Wax Precipitation and Deposition Risk: Issues on Ethics and Professionalism

Nura Makwashi[1*], Tariq Ahmed[1], Stephen Arome Akubo[2]

[1]Department of Chemical and Petroleum Engineering, Bayero University, Kano, Nigeria
[2]Department of Mineral and Petroleum Resources Engineering, Kogi State Polytechnic, Lokoja, Nigeria

ABSTRACT: The deposition of wax on pipelines causes problems that affect oil production rate and the facilities. Several preventive and control measures were employed to manage this problem. However, there is no single technique that is hundred per cent effective for different fields. Therefore, this article provides new interpretation of the associated risk of the problem – such as the impact of ethical and professionalism on wax deposition. It sheds more light on the need for the implementation of sound engineering practices during pipeline design, construction, and operations to reduce wax deposition risks and the associated remediation costs. The laboratory case study revealed that crude oil properties (such as wax appearance temperature (WAT), pour point (PP), and density), standard operating conditions and procedures must be accurate and continuously updated throughout the production life cycle. The results showed that maintaining crude oil temperature above wax appearance temperature (30°C) and at a relatively high flow rate particularly within the turbulent flow region (7, 9 and 11 l/min) provides a safe and uninterrupted production of waxy crude oil ($\delta wax \approx 0$ mm).

KEYWORDS: Crude oil; Wax deposition; Pipeline; Ethics; Professionalism.

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I. INTRODUCTION

Flow assurance is key to the optimum oil and gas production and vital during pipeline design, and construction. Flow assurance has been defined according to the study by Hammami and Ratulowski (2007) and Gao (2008) as guarantee of flow of hydrocarbon from the reservoir to the surface processing facilities and point of sale. The oil and gas industries are prone to several challenges regarding flow assurance. This includes wax formation and deposition on the pipeline, asphaltenes agglomeration, formation of gas hydrates, corrosion, scales, and slug flow (Bai and Bai, 2005; Chala et a.l, 2018; Kang et al., 2019). These problems are heightened as the oil and gas exploration and production moves towards deeper higher pressure higher temperature wells (El-Dalatony et al, 2019; Huang et al, 2015).

Many uncertainties affect the oil and gas operations, particularly in managing economics and safety of production, refining, and delivering hydrocarbons. According to Ershaghi (2019), the intrinsic risk and ethical issues confronting the oil and gas fields are related to the uncertainties and associated hazards. Generally, the risk issues, particularly in the upstream sector are higher and are divided into two (Ershaghi, 2019). These include the economic or soft issue and operational or hard issues. The soft issues include discriminating policies related to employment or working conditions, resource evaluation (such as overbooking), negligence on record keeping, and incident documentation and reports. The hard issues include operational processes and decision making. These could directly or indirectly affect the health and safety of the people and the environment and directly cause severe economic losses to the operations (Ershaghi, 2019). However, good ethical and professional behaviour plays a vital role, especially in the design and management operations of a reservoir that is naturally waxy.

Apart from having safe oil and gas production activities, oil industries have other goals of protecting the public, employees, the environment, and the risk of investors' capital in initiating and maintaining the project. In all of these, wax deposition poses a lot of concerns. A typical example is the Staffa oil field, which was operated by Lasmo Oil Company in the UK. The field was abandoned after four years of production because of difficult and recurrent deposition of wax (Nguyen *et al.*, 2001; Singh *et al.*, 2000), which reported more than $100,000,000 losses as a result of wax deposition.

In line with the current practice, it is worth noting that the recent track of ethical issues on production technology has shifted focus from the industrial revolution to the social revolution (Mitcham, 2020). Particularly for waxy crude production where non-compliance to the ethical and professional practices could harm the revenue generation, the life span of the oil field (as in the Staffa oil field), and the environment. Another typical example is the consequential impacts on the aquatic environment and vegetation caused by the use of some chemical wax inhibitors during remediation activities as a result of wax blockages (Bai and Bai, 2005; Ershaghi *et al.* 20118; Sharma, R. *et al.*, 2020). However, in line with the best ethical and professional practices through proper planning, training and regulation the impact can be substantially reduced.

*Corresponding author: nmakwashi.cpe@buk.edu.ng

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Therefore, one of the objectives of this study is to theoretically evaluate and explore the essential ethical practices required for prevention of wax deposition. This includes conditions that must be met to avoid the devastating effect of wax deposition. Secondly, the paper also presents a practical demonstration of wax deposition issues. Therefore, a pipeline flow loop experiment was designed through which the standard operating procedure was altered – leading to the deposition of wax. The designed was done in accordance with the best professional and ethical practices that allow a smooth flow of hydrocarbon.

A. Wax Deposition Concern During Oil Production

Paraffin wax is a soft, colourless, soluble solid that precipitates as the crude oil temperature drops below the precipitation temperature (Wax Appearance Temperature, WAT) (Soedarmo et al., 2017). WAT is generally dependent on many factors: such as the ambient conditions, the composition of the oil (Saturate, Aromatics, Resins, Asphaltenes (SARA) fractions), and wax content (Wang and Huang, 2014). Wax precipitates as a clusters of crystals molecules that form an interlocking network configuration (Paso et al., 2005). However, the deposition of wax is regarded as a molecular diffusion process of crystalized wax particles on the pipe wall. Therefore, the deposition of wax reduces the pipe flow area, and if not prevented could lead to loss of production through unmanageable pipe blockage (Wang and Huang, 2014; Soedarmo et al, 2017).

