Experimental Study on the Effect of Polyacrylate Polymer (C16-C22) on Wax Deposition

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Wax can precipitate as a solid phase on the pipe wall during hydrocarbon production when its temperature (inlet coolant temperature) drops below the Wax Appearance Temperature (WAT) causing an artificial blockage leading to a reduction or interruption in the production. An experimental flow loop system was built in the lab to study the variation of wax deposition thickness under the single phase transport. The Bohlin Gemini II Rheometer has been used to analysis the effect of the inhibitor W802 (polyacrylate polymer (C16-C22)), at different concentration (250, 500, 750, 1000 and 2000 ppm), on the crude oil viscosity and WAT. The results show that 1000ppm of W802 produced the greatest reduction in viscosity compared with other concentrations, which means reduction in the wax deposition; and it was selected to examine with the crude oil at different flow rates (2.7 and 4.8 L/min) using the flow rig. A series of experiments were carried out to study wax deposition and measure the wax thickness using four different techniques including pigging, pressure drop, heat transfer, liquid displacement-level detection (LD-LD). The effect of factors on wax formation such as inlet coolant temperature, pressure drop, flow rates, time, and inhibitor has been examined. The results show the wax inhibition percentage (WI) % of inhibitor W802 (polyacrylate polymer (C16-C22)) at flow rate 4.8 L/min increased at different inlet coolant temperatures from 40% at 14 ºC, to 57% at 24 ºC and 100% at 33 ºC. This percentage of inhibition will increased rapidly by increasing the inlet coolant temperature.

Index Terms—**Waxy crude oil, inhibitor, WAT, Viscosity.**

I. 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 [1]. 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 [2]-[4]. Wax appearance temperature (WAT) is the temperature at which paraffin wax start to precipitate [5].

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.

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 [6]. 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, and 1000ppm of the inhibitor W802 polyacrylate polymer (C16-C22), wax deposition experiments are carried out. Four different techniques were followed to measure wax thickness including pigging, pressure drop, heat transfer and liquid displacement-level detection (LD-LD).

The results show a good inhibition percentage at flow rate 4.8 L/min and different coolant temperature reach to 100% at inlet coolant temperature 33 ºC. This percentage of inhibition will increased rapidly by increasing the inlet coolant temperature.

II. Experimental Methodology

A. 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

B. Wax Deposition Methodology

The performance of the wax inhibitor W802 (polyacrylate polymer (C16-C22)) was evaluated with the crude oil at different concentration (250, 500, 750, 1000 and 2000 ppm) to determine its effect on the viscosity and wax appearance temperature using the Bohlin Gemini II Rheometer. The optimum concentration of the inhibitor to reduce wax deposition has been selected (1000ppm) to study its effect on the wax deposition in the flow rig.

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 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 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.

C. 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 techniques of pressure drop, pigging, heat transfer, and LD-LD. 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.

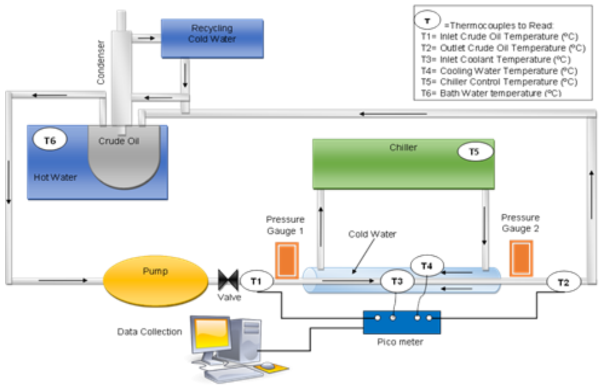


Figure1. Schematic of wax deposition test flow loop in this study.

D. 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).

Pigging method is based on the concept of passing spheres through the test section and measuring the wax volume removed [7]. In this study a plastic conical has been used instead of the sphere to pigging the wax.

Pressure drop 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 [7],[2]. The wax thickness present in the pipe wall can be calculated accurately from the following equation presented by Chen et al, (1997) [8]:

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

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, [7]. Chen et al, (1997) [7] stated that the pressure drop method is an on-line technique that does not require depressurization and restart in order to obtain wax measurements.

