INVESTIGATION OF WAX DEPOSITION DEVELOPMENT IN SARIR-TOBRUK PIPELINE

Hamza E.Almansour*, Sabri M. Mrayed** and Ezeddine E. Zorgani***

Abstract: Wax deposition in pipelines is one of the biggest flow assurance challenges in the oil industry. The need for understanding deposition becomes greater as hydrocarbons are being transported over increasingly greater distances. Transportation of waxy crude oil in a cold environment can result in wax depositions on the pipe wall. The problem of wax deposition seriously adversely affects the normal operation of a pipeline that might lead to a complete shutdown in some cases and imposes considerable loses in production. This study takes a look at the wax deposition phenomena which has been experienced recently in the onshore Sarir-Tobruk pipeline. The pipeline carries an average of 200,000 barrel per day from Sarir Field to the Al-Hariga Port at Tobruk (514km). The study aims to understand the behavior and mechanism of wax deposition in the pipeline and how it is influenced by the operational parameters. Software HYSYS was used to examine the effects of inlet operation conditions including inlet crude oil temperature and flow rate and environmental conditions (ambient temperature) on wax deposition development in the pipeline. It also aims to investigate the energy requirement for heating the crude before it is pumped into the pipeline in both winter and summer seasons. Important results of wax deposition have been reported from the simulation. Increasing of inlet crude oil temperature and time duration cause increases of wax thickness layer. However, increases of ambient temperature causes decreasing of wax thickness layer. The temperature effect of both inlet crude oil and ambient indicates that wax deposition development is predominantly thermally driven. Also, investigation of energy requirement shows that 130ºF is suitable inlet operation temperature, especially in the winter season to avoid any jelly formation phenomena for the crude oil before reaching its destination at Al-Hariga Port. The effect of flow rate showed that increasing of flow rate causes an increase in the wax thickness layer. This result relates to the fact that models based on molecular diffusion do not account for the shear forces where the effects of shear removal start to act. It is recommended to conduct further studies incorporating other methods and compare with real operating data once the pipeline is taken for maintenance or renewing; wax thickness measurements become possible and the real wax profile can be obtained.

Keywords: Wax Deposition, Sarir-Tobruk Pipeline.

INTRODUCTION

Crude oil is a complex mixture of hydrocarbons consisting of paraffins, aromatics, naphthenes, resins and asphaltenes. Among these groups of hydrocarbons, high molecular weight paraffins (interchangeably referred to as waxes) are responsible for some of the problems that are encountered during transportation and processing of the crude oil (Singh & Venkatesan, 2001).

Wax deposition is a mainly problem in oil transportation pipelines either in subsea or land. The problem of wax deposition begins when the inner wall temperature of the pipe falls below the wax appearance temperature (WAT); wax deposition occurs and paraffin components present in crude oil precipitate and deposit on the cold pipeline wall. If remediation or prevention techniques are not used regularly, wax deposit will accumulate in the pipeline wall, and wax gel layer will grow rapidly in thickness and impedes the flow of oil due to the flow restriction, as shown in (Fig. 1).

*University of Benghazi1/ Chemical Engineering Department, Benghazi, Libya.
**University of Tripoli. Chemical Engineering Department, Tripoli, Libya.
***National Oil Corporation (NOC) Planning and Studies Department, Tripoli, Libya. Email: hamza.almansouri@uob.edu.ly

Fig. 1. Wax deposit reducing the effective diameter in a retrieved pipeline (Singh et al, 2000).

This paper aims to understand the behavior of wax deposition in the system of pipelines named Sarir-Tobruk and how it is influenced by the operational parameters. Moreover, in this paper, the ASPEN Tech. HYSYS is used to examine the effect of inlet conditions (such as T, P, and Flow rate) and environmental conditions (ambient temperature) on wax deposition. The HYSYS pipe module contains wax deposition models. The wax deposition model in HYSYS uses a theoretical approach that based on molecular diffusion. It uses a wax attribute in HYSYS called *Profes* method, which is described in the HYSYS User Guide, it evaluates the concentration by calculating equilibrium wax quantities at the two different temperatures involved, the temperature at the wall and the temperature in the bulk fluid.

PHYSICS OF WAX DEPOSITION PHENOMENON

At reservoir temperatures (70-150ºC) and pressures (55-103MPa), wax molecules are dissolved in the crude oil. Once, the crude oil leaves the wellhead and flow through pipelines, its temperatures beings to drop because of heat losses to the surroundings (Singh & Venkatesan, 2001). The Temperature loses is the most common cause of wax deposition because wax solubility in hydrocarbon fluids decreases as the temperature is lowered. Consequently, a radial temperature gradient over the cross section area of the pipe is established, reaching a minimum value at the pipeline wall. Because the concentration is temperature dependent, a concentration gradient is established by the temperature gradient. If the temperature of a wax-oil mixture drops below the solubility limit of wax, also known as Wax Appearance Temperature (WAT), the waxy components start to precipitate out of the crude oil and form solid crystals in the solution as shown in (Fig. 2). If the temperature of the bulk reaches the minimum ambient temperature, that is the wall temperature, there will no longer be a radial temperature gradient across the pipe section, and the precipitation of wax ceases from this point on. Similarly, if all the wax molecules initially dissolved in the solution has precipitated out, further solidification is not possible (Sircar & Gupta, 2015).

WAX PRECIPITATION CURVE (WPC)

Wax precipitation curve or wax solubility curve gives the amount of wax that precipitates from the crude at different oil temperatures. It is an important parameter for wax deposition model, which is necessary for accurate prediction of wax deposition (Han *et al*, 2010). The wax solubility curves (plots of solubility versus temperature) are widely used to quantify wax deposition process. Typical solubility curves are shown in (Fig. 3). As seen here, the solubility curves can be concave upwards or downwards. Its concavity depends on the crude oil composition. The Shape of solubility curve has a significant effect on wax deposition process, especially on the effect of crude oil temperature on wax deposition as explained in the study of (Huang *et al*, 2012). A number of techniques have been developed to determine the amount of precipitated

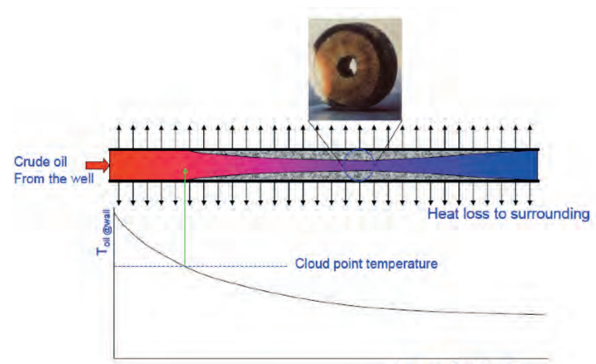

Fig. 2. Wax deposition occurs when the inner wall temperature is below the cloud point temperature.

