ASPES
Volume 5, Number 2

ISSN: 1937-7991

EXPERIMENTAL STUDY OF WAX DEPOSITION IN SINGLE-PHASE SUBCOOLED OIL PIPELINES

O. A. Adeyanju*[*] *and L. O. Oyekunle
University of Lagos, Nigeria

ABSTRACT

The ability to determine the severity of wax deposition is an extremely important issue, particularly in the design and development of deepwater oilfields. Though much progress has been made in the last decades to better the understanding of this complex process, yet the ability to accurately account for all the factors that affect wax deposition are currently not in existence in the wax simulators used presently in the industries. In this study an experimental methodology constructed to simulate wax deposition process was employed to investigate the influence factors controlling paraffin wax deposition to the pipe wall surface (namely, inlet oil temperature, inlet coolant temperature, oil flow rate and the wax content). Series of tests were designed to determine the effects of these influence factors on the wax content in the deposit. The experimental results revealed that the amount of wax deposited initially increases with time, attained a maximum value and gradually erode off. Also it was discovered that the wax deposition decreases with flow rates and also with the temperature difference between the flowing oil and the pipe wall, when the oil temperature is above its Wax Appearance Temperature (WAT), while the reverse is the case when the oil temperature is below its WAT. The study also established that shear dispersion, defined as the movement of wax crystals towards the pipe wall as a result of the velocity variation along the radial direction during oil flow in the pipe ignored in most of the existing models used in the existing wax deposition commercial codes was found not to be inconsequential. The flow rate rather than the flow regime was also discovered to responsible for the shear stripping of wax deposit at the wall. This experimental observation will provide a reference point and an insight for further study on wax deposition in actual pipelines. This is particularly so for oil characterized by high wax content and high gel point temperature like those produced from most fields in Nigeria's Niger Delta.

NOMENCLATURE

d = diameter (m)
L = length (m)
R = pipeline radius (m)

---

[*] E-mail: oadeyanju@unilag.edu.ng

T = temperature (K)

Greek Letters

ρ = Fluid density (kg/m^3)
δ = wax thickness (ratio)
μ = viscosity (cp)

INTRODUCTION

Risk associated with the transportation of waxy crudes is one of the most critical operations hazards of deepwater offshore pipelines. The challenge that engineers will face in offshore operation is, thus, how to design the pipeline and subsea system to assure that multiphase waxy crudes will be safely and economically transported from the bottom of the wells through deepwater pipelines all the way to the downstream processing plant (Guo et al, 2005). The practice of identifying, quantifying and mitigating of all the flow risks associated with offshore pipelines and subsea systems is called flow assurance. Flow assurance is tedious for deepwater pipelines and system operations. In deepwater, the seawater temperature is usually much colder than the fluid temperature inside the pipeline (Al-Yaari, 2011). If the fluid temperature inside the pipelines becomes too low due to heat loss, wax deposit will form on the pipe wall. Thus, effective protection of fluid heat is one of the most important design parameters for offshore pipeline. Thus, factors affecting wax deposition mechanisms need to be extensively studied.

Wax deposition occurs when paraffinic components in crude oil (alkanes with carbon numbers greater than 20) precipitate and deposit on cold pipeline wall when the inner wall temperature falls below the Wax Appearance Temperature (WAT) (solubility limit). Whereas wax precipitation during oil flow results in wax deposition and flow restriction, wax precipitation during a production shutdown results in problems when attempting to restart the flow (Al-Yaari, 2011).

When the transportation in a pipeline is stopped due to a planned maintenance or an emergency situation such as severe weather conditions on offshore platform the temperature and solubility of wax decreases and wax molecules precipitate out of liquid phase in static condition (Fung et al, 2006, Thomason, 2000)

When waxy oil flowing in cold lines is cooled, it gels due to the formation of a network of wax crystals. Unlike in the case of inorganic solutions, where there is hardly any interaction among the salt crystals, the wax crystals have a strong interaction and affinity, resulting in the formation of the network.

Although oil (solvent) and wax (solute) have a similar chemical nature, their molecular weights are quite different. Waxes have a higher molecular weight and they tend to form stable wax crystals that interlock to form a solid network. The network of wax traps a large quantity of oil (Holder and Winkler, 1965). Hence, the initial stage of the deposition of the waxy oil mixture on a cold surface is the formation of a gel layer with large fraction of trapped oil.

The wax deposition process can be described by the following steps (Hernandez et al, 2004).

1. Gelation of the waxy oil (formation of incipient gel layer) on the cold surface.
2. Diffusion of waxes (hydrocarbon with carbon numbers greater than the critical number) towards the gel layer from the bulk oil.
3. Internal diffusion of these molecules through the trapped oil.
4. Precipitation of these molecules in the deposit.
5. Counter-diffusion of de-waxed oil (hydrocarbon with carbon numbers lower than the critical carbon number) out of the gel layer.

The last three steps result in an increase of the solid wax content of the deposit. Though there is ongoing efforts to gain insight into the physical phenomenon of wax deposition, a model to give reliable guesses of the wax build up is still lacking (Gjermundsen and Duenas, 2006; Mehrotra and Bhat, 2007). A reliable wax deposition experimental study will be an invaluable tool for the development of such effective model for optimal scheduling and removal of the deposited gel.

Various mechanisms, by which wax deposition could occur, such as molecular diffusion (when the temperature variation in radial direction makes the dissolved wax diffuse from bulk towards the pipe wall), shear dispersion (deposition of the already precipitated wax by shear dispersion), Shear Stripping reduction (deposition rate reduction due to shear stripping) , Brownian diffusion, and gravity settling; have been proposed (Bern et al., 1980; Burger et al. 1981; Majeed et al., 1990). Mechanism such as shear dispersion, Brownian diffusion, and gravity settling had been identified to play a role only for particulate deposition of wax. However, most models studied in the literature neglected the effect of particulate deposition as they believe its effect is inconsequential. Hence, molecular diffusion and shear stripping are currently considered as the predominant mechanisms underlying the wax deposition process. A series of experimental studies had been carried out to study the mechanisms affecting wax deposition, Vankatesan and Creek, (2007) in their study articulated the difference between the laboratory conditions and those prevailing in the fields and recommended that the existing laboratory methods should be reviewed.

Hilbert, (2010) experimentally studied the effect of different crude mixtures, emulsion, and pipeline cooling properties on wax behaviours in subsea pipelines and concluded that the shear yield stress of the pipeline fluid decreases with increasing water cut. Al-Yaari, (2011) used a experimental petroleum production model, to review the wax deposition problem in flow and during shut in condition and proposed important wax deposition processes and mechanisms that will enhance the wax deposition study. Dwivedi, et al., (2012) conducted an experimental study in a small-scale loop to determine the effect of turbulence/shear and thermal driving force on wax deposition. It was observed that the paraffin deposition is highly dependent on the thermal effective drive force which is the temperature difference between bulk oil and initial inner pipe wall and also on the turbulence effect. There are currently little studies on wax particulate deposition in the literature hence further study on this area cannot be over emphasized.

In this study, the oil a field in Nigeria characterized by high wax content and high gel point temperature was selected as the experimental sample. Different mechanisms leading to wax deposition such as molecular diffusion, shear dispersion and shear removal were modeled, and key factors affecting wax deposition in pipelines (namely, inlet oil temperature, inlet coolant temperature, oil flow rate and the wax content) were experimentally studied.

Preliminary investigations were first conducted on the oil sample to determined its Wax Appearance Temperature (WAT) using a programmable Rheometer that measured the viscosity of the crude at different temperatures under different shear rates, the result is given in figure 1, the WAT of the sample oil was determined to be 43^{o}C, which is the temperature at which the oil start to exhibit non-Newtonian behavior i.e. viscosity starts to show dependence on the shear rate.

EXPERIMENTAL FACILITY DESCRIPTION

The experimental setup consisted of test flow loop that is shown in figure 2. This flow loop was used to perform the wax deposition experiments under the single oil phase conditions.

This flow loop is made of mild steel pipe of length 140 cm with an inside diameter of 1.5cm. The experimental setup has two sections, the test section and the reference section. The crude oil temperature was regulated with a temperature regulators, the oil is pumped through the test section and the then through reference after passing through the liquid mass flow-meter along the flow lines.

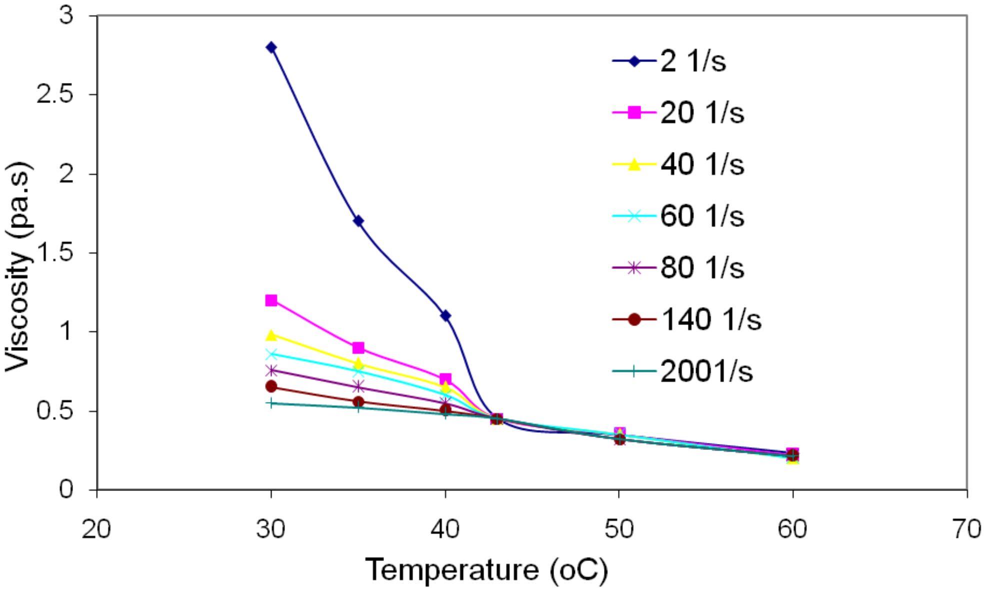

Figure 1. Viscosity profile of the oil sample at different shear rate at different temperature.

The test section is jacketed with a steel jacket in which cold water pumped from a cooling bath are circulated. The purpose of the test section is to maintain the inner pipe wall at a lower temperature than both the bulk oil temperature and Wax Appearance Temperature

(WAT) so as to generate the wax deposit on the inner pipe wall, just like what would be encountered in actual pipelines.

The configuration of the reference section is completely identical with the test section. However, contrary to the test section, the inner pipe wall temperature in the reference section is maintained at a higher temperature than the bulk oil temperature to prevent wax deposition by circulating the heated water into the jacket of reference section.

Thermocouples were placed both at the inlet and outlet of the test tube and the reference tube to determine the temperatures at both the inlet and outlet of the test and reference section.

Thermocouples were also attached to the cooling water tank and crude oil tank to take temperature reading. The oil in the previous experimental run was ensures to be removed by flowing hot oil for few hours before the commencement of subsequent experimental run.

METHODOLOGY OF THE EXPERIMENT

Flow loop experiments were performed to observe the growth and aging of the gel deposit.

The waxy oil sample was made to enter the test section at a relatively higher temperature than the wall/coolant temperature in order to generate wax deposit in the inner section of the flow-line.

Experiments for four different flow rates 1.0 liter/min, 1.4 liter/min, 1.8 liter/min and 2.2 liters/min, were carried out at the same aging time of about 26 hours to determine the effect of oil temperature on wax deposition. The experiments were performed:

- At the same flow rate of 1.4 liter/min., at the same oil temperature of 55°C, but at different wall temperatures of 40°C, 35°C and 30°C to investigate the dependence of wax deposition on the pipe wall temperature.
- At the same flow rate of 1.4 liter/min. and at a wall temperature of 37°C at different bulk oil temperatures of 52°C and 56°C to study the effect of oil temperature on wax deposision.
- At the same flow rate of 1.4 liter/min. and at the wall temperature of 28°C at different oil temperatures of 34°C, 37°C and 40°C which are below the Wax Appearance Temperature (WAT) of the crude to determined the diffusion effect of the precipitated wax.
- The experiments were then repeated at wall temperature of 30°C, oil temperature of 55°C at four different aging time of 6 hours, 12 hours, 18 hours and 24 hours at a constant flow rate of 1.0 liter/min and samples of the wax-oil gel deposit were collected from the wall of the tubing after each experiment and were analyzed for the wax content through their densities determination.
- The effect of shear dispersion was investigated by neutralizing the molecular diffusion effect by putting the oil and wall temperature at 38°C which has to be below the Wax Appearance Temperature (WAT) of the crude earlier determined to be 43°C in order to allow the wax to be precipitated and flowing it at a rate of 1.4 liter/min.