Generally, several factors (such as oil temperature and composition, oil flow rate, pipe surface roughness and system pressure) and physical mechanisms (e.g., molecular, and Brownian diffusion) govern the precipitation and deposition of wax crystals on the colder surface (Chi et al., 2017; Harun et al., 2016). Hence, wax deposition is typical in the offshore environment, where the ambient condition is extremely harsh. As the hydrocarbon arrive at the sea environment (< 4 ℃), a thermal gradient occurs between the fluid and pipe wall (Lee, 2009). However, sound professionalism and ethical practices could enhance and improve wax management and remediation.

It should be noted that a pipe is the most used material for the production and transportation of oil and gas, mainly due to safety and economic reasons (Alamri, 2020; Chen et al, 2019). However, at a temperature lower than the WAT of crude oil, wax molecules begin to appear, leading to a deposition problem. According to a study by Shahriar et al. (2012), several factors are significant for the system design and construction of pipelines to produce waxy crude oil such as nature and properties of the fluids, volume flow rate, length of the pipeline, terrain and medium traversed by the pipeline, i.e., soil/water, and climatic conditions – extreme heat/cold. Other includes environmental constraints, standards and regulations governing the design, construction and operation of the pipeline, Seismic conditions, economics, materials, and construction, operation, and maintenance of the pipeline.

B. Existing Practices for Wax Prevention and Remediation

Wax deposition on the pipe wall could be catastrophic if there is no prevention strategy in place. Ethical practices, including adherence and adoptions to standards, are essential in wax management and environmental sustainability in wavy oil production. As wax deposition begins to build-up and eventually plug the pipeline, the reliability of the pipeline is being jeopardized. Currently, there are several wax management strategies used by oil and gas industries that require technical and ethical practices to yield the desired goal. These strategies are categorized as preventive and corrective measures (White et al., 2018; Paso et al., 2005). These measures could be achieved either by chemicals (e.g., wax inhibitors), mechanical (e.g. pigging process), and thermal methods (e.g. steam injection, electrical heating traces) (Bai and Bai, 2005; Paso et al., 2005). Some of these methods are efficient for use in a short distance pipe only. For instance, the thermal method is frequently employed in a short-distance pipe of around 500 m water depth. It is worth noting that most of the prevention techniques are employed to keep the flow line temperatures above WAT. As such, the wax crystals are kept dissolved in the crude oil matrix.

On the other hand, chemical inhibitors such as the wax crystals modifiers are widely used in long-distance pipes (Bai and Bai, 2005; Chala et al., 2018; Paso et al., 2005). Naturally, chemical inhibitors exhibit comparable structure with the molecules of wax. This makes the chemicals form a lattice structure within the crude oil matrix which substitute the wax molecules on the crystal lattices, and hence prevents the networking molecules of crystals (White et al., 2018; Kelland, 2009). However, study by Fan and Llave (1996) revealed that some inhibitors are usually limited to remediation purposes only because of the safety issues (e.g., chlorinated hydrocarbons).

The mechanical methods (e.g., pigging operation) are widely used for remediating affected facilities. This process is complex and requires a shutdown of the entire production and physical removal of wax by a pigging process (Bai and Bai, 2005; White et al., 2018). In addition to the complex nature of this process, in most cases some part of the pipeline is cut-off and replaced with completely new material. Which could result to an oil spill that could contaminate the sea water. Consequently, this could subject the living organism around the sea (the aquatic life, vegetation and even humans) to a severe risk. It is important to note that as of today, there is no distinctive practice that could successfully works for all the different types of crude oil. Similarly, there is no single technique that could be 100% effective in preventing wax deposition. Hence, the need and search for a viable and robust design and development of wax management strategy continues. Which could rely upon effective adherence to the professionalism and ethical practices within the industry.

C. Indicative Factors on Good Practices for Waxy Oil Production

The following key factors are related/highlighted as to the best practices that ensure safe operation and production of waxy oil from the reservoir to processing facilities. The factors are also paramount in selection and application best wax mitigation strategy. These factors include;

1) Material selection

This entails meeting the standard specifications through appropriate material selection. It is vital to ensure proper materials are selected, because wax deposition is as result of decrease in temperature gradient. This implies the choice of materials that are less conductive, non-corrosive and can withstand high pressure and high temperature within acceptable standards and specifications is essential. According Rashidi et al. (2016), a steel material (such as carbon steel and stainless steel) is commonly used for oil and gas pipeline production and transportation due to its strength, toughness, ductility, and weldability. It is also essential to consider the surface roughness, especially in the subsea environment. Low-friction surfaces provides very low tendency of wax to stick on the pipe walls (Pedersen and Rønningsen, 2003; Rashidi et al., 2016). Design engineers use coated pipe to prevent deposition or at least minimise the rate of deposition.

2) Pipeline design

The most important engineering considerations that should be made while designing an oil and gas pipeline include the pipeline diameter, length, thickness, and even the pipe curvature. The effect of pipe bends and elbows needs to be carefully considered to avoid an increase in the severity of wax deposition. Pipe size should be designed to meet the target reservoir flow conditions (i.e., the flow rate and pressure). Under a laminar condition, higher wax depositions are reported (Makwashi *et al.*, 2019; Wang *et al.*, 2019).

3) Sound engineering practