International Journal of Smart Grid and Clean Energy

Experimental Study of Wax Deposition in Pipeline – Effect of Inhibitor and Spiral Flow

Muhammad Ali Theyab[a], Pedro Diaz[b] a*

[a,b] *London South Bank University, 103 Borough Rd, London SE1 0AA, UK*

Abstract

Wax deposition is one of the main flow assurance problems in the oil industry. It can result in the restriction of crude oil flow in the pipeline, creating pressure abnormalities and causing an artificial blockage leading to a reduction or interruption in the production. Wax can precipitate as a solid phase on the pipe wall when its temperature (inlet coolant temperature) drops below the Wax Appearance Temperature (WAT). An experimental flow loop system was built in the lab to study the variation of wax deposition thickness under the single phase transport. A series of experiments were carried out at different flow rates (2.7 and 4.8 L/min) to study wax deposition and measure the wax thickness using four different techniques including direct technique (pigging method), pressure drop technique, heat transfer technique, liquid displacement-level detection technique (LD-LD). The effect of factors on wax formation such as inlet coolant temperature, pressure drop, flow rates, time, inhibitor and spiral flow have been examined. The results shows the wax inhibition percentage (WI) % of inhibitor W802 (polyacrylate polymer (C16-C22)) and spiral flow at flow rate 2.7 L/min, inlet coolant temperature14 ºC, was 40% while with the spiral flow was 65%. At flow rate 4.8 L/min, inlet coolant temperature 14 ºC and 1000ppm inhibitor W802, the wax inhibition percentage was 45% while with the spiral flow was 73%. This percentage of inhibition will increased rapidly by increasing the the inlet coolant temperature.

Keywords: Wax inhibitor, spiral flow, wax inhibition, wax measuring techniques

1. Introduction

Wax deposition is one of the main flow assurance problems in the oil industry. Wax deposition can result in the restriction of crude oil flow in the pipeline, creating pressure abnormalities and causing an artificial blockage leading to a reduction or interruption in the production. However, in an extreme case, this can cause a pipeline or production facility to be abandoned (Singh et al., 2011). Wax can precipitate and arises when paraffin components in crude oil precipitate and deposit on the cold pipeline wall when the inner wall temperature (inlet coolant temperature) drops below the wax appearance temperature (Huang et al., 2015; Adeyanju and Oyekunle, 2013; Lee, 2008). Wax appearance temperature (WAT) is the temperature at which paraffin wax start to precipitate (Tordal, 2006).

Time, (2011) mentioned that wax contains high molecular weight n-paraffin and asphaltenes components of the crude. They consist of long-chain alkanes with 20 to 50 carbon atoms, but also enclose minor quantities of branched and cyclic hydrocarbons. The solid phase of wax begins to precipitate characteristically around 30 to 40 ºC, but may possibly be as high as 50 to 55 ºC (Time, 2011). WAT is dependent on the wax content, the amount of solvents including dissolved gases, and to a smaller extent on the pressure (Tordal, 2006).

The main factor that affects the wax deposition process is the low temperature, which means that subsea pipelines are especially vulnerable. Therefore, wax deposition prevention becomes very important in deep- water oil production.

* Manuscript received MM DD, 2013; revised MM DD, 2013.
Corresponding author. Tel.: +0-000-000-0000 ; *E-mail address*: author@institute.xxx .

Wax deposition in crude oil production systems can be reduced or prevented by one or combination of chemical, mechanical, and thermal remediation methods. However, with the advent of extremely deep production, offshore drilling and ocean floor completions, the use mechanical and thermal remediation methods becomes prohibitive economically, as a result, use of chemical additives as wax deposition inhibitors is becoming more prevalent (Adeyanju and Oyekunle, 2014, Al-Yaari 2011). Selected chemical inhibitor was tested in the current work to study its effect on wax deposition.

In the current research, to study the influence of factors that affect the formation of wax deposits such as inlet coolant temperature, flow rate (2.7 and 4.8 L/min), pressure drop, deposit time, inhibitor W802 polyacrylate polymer (C16-C22) and spiral flow, wax deposition experiments are carried out. To measure wax thickness four different techniques were used including direct technique (pigging method), pressure drop technique, heat transfer technique, liquid displacement-level detection technique (LD-LD).

The results shows at flow rate 2.7 L/min, inlet coolant temperature14 ºC, and 1000ppm concentration of W802, the percentage of wax inhibition was 40% while with the spiral flow was 65%. At flow rate 4.8 L/min, inlet coolant temperature 14 ºC and 1000ppm inhibitor W802, the wax inhibition percentage was 45% while with the spiral flow was 73%. This percentage of inhibition will increased rapidly by increasing the the inlet coolant temperature. This study shows a comparison between the techniques for measuring wax thickness; and a comparison between the mitigation techniques to reduce wax thickness.

2. Experimental Methodology

2.1. Characterization of Crude Oil

The crude oil that has been used in this study is one of the oil fields reservoirs with waxing problems of Arunachal Pradesh state in the extreme north eastern part of India. All the crude oil characteristics were carried out in the lab of this work through the experimental methods and the standards analytical techniques as shown in table 1.

Table 1. Crude oil characteristics

Characteristics	Unit	Value	Experimental Method
Density	kg/m³ (15ºC)	850	mass/volume
Sp. Gravity	60/60 ºF	0.85	Calculated
API Gravity	60 ºF	34.97	API Method
WAT at shear rate 10 1/s	ºC	39	Rheometer
WAT at shear rate 120 1/s	ºC	30	Rheometer
Pour Point	ºC	27.6	Rheometer
Wax Content	wt%	20.15	ASTM D721
Saturates	wt%	74.91	SARA
Aromatics	wt%	20.44	SARA
Resins	wt%	4.26	SARA
Asphaltene	wt%	0.39	SARA

2.2. Experimental Methodology of Wax Deposition

Regarding to study wax deposition process, the waxy crude oil was pumped through the inner pipe at a relatively higher temperature than the wall coolant temperature, to create the appropriate environment for the deposition inside the test section. The pressure drop along the length of the pipe was then measured. Experiments for different flow rates (2.7 and 4.8 L/min) were carried out, with and without inhibitors, with and without spiral flow at different aging time (2, 4, and 6 hr), and different coolant temperature (14, 24, 33, and 40 C).

The general research strategies that outline the way to determine the parameters which affect the wax deposition are included:

- Study the influence of some factors on wax deposit such as inlet coolant temperature, flow rate, pressure drop, inhibitor, spiral flow and experimental time, to build a wide understanding of the wax deposition process.
- Investigation of the dependence of wax deposition on inlet coolant temperatures by carrying out the experiments at the same flow rate, at the same oil temperature, but at different inlet coolant temperatures.
- Evaluation of the dependence of wax deposition on the flow rate by running the experiments at the same inlet coolant temperature, at the same oil temperature, but at different flow rates.
- Study the influence of the chemical inhibitor polyacrylate based polymer (C16-C22) on wax deposition.
- Evaluation the effect of spiral flow on wax deposition.

2.3. Wax Deposition Experimental Rig Design

This rig was built in the lab of this work to study the variation of wax deposition thickness under the single phase transport using the pressure drop method, pigging method, heat transfer method, and LD-LD method. This system allowed the study of the influence of some of the factors that control the wax deposition process, such as inlet coolant temperature, flow rate, pressure drop, oil temperature, shear stress, time and oil viscosity. High thermal conductivity of copper pipe provides the opportunity for more wax precipitation during a short time compared with other metals. This will also provide advantage to quick formation of wax in the copper pipe (for the purpose of studying wax thickness) due to high heat exchange through the pipe wall. The test flow loop consists as shown in figure 1 of:

- A crude oil pipe made of a 150 cm long copper tubing with an inside diameter of 1.35 cm.
- The crude oil pipe is jacketed with a copper pipe jacket in which cold water is pumped from the chiller to maintain pipe wall temperature lower than wax appearance temperature.
- A pump used for crude oil recycling, connected with a valve to control the desired flow rate.
- Three-neck flask containing crude oil; one of these necks allows entry of the crude oil into the flask after recycling in the test section, the second neck allows exit of the crude oil to the pump, and the third neck is for the condenser. This flask is fixed in a controlled heating bath.
- A condenser used to condense the light components that were evaporated from heating crude oil.
- Two thermocouples to measure temperatures of crude oil at the inlet and outlet of the pipe.
- Two thermocouples used to measure the recycling cooling water and the inner pipe wall surface temperatures.
- Two pressure meters to measure the pressure drop along the test section.
- Pico meter connected to the computer to read the temperatures of thermocouples.

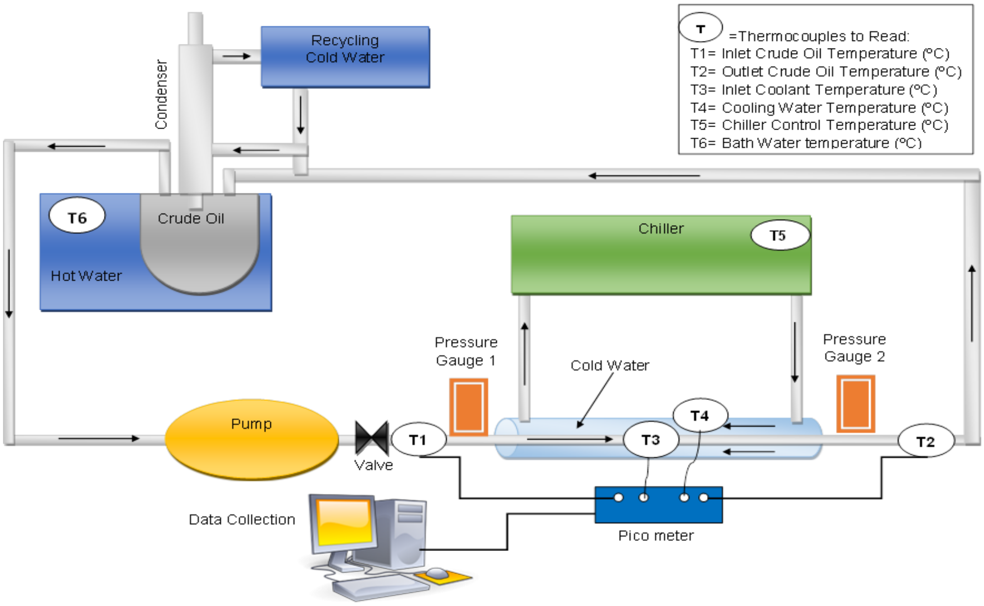

Figure 1. Schematic of wax deposition test flow loop in this study.

2.4. Techniques for Measuring Wax Thickness

Four different techniques have been used in this work to measure wax deposit thickness inside the pipe. These methods are called pigging method, pressure drop method, heat transfer method and liquid displacement–level detection technique (LD-LD).

2.4.1. Direct Technique (Pigging Method)

Pigging method is the technique used for measuring wax thickness in the test section of the pipeline. This method is based on the concept of passing spheres through the test section and measuring the wax volume removed (Chen et al, 1997). In this study a plastic conical has been used instead of the sphere to pigging the wax. This method is direct and simple, because it is providing a visual examination of the wax deposit. It is still widely used in experimental studies of wax deposition in low pressure and single phase flow (Chen et al, 1997).

