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Development of Model and Flow Loop for Predicting Wax Deposition in Oil Pipelines Under Lamina Flow Regime/

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ABSTRACT----*The deposition of wax from waxy crudes to the inner walls of pipelines presents a costly problem in crude oil production and transportation operations. Waxy crudes characteristics vary from location to location. Waxy crudes from Bonny light crude oil in Niger Delta oil fields have not received sufficient research attention compared to other crudes globally.an experimental flow loop system for crude oil transportation operations was developed and fabricated to investigate factors affecting wax deposition A mathematical model for a hypothetical cylindrical pipeline transporting crude oil was also developed. Somel factors affecting wax depositionin crude oil transporting pipelines were determined. Results showed that wax deposition increased with increase in temperature difference and residence time, but wax concentration weight slightly varied with time as the temperature changed at a constant flow rate. Comparing the results obtained from the computational model with experimental data using Absolute Deviation method, it was found that for temperature, the maximum absolute deviation (AD) was 10.5% and average absolute deviation (AAD) was 10.6%. For the amount of wax deposited at different flow rates, the absolute deviation was 9.7% and the average absolute deviation was 7.6%. Residence time had the highest maximum average deviation of 13.7% and an average absolute deviation of 8.2%. Comparatively, there was an acceptable match between experimental results using the developed Flow Loop and results obtained from the computational model.*

***KEYWORDS*:** Wax deposition, Laminar flow regime, Computational model, Flow loop.

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I INTRODUCTION

Wax deposition problems have been recognized as one of the major flow assurance challenges in the production and transportation of crude oil. Petroleum industry loses hundreds of millions of dollars yearly for controlling these problems.Crude oils are complex mixtures containing several components, including paraffins, aromatics, naphthenes, asphaltenes and resins. The higher molecular weight paraffins (or n-alkanes) are referred to as waxes. At reservoir conditions, with temperatures in the range of 70-150°C and pressures in the range of 50-100 MPa, these waxes remain dissolved in the crude oil, which behaves as a Newtonian fluid (Lee and Fogler, 2001).

At the lower temperatures and pressures that exist during crude oil transportation, the high molecular weight n-alkanes or waxes tend to form macro and micro crystalline structures that precipitate out of the oil (Venkatesan and Fogler, 2004) and deposit on the cooler walls of the pipeline. The precipitated wax imparts complex non Newtonian and nonlinear characteristics to the flow properties of the crude oil (Zheng, 2017).

The temperature at which the first crystals of paraffin wax start to appear in the crude oil is called the Wax Appearance Temperature (WAT) or the Cloud Point Temperature (CPT). It has been shown that a "waxy" mixture containing as small as 2 mass% of wax is sufficient to undergo deposition (Kasumu, 2014), provided the temperature of the contact surface is less than or equal to the WAT of the crude oil or "waxy" mixture. Wax deposition can damage oil reservoir formations and wells, and cause blockage of pipelines and process equipment. The deposition of wax in pipelines and process equipment leads to increased pressure drop, increased pumping power requirements and/or reduction in pumping efficiency. Wax deposition problems are more severe in cold environments, most notably in subsea conditions, where temperatures at the bottom of the ocean can reach 4^{o}C (Venkatesan and Fogler, 2004).

Determination of the WAT and the amount of wax precipitated at a given temperature are critical for understanding the crude oil rheology and solids deposition (Schulkes, 2006; Hammani, 2003; Ekweribe, 2008). Ramirez-Jaramillo et al, (2004) have developed and tested a simulating wax deposition model in pipelines based on work done by Singh (2000), Svendsen (1993), Elphingstone et al, (1999). Results found in model pipelines indicate that deposition occurs due to radial mass diffusion driven by a concentration gradient induced by a temperature gradient. They conclude that the Reynold numbers and the mass Peclet number profoundly influence the mass deposition rate. They found a steep increase in the solid deposition with Reynolds number up to Re ≈ 100, where a more gradual increase is observed for higher Reynolds number. A further observation in their study was a decrease in the mass deposited when Re > 2000. They state that the reason for this phenomenon from the fact that the shear forces acting on the deposit layer will become larger with higher Reynolds number. At some point the shear forces will remove deposit on the wall and thereby decrease its thickness. When estimating the average molecular dilution coefficient, they found that there is an important connectionbetween the mass Pellet number and the radial mass ux. A substantial dependence of the deposited mass layer-thickness on the determined average diffusion coefficient was observed.