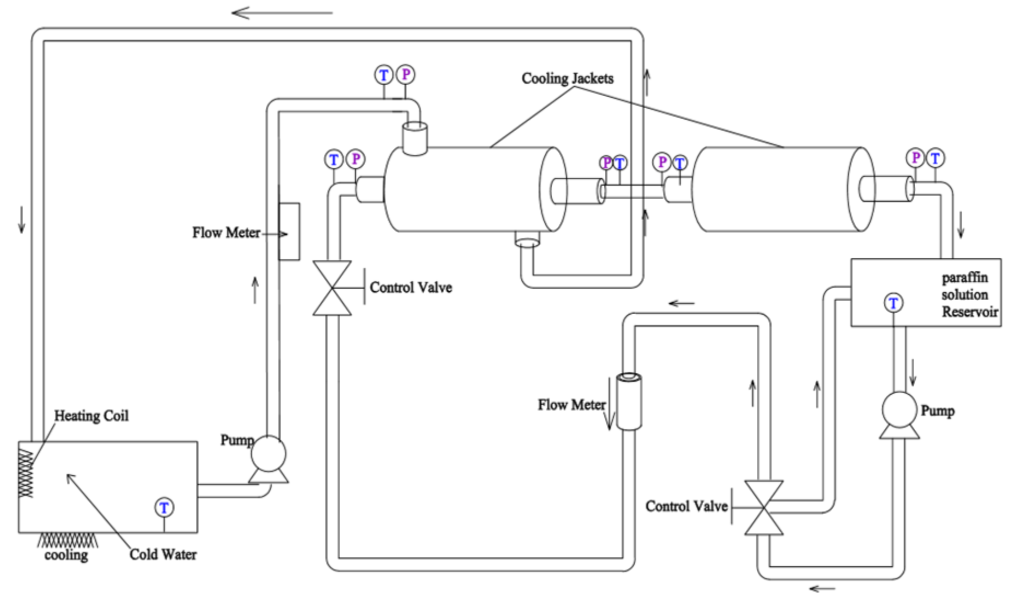

Figure 2. Schematic diagram of wax deposition test flow loop.

WAX DEPOSITION DETERMINATION METHOD

The pressure drop method was used to determine the thickness of the deposited wax.

This method is based on the concept that wax deposition in a pipe section reduces the hydraulic diameter of the flowing fluid inside the pipe, resulting in an increase in frictional pressure drop over the pipe section.

The pressure drop method is an on-line wax measurement technique that does not require depressurization and restart in order to obtain the measurements. Neither does it impose any influence on the in-situ and overall heat transfer.

Once the frictional pressure drop across a pipe section is measured and the flow rate, density and viscosity of the crude oil in the pipe section are determined, the wax thickness present in the pipe wall can be calculated accurately from the following equation (Chen et al, 1997)

$$(d_i - 2\delta_w)^{5-n} = \frac{2c\rho L}{\Delta P_f}\left(\frac{\mu}{\rho}\right)^{n}\left(\frac{4Q}{\pi}\right)^{2-n} \tag{1}$$

where ΔP_f is the pressure drop

L is the length of pipe section, d is the hydraulic diameter or effective inside diameter, Q is the volumetric flow rate, ρ is the fluid density, Where μ is the apparent viscosity of the crude oil. c = 16, n = 1 for laminar flow and c = 0.046, n = 0.2 for turbulent flow. Laminar flow exists when $N_{\mathrm{Re}} < 2000$ (Chen et al. ,1997).

RESULT AND DISCUSSION

Generally it was observed in all the experimental runs that the wax thickness initially increases gradually reaching a peak and then starts diminishing. This is due to wax-oil gel formed initially consisting of oil entrapped in the wax deposit until the oil start diffusing out of the gel deposit at the later period when the wax-gel deposit begins to harden.

EFFECT OF INLET COOLANT TEMPERATURE

As in the literature, that wax precipitates out of the transported crude oil to form wax deposit at the wall of cold pipe when oil temperature drop below Wax Appearance Temperature (WAT) of the crude. It has been recognized that the pipe wall temperature has a significant impact on wax deposition. Consequently, the effect of the pipe wall temperature on wax deposition had been studied experimentally and reported in a lots of recently published literature source (Dwivedi, 2012; Semenov, 2012; Noville and Naveira, 2012; Leontaritis and Geroulis, 2011; Al-Yaari, 2011), where the thickness of wax deposits is believe to increase with the decreasing pipe wall temperature (Coolant temperature).

Considering the practical situation where the ambient temperature may be around the gel point temperature of the waxy crude oil in subsea pipeline, accordingly, the effect of the pipe wall temperature around the gel point temperature of the oil becomes the research emphasis. Obviously, adjusting the inlet coolant temperature can control the pipe wall temperature in the experiments.

The inlet coolant temperatures studied in the experiment were selected at 40^{o}C, 35^{o}C and 30^{oC} respectively, while the inlet oil temperature was kept constant at 55^{o}C. However unlike the convectional phenomenon that the thickness of wax deposit would increase with the decreasing inlet coolant temperature, from the result shown in Figure (3) It can be seen that under the same inlet oil temperature conditions the dimensionless thickness of wax deposit actually decreases with the decreasing inlet coolant temperature around the gel point temperature.

The reasonable explanation for the phenomenon is the fact that when the inlet coolant temperature is lowered around the gel point of the oil, the viscosity of the oil at the liquid-deposit interface will increase sharply as the inlet coolant temperature decreases. Figure (1), shows that the oil viscosity at temperature of 35^{o}C is almost 50% higher than that of 40^{o}C. Consequently, the higher oil viscosity close to pipe wall can lead to the following significant influences:

- Under the same oil velocity conditions, the shear stress at the liquid-deposit interface will increase sharply with increasing oil viscosity at the liquid-deposit interface caused by the decreasing inlet coolant temperature, this will enhance the effect of shear stripping, leading to decrease in the amount of wax deposit.
- In terms of the Fick’s mass fusion law, both the radial temperature gradient and the concentration gradient with respect to temperature will increase as the inlet coolant temperature decreases under the same oil temperature conditions, which will have a positive effect on wax deposition, however, the increasing oil viscosity at the liquid-

> deposit interface caused by the decreasing inlet coolant temperature will diminish the molecular diffusion coefficient, which will have a negative effect on wax deposition.

