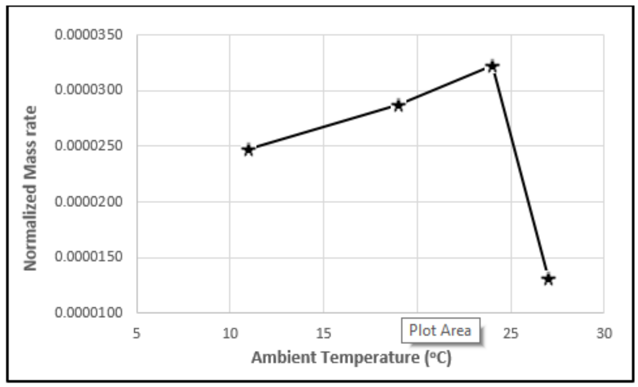

Figure 4. Average normalized mass rate for all samples with ambient temperature for all samples

From Figure 3, if the API of the waxy crude oil sample is known and fall within the range presented in the graph, the normalize mass rate at a given ambient sea temperature can be obtained which could be inserted into the model in Equation (12) to estimate the mass of wax that will be deposited in the production pipe line. The average normalized wax deposition rate of samples A to G as a function of ambient temperature is shown in Figure 4.

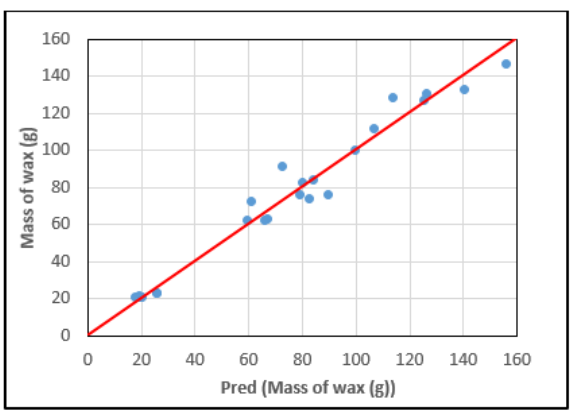

Figure 5. Experimental wax deposited to wax predicted from model for Sample A

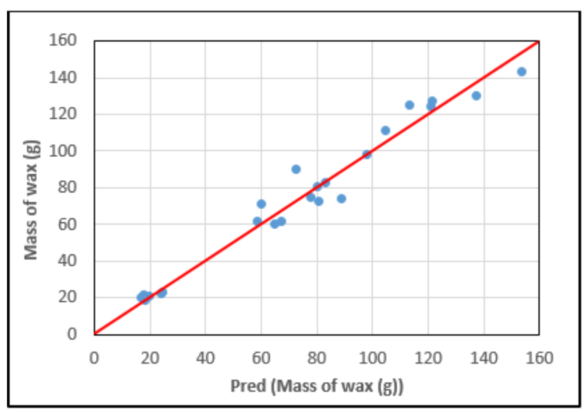

Figure 6. Experimental wax deposited to wax predicted from model for Sample B

The model for predicting the total mass of wax deposited gave reliable result, as seen in the cross-plots of the mass deposited from the experiment against the predicted mass deposited from the model (Figures 5 and 6.) Most of the data points fell close to the 45° diagonal line, which indicates that the mass of wax deposited from the laboratory experiment and the mass of wax predicted from the model gave good match. The same trend was also observed for other samples.

4.2. Up-scaled wax deposition

The wax deposition of an up-scaled pipe was investigated by taking a parameter that is similar to field operating conditions. Table 2 and 3 shows the input parameters used to investigate wax deposition in a production pipeline while Table 4 gives the result of wax accumulation in 24hrs. Figures 7 shows the mass of wax deposited using the model developed in this study within 24 hrs operation with respect to variation in pipe length with other factors kept constant as the ambient temperature drops below the WAT. The result in Figure 7 shows that as the ambient temperature drops below the WAT, the mass of wax deposited in the transportation pipeline increases. The figure also shows that wax deposition increased and peaked when the length of the production pipeline was between 20-30km for ambient temperatures (11°C, 19°C, 24°C, and 27°C) and reduction in wax deposition started afterward. The reduction in wax deposition after this length was probably due to the clogging of the pipeline by wax. The increase in wax deposition with respect to decrease in the ambient temperature of the production pipeline supports the work done by [2, 13].