Todi and Deo(2006) have performed experimental and modelling studies of wax deposition in crude-oil-carrying pipelines. They studied the deposition phenomena in relation to particle transport at all types of heat fluxes (positive (cooling), negative (heating) and zero). They considered laminar flow with low Reynolds number and found that deposition of the crude tested will occur independently of the three different types of heat fluxes, as long as the temperature of the deposition surface is below the WAT. They also found that the distribution of the wax particles is established as a result of Brownian diffusion and shear dispersion. During the experiments they observed very thin layers, and the pressure transducers did not register the decrease in diameter. Confirmation of deposition was via a visual notice of inner pipe wall deposition. Ramachandran and Fogler, (2004) studied and tested the well-known Colburn analogy for the heat and mass- transfer in turbulent pipe flow. For the crudes tested they presumed the systems to be in thermodynamic equilibrium in the sense that the kinetics of para-n precipitation is much faster compared to the transport rates. They further showed that the Sherwood number must be less than the Nusselt number for a sub cooled system. From the Colburn analogy they achieved a larger Sherwood number than the Nusselt number, and this caused an over-predicted mass-transfer rate. Ramachandran and Fogler consequently showed that the Colburn analogy is very wrong for a few selected oils. Kok and Saracoglu, (2000) developed a mathematical model for prediction of wax deposition in turbulent pipeline flow. An interesting aspect of their work is that they transformed the balance equations to the form of the Stefan problem. They found that wax continuously occupy more of the free pipe surface along the pipeline when the bulk temperature reaches, or is lower than, the WAT. They noted that whereas the layer grows monotonically along the pipe when its thickness is small, a maximum appears at some local cross section of the pipe when the layer is thick. This is connected to the fact that when there is considerable wax-thickness, the heat dissipation capacity increases and thereby rises the bulk temperature. Accordingly, the temperature of the layer increases and thereby decreases the migration ow of para-ns. For large time scales (several days) they also observed that there is a minimum concentration of waxes corresponding to the maximum thickness of the layer and vice versa. Svendsen(1993) has given an important contribution to the understanding of wax deposition in both closed and open pipeline systems through his mathematical model based on analytical and numerical methods. His model is widely referred to by other researchers. In the introduction he makes it clear from the assumptions that a negative radial temperature gradient must be present in the flow. He assumes that with a zero gradient, approximately no deposition will occur. He further assumes that the temperature of the wall must be below the precipitation temperatures, and that the roughness of the wall must be large enough so that wax crystals can stick to it. In any case the model predicts that wax deposition can be considerably reduced even when the wall temperature is below the WAT, provided the liquid/solid phase transition is small at the wall temperature. He finally concludes that whether the model is good must be determined experimentally.

Singh et al, (2000) developed and tested a mathematical model describing the wax deposition process in a laboratory flow-loop. He found that an increase in the wall temperature results in a decrease in the thickness of the deposit, and consequently an increase in the wax content of the deposit. He also observed that an increase in the flow rate has a similar effect; a decrease in the thickness and an increase in the solid wax fraction. The results from his mathematical models presented in his work show an excellent agreement with the experimental data. There is an interesting discussion related to some of the results. For three different flow-loop tests of laminar flow, the wax deposit virtually stopped after a certain period of time. From his point of view this condition arises as a result of the insulating effect of the wax deposit, i.e., the thermal resistance of the wax deposit is sufficient to prevent further deposition in the flow-loop. Singh et al seems to have noticed a connection between the flow rate, the inner wall temperature, and the thickness of wax. He writes that for a higher flow rate, the rate of heat transfer is higher; hence, the rate of increase of the interface temperature is higher. His research seems to have been an important contribution to the understanding, and predication of wax deposition. Zheng (2017) developed a mathematical model for prediction of wax deposition in both open and closed pipeline systems. They combined phase equilibrium, phase transition and fluid dynamics to model wax deposition in pipelines. They concluded in large coefficient of thermal expansion some components may separate and move in the opposite direction at temperature below wax appearance temperature. Ramachandran and Fogler (2004) developed a wax deposition scale up model. They considered the effect of molecular diffusion and shear dispersion to scale up the experimental results for waxy crude production lines. They concluded that the flow turbulence effect has significant impact on wax deposition and cannot be neglected in wax deposition modelling. Kelechukwu (2010) investigated the effect of flow rate on wax deposition. Their study revealed a significant change in the wax deposition rate when the flow shifts from laminar to turbulent flow. Recently, Thabet (2017) concluded that the deposition rate decreases with increasing flow rate rather than increasing as suggested by a number of authors. Fogler et al. (2000) investigated the effect of pipe wall temperature on wax deposition. They reported that an increase in the wall temperature results in a decrease in the deposit thickness. An increase of flow rate also has a similar effect. Kok and Saracouglu (2000) developed a mathematical model for estimation of wax deposition in pipelines. They concluded that as the temperature of the fluid declines along the pipelines, the wax mass fraction, solid-liquid equilibrium constant and wax thickness increases. Soleymaninazar et al. (2001) developed a mathematical model both in laminar and turbulent flow regime. For turbulent flow regime they used $k-\varepsilon$ to predict the velocity and temperature distribution. They reported in the turbulent flow regime that there is critical flow rate for any system. Increasing flow rate beyond the critical rate leads to decreasing the amount of deposit.

Waxy crudes characteristics vary from location to location. Waxy crudes from Niger Delta oil fields have not received sufficient research attention compared to other crudes globally. This paper presents a computational model developed using energy and mass equations to predict the deposition of wax on pipe surface in the Niger Delta region under laminar flow regime, considering factors such as wax concentration, residence time, flow rate, and temperature difference between mixture and pipe wall. Then, a laboratory flow loop is designed and developed to carry out a series of experiment to validate the model results.

II MATERIALS AND METHOD

2.1 Materials

The flow-loop consist of a cylindrical stainless steel vessel housing the coolant (water) in the form of a heat exchanger, a 12 Litrereservoir stainless steel tank (internal diameter = 240 mm; Height = 265 mm; an external temperature-regulated heater rating = 240 V/ 3 KW), with a hydromantic submersible pump, for recirculating the wax-solventmixture, a temperature-regulated refrigerated bath system. A centrifugal pump for circulating the coolant (water), a flow meterand valves for regulating the flow of wax-solvent mixture and thermocouples were connected. A straight stainless steel pipe (2.54 cm (internal diameter) x 3.8 cm (outer diameter) x 1.40m long) and stainless valve was used before the wax-solvent mixture entered thecylindrical stainless steel vessel housing the coolant (water).

2.2 Methods

The characterisation of the waxy crude was carried to determine the Wax Physical Properties and Operating Conditions. Then the energy and mass equations were used to develop a computational model to determine the effect ofwax concentration, residence time, flow rate, and temperature difference between mixture and pipe wall on wax deposition. Thereafter, a laboratory flow loop is designed and developed to carry out a series of experiment to validate the model results.

2.2.1 Operating parameters

Waxy crude from different sources has different physical and chemical properties due to varying geological surrounding environments, i.e. terrains and climates. The physiochemical characteristics of the crude and deposited wax are issues associated to flow assurance.

Characterizations of OML 11 Niger Delta crude were performed based on several ASTM methods in NNPC Flow Assurance Laboratory, Eleme. ASTM is a protocol based on the standard method for the analysis of petroleum waxes. The Gas Chromatography Mass Spectrometer (HP 6890 series) was used to determine carbon number distribution of crude. The system was equipped with a fused-silica non-polar column measuring 10 m x 0.53 mm x 0.88 μm film. A flame ionization detector (FID) was used to detect the hydrocarbon contents. The analyses were performed in a gas chromatograph equipped with an auto injector, a cool-on-column (COC) injection port and a flame ionization detector (FID). The samples were diluted in carbon disulfide (CS2) at a concentration of 2% by weight, using a sample injection size of 1 μL.

Table 1:Wax Physical Properties and Operating Conditions

Parameter	*Value*
Inner pipe radius	0.0162 (m)
Pipe length	2.44 (m)
Inlet temperature	22.2 (°C)
Wall temperature	7.2 (°C)
WAT	13.9(°C)
Flow velocity	0.387 (m/s)
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	4.012 cp

2.2.2Mathematical formulation

Figure1 depicts a hypothetical representation of a cylindrical co-ordinate through which waxy fluid flows. Applying the law of conservation of mass to a volume element (r, ϕ, z) fixed in a space through which a binary mixture of wax and oil is flowing simultaneously.

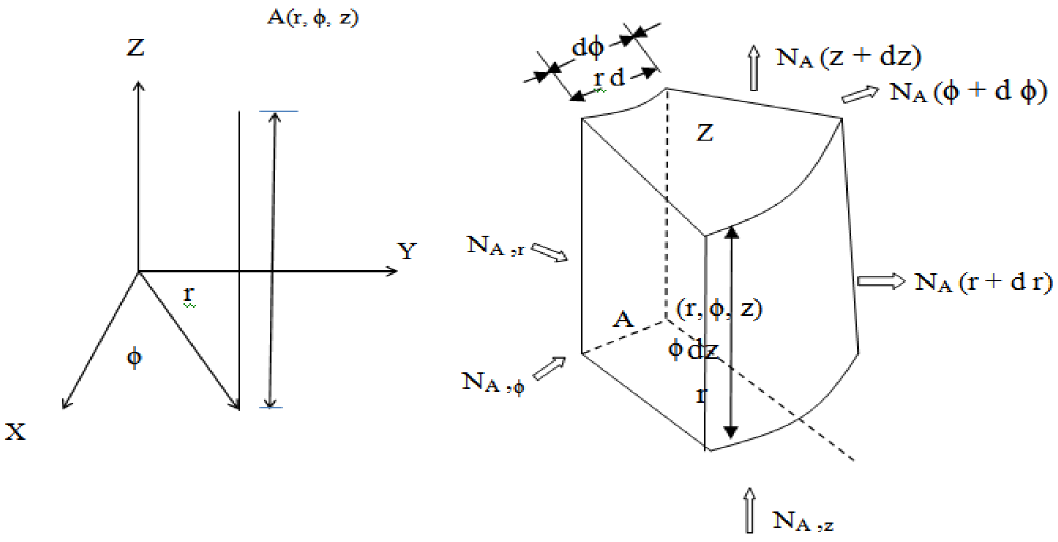

Figure 1 Elemental volumes for three dimensional mass transfer analysis- cylindrical co-ordinates

Where, $N_{A,r}$, $N_{A,\phi}$ and $N_{A,z}$are the mass flux in (r, ϕ, z) direction. (r, ϕ, z) are the radial, tangential and axial direction respectively.

The following assumptions are made in the derivation of the model.

- The fluid is Newtonian and incompressible while density of paraffin is assumed to be equal to that of the oil.
- The wax appearing temperature depends on the maximum amount of wax dissolved in solution.
- The flow is considered a single component and also a mixture of oil and paraffin above the WAT.
- The oil is free of water and gas.
- The model only considers the convective transportof mass and heat in the axial direction in the fluid phase while the molecular transport in the radial direction in the deposit and in the fluid phase.
- This model applies for pipelines considered working under pseudo steady conditions neglecting any *thermal energy generation in the fluid.*

Applying the principle of conservation of mass on species A for the control volume gives;

$$\begin{pmatrix} net\ rate\ of\ mas \\ efflux\ of\ A\ from \\ control\ volume \end{pmatrix} + \begin{pmatrix} net\ rate\ of \\ accumulation\ of\ A \\ within\ control\ volume \end{pmatrix} - \begin{pmatrix} rate\ of\ chemical \\ production\ of\ A \\ within\ the\ control\ volume \end{pmatrix} = 0 \qquad (1)$$

Introducing appropriate parameters into equation(1) and simplifying for temperature and concentration of wax deposition gives equation (2) and (3.)

$$v_z \frac{\partial T}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\alpha_r \frac{\partial T}{\partial r}\right) \quad (2)$$

$$v_z \frac{\partial C}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_{wo} \frac{\partial C}{\partial r}\right) \quad (3)$$

Where,α_r is the thermal diffusivity and D_{wo} is the paraffin diffusivity in the oil. The boundary conditions for mass and energy balances in the fluid are as shown

Analysis of the paraffin deposit takes molecular diffusion as the dominant mechanism of wax diffusion inside the deposit: therefore, mass transport within the deposit contributes to increasing the wax fraction and the deposit thickness. To determine the flux transported from the pipe middle section to the wall one assumes that the convective transport in the deposit is negligible and that the diffusive transport of wax can be approximated by the diffusive transport of wax in the fluid phase evaluated on the interface.F_w is the mass fraction of the gel, L is the length of the pipe, ρ_{gel} is the wax density, C_{ws} is the paraffin solubility in the oil and D_e is the effective diffusivity in the deposit as given in equation 2.4.

$$D_e = \frac{D_{wo}}{1+\alpha^2 F_w^2/(1-F_w)} \quad (4)$$

Where, α is the aspect ratio of the wax crystals in the deposit, D_{wo} *is the molecular diffusivity of wax in oil.*

$$D_{wo} = 13.3x10^{-8}\left(\frac{T^{1.47}\mu^{r}}{v_A^{0.71}}\right) \quad (5)$$

$$\gamma \equiv \frac{10.2}{V_A} - 0.791 \quad (6)$$

In equation 5, Tis absolute temperature, μ is solvent viscosity and V_A *is the wax molar volume, while in equation 6, γ is the function of* V_A.

$$\alpha_{ro} = \frac{k_o}{\rho_o Cp_o} \quad (7)$$

k = thermal conductivity of the pipe, ρ = oil density of waxy fluid

C_p*= oil heat capacity*

Regarding the interface, an interfacial balance of wax, is shown in equation 2.8:

$$2\pi r_i F_w(t)\rho_{gel}\frac{dr_i}{dt} = 2\pi r_i k_1[C_{wb}(T_i)] - 2\pi r_i\left(-D_e \frac{dC_{ws}}{dr}\bigg|_{r_i}\right) \quad (8)$$

Where k_1 is the mass transfer coefficient andC_{wb} is the bulk concentration of wax molecules. Equation 8 implies that the growth speed of the deposit is determined by the difference between the wax flux normal to the interface in the deposit and the fluid phase, evaluated at the interface.

2.2.3Solution technique

A computer program was designed to solve the energy (Equation 2) and mass balances (Equation 3) accordingly. It is necessary to establish if the pipe wall temperature was lower than the WAT of the crude mixture. If this was the case, proceed to calculate the thermal and concentration gradients in this position. Thereafter, mass balances in the solid phase (Equation 4) and in the fluid-gel interface (Equation 8) were solved to obtain the thickness and paraffin fraction of the deposit. The procedure described above was repeated over all the axial domain ofthe pipe, namely, from L = 0 to L = z. Finally, this process was repeated for the desired time span chosen to evaluate the deposit, but not before updating the temperature in the fluid-gel interface since it increased as the deposit grew.

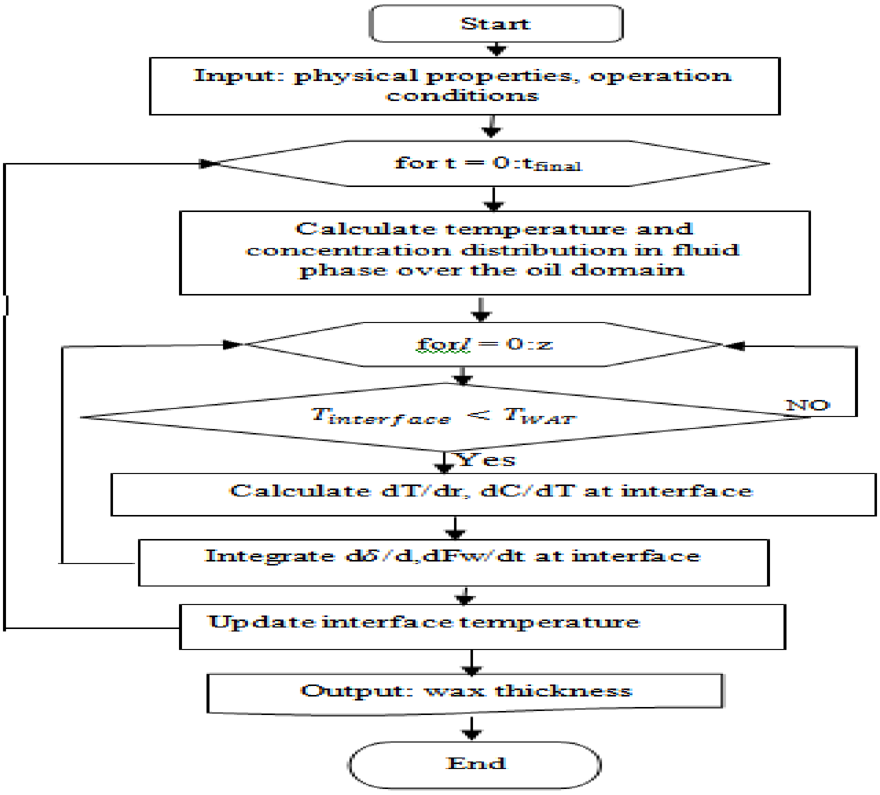

Figure 2.2:Program flowchart for amount of wax deposition

The above computer program was implemented using PHP. PHP is a server side scripting language designed for web development but also used as general-purpose programming language. PHP code is usually processed by a PHP interpreter implemented as a module in the web server or as a common Gateway Interface (CGI) executable. PHP code may also be executed with a command-line interface (CLI) and can be used to standalone graphical applications. PHP codes runs much faster because it runs in its own memory space. PHP is open source software that can be used on all major operating systems, including Linux, Microsoft Windows, Mac OS X, etc. With PHP, you have the freedom of choosing an operating system and a web server. You also have the choice of using procedural programming or Object Oriented Programming (OOP), or a mixture of both of them.

2.2.4Flow loop development

Figure 3.1 shows the Schematic diagram of the Laboratory Flow Loop. In this design, a hole was drilled on one side of the 12 Litre waxy fluid reservoirs. Three other holes at the top, one of the holes which is the biggest of the three holes was to enable the entrance of the feed, another was for recycling and the last was well sealed to house a thermometer to regulate the temperature of the reservoir. A 6 x 1.5" (L x ID) stainless steel pipe was welded to the hole on the side of the reservoir and connected toa stainless steel union joint with a 4" stainless steel pipe threaded at both ends which was screwed into a Tee socket along with two other 4" length stainless steel pipe which were each connected to Two different stainless steel valves, one leading to the inlet of a centrifugal pump and the other as a bypass control.