Hence, whether the wax deposition rate increases or not depends on which influence factor mentioned is dominant. The combination of the two aspects mentioned above ultimately leads to decrease in the thickness of wax deposit with decreasing inlet coolant temperature.

In other words, both the shear stress and the oil viscosity at the liquid-deposit interface are dominant in the process of wax deposition for the inlet coolant temperature being around the gel point temperature of the oil.

EFFECT OF INLET OIL TEMPERATURE

In the previous literature (Dwivedi, 2012; Semenov, 2012; Noville and Naveira, 2012), the selection of oil temperature which were studied in the experiment was differentiated in term of wax appearance Temperature (WAT) of the oil sample. However, whether the bulk oil temperature is below its WAT or not does play an important role in the precipitation of wax molecules. Therefore, in the study the selection of oil temperatures was differentiated in term of wax appearance temperature of 43^{o}C.

CASE 1: THE INLET OIL TEMPERATURE IS ABOVE ITS WAT

In this case, the inlet oil temperatures studied in the experiment were selected at 48^{o}C, 52^{o}C and 56^{o}C, respectively.

The inlet coolant temperature was kept constant at 37^{o}C, Figure (5) shows the dimensionless thickness of the wax deposits as a function of inlet oil temperature at oil flow rate of 1.4 liter/min.

The results indicate that the thickness of wax deposits decreases with the increasing inlet oil temperature which is above the WAT under the fixed inlet coolant temperature and oil velocity conditions.

The reasons may be due to the fact that when the bulk oil temperature is above its WAT, there are no wax molecules precipitating out of the bulk oil, which results in the decrease in wax deposition with increasing oil temperature. In addition, under the fixed inlet coolant temperature conditions, the higher oil temperature will generate higher temperature at the liquid-deposit interface which can increase the solubility of wax molecules, ultimately leading to the fewer amounts of wax deposits.

CASE 2: THE INLET OIL TEMPERATURE IS BELOW ITS WAT

In this case, the inlet oil temperatures studied in the experiments were selected at 34^{o}C, 37^{o}C and 40^{o}C, respectively. The inlet coolant temperature was kept constant at 28^{o}C, figure (6) show the dimensionless thickness of wax deposit as a function of inlet oil temperature for different oil velocities. Contrary to the results in case 1, the results of case 2 indicate that the thickness of wax deposits increases with increasing inlet oil temperature which is below the WAT under the fixed inlet coolant temperature and oil velocity conditions. The reasons may be due to:

- When the coolant temperature is below its WAT, the zone of wax precipitation will be enlarged with the increasing oil temperature accordingly, enlarged zone of wax precipitation caused by the increase in oil temperature will be prone to make more amount of wax deposit.
- For the fixed inlet coolant temperature, the higher inlet oil temperature can exert much bigger thermal driving force (i.e. temperature difference) which enhances its potential to generate more amounts of wax deposits.

EFFECT OF OIL FLOW RATE

Flow regimes were generally believe to have great impacts on wax deposition (i.e. the higher oil flow rate could generate more wax deposit for the laminar flow regime, and less wax deposit for the turbulent flow regime due to the effect of shear stripping). In this study, the oil flow rate rather than flow regime is considered the dominant factor affecting the thickness of wax deposit.

In the laminar flow conditions the wax deposit was observed to be govern by the following principles;

- The increased oil flow rate can increases the shear stress at the liquid-deposit interface, which will reinforce the intensity of shear stripping, consequently reducing the wax deposit thickness.
- The internal heat transfer coefficient increases with the increasing oil flow rate for laminar flow, which increases the radial temperature gradient, consequently leading to increase in deposit wax thickness.

Obviously, these two effects caused by oil velocity are simultaneous. Hence, whether wax deposition is promoted or hindered depends on which one of the two effects caused by oil velocity/flow rate is dominant in the process of wax deposition.

In the experimental study, as the experiment were performed in both laminar and turbulent flow regimes, the results show that as the velocity increases from laminar flow regime (flow rates of 1.00, 1.40, and 1.80 liter/min) to turbulent flow regime (flow rate of 2.20 liter/min), the effect of shear stripping becomes dominant Fig (6), with the deposit thickness increasing when the radial temperature gradient is dominant (i.e. during the laminar flow regime) and deposit thickness decreases when the shear stripping is dominant (during the turbulent flow regime).

The wax that deposit at a higher flow rate is harder and more compact judging by the increase in density of the deposited wax during the turbulent flow regime. In other words, only those wax crystals and crystal cluster capable of firm attachment to the surface, with good cohesion among themselves will not be removed from the deposit surface (Kelechukwu et al, 2010). In conclusion, it is not the flow regime but the fluid velocity that is responsible for shear stripping.

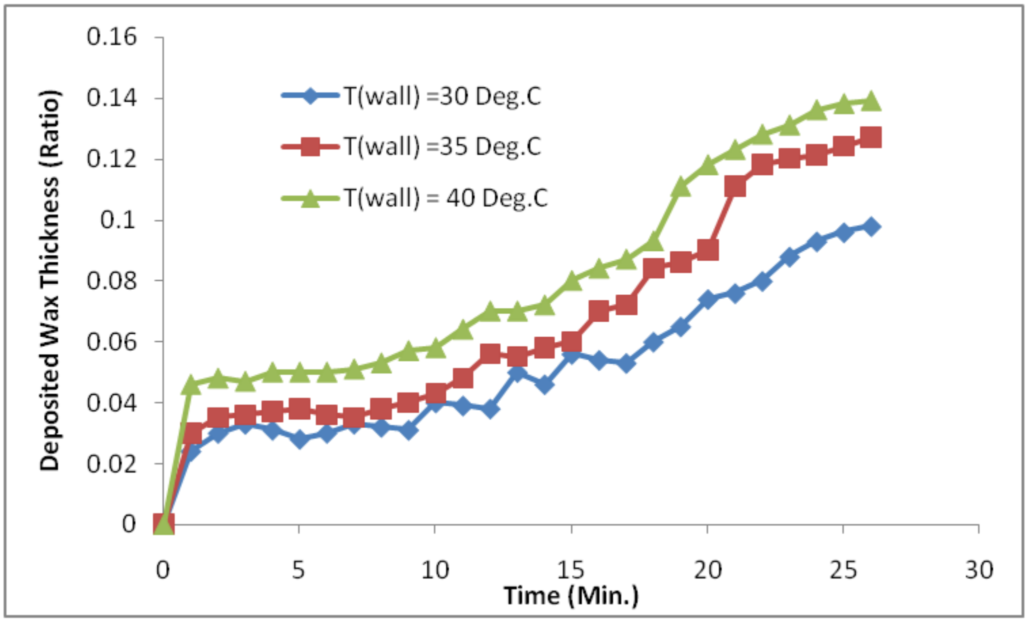

Figure 3. Dimensionless thickness of wax deposit versus time at different wall temperatures at oil flow rate of 1.4 liter/minutes.