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. A thermal resistance term due to heat conduction through the wax layer is added to the total resistance to heat transfer from the flowing fluid to the environment. The wax thickness can be measured from the heat transfer equation.

$$\frac{T_f - T_o}{q_o} = \frac{1}{h_w} \frac{r_o}{r_i - \delta_w} + \frac{r_o}{k_w} \ln \frac{r_i}{r_i - \delta_w} + \frac{r_o}{k_p} \ln \frac{r_o}{r_i} \qquad (2)$$

Where T_f is the bulk fluid temperature in the pipe, T_o is the outside pipe wall temperature, q_o is the heat flux through the outside pipe wall, r_o and r_i are the outside and inside diameters of the pipe, respectively, h_w is the film heat transfer coefficient from the flowing fluid to the wax layer, k_p and k_w are the thermal conductivities of the pipe wall and deposited wax, respectively, and δ_w is the thickness of wax layer.

The last technique to measure wax thickness is called liquid displacement-level detection technique (LD-LD), where it is work by replacing the test tube by liquid (water in this study) and measure the volume of the tube before and after carrying out the experiment, the difference between the two volumes represent the volume of wax inside the pipe.

These measuring techniques present accurate results comparing between them.

III. Results and Analysis

A. *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, and table 3 shows a comparison between the four techniques to estimate the wax thickness at different flow rates. The results show a large correspond between the wax volumes measured during the pigging method and LD-LD method, this is illustrate the validity of the methods. The pressure drop method and heat transfer method are shows a similarity in the results at high pressure drop and slightly different at lower pressure drop at the same flow rate.

Table 2. Wax thickness at flow rate 4.8 L/min. using different techniques.

Coolant Temp. (ºC)	Wax Thickness mm(Pigging Method)	Wax Thickness mm(Pressure Drop)	Wax Thickness mm(Heat Transfer)	Wax Thickness mm (LD-LD)
14	1.5	1.72	1.72	1.52
24	1.36	1.45	1.27	1.36
33	0.63	0.79	0.65	0.67
40	0	0.054	0	0

Table 3. Measuring wax thickness using different techniques at flow rate 2.7 L/min.

Coolant Temp. (ºC)	Wax Thickness mm(Pigging Method)	Wax Thickness mm(Pressure Drop)	Wax Thickness mm(Heat Transfer)	Wax Thickness mm(LD-LD)
14	1.82	1.83	1.83	1.84
24	1.5	1.61	1.3	1.5
33	0.7	0.69	0.71	0.73
40	0	0.04	0.06	0

B. *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, 40°C) respectively and stopped to precipitate at 40°C as shown in figure 2, where this temperature is above wax appearance temperature.

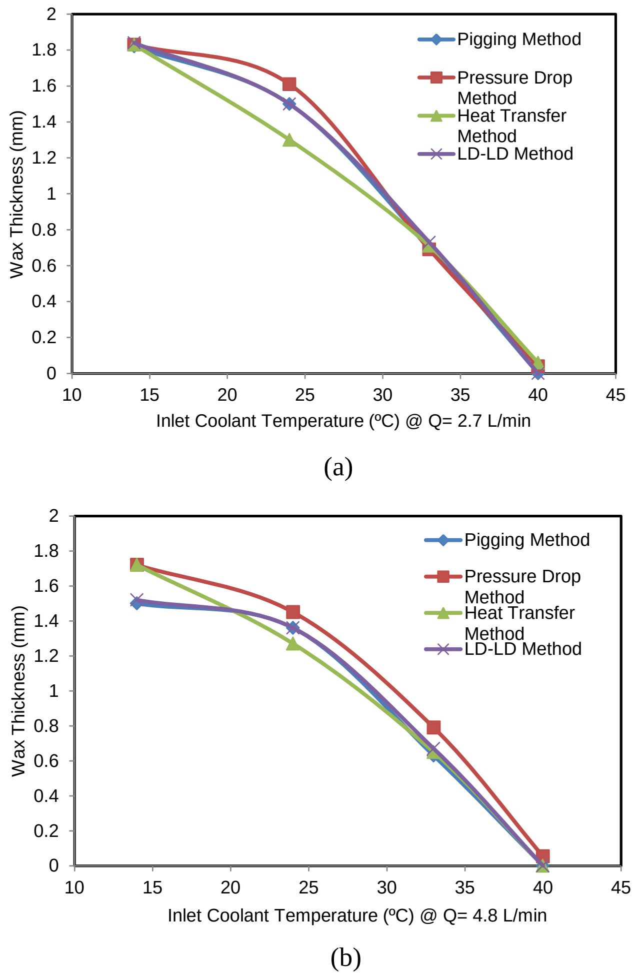


Figure 2. The effect of inlet coolant temperature on wax thickness at different flow rates (a) 2.7 L/min (b) 4.8 L/min, and different techniques.