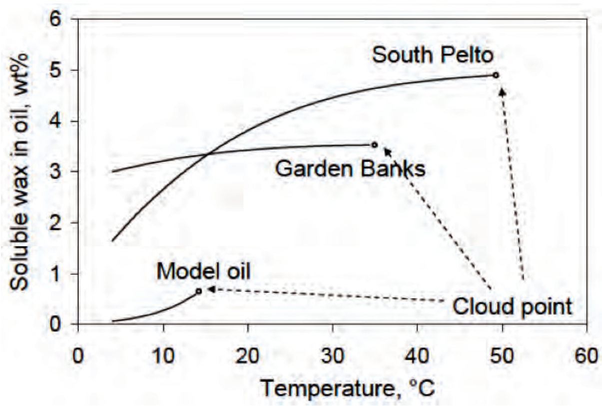

Fig. 3. Solubility curves for different crude oils.

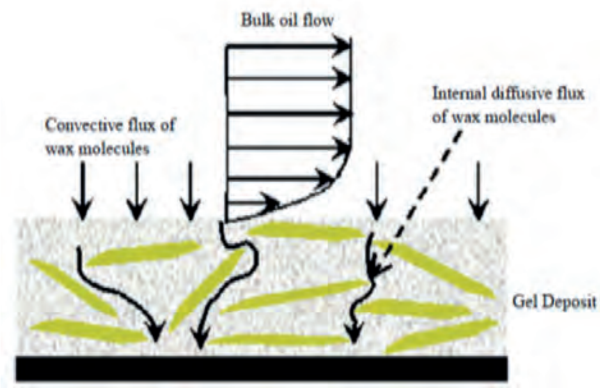

Fig. 4. Show how wax molecules diffuse into the deposit.

wax in crude oil at different temperatures, including Differential Scanning Calorimetry (DSC), Fourier Transform Infrared Spectroscopy (FTIR), Nuclear Magnetic Resonance (NMR), High-Temperature Gas Chromatography (HTGC), filtration and centrifugation.

WAX DEPOSIT AGING

The work by (Singh *et al*, 2000) showed that an external convective mass flux of wax molecules from the bulk oil flow towards the cold wall and an internal diffusive flux within the gel layer are responsible for the growth and aging of the gel deposits (Singh *et al*, 2000). This internal diffusion and subsequent precipitation of wax molecules inside the gel layer leads to an increase in the wax fraction in the deposit (Huang *et al*, 2012 and Fig. 4). The wax fraction is an indicator of gel strength which is an important parameter for designing remediation methods such as pigging (Huang, 2011). The phenomena of wax aging were quantitatively studied by (Singh *et al*, 2000), as shown in (Fig. 5). According to (Singh *et al*, 2000) the wax content of the deposit increases as time goes and wax diffuse into the deposit and oil is squeezed out. However earlier studies have assumed that the wax fraction in the deposit is constant during the wax deposition process.

REVIEW OF PREVIOUS WORK

To study the wax deposition in the pipelines, many experimental and theoretical studies have been carried out under different operating conditions. A quick review of the most common studies is made below.

Creek *et al* (1999) did a series of experiments in flow-loop apparatus to study the effect of crude oil temperature and flow rate on the deposition rate. They studied the temperature gradient by varying the temperature difference between the oil and coolant/wall. They found that greater temperature difference between oil and wall gave a greater deposition rate. The second portion of experiments was to study the effect of flow rate on wax deposition where five different flow rates were studied while the temperature difference was constant. They found that wax deposition rate decreases with increasing flow rate. Jennings *et al* (2005) found similar results using a coldfinger apparatus to study wax deposition for different coolant temperatures and different stirring speeds. For studying the effect of flow rates, both Creek *et al* (1999) and Jennings *et al* (2005) attributed the reason to the ‘’shear removal’’ due to sloughing where a layer of deposit is suddenly removed especially in high velocity.

Bidmus *et al* (2009) used a flow loop experiment based on heat transfer to investigate solids deposition on the pipe wall. They studied the effect of inlet

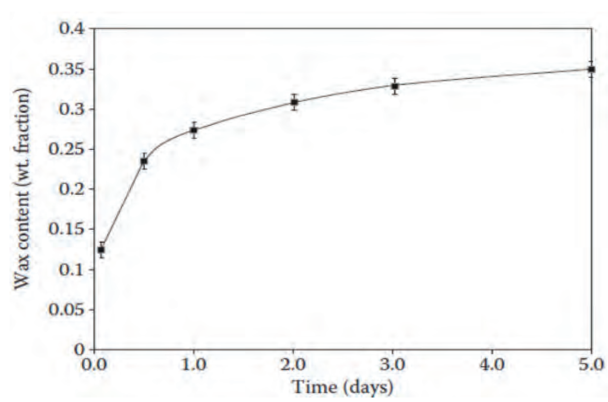

Fig. 5. Evolution of wax fraction in the deposit observed by Singh et al (2000).

temperature of crude oil on wax deposition where four different inlet temperatures were examined while the coolant temperature was kept constant. It was found that a decrease in the oil temperature (decreasing thermal driving force) to near ambient or pipe-wall temperatures could substantially decrease the wax deposition tendency. Similar results were found on the study of (Lashkarbolooki *et al*, 2010) used a crude oil with a 13°API from the Kermanshah Oil Field in a flow loop experiment. They found that wax deposition was decreased with increasing coolant temperature. On other hands wax deposition increased with increasing the inlet crude oil temperature. They concluded that the wax thickness was highly dependent on the temperature difference between the inlet oil and coolant temperatures (ΔT).