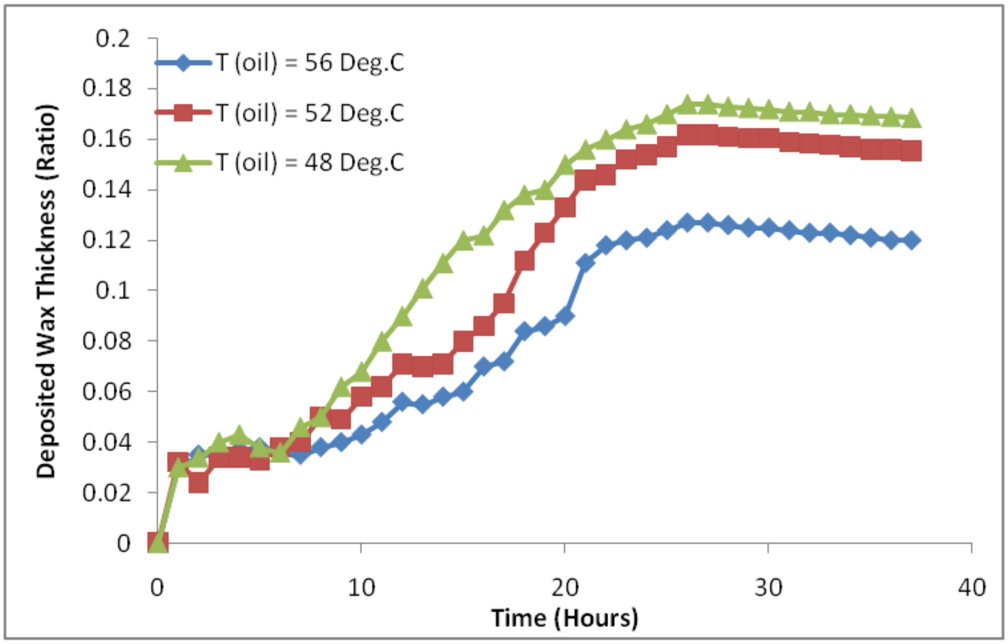

Figure 4. Dimensionless thickness of wax deposit versus time at different inlet oil temperatures above WAT at inlet coolant temperature of 37^{o}C and oil flow rate of 1.4 liter/min.

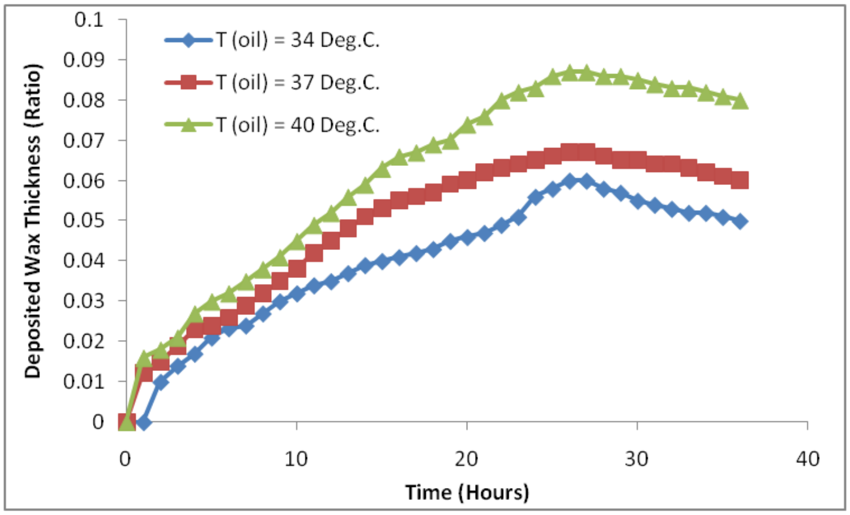

Figure 5. Dimensionless thickness of wax deposit versus time at different inlet oil temperatures below WAT at inlet coolant temperature of 28°C (below WAT) at oil flow rate of 1.4 liter/min.

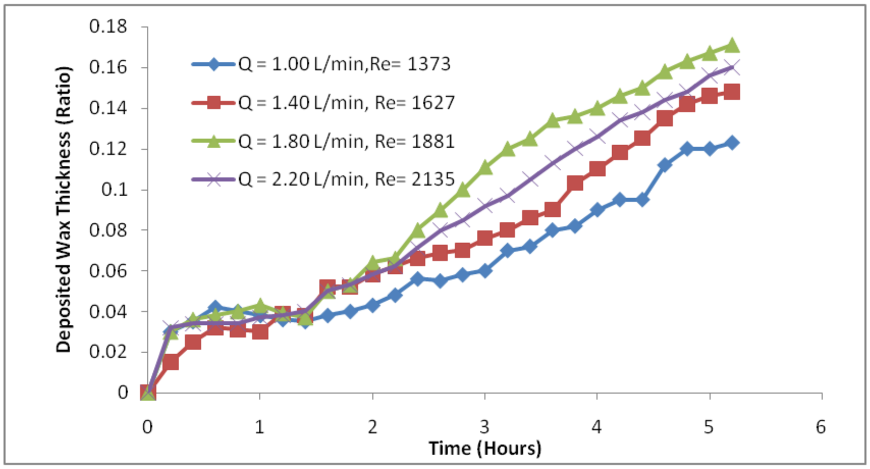

Figure 6. Dimensionless thickness of wax deposit versus time under different flow rates at oil temperature of 56°C at wall temperature of 37°C.

SENSITIVITY INVESTIGATION OF VARIOUS SHEAR DISPERSION INFLUENT FACTORS

The effects of various factors influencing the wax deposition tendency during shear dispersion/gravity settling processes, which include bulk wall and oil temperature, the oil flow rate and the wax content of the oil sample, were experimentally investigated in term of dimensionless wax deposit defined as the ratio of the wax thickness to the initial inner radius of the pipe, $\frac{\psi}{R}$,in order to determine their effect on wax deposit.

EFFECT OF BULK OIL AND WALL TEMPERATURE DEPRESSION BELOW THE WAT

Keeping the wax content at 20% and oil flow rate at 1.4 liters/min. and varying the bulk oil and wall temperature showed that the amount of wax deposition increases with decrease in bulk oil and wall temperature (as shown in Figure 7).

This is due to the facts that more wax precipitates as the temperature depress further below the wax appearance temperature, leading to bigger wax crystal formation in the bulk oil. Bigger the wax crystal indicate higher the shear dispersion coefficient, this is in agreement with the Bhattacharya (1991) equation.

EFFECT OF FLOW RATE

Decreasing the flow rates in the experimental run and keeping the bulk oil and wall temperature at 40^{o}C and wax content at 20%, result in increase in the dimensionless wax deposit thickness after twenty-eight (28) hours of experimental run. This is partly due to the increase in velocity gradient in the radial direction as a result of decrease flow rate and partly due to the longer residence time of the waxy oil in the pipe-line, resulting in more wax crystals diffusing towards the pipe wall. This is shown in Figure 8.

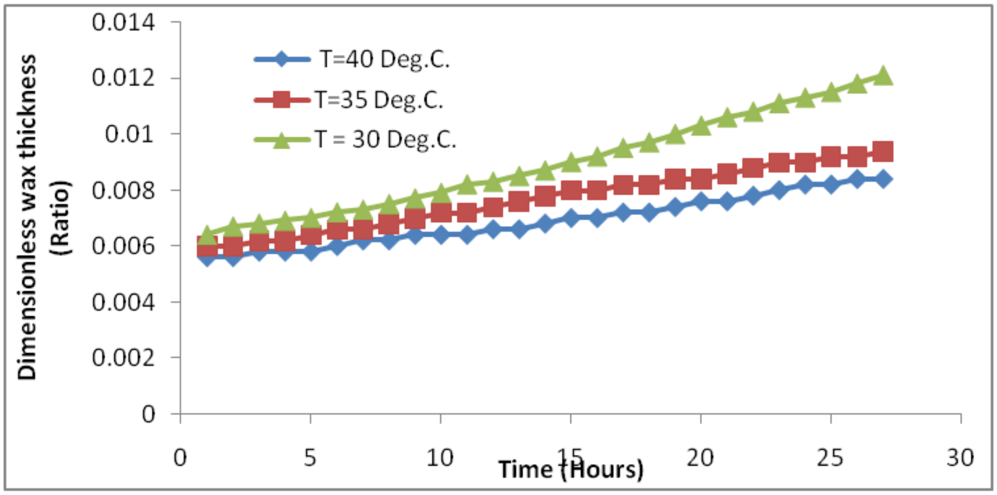

Figure 7. Plot of Dimensionless wax thickness due shear dispersion effect against time at different temperatures.

EFFECT OF WAX CONTENT

Increasing the wax content of the sample oil to 32% by adding the wax deposit scrapped from earlier experimental run to a new oil sample results in the increase in the wax deposit thickness increasing after almost twenty-eight (28) hours of experimental run.

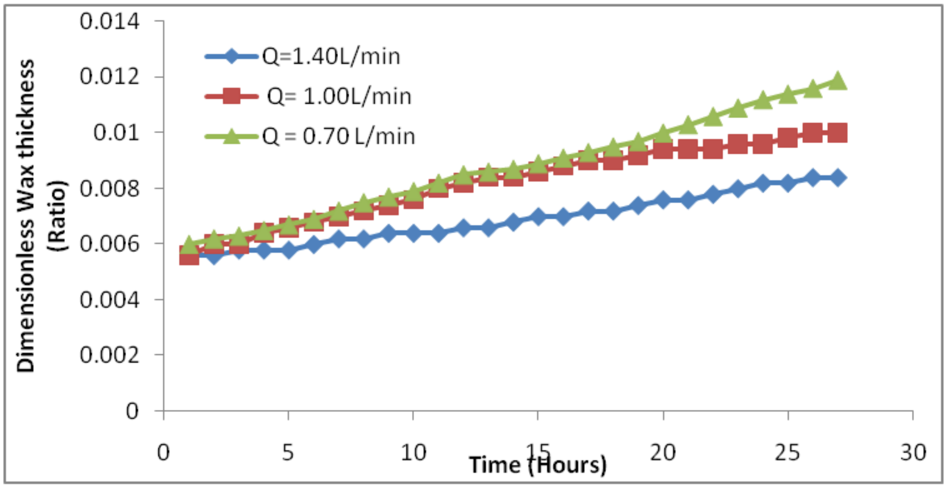

Figure 8. Plot of Dimensionless wax thickness due shear dispersion effect against time at different flow rates.

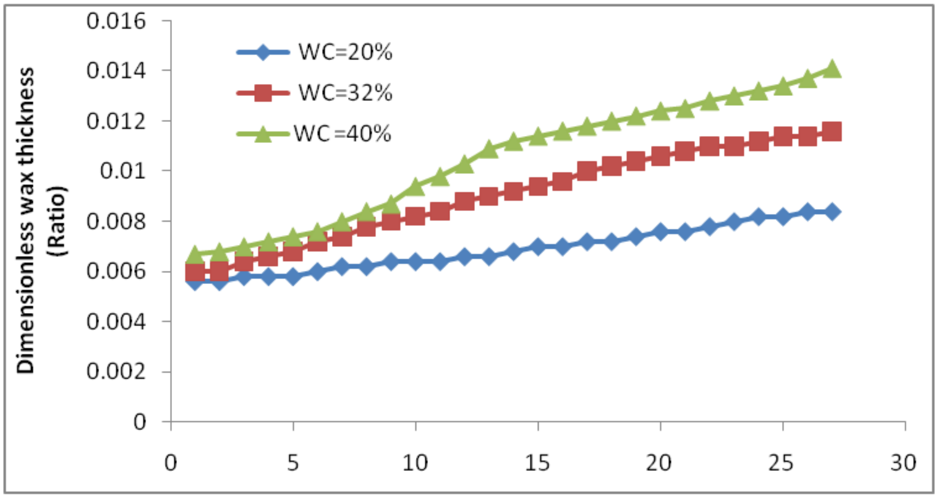

Figure 9. Plot of Dimensionless wax thickness due shear dispersion effect against time at different wax contents.