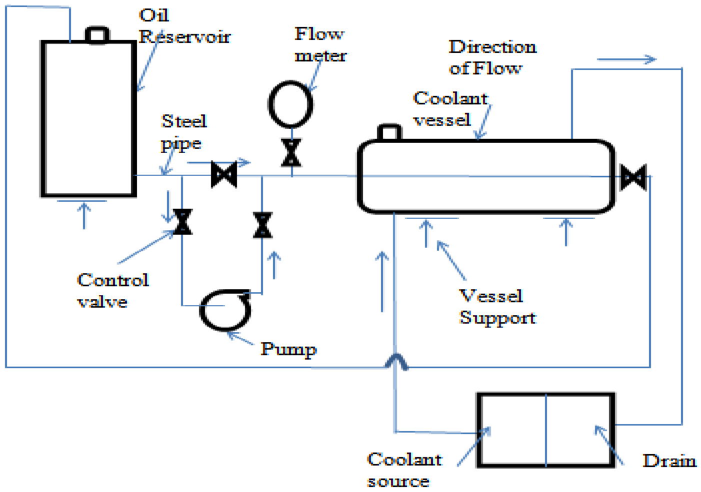

Figure 2.3: Schematic diagram of Laboratory Flow Loop

The other end of the bypass control valve was attached to another 4 x 1.5" stainless steel pipe threaded at both ends and screwed into a second Tee socket which had two 4 x 1.5" stainless steel pipe one of them leading from the outlet of the centrifugal pump controlled by a third stainless steel valve and the other connected to a flow meter which was fixed to another union joint together with a 150 x 1.02 mm cylindrical coolant vessel, each connected to the Tee socket. The coolant vessel has an open socket on one end and a cork fitted on the other end in which a 140 x 16 mm (L x ID) stainless steel pipe through which the wax was deposited can be detached or fixed back without any contact with the content of the vessel yet allows flow of the waxy fluid all the way through. The coolant vessel also have an inlet from the coolant source, an outlet to the drainage and an opening to view inside of it to enable the user properly detach or fix the140 x 16 mm (L x ID) stainless steel pipe or check the level of the content of the coolant vessel. The 140 x 16 mm (L x ID) stainless steel pipe was connected to a fourth stainless steel valve which was connected to a 90^{o} stainless steel elbow which was in turn connected to an 8 x 1.5" (L x ID) stainless steel pipe threaded on one end while a host can be connected to the other end that is not threaded back to the reservoir as recycle or samples can be collected from this point as well.

2.2.5 Experimental procedure

The procedure of the experiments is as follows. First, the waxy fluid was prepared by dissolving a specificamount of paraffin wax into kerosene solvent and then transferring it into the tank. Waxy fluid was pumped into the steel pipe at constant flow rate. A coolant fluid (water) was placed around the pipe for cooling the pipe wall down to a temperature below the Wax appearing point (WAP). The temperature of the heater and chiller and inlet flow rate of waxy fluidwascontrolled. Waxy fluid cools down when it passed through the cold pipe. It was expected that when the bulk temperature of waxy fluid reaches below WAP, wax crystals started to form due to different mechanisms of moving toward the pipe wall. The waxy fluid wasrecirculated through the pipe following the same procedure. After some time the flow of waxy fluid was stopped and the steel pipe was evacuated from oil cut as the cold flow still exists. After complete evacuation, pipe sections are detached from each other and all the sections werewashed with hot Kerosene to gather the deposited wax on the pipe wall. The collected solution of each section was heated until the kerosene vaporizes and solid wax remains. The amount of wax that wasdeposited in each section of the pipe, and as a result total deposit in the pipe was measured using a scale.

2.2.6Comparison method

This section presents the method used for comparing the experimental results from the use of the developed Flow Loop with computational model data to validate the computational result. Finally, the findings of the correlations are discussed.

To find the absolute deviation of a data item between the two methods, equation 9 was used.

$$Absolute\ Deviation\ (AD\%) = \left|\frac{Experimental\ \ value - Model\ \ value}{Experimental\ \ value}\right|\ x\ 100 \qquad (9)$$

Furthermore, the average differences in wax deposit using both methods were calculated using equation 10.

$$\text{Ave Absolute Deviation (AAD\%)} = \left|\frac{\text{Total Experimental value} - \text{Total Model value}}{\text{Total Experimental value}}\right| \times 100 \qquad (10)$$

III RESULTS AND DISCUSSION

A. Temperature difference

In order to examine the effects of different parameters on wax precipitation, sensitivity analysis of different parameters was done by changing just one parameters and keeping the other parameters constant. The results of the model are compared with the measured experimental data. The results are depicted in Figs. 1 – 4. Experimental results are very well predicted by the simulated wax deposition model that shows the molecular diffusion is a dominant mechanism in the laminar flow.

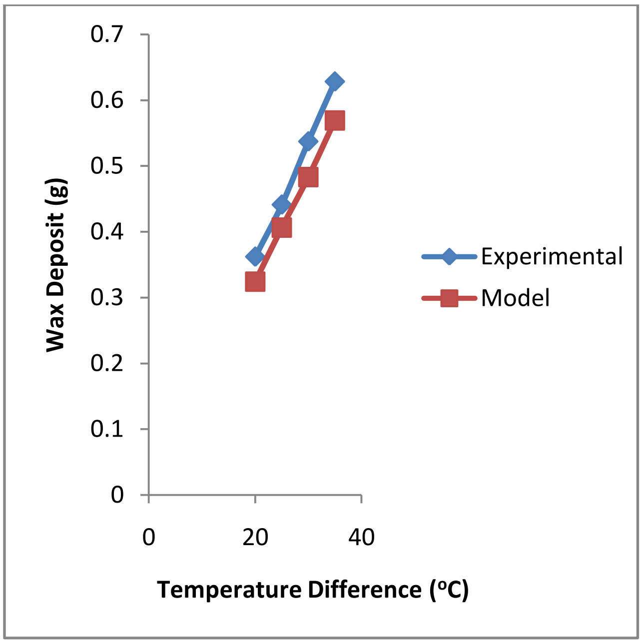

Figure 1: Comparison of the model and experimental data: Effect of temperature difference.

The temperature difference between inlet fluid and pipe wall play a key role on wax precipitation phenomena. The model and experimental results of this key parameter have been depicted in Fig. 1. As is clear with its trend, increasing this temperature difference causes an increase in the amount of wax precipitation, but it should be remembered that wax starts to precipitate in such a condition that the temperature of the pipe wall is lower than the solution temperature and Wax Appearance Point. Increasing the temperature difference increases the heat transfer rate and this factor increases the wax precipitation. One important point is that in the beginning, the rate of wax precipitation increases but by the passage of time the rate of wax precipitation decreases because of increasing the amount of wax precipitate. In other words, after some time the thickness of the wax layer increases, and this layer plays the role of insulator and this factor therefore decreases the rate of heat transfer.

B. Flow rate

The other parameter studied is the flow rate of waxy fluid. The effect of this parameter in laminar flow regime is shown in Fig. 2. More solid particles exist in high flow rates and for this reasons the heat transfer rate increases and so wax precipitation increases.

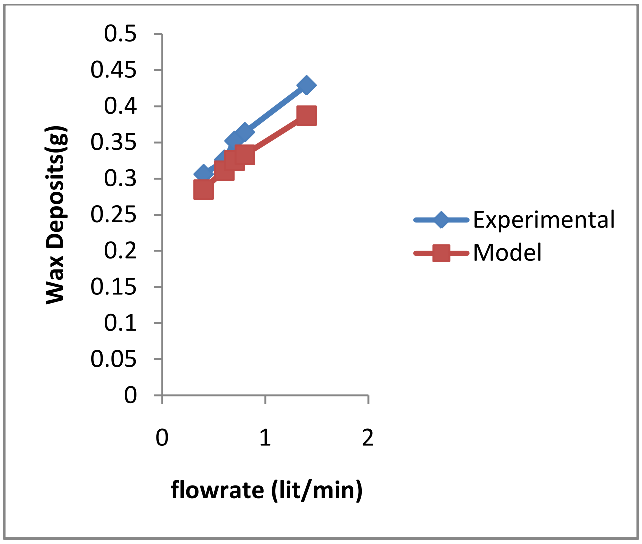

Figure 2:Comparison of model and experimental data: Effect of flow rate.

Despite the fact that many studies intuitively attribute the reason to "shear removal",Singh et al (2000) identified three effects that give rise to an alternative explanation that has been overlooked in previous studies. They found that these three effects include the effect of the boundary layer thickness on mass transfer (effect 1), the diffusivity at the interface on mass transfer (effect 2), and the interface wax concentration on mass transfer (effect 3). Both effects 1 and 2 tend to increase the growth rate of the wax deposit, while effect 3 tends to have the opposite effect. The overall growth behaviour of the wax deposit is the result of the competition between these three effects.The shear dispersion causes the wax deposit to detach from the pipe wall inside the bulk flow.