Hoffmann & Amundsen (2010) did a series of experiments used a flow-loop to investigate wax deposition under different temperature and flow conditions. Two series of experiments were carried out. The first series of experiments the oil temperature was increased with constant temperature difference with the coolant. In a second series, oil flow rates were varied to measure the influence of shear forces on the wax thickness. Firstly, they studied the effect of the gradient of solubility curve (dC/dT) on the total concentration gradient [dC/dr=(dC/dT)*(dT/dr)] by keeping temperature gradient (dT/dr) constant while absolute temperature was varied. They found that wax thickness was decreased with increasing temperature measured. The result from large flow-loop apparatus was compared with a small scale lab method Differential Scanning Calorimetry (DSC), where the wax deposition in term of mass precipitation was also decreased. This similarity showed that wax solubility gradient is one of an important parameter for wax deposition. Moreover, they examined the effect of oil temperature while the coolant temperature was constant. They found that wax thickness increased faster at low temperature. This result was consistent with the solubility curve that showed the highest gradient in the low-temperature region. Secondly, they studied the effect of flow rate on wax deposition and they observed that wax thickness decreased with increasing flow rate. However, the total concentration gradient was increased in the high flow rate. They attributed the reason for decreasing wax thickness because of increasing shear stress at the oil deposit interphase.

Huang *et al* (2012) studied the effect of changing oil/coolant temperatures on wax deposition rate in a series of flow loop experiments. They found that wax deposition decreased with increasing oil temperature while an increase in coolant temperatures led to decrease wax deposition. They attributed the reason to mass driving force, not to thermal driving and they found that a higher mass driving force a greater increase in the deposition rate. In order to make a theoretical analysis of these trends, they compared the experimental results with a wax model called Michigan Wax Predictor (MWP), which showed a good agreement with experimental results. They studied the importance of the shape of the wax solubility curve on the effects of oil temperatures on wax deposition by comparing the results from two different crude oil using the MWP. Two different crude oil has different solubility curves, one is a straight line and the other is a concave curve. They showed that the difference in the solubility curves could be led to getting opposing trends for studying the effect of Toil. Results from MWP showed a major difference in the wax deposition with changing the temperature conditions between two crude oil. They found that increasing Toil lead to decrease wax deposition of the crude oil has a concave curve while wax deposition increased with increasing Toil for crude oil has straight line solubility curve. They concluded that the shape of solubility curve can greatly affect the mass driving force by affecting the equilibrium concentrations of wax in the bulk oil (Coil(eq)) and at the wall (Cwall(eq)), where the changing in the equilibrium concentrations leads to a difference in the behavior of mass driving force which explains the opposing trends in the amount of deposit between two crude oil. Therefore, they thought that the mass driving force for wax deposition is a more appropriate parameter to quantify the temperature effects of wax deposition in comparison to the thermal driving force.

(Lu *et al*, 2012) showed that other effects focus on the heat and mass transfer phenomena at the oil–deposit interface may affect wax deposition when the oil flow rate is changed and may either increase or decrease the growth rate of the deposit. They 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 behavior of the wax deposit is the result of the competition between these three effects. They found that effect 1 changes insignificantly with time, while effect 2 weakens with time and effect 3 strengthens as time increases because of the insulation effect by the buildup of the wax deposit on the wall. Therefore, they found that effect 3 eventually dominated the competition over the other two as time progresses. Therefore, they summed up that, the reason for decreasing wax deposition with increasing flow rates in the flow-loop apparatus was not the shear removing mechanism as claimed in many previous studies. They attributed the reason to the heat and mass transfer phenomena at the oil-deposit interface was not a viewpoint to those studies.

Shahrabadi *et al* (2013) used model oil prepared by solving paraffin wax into toluene solvent, with different wax content in a flow-loop apparatus to investigate the wax deposition on the pipe surface under different conditions. They observed that wax deposition was increased with increasing temperature difference and time residence. This was because of increasing time leads more heat loss, which leads to reduce crude oil temperature, therefore, cause increasing in a wax deposition. But it was reported that as the time progress wax deposition was decreased because of the increasing wax thickness layer on the pipe wall led to an increase the insulation effect, therefore, decreased the heat transfer rate. Also, they studied the effect of flow rate which found to be depended on flow regime. They found that wax deposition increased in laminar flow whereas it decreased under turbulent flow. However, they did not give an explanation for decreasing wax deposition in turbulent flow they believed in the three effects were identified by (Lu *et al*, 2012).

Wang *et al* (2015) used an oil sample with 7.1 mass% of wax dissolved and WAT of 20ºC in a small- scale flow loop apparatus in combination with DSC technique, to examine the effects that effect on wax deposition. They studied the influence of oil temperature, wall temperature and the flow velocity. For a deposition experiment at a constant wall temperature, they observed that an increase in the oil temperature resulted in a higher deposition rate, whereas an increase in the wall temperature for a constant oil temperature led to a lower deposition rate. All of the above observations were compared with wax solubility curves (WPCs) generated from the DSC technique which showed a remarkable similarity with flow-loop experiments. Hence, they concluded that the wax solubility curve and its gradient (dC/dT) was greatly affected the wax deposition as the thermal driving force ΔT. In addition, they studied the effect of flow velocity on the wax deposition where it found to be decreased with increasing flow velocity. They thought the reason for this trend that because of the adhesion of lighter hydrocarbons was so low that was easily stripped down by the flow shear due to the sloughing effect, therefore, the mass percentage of the heavier hydrocarbons in the deposit becomes relatively higher which may lead to an increase of deposit hardness. For every flow velocity investigated, the results obtained were explained in term of wax deposit composition (WPCs shape). The WPCs also showed that for the higher operating flow velocity the wax species deposited changed toward a higher carbon number (a higher molecular mass distribution).