This may be due to more wax crystals available for diffusion towards the pipe wall at that temperature below the WAT as the wax content in the oil increases; this ultimately leads to increase in wax thickness due to increase in shear dispersion/gravity settling.

Comparison of Shear Dispersion and Molecular Diffusion Contribution to Wax Deposition Processes

Figure 10 shows the comparison between the deposited wax due to shear dispersion and those due to molecular diffusion, though more wax is deposited through the molecular diffusion process, the effect of shear dispersion on wax deposition cannot be assume to be inconsequential as assumed by most of the current wax deposition models. Hence the wax deposition is more of temperature gradient than velocity gradient process.

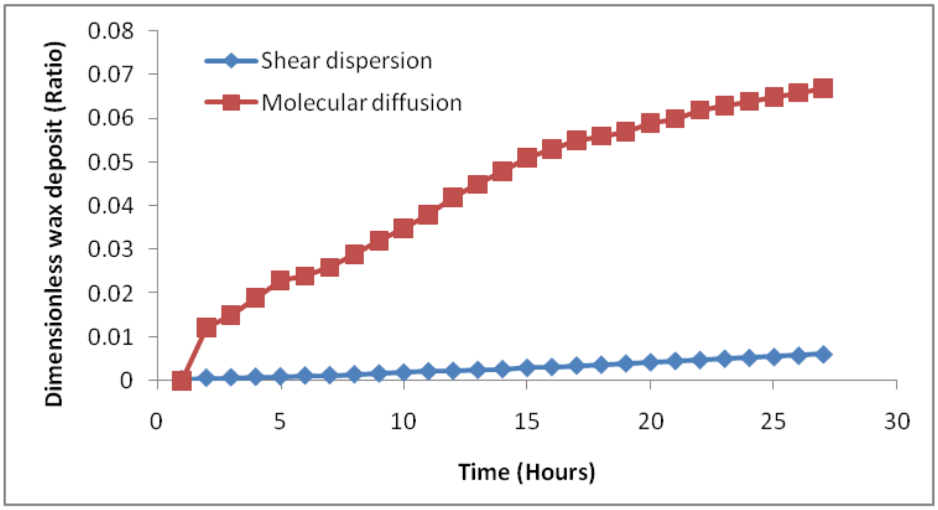

Figure 10. Plot of Dimensionless wax thickness due shear dispersion and molecular diffusion effect against time.

The Wax Content of the Deposit Changes with Time

The change in wax fraction in the deposited wax was confirmed by changes in the density of deposited wax with time as shown in figure 11. This agrees with the theoretical concept of wax continuously diffusing into the deposit and the oil seeping out of the deposit ultimately leading to the net wax deposit density to increase with time.

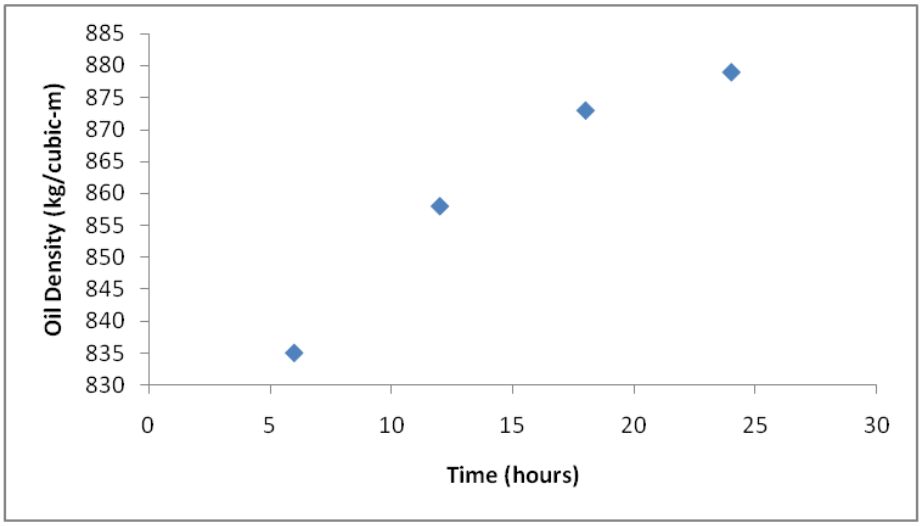

Figure 11. The change in density of the deposited wax deposit with time at oil flow rate of 1.00 liters/min.

OUTLET TEMPERATURE OF TEST SECTION VARIATION WITH TIME

At initial oil temperature of 55°C and coolant temperature of 35°C, the change in outlet bulk oil and coolant temperatures was observed at different periods. The result is as shown in Figure 9, where the outlet bulk oil temperature increases with time, while the outlet coolant temperature decreases with time. This indicates that the wax deposit acts as an insulator, thereby reducing the heat lost by the bulk oil to the pipe wall as the wax deposit grows.

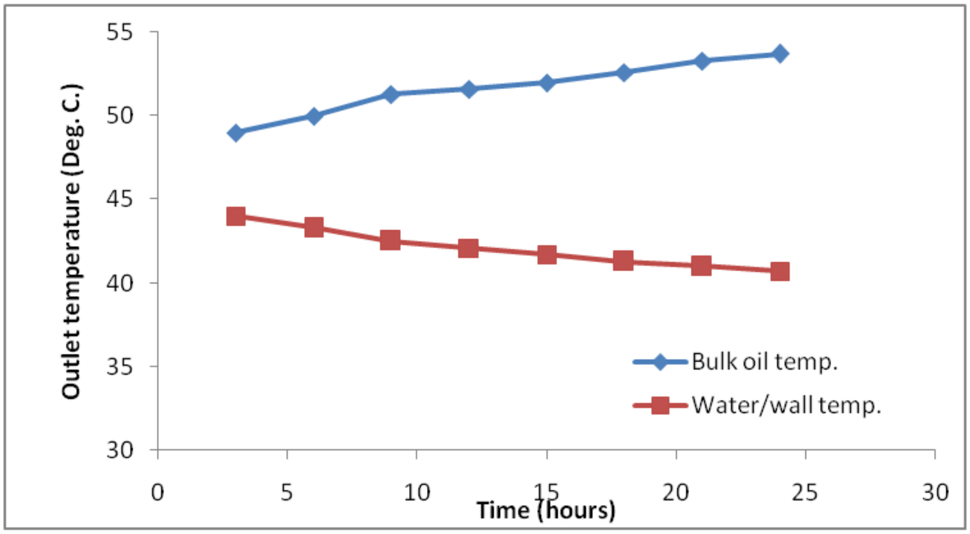

Figure 12. Outlet temperatures of the bulk oil and the water/wall temperature at different time.

CONCLUSION

The conclusion established based on the observation, discussions, and applications carried out in this study is summarized as the followings

- Contrary to the general theory that wax deposit increases with an increase in the temperature difference between the pipe wall and the bulk oil, it was observes that when the oil temperature is above its Wax Appearance Temperature (WAT) and the pipe wall temperature below its WAT, the wax deposit decreases with an increase in temperature difference, while the reverse is the case when both the oil and pipe wall temperature are below the oil WAT.
- It takes some time before wax start to deposits in a cold pipe during warm crude oil passage through the pipe. As the deposits grow it act as an insulator and reduces the heat exchange between the oil and the pipe wall.
- The effect of shear dispersion/ gravity settling contributions to wax deposition though relatively less than the contribution by molecular diffusion but it is not negligible as assumed by most of the currently available wax deposition models.

- The shear removal flux in the existing models is currently considered to be constant in time, More dynamic tests, such as those conducted with the crude oil , are required to obtain more information on the shear stripping term. This term needs to be studied as a function of shear stress, Reynolds number, and fluid viscosity.

REFERENCES

Al-Yaari, M., (2011) "Paraffin Wax Deposition: Mitigation and Removal Techniques" *Presented at the 2011 SPE professionals Technical Symposium held in Dhahran*, Saudi-Arabia.

Bhattacharya, A. (1991), "Effect of Thermal Environment on Wax Deposition in a Crude Oil Pipeline: Analysis of some Critical Aspects" *Proceedings of the first (1991) International offshore and Polar Engineering Conference*, Edinburgh, United Kingdom.

Bern, P. A., Withers, V.R. and Cairns, J.R.,(1980), "Wax Deposition in Crude-oil pipelines" Euro. *Proc. Offshore Petrol. Conference and Exhibition*, London, 571.

Burger , E.D., Perkins, T.K. and Striegler, J.H. (1981), "Studies of Wax Deposition in the Tran Alaska Pipeline," J. Pet. Tech, 33, 1075.

Chen, X.T., Volk, B. M., Bwith Stuck Pig," rill, J.P. (1997), "Techniques for Measuring Wax Thickness during Single and Multi-phase Flow" *Presented at SPE Annual Technical Conference and Exhibition held in San Antonio*, Texas, USA.

Dwivedi, P., Sarica, C. and Chang, W., (2012), "Experimental Study of Wax deposition Characteristics of a Waxy Crude oil under Single Phase Turbulent Flow Conditions" Paper no., OTC 22953, *Presented at the 2011 Offshore Technology Conference*, Houston, Texas, USA.

Fung, G., Bechhaus, W.P., McDaniel, S. and Erdogmus, M.(2006), "To Pig or Not To pig: The Marlin Experience with Stuck pipe" *Offshore Technology Conference*, Houston, TX.

Gjermundsen, I. and Duenas Dietz, M.(2006), In proceedings of the 7th International Conference on Petroleum Phase Behaviour and Fouling; Kilpatrick, Ed., Asheville, NC, USA

Guo, B, Song, S, Chacko, J and Ghalambor, A, (2005) "*'Offshore Pipelines*" Elsivier Inc. Oxford, UK, .

Hernandez, O.C., Hensly, H. and Serica, C., (2004), "Improvements in Single-Phase paraffin Deposition Modeling" *SPE Production and facilities* (11): 237-244.

Hilbert, J., (2010), "Flow Assurance: Wax Deposition and Gelling in Subsea Oil Pipelines" SPE 133948, *Presented at the 2010 SPE Annual Technical Conference and Exhibition held in Brisbane*, Queensland, Australia.

Holder, G.A. and Winkler, J.(1965), "Wax Crystallization from Distillate Fuels: I. Cloud and Pour Phenomena Exhibited by Solutions of Binary n-Paraffin Mixtures,. *Journal of Institute of petroleum,* 51, 235.

Kelechukwu, E.M., Al Salim, H.S. and Yassin, A.M. "Influencing Factors governing Paraffin Wax Deposition during Crude Production" *International Journal of the Physical Sciences* Vol 5(15), 2351-2362.

Leontaritis, K. J. and Gerouulis, E., (2011), "Wax Deposition Correlation-Application in Multiphase Wax Deposition Models" *Paper no. OTC 21623, Presented at the 2011 Offshore Technology Conference,* Houston, Texas, USA.

Majeed, A., Bringedal, B. and Overa, S., (1990), "Model to Calculates Wax deposition for N. Sea Oils," *oil Gas J.,* 88, 63.

Mehrotra, A.K., Bhat, N.V., (2007), "Modeling the Effect of Shear Stress on Deposition from Waxy Mixtures under Laminar Flow with Heat Transfer" *Energy and Fuels*, 21, 1277.

Noville, I. and Noveira, L., (2012), "Comparison between Real Field data and the Results of Wax Deposition Simulation" SPE 152575, *Presented at the 2012 SPE Latin American and Caribbean petroleum Engineering Conference held in Mexico City*, Mexico.

Semenov, A., (2012), "Wax Deposition Forecast" SPE 149793, *Presented at the 2012 SPE North Africa Annual Technical Conference and Exhibition held in Cairo*, Egypt.

Thomason, W.H., (2000) "Start-Up and Shut-In Issues for subsea Production of High Paraffinic Crudes" *Offshore Technology Conference,* Houston, TX.

Venkatesan, R., and Creek, J.L.,(2007), " Wax Deposition during production Operations: SOTA" paper OTC 18798, *Presented at the 2007 Offshore Technology Conference*, Houston, Texas, USA.