2.4.2. Pressure Drop Technique

One of the main techniques that have been used to calculate wax thickness inside the pipe of this study is pressure drop method. 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 (Chen et al, 1997; Huang et al., 2015). The wax thickness present in the pipe wall can be calculated accurately from the following equation presented by Chen et al, (1997):

$$(d_i - 2\delta_w)^{5-n} = \frac{2c\rho L}{\Delta P_f}\left(\frac{\mu}{\rho}\right)^n\left(\frac{4Q}{\pi}\right)^{2-n} \qquad \text{Equation (4.2.1)}$$

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 NRe < 2000, Chen et al, (1997).

Chen et al, (1997) stated that the pressure drop method is an on-line technique that does not require depressurization and restart in order to obtain wax measurements.

2.4.3. Heat Transfer Technique

After the wax deposition layer is formed on the pipe wall, a convective heat transfer will apply between the flowing fluids and the deposited wax layer.

3. Results and Discussion

3.1. Measuring Wax Thickness at Different Techniques

Four different techniques have been used to evaluate the wax thickness in the test section of pipe include the direct technique (pigging method), pressure drop technique, heat transfer technique, liquid displacement-level detection technique. Table 2 shows a comparison between the four techniques to estimate the wax thickness.

Table 2. Measuring wax thickness using different techniques at flow rate 2.7 L/min.

Coolant Temp. (ºC)	Pressure Drop(Pa)	Exp. Wax Volume(ml)	Wax Volume (ml) LD-LD	Wax Thickness mm(Pigging Method)	Wax Thickness mm(Pressure Drop)	Wax Thickness mm(Heat Transfer)	Wax Thickness mm (LD-LD)
14	1200	125	126	1.82	1.83	1.83	1.84
24	1000	83	83	1.5	1.61	1.3	1.5
33	900	19	20	0.7	0.69	0.71	0.73
40	600	0	0	0	0.04	0.06	0

Table 3. Measuring wax thickness using different techniques at flow rate 4.8 L/min.

Coolant Temp. (ºC)	Pressure Drop(Pa)	Exp. Wax Volume(ml)	Wax Volume (ml) LD-LD	Wax Thickness mm(Pigging Method)	Wax Thickness mm(Pressure Drop)	Wax Thickness mm(Heat Transfer)	Wax Thickness mm (LD-LD)
14	3000	85	87	1.5	1.72	1.72	1.52
24	2700	70	70	1.36	1.45	1.27	1.36
33	2100	15	17	0.63	0.79	0.65	0.67
40	1200	0	0	0	0.054	0	0

3.2. Effect of Inlet Coolant Temperature

In this study, it was observed that the inlet coolant temperature affects the wax deposition inside the pipe. During run the experiments, it was noted that the deposit thickness is increased with decreasing the inlet coolant temperature even when was the crude oil temperature above wax appearance temperature, that means wax deposition depend on the inlet coolant temperature more than it depend on the crude oil temperature. Wax thickness increased to 1.83 mm at the end of the experiment when the inlet coolant temperature was equal to 14°C. The wax thickness decreased when the inlet coolant temperature increased (24, 33, 37°C) respectively and stopped to precipitate at 40°C as shown in figure 2, where this temperature is above wax appearance temperature.

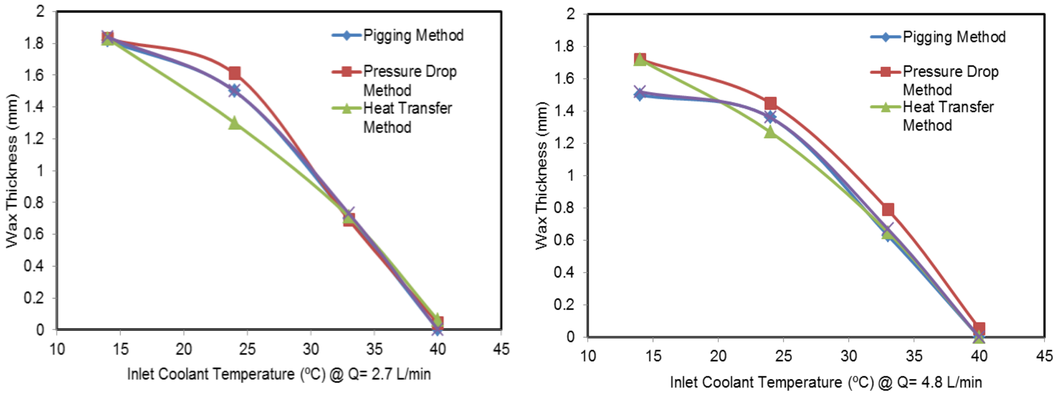

Figure 2. The effect of inlet coolant temperature on wax thickness at different flow rates and different techniques.

3.3. Effect of Pressure Drop

Experimentally, it was noticed that the pressure drop affects to wax thickness. It was observed that a continuous smooth increase in deposit thickness with time resulted in an increase in pressure drop across the test section; because of the pipe cross sectional area will decrease due to wax deposition inside the pipe as shown in figure 3.

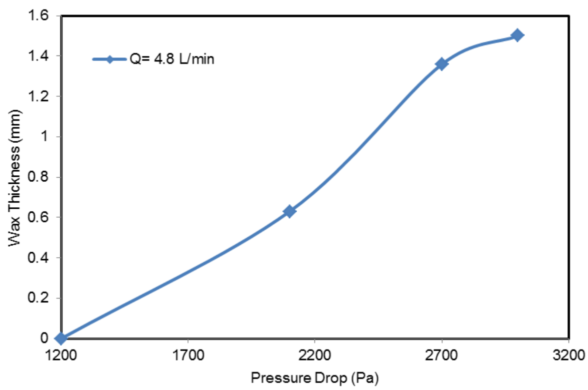

Figure 3. The effect of pressure drop on wax thickness at different flow rates and inlet coolant temperature 14 ºC.

3.4. Effect of Flow Rate on Deposition

It was observed that at a given temperature the wax deposit thickness increases at low oil flow rate (2.7 L/min.) while the deposit thickness decreases at higher oil flow rate (4.8 L/min.), as shown in figure 4.

This can be interpreted as: an increase in the oil flow rate increases the strength of adverse forces (the opposite force for wax deposition) of wax deposition, these adverse forces work as a kind of viscous force which tends to drag or slough the wax deposits from the pipe wall. When this viscous drag exceeds the resistance to shear in the deposits, the wax then sloughs and is lodged back into the liquid (Zhu et al, 2008). This means that the wax deposition reduced by increasing the flow rate, which means increased the oil velocity and changed from laminar to turbulent flow rate according to the calculations of Reynolds number.

The wax deposition reduced by increasing the flow rate due to the cohesive and adhesive forces properties of the paraffin wax molecules and the deposition surface are overcome by the rate of shear (Bott and Gudmunsson, 1977). This removal mechanism has a significant impact on the wax deposition rate (Zhu et al, 2008).

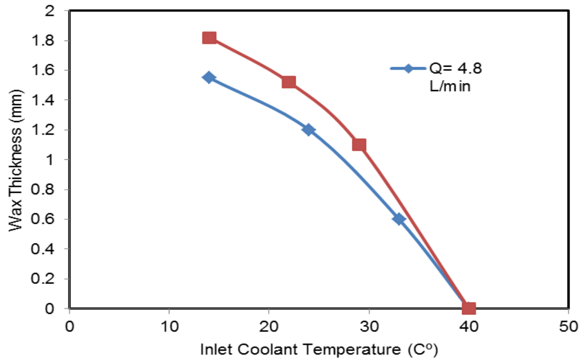

Figure 4. The effect of flow rate on wax thickness.

3.5. Effect of Time on Wax Thickness

It was observed in this study that all the deposit increased regularly by the first two hours of running the experiments at different flow rates due, as mentioned by Abdel-Waly (1999), to the fact that the initial increase in deposition was because more and more paraffin was carried out by the moving oil rotation, providing a greater opportunity for deposition upon the cold surface.

The amount of deposition increases with circulated time, irrespective of the operating conditions, until it reaches an asymptotic value at steady state conditions (Kasumu, 2014). Studies have shown that a thermal pseudo-steady state is attained in less than 30 minutes during deposition from wax solvent mixtures under laminar and turbulent conditions (Kasumu and Mehrotra, 2013; Tiwary and Mehrotra, 2009). Laboratory studies also had shown a negligible increase in the mass of the deposit after 4 hours (Kasumu A.S., 2014).

The interpretation of increasing the deposit regularly by the first two hours of carrying out the experiment is that the heat exchange between the oil and pipe wall was high depending to the pipe material (high thermal conductivity of copper pipe in this study). After two hours the heat exchange between oil and pipe wall reduced due to the formation of wax layer inside the pipe, where this layer work as insulation between the crude oil temperature and the pipe wall. This led to a relative increase in oil temperature and a reduction in the deposition process. Therefore after two hours of carrying out the experiment the deposit thickness along the pipe will be in the shape of a curve due to an increase in wax solubility as shown in figure 5.

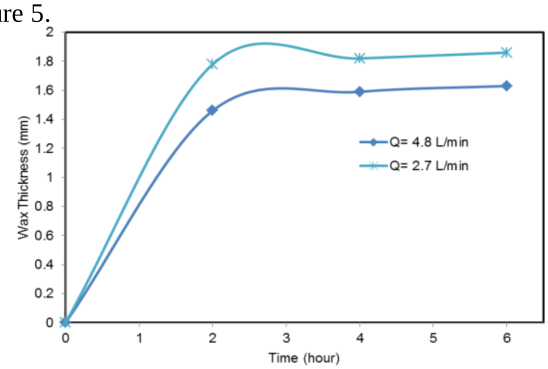

Figure 5. The effect of time on wax deposition thickness at different flow rates.

3.6. Effect of Inhibitor on Wax Thickness

The performance of some of wax inhibitors was evaluated at concentration 1000ppm to determine their effects on the wax precipitation using the Bohlin Gemini II Rheometer. The effect was appeared on the wax appearance temperature and the viscosity of the crude oil.

The analysis of the crude oil with the inhibitors shows that the inhibitor W802 (polyacrylate polymer (C16-C22)) produced the greatest reduction in viscosity, which means reduction in the wax appearance temperature. This inhibitor has been used to study its effect on the wax deposition at different flow rates (2.7 and 4.8 L/min).

Figure 6 shows that the inhibitor reduced the wax thickness at flow rate 2.7 L/min and inlet coolant temperature 14 ºC from 1.86mm to 1.42mm, this consider a great reduction at this low temperature. Also, it reduced the wax thickness from 1.63 mm to 1.3 mm at flow rate 4.8 L/min and inlet coolant temperature 14 ºC.

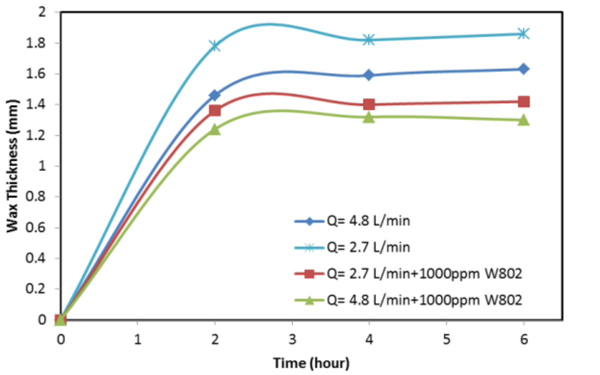

Figure 6. The effect of inhibitor W802 on wax thickness at 2.7 and 4.8 /min, and inlet coolant temperature 14 ºC.

The inhibitor has been used in the current work are based on polymers which are normally used as pour point depressant. The reduction in the pour point and the crude oil viscosity had been making the transportation of the crude oil easier (Pedersen and Ronningsen, 2003, Adeyanju and Oyekunle, 2014). This inhibitor was reducing the wax deposition process by interfering with wax crystallization and growth process. However, this interfering mechanism has not yet been fully understood (Jennings and Newberry, 2008).

Major theory stated the possibility of wax inhibitor polymers containing similar structure to the wax structure, thereby allowing the inhibitor crystal to be incorporated into the wax crystal growth. Sometimes the structural part of the polymer covers the wax site, thereby preventing further wax crystal growth and promoting the formation of smaller wax aggregates (Jennings and Newberry, 2008, Adeyanju and Oyekunle, 2014). The effect of the inhibitor on wax structure have been examined using the Scanning Electron Microscopy (SEM) as shown in figure 7, where it can be seen the clearly how the inhibitor effect and changed the wax structure.

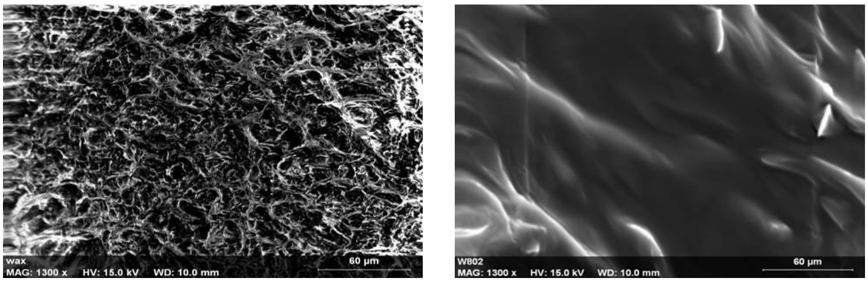

Figure 7. The structure of wax before (a) and after (b) adding the inhibitor W802 using SEM

3.7. Effect of Spiral Flow on Wax Thickness

In this study, spiral flow was used as an instrument to mitigate wax deposition inside the pipe, this kind of flow was created by insert a thin twisted Aluminum plate inside the test section of pipe. The length of the twisted plate is equal to the pipe length.

In this case the spiral flow was created and examined in the rig, where the experiments were carried out at different flow rates, different coolant temperatures, and different times.

During carrying out the experiments it was noticed that the pressure drop along the pipe was huge, due to the twisted plate inside the pipe where the crude oil flow will take long time compare with the flow in the pipe without twisted plate. In this case, the shear stress will be high due to increase the velocity of the flow, and the force of the shear stress will be higher than the force of wax deposition. On another hand, it was noticed that the temperature drop of the crude oil along the test pipe was double compare with the temperature drop of the crude oil without twisted plate. This drop in temperature happened due to increase the length of the crude oil flow, where it leading to loss temperature to surrounding.

Despite of increasing both of the pressure drop and the temperature drop, the volume of the wax deposit inside the pipe was too low comparing with the wax volumes of the experiments with laminar or turbulent flow, because of increasing the shear stress inside the pipe.

The spiral flow works as a kind of inhibitor where it was reduced the wax thickness from 1.86 to 1.07 mm at inlet coolant temperature 14 C, flow rate 2.7 L/min and 6 hours the time of the experiment. While, the reduction in wax thickness at inlet coolant temperature 14 C, flow rate 4.8 L/min and same experiment period, was from 1.63 to 0.85mm as shown in figure 8.

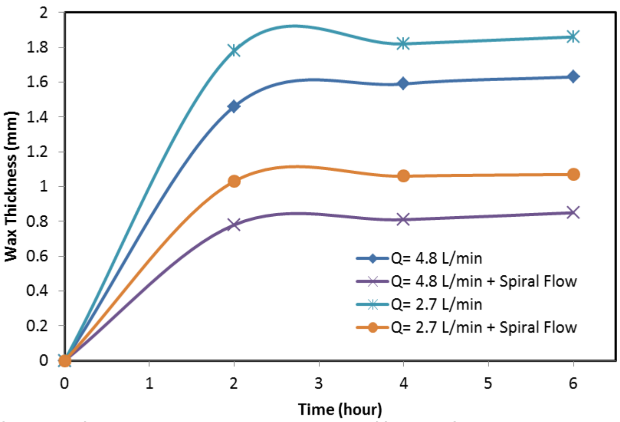

Figure 8. The effect of spiral flow on wax thickness at different flow rates.

3.8. Evaluation of Wax Inhibition

Wax Inhibition WI (%): The ratio of the difference of wax deposition rate with and without inhibitor to that of the blank oil at a specific temperature.

$$Wax\ inhibition, WI\ (\%) = 100\frac{W_b - W_{wi}}{W_b}$$

W_b= Wax deposit by volume of the blank oil (ml).
W_{wi}= Wax deposit by volume during the same period of time treated oil (ml).

Figure 9, shows the wax inhibition percentage (WI)% of inhibitor W802 and spiral flow, where at flow rate 2.7 L/min, inlet coolant temperature14 ºC and 1000ppm inhibitor W802, the wax inhibition percentage was 40% while with the spiral flow was 65%. At flow rate 4.8 L/min, inlet coolant temperature 14 ºC and 1000ppm inhibitor W802, the wax inhibition percentage was 45% while with the spiral flow was 73%. This percentage of inhibition will increased rapidly by increasing the the inlet coolant temperature.

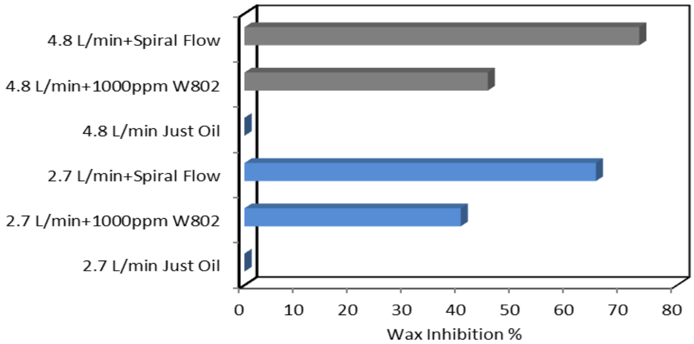

Figure 9. Wax inhibition % of the inhibitor W802 and spiral flow.

Conclusion

The current work studied one of the main flow assurance problems in the oil industry: wax deposition. An apparatus was built to study the effects of factors on wax formation such as inlet coolant temperature, pressure drop, flow rates, time, inhibitor and spiral flow. Four different techniques have been used to evaluate the wax thickness in the test section of pipe include the direct technique (pigging method), pressure drop technique, heat transfer technique, liquid displacement-level detection technique.

It is concluded that wax deposit increases with decreasing the inlet coolant temperature, and decreases and stops above WAT. On the other hand, an increase in flow rate results in a decrease in the wax deposition due to increasing the shear stress. It was observed in all experiments that at the first two hours of carrying out the experiment the wax deposition rate increased linearly with time.

In this study, the chemical additives based on polymers (polyacrylate polymer (C16-C22)) were used to study its effect on wax appearance temperature and the viscosity of the crude oil. The effect of spiral flow on wax deposition was examined in the current work and the results show a huge reduction in deposition reach to 73% at inlet coolant temperature of 14 ºC.

This technique of creating spiral flow by using twist material will provide a step forward in flow assurance technology.

Acknowledgements

The authors would like to thank the Ministry of Higher Education and Scientific Research/Iraq for the financial support.

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Author name	Title	Membership	Contact	Author affiliation
Given name Family name	Prof./A. Prof./ Dr./S.E.*	IEEE Member, SM, Fellow**	E-mail/ Mobile phone	Affiliation, Address, City and Postcode, Country