DESCRIPTION OF STUDY

Current Study

Nowadays Libya exports about 1 Million BPD of crude oil according to National Oil Corporation (NOC). The oil is normally carried across several terminals through different pipelines which represent the most economic and safest carriage system for mineral products (Shamekh *et al*, 2014). One of those pipelines is Sarir/Tobruk Pipeline, which is the target of this study (Fig. 6). The study aims to investigate the wax deposition phenomena in Sarir/Tobruk pipeline, where the crude oil is shipped from Sarir field to the Al-Hariga port at Tobruk (a distance of 514km). Sarir crude is waxy crude which has a wax content range from (13-24)%wt. (Shamekh *et al*, 2014). Thus, it is important to study wax deposition in this pipeline where the deposition is certain to occur. This pipeline is considered as one of

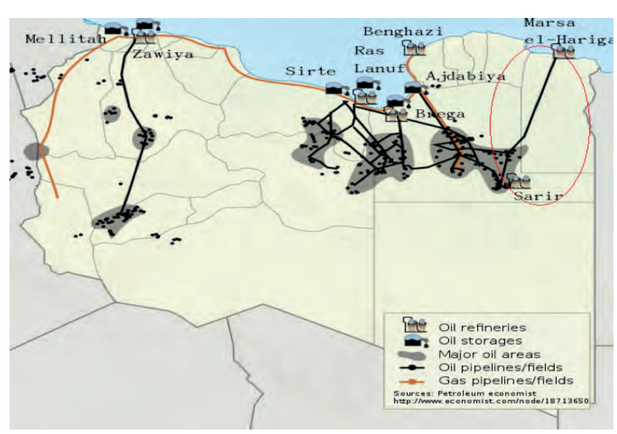

Fig. 6. Show systems of pipelines of gas and oil around the Libya.

the important pipeline in Libya. Economically, this pipeline was the only artery which kept uninterrupted and provides continuous flow of crude during the conflict in the country as it maintained an average of 200,000BPD.

Sarir Field (SF)

Sarir Field (SF) was discovered in southern of Cyrenaica area during 1961 and is considered to be the earliest and the largest oil field in Libya. It is operated by the Arabian Gulf Oil Company (AGOCO), a subsidiary of the state-owned National Oil Corporation (NOC). The field has estimated oil reserves of 12Gbbl, 6.5Gbbl ultimate recoverable reserves and 312,500BPD maximum production rate.

Characterization of Sarir Crude Oil

Sarir crude is classified as paraffinic crude oil having a gravity of 36.5°API and a total sulphur content of 0.12wt%. The crude is paraffinic in nature in the middle and upper part of its boiling range, although it is less paraffinic in the lower boiling range. Sarir crude has a high pour point of (+21ºC) and a kinematic viscosity of 10.63cSt at 37.7ºC. In addition, the experimental work done by (Alghanduri *et al*, 2010), gave us good knowledge about characterization of waxy of Sarir crude oil such these important information the WAT and wax content. According to (Alghanduri *et al*, 2010) the WAT of Sarir was (48.7± 0.36ºC/ 49.6± 0.1ºC), measured using the differential scanning calorimetry (DSC) with two different cooling rates and wax content was 13.6% wt. determined by the UOP 46-64 method.

Table 1. Sarir Crude Oil Properties (Alghanduri et al, 2010 and Shamekh et al, 2014).

PROPERTY	VALUE	REF.
Density @ 15°C g/ml	0.8415	[28]
API gravity @60°F	36.5	[28]
Sulphur Content, wt.%	0.120	[28]
Asphaltenes Content, wt.%	0.20	[22]
Mercaptan Sulphur ppm wt.	8	[22]
Water and Sediment Content, vol.%	0.05	[27]
Wax Content, wt.%	13.6	[27]
Cloud point/WAT °C	48.7 - 49.6	[27]
Pour point °C (°F)	+21(+70)	[27]-[28]
Melting point of wax °F	127	[22]
Viscosity @100°F cSt	10.63	[28]
Avg. Molecular Weight Mw	244.7	[27]

RESULTS AND DISCUSSIONS

This section presents the summary results of the main parameter examined by HYSYS simulation (V9, 2016). All the presented data and findings will be mentioned and discussed further, in the following sections.

The following (Fig. 7) shows the simulation of elevation profile of Sarir/Tobruk pipeline which has been used in the following calculations. The pipeline go through different elevations, approximately 90 meter (296ft) at Sarir Field and 98 meter (321ft) at Tobruk Terminal and cross through the highest point at the line which is 188 meter (617ft).

Temperature Profile

Figure (8) shows the temperature profile of Sarir/Tobruk pipeline. As shown in the figure the temperature of crude oil decrease gradually along pipeline due to heat losses to the surrounding. This temperature profile has been calculated in case of winter season where ambient temperature considered to be the lowest temperature compared to other seasons. The crude oil pump at 125ºF

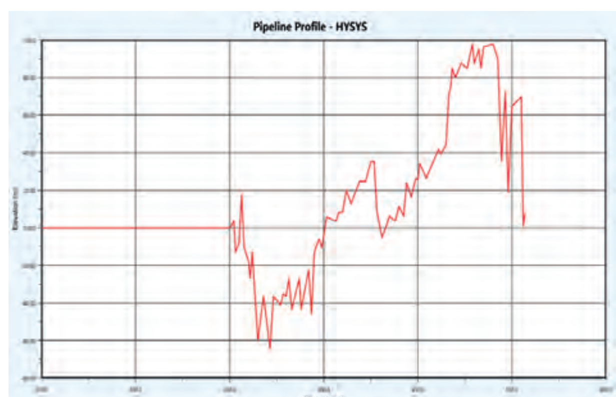

Fig. 7. Elevations Profile of Sarir-Tobruk Pipeline in HYSYS.

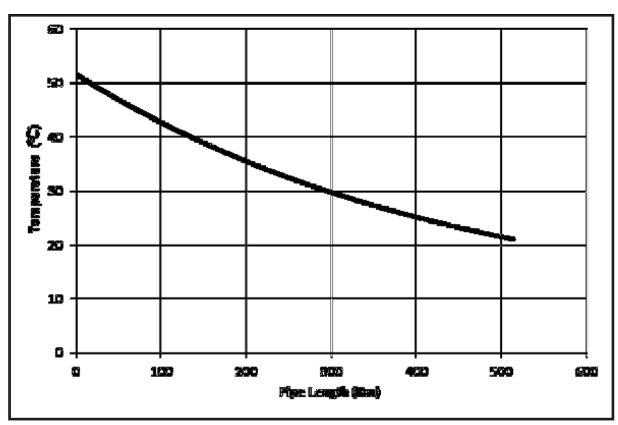

Fig. 8. Temperature Profile along the Sarir-Tobruk Pipeline.