C. Residence time

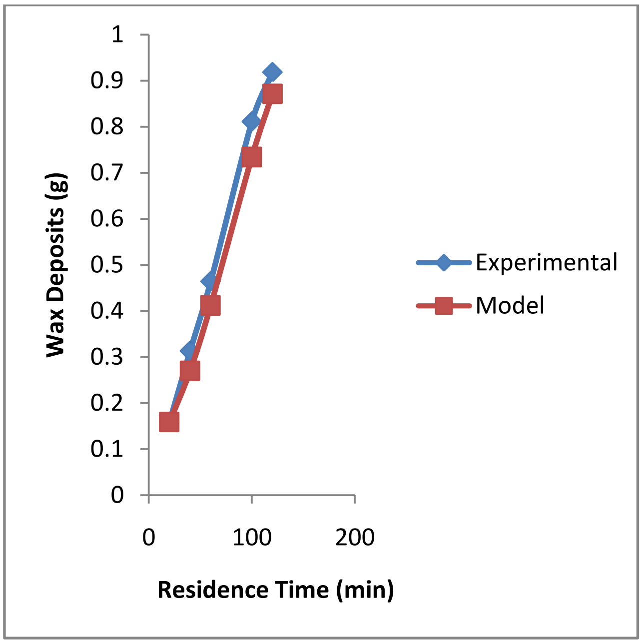

Figure 3: Comparison of model and experimental data.Effect of residence time.

The effect of residence time on wax deposition for different wax content has been shown in Fig. 3. As expected, increasing time causes an increase in the amount of precipitation. The residence time permits more heat loss and leads to a lower oil temperature, which in turn leads to wax precipitation and deposition.

D. Wax concentration in fluid

The effect of wax content in the feed on the total deposition of wax is shown in Fig. 4. Increasing the concentration of wax in feed increases wax deposition. From the figure it could clearly be observed that the higher the paraffin content (the supersaturation level), the more wax deposit produced at any given time; the faster the deposition rates; and the quicker it reaches the 100% wax deposition. These results are well expected: with the increase of the paraffin wax content in solution, there are more wax molecules available to produce wax crystals.

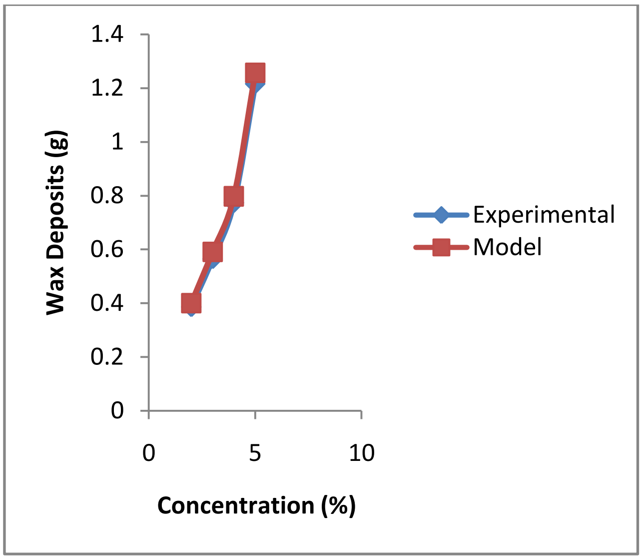

Figure 4:Comparison of model and experimental data. Effect of concentration.

As it can be observed in those Figures, the proposed model predicts the amount of wax deposition 6 to 13 percent less than real amount of wax. In order to analyse the accuracy of the experiments the following test was done. Four different samples were made by solving different percentage of wax in kerosene which was then heated on a heater in order to vaporize the kerosene and after weighting of the containers the amount of wax in any sample was measured. After that, the amounts of initial added waxes were compared with the extracted waxes. The results have been shown in Fig. 1 to Fig. 4. Comparing the results obtained from the computational model with experimental data using Absolute Deviation method, it was found that for temperature difference, the maximum absolute deviation is 10.5% and average absolute deviation is 10.6%. For the amount wax deposited at difference flow rate, the absolute deviation is 9.7% and the average absolute deviation 7.6%. Residence time has the highest maximum average deviation of 13.7% and an average absolute deviation of 8.2%. The deviations may be due to existence of some error margin in data collection.

So it can be said that the percent disagreement between the results of model and experimental data is related to the measurement error. Therefore, the developed laboratory flow loop was effective in investigating factors affecting wax deposition and our model has good capability for prediction of wax deposition in pipelines.

IV CONCLUSION

The main aim of this study was to investigate some problems related to the precipitation of wax in oil pipelines. A laboratory flow loop system was designed and fabricated to investigate the factors affecting wax deposition. Based on this target some experiments were done using a mixture of waxy crude. Then, using the available thermodynamic formulation and transport equations, a computational model was developed to predict the amount of wax precipitate. The results of the model and the experimental data were compared and good agreement between them was observed.There the conclusions of this work can be expressed as follow:

- In laminar flow regime, increasing the inlet flow rate intensifies the heat transfer rate and this causes more solid particles to form. In other words, increasing the flow rate increases wax precipitation rate.
- Increasing the temperature difference between inlet fluid and pipe increases the amount of wax precipitate and this is because of increasing heat transfer.
- Increasing the residence time increases the amount of wax precipitate.
- Inlet fluid samples have greater potential for wax precipitation, therefore the amount of wax precipitation increases as the concentration of inlet fluid sample increases.

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