Table 2. Pipeline input parameters and their values

Waxy Crude Oil Parameters	Values
Thermal conductivity of waxy crude oil, k_0 [Btu/ft-h-°F]	0.0775
Thermal conductive of pipeline (stainless steel AISI 304), k_p [Btu/hr-ft^2-°F]	8.42
Thermal conductive of insulation material (polyurethane), k_{ins} [Btu/hr-ft^2-°F]	0.17
Heat capacity of waxy crude oil, Cp [Btu/lb$_m$-°F]	0.51
Waxy Crude oil gravity [API]	38
Pour-point temperature, Tp [°C]	23.3
WAT [°C]	28.2
Flow Time [hr]	24
Flow Rate [bbl/day]	13000
wax density [lb/cuft]	56
Inlet Temperature [°C]	37
Outlet Temperature [°C]	26
Ambient Temperature [°C]	24
Ambient convective heat transfer coefficient [Btu/hr-ft^2-°F]	500

Source: (Cengal and Ghajar, 2014 and TEMA Standard, 2007) [16-17]

Table 3. Pipeline parameters and their values

Pipeline parameters	Values
Pipeline length, L [km]	20
Inner pipeline diameter , *d* [in]	24
Outer pipeline diameter, D [in]	25
Outer diameter of pipeline and insulation, OD [in]	26
Thermal conductive of pipeline, k_p [Btu/hr-ft^2-°F]	8.42
Thermal conductive of insulation material, k_{ins} [Btu/hr-ft^2-°F]	0.17

Source: (Cengal and Ghajar, 2014 and TEMA Standard, 2007) [16-17]

Table 4. Calculations based on the parameters of waxy crude oil and pipeline

Output parameters	Calculated values
Overall heat transfer coefficient, U [Btu/hr-ft^2]	0.4727
Average oil temperature [°C]	31.5
Oil viscosity [cP]	6.4475
Normalized mass rate	0.0000313
Mass deposited [lb]/24hrs	151654.4
Mass deposited [kg]/24hrs	68,851.1

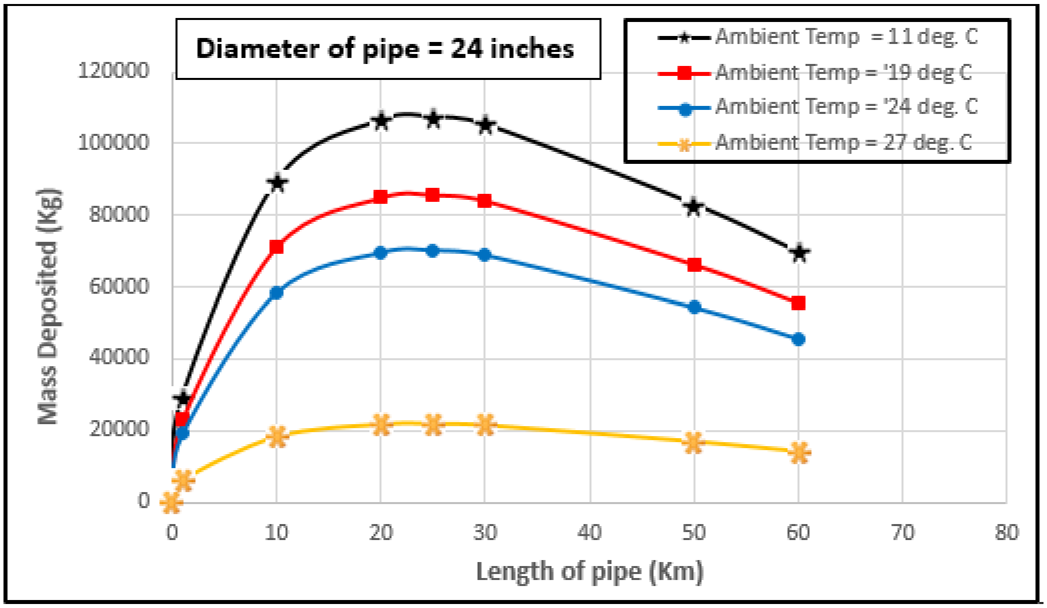

Figure 7. Wax deposition in an up-scaled pipe (variation in length of pipe)

5. Conclusion

In order to monitor the mass of wax deposited, a laboratory wax flow loop of 1/2" stainless steel tubing 20ft long simulated pipeline was fabricated, tested and experiment conducted to monitor the mass of wax deposited at a temperature below the wax appearance temperature. An upscale equation was developed to account for all variables that influence wax deposition with the normalized mass rate m_n obtained from the laboratory wax flow loop experiment conducted. Given the conditions of the case study, it was estimated that 68.851 Kg of wax (total immobile wax) would be deposited within 24hrs in a 24 inches diameter pipe of 20km. The mass of wax deposited with respect to increase in length of the of pipe at constant diameter was found to increase with drop in ambient temperature up to some distance along the pipe, and further deposition reduced probably due to clogging of the pipeline by wax. Average and individual Normalized mass rate m_n were determined for the samples for the range of API (30 – 40 degree) which could serve as an input data to estimate the mass of wax content(total immobile wax) in the production pipeline and provide an informed decision on the frequency of pigging the production pipeline to optimize waxy crude oil production The study had shown that the deposition of wax within 24 hrs in the case study is indeed a serious challenge that should be avoided with the application of sound production and engineering practice that would prevent the precipitation and deposition of wax in production pipelines

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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