(51.67ºC) in Sarir Field reaches to Tobruk at 70ºF (21ºC). The outlet temperature of the crude oil was calculated using HYSYS and was found to be in a good agreement with the measured field value according to AGOCO Operations Department and T.A.D. The final temperature where found to be the temperature of crude pour point. The crude oil is then heated in the storage tanks to increase the crude oil temperature above the pour point to prevent any possible blockage in the last section of the delivery system in Tobruk terminal.

Pressure Profile

Figure (9) shows the simulated pressure profile along the pipeline. The overall pressure is decreased along the pipeline, however, some points in the profile show increase in the pressure due to the hydrostatic pressure. This variation of pressure caused by the topography, where the pipeline goes through different elevations as shown in (Fig. 5). The Crude oil pump at 475psi (3275kpa) in Sarir Field reaches to Tobruk at 152.4psi (1054.54kpa) with overall pressure drop equal 322.6psi (2220.46kpa).

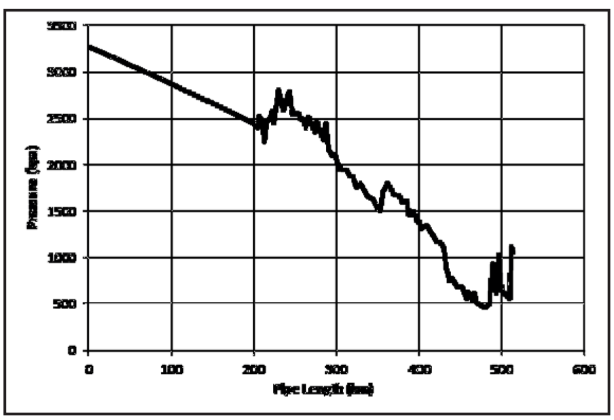

Fig. 9. Pressure Profile along the Pipeline.

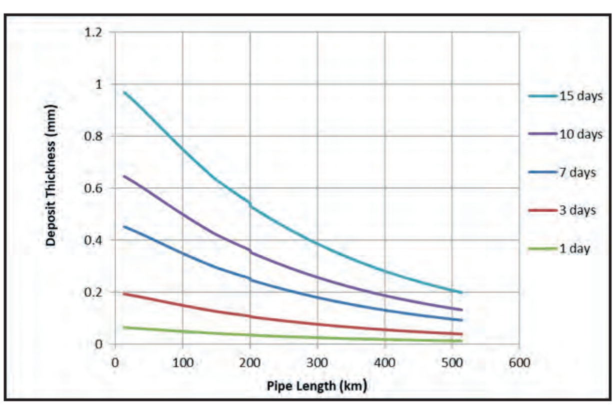

Fig. 10. Wax Thickness Layer along the Pipeline at different simulation times.

Wax Thickness Layer Profile

Figure (10) shows the change of wax thickness layer along the pipeline at different simulation times. Wax thickness layer is the only variable that changes with time in HYSYS simulation and even in other recognized wax simulations, in contrary to other variables. Therefore, different simulation times were conducted and the results show a significant difference between them and it should be mentioned that the subsequent calculations are based on three days simulation time. From observing (Fig. 10) the wax thickness layer changes gradually along the pipeline and wax deposition seems to be steady at 400km. Figure (11) shows the change of wax thickness layer with different times simulation at the different locations in the pipeline, where the wax thickness is increased with an increasing time duration. A similar observation has been found in the experimental study of (Creek *et al*, 1999; Hoffmann & Amundsen, 2010; Lashkarbolooki *et al*, 2010 and Huang *et al*, 2011). This may be because of increasing time leads more heat loss, which leads to reduce crude oil temperature, therefore, cause increasing in a wax deposition. This phenomenon is known as ‘’deposit’s aging’’, where was quantitatively studied by (Singh *et al*, 2000), which showed that the wax content of the deposit increases as time goes and wax diffuse into the deposit and crude oil is squeezed out. That means to reduce the amount of entrained crude oil in the deposit, thereby, lead to more wax species available to produce wax crystal within the deposit itself (Fig. 4).

Effect of Crude Oil Inlet Temperature on Wax Thickness Layer

According to AGOCO Operations Department and T.A.D, the crude oil inlet temperature range from 130ºF to 120ºF in summer and winter seasons. Thus, we have examined the development of wax thickness layers with four different inlet crude temperature including the operation temperatures range, while the ambient temperatures is kept constant. Figure (12) illustrates the wax deposition along the pipeline increases with increasing inlet crude temperature. More illustration in (Fig. 13) which shows wax thickness wax increase with increasing inlet crude oil temperature. Similar trend have been found in work of (Creek *et al*, 1999; Bidmus *et al*, 2009; Lashkarbolooki *et al*, 2010 and Wang *et al*, 2015). They found that a decrease in the oil temperature (decreasing thermal driving force) could result in decreasing wax deposition. However,

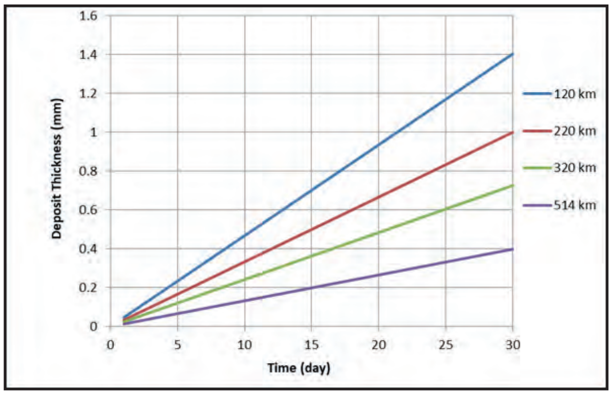

Fig. 11. Wax Thickness Layer versus Time at Different Locations in the Pipeline.

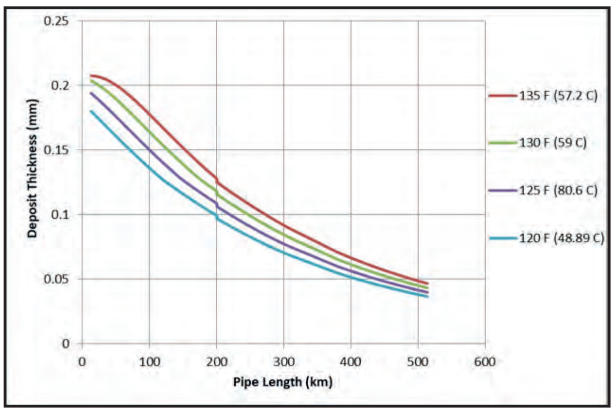

Fig. 12. Effect of inlet crude temperature on wax thickness layer along the pipeline.

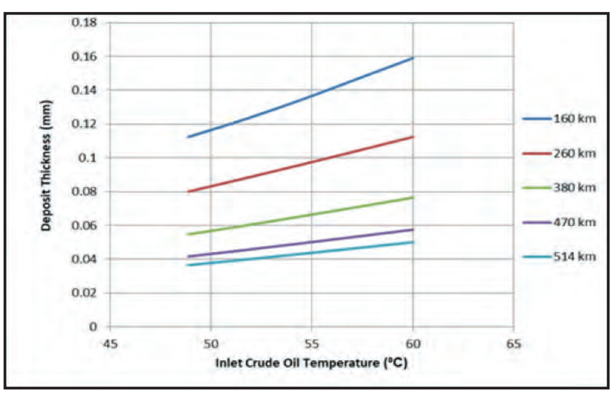

Fig. 13. Wax thickness layer versus inlet crude oil temperature at different locations in the pipeline.SW Libya.

study of (Hoffman and Amundsen, 2009) and (Huang *et al*, 2011) showed opposing trends, where wax deposition was decreased with increasing oil temperature.

Effect of Ambient Temperature on Wax Thickness Layer

Four different ambient temperatures have been examined, and 7ºC ambient temperature is chosen to

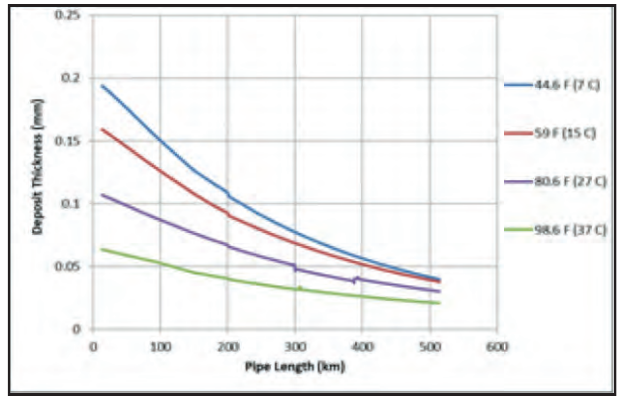

Fig. 14. Effect of ambient temperature on wax thickness layer along the pipeline.

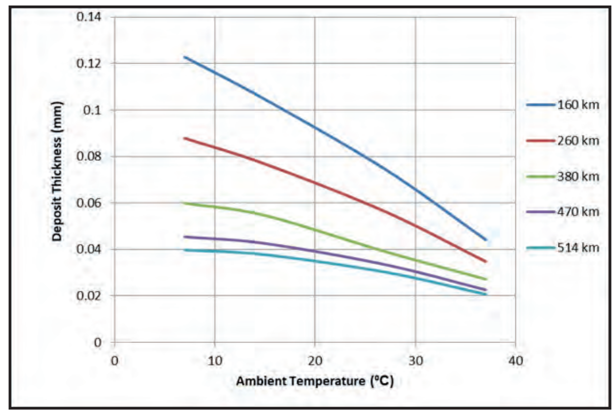

Fig. 15. Wax thickness layer versus ambient temperature at different locations in the pipeline.

be the lowest temperature as the worst case for wax deposition occurrence (as mention previously). Figure (14) shows the change of wax thickness layer along the pipeline at different ambient temperatures. This figure exhibits that the wax deposition along the pipeline decreases with increasing ambient temperature. More illustration in (Fig. 15), which shows wax thickness decreased with increasing ambient temperature. Similar trends have been observed in experimental work done previously by (Creek *et al*, 1999; Jennings *et al*, 2005; Lashkarbolooki *et al*, 2010; Huang *et al*, 2011 and Wang *et al*, 2015). In their work they found that deposit thickness decreased when the coolant temperature increased (increasing ambient temperature).

In all the above results, a generalization was made that the deposit thickness decreases when thermal driving force decreases (decreasing ΔT). The focus on the thermal driving force for wax deposition is based on the fact that molecular diffusion was assumed to be the main mechanism for wax deposition. In this mechanism, the concentration gradient is established by thermal gradient, which means that more wax molecules can precipitate and form thicker deposits with increasing temperature gradients. Thus, increasing inlet crude temperature and decreasing ambient temperature, lead to increase the thermal driving force ΔT and, that is, explained the behavior we obtained above. Many previous studies were based on the fact that thermal driving force on molecular diffusion equation are response to decrease or increase wax deposition (Creek *et al*, 1999; Jennings *et al*, 2005; Bidmus *et al*, 2009; Lashkarbolooki *et al*, 2010 and Wang *et al*. 2015).

Although the study of (Huang *et al*, 2011 and Hoffman & Amundsen, 2010) showed that solubility gradient (dC/dT) has a significant effect on wax deposition as the thermal gradient. (Huang *et al*. 2011) made a comprehensive study to examine the effect of the shape of solubility curve. The study showed that mass driving force and shape of solubility curve were affecting the deposition rate rather than thermal driving force. They found that the shape of the solubility curve had a major impact to affect the change in characteristic mass flux for wax deposition when the oil and the coolant (ambient) temperatures are changed.

Effect of Crude Oil Inlet Temperature on Energy Requirement

To investigate the possibility of heating the inlet crude oil to a temperature at which the pour point temperature (PPT) of the crude oil is avoided two cases are studied in both winter and summer season, where the ambient temperatures are 44.6ºF (7ºC) and 98.6ºF (37ºC) respectively. Figures (16 & 17) show temperature profile for different inlet crude oil temperature in both winter and summer season. As shown in the figures there is a significant difference between two seasons. In the summer season, the output crude oil temperatures for all range of inlet operating temperatures remain fairly remote from the PPT. The results show that an inlet temperature of 130ºF (54.4ºC) is high enough to avoid any possibility of jelly formation during the crude transportation in winter season while in summer season where the ambient temperature is relatively higher compared to the winter season and the rate of heat transfer as consequence is minimal, a reduction in the crude temperature along the pipeline was found to be very low and even with an inlet temperature of 120ºF (48.89ºC) the formation of jelly is not possible. The results obtained can be used to determine what inlet temperature the crude should be and how much energy that must be used to heat the inlet crude oil to the optimum temperature.

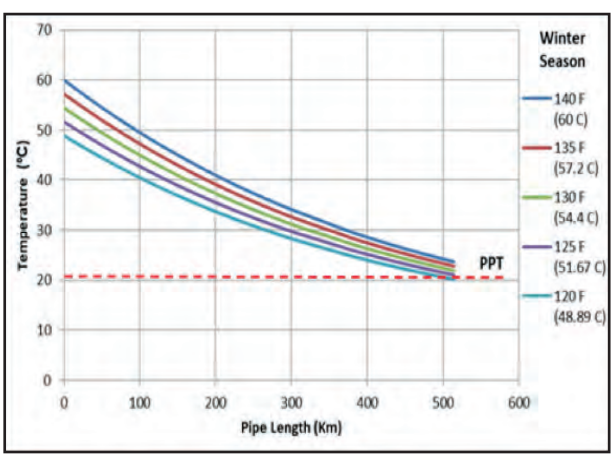

Fig. 16. Effect of inlet crude temperature on temperature profile along the pipeline in winter season.

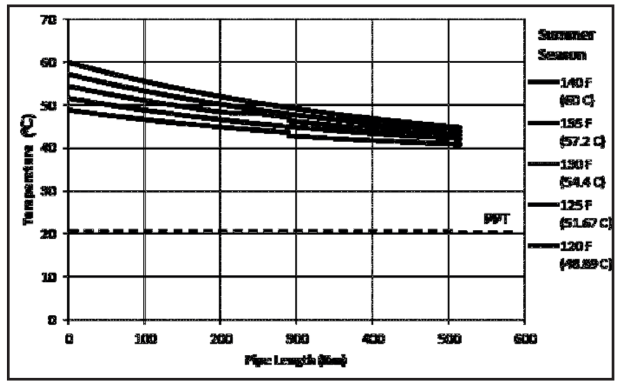

Fig. 17. Effect of inlet crude temperature on temperature profile along the pipeline in summer season.

Effect of Flow Rates

The effect of crude oil flow rate on wax thickness layer along the pipeline is shown in (Fig. 18). The results show that the wax thickness layer increases with increasing flow rates. Results showed opposing trends to those have been observed in a series of experimental studies, where wax deposit reduced with an increase in the flow rate. This might be attributed to the fact that the model used in the prediction of the wax layer thickness based on molecular diffusion as the main mechanism and does not take into account the effect of shear removal. Many previous studies thought that an increase in shear stress forces at the oil-deposit interface with increasing flow rates was behind the reduction of wax thickness layer (Creek *et al*, 1999; Jennings *et al*, 2005; Hoffman & Amundsen, 2010 and Wang *et al*, 2015). However, the results obtained in the study made by (Lu *et al*, 2012) showed that other effects focus on the heat and mass transfer phenomena at the oil–deposit interface may affect wax deposition when the oil flow rate is changed and may either increase or decrease the growth rate of the deposit. They 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). The overall growth behavior of the wax deposit is the result of the competition between these three effects.

Although wax deposition decreases with increasing flow rate some other studies report that wax deposition some while increases with increasing flow rates (Jennings *et al*, 2005; Hoffman & Amundsen, 2010 and Wang *et al*, 2015). Figure (19) illustrates that wax thickness layer increased with increasing flow rates in the pipeline. This observation shows that shear removal force work as a side effect for increasing flow rate, although, recent research has an argument about the main mechanism behind the reduction in thickness of wax with increasing flow rate. The reason behind the increase of wax deposition with increasing flow rates comes from increasing wax concentration species in the deposit itself where this increasing was thought to be from the reduction in the amount of entrained crude oil in the deposit which means an increase in a wax fraction in the deposit. This was also explained by (Singh *et al*. 2000), in which he was able to show that the external convective mass flux of wax molecules from the bulk oil flow towards the cold wall and internal diffusion are responsible for the growth of wax deposits. Which means that more reduction in the amount of entrained crude oil in the deposit more precipitation of wax molecules inside the deposits layer. This phenomenon is caused by internal diffusion and well known as ‘’wax aging” which increases as time increases as shown in (Fig. 11).

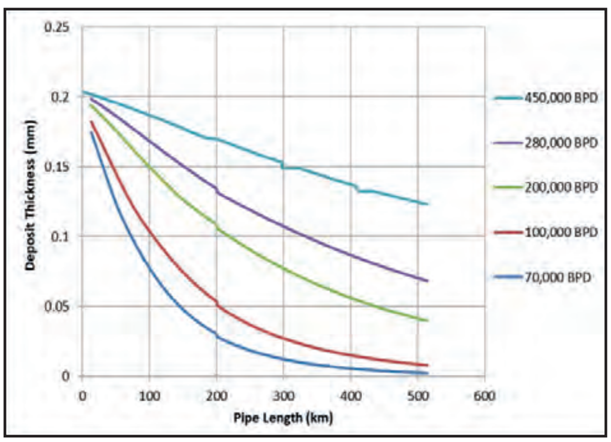

Fig. 18. Effect of flow rates on wax thickness layer along the pipeline.