C. *Effect of Flow Rate on Wax 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.), and the effect of adding the inhibitor W802 to crude oil present great results by reducing the wax thickness from about 1.8 mm to about 1.2 mm at low temperature 14 ºC as shown in figure 3.

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 [8]. 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 inhibitor affected to the chain of the wax where its broken the wax series to small chains leading to reduce the oil viscosity and as a result decreasing wax thickness.

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 [9]. This removal mechanism has a significant impact on the wax deposition rate [8].

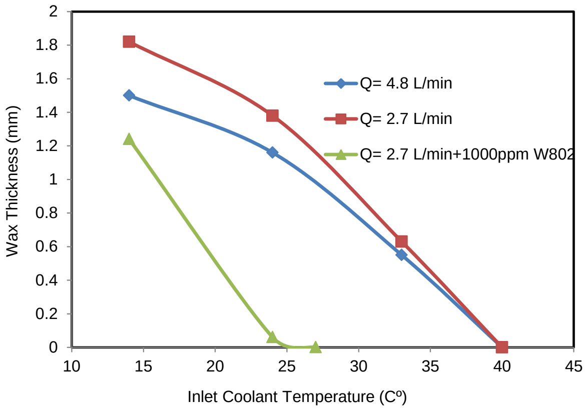


Figure 3. The effect of flow rate on wax thickness.

D. *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) [10], 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 [11]. 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 [12], [13]. Laboratory studies also had shown a negligible increase in the mass of the deposit after 4 hours [11].

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 4.

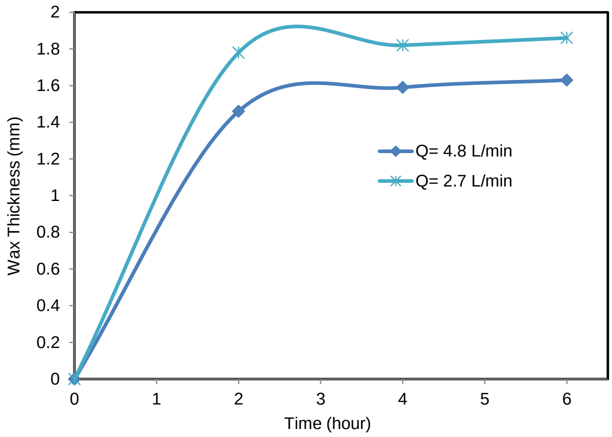


Figure 4. The effect of time on wax deposition thickness at different flow rates.

E. *Effect of Poly Acrylatepolymer on Wax Deposition*

The analysis results of the crude oil with the inhibitor W802 (polyacrylate polymer (C16-C22)) at different concentration (250, 500, 750, 1000 and 2000 ppm), shows that the concentration 1000ppm produced the greatest reduction in viscosity compared with other concentrations, which means reduction in the wax appearance temperature. However, any further increase of inhibitor concentration 2000ppm had only a small additional effect on the viscosity.

This inhibitor W802 at a concentration 1000ppm has been examined with the crude oil at different flow rates (2.7 and 4.8 L/min) using the flow rig.

Figure 5 shows that the inhibitor reduced the wax thickness at flow rate 2.7 L/min and inlet coolant temperature 14 °C 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 °C.

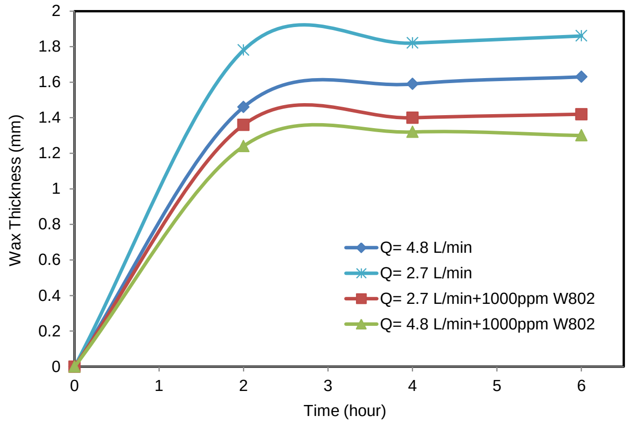
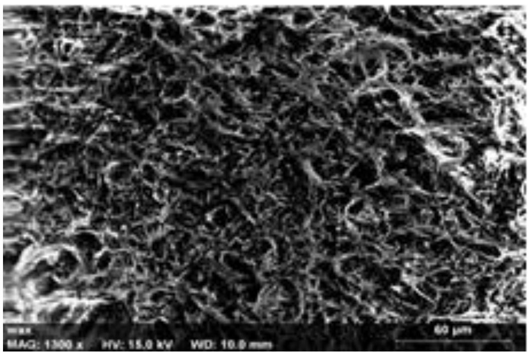
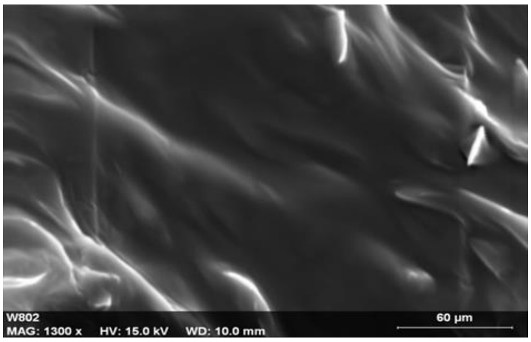


Figure 5. The effect of inhibitor W802 on wax thickness at 2.7 and 4.8 L/min, and inlet coolant temperature 14 ºC.

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 [14], [6]. The effect of the inhibitor on wax structure have been examined using the Scanning Electron Microscopy (SEM) as shown in figure 6, where it can be seen the clearly how the inhibitor effect and changed the wax structure.



(a)



(b)

Figure 6. The structure of wax before (a) and after (b) adding the inhibitor W802 using SEM.

Experimentally, the effects of the inhibitor clearly obvious on the wax deposit inside the pipe as shown in figure 7 (a) without inhibitor and (b) with inhibitor.

(a) (b)

Figure 7. The effect of W802 on wax deposition inside the pipe (a) without inhibitor and (b) with inhibitor.

F. *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 [6].

$$WI(\%) = 100\frac{W_b - W_{wi}}{W_b} \quad (4)$$

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).

It was shown from figure 8 that the wax inhibition percent at flow rate 4.8 L/min. increased at different inlet coolant temperatures from 40% at 14 °C, to 57% at 24 °C and 100% at 33 °C.

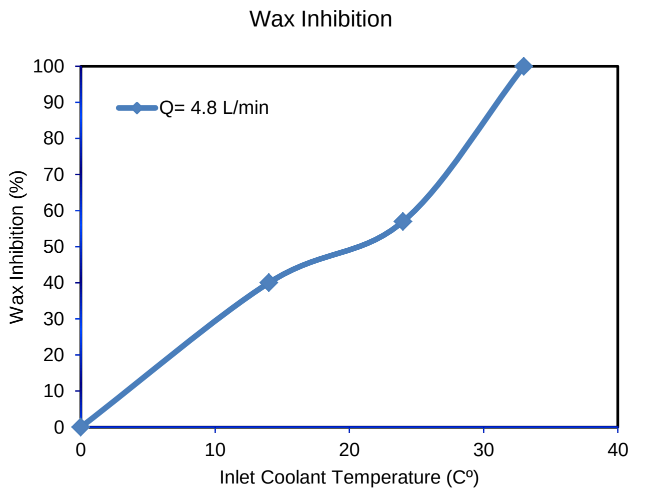


Figure 8. Wax inhibition % of the inhibitor W802 at different inlet coolant temperature.

IV. 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 and inhibitor. Four different techniques have been used to evaluate the wax thickness in the test section include pigging, pressure drop, heat transfer and 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. A Bohlin Gemini II Rheometer has been used to evaluate the viscosity of the crude oil with the inhibitor W802 at different concentration (250, 500, 750, 1000 and 2000 ppm) to select the optimum concentration to run the experiments. The analysis results show that 1000ppm was the optimum concentration to be examined with the crude oil at different flow rates (2.7 and 4.8 L/min) using the flow rig.

The results show that the wax inhibition percent increased at different inlet coolant temperatures from 40% at 14 °C, to 57% at 24 °C and 100% at 33 °C. This inhibitor W802 shows a great inhibition for wax, and it recommended for the oil companies suffering from wax deposition.

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 [15], [6]. 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 [14].

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