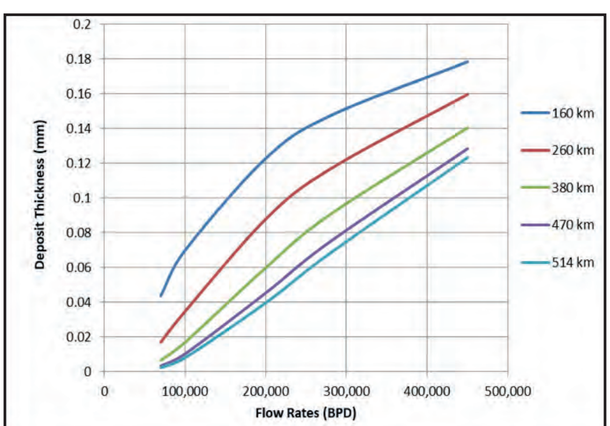

Fig. 19. Wax thickness layer versus crude oil flow rates at different locations in the pipeline.

CONCULTIONS AND FUTURE WORK

Conclusions

The wax deposition models built in the commercial software Aspen HYSYS were used to simulate the phenomena of wax deposition in Sarir/Tobruk oil pipeline. The study involved the prediction of both temperature and pressure profiles along the Sarir/Tobruk pipeline. The prediction of temperature profile showed a good agreement with operational data measured at the pipeline outlet condition.

Profes method was used to simulate wax thickness layer under different time simulations, inlet crude oil temperatures, ambient temperatures and crude oil flow rates.

Increasing of inlet temperature and elapsed time cause an increase in the wax thickness. On the other hand, increasing of ambient temperature causes decreasing of wax thickness layer.

The temperature effect of both inlet crude oil and ambient indicates that wax deposition development is predominantly thermally driven.

The effect of flow rate showed that increasing of flow rate causes an increase in the wax thickness.

Investigation of the effect of inlet temperature on the jelly formation phenomena shows that heating the crude oil to 130ºF in winter season is sufficient to avoid any jelly formation for the crude oil before reaching its destination at Al-Hariga Port in Tobruk.

Future work

Accuracy of the results obtained in this study can be improved by using the wax precipitation curve (WPC) in Aspen HYSYS simulation.

The same investigation can be carried out using computational fluid dynamics (CFD) simulation techniques for better accuracy.

Experimental techniques such as flow-loop and cold flow apparatus are strongly recommended to verify the results obtained from the simulation.

It would be better in the future when this old aged pipeline is renewed and reliable data from the actual field can be obtained and compared to simulation results to give a good approximation to what happens in the real field.

REFERENCES

Alghanduri, L. M.; Elgarni, M. M.; Daridon, J. L. & Coutinho, J. A. P. (2010). Characterization of Libyan Waxy Crude Oils. Energy & Fuels, 24: 3101-3107.

Bidmus, H. O. and Mehrotra, A. K. (2009). Solids Deposition During "Cold Flow" of Wax Solvent Mixtures in a Flow-Loop Apparatus with Heat Transfer. Energy & Fuels, 23: 3184-3194.

Creek, J.; Lund, H. J.; Brill, J. P. and Volk, M. (1999). Wax Deposition in Single Phase Flow. Fluid Phase Equilibria, 158/160: 801-811.

Han, S.; Huang, Z.; Senra, M.; Hoffmann, R. and Fogler, H. S. (2010). Method to Determine the Wax Solubility Curve in Crude Oil from Centrifugation and High Temperature Gas Chromatography Measurements. Energy & Fuels, 24: 1753-1761.

Hoffmann, R. & Amundsen, L. (2010). Single-Phase Wax Deposition Experiments. Energy & Fuels, 24: 1069-1080.

Huang, Z.; Lu, Y.; Hoffmann, R.; Amundsen, L. & Fogler, H. S. (2012). The Effect of Operating Temperatures on Wax Deposition. Energy & Fuels, 25: 5180-5188.

Jennings, D. W. and Weispfennig, K. (2005). Effects of Shear and Temperature on Wax Deposition: Coldfinger Investigation with a Gulf of Mexico Crude Oil. Energy & Fuels, 19: 1376-1386.

Lashkarbolooki, M.; Seyfaee, A.; Esmaeilzadeh, F. and Mowla, D. (2010). Experimental Investigation of Wax Deposition in Kermanshah Crude Oil Through a Monitored Flow Loop Apparatus. Energy Fuels, 24:1234-1241.

Lu, Y.; Huang, Z.; Hoffmann, R.; Amundsen, L.; Fogler, H. S. & Sheng, Z. (2012). Counterintuitive Effects of the Oil Flow Rate on Wax Deposition. Energy & Fuels, 26: 4091-4097.

Shahrabadi, A.; Sadi1, M.; Hendi, S. and Dabir, B. (2013). Modelling and Experimental Study of Wax Deposition in Transportation Line Using a Flow Loop System. Iranian Journal of Chemical Engineering (IAChE), 10(1): 3-16.

Shamekh, A.; Masheiti, S. and Ben Soud, S. (2014). A Simulation Study of the Sarir Field/Tobruk Terminal F Crude Oil Pipeline. UKSim-AMSS 16th International Conference on Computer Modelling and Simulation: 368-373.

Singh, P. and Venkatesan, R. (2001). Morphological Evolution of Thick Wax Deposits During Aging. AIChE Journal, 47: 6-18.

Singh, P.; Venkatesan, R.; Fogler, H. S. and Nagarajan, N. (2000). Formation and Aging of Incipient Thin Film Wax-Oil Gels. AIChE Journal, 46: 1059-1074.

Sircar, A. and Gupta, A. (2015). Flow Assurance and Comparison of Modeling & SCADA Results for Onshore Crude Oil Trunk Line, (IV): 2278-2540.

Wang, W.; Huang, Q.; Wang, C.; Li, S.; Qu, W.; Zhao, J. and He, M. (2015). Effect of Operating Conditions on Wax Deposition in a Laboratory Flow Loop Characterized with DSC Technique. J. Therm Anal Calorim, 119: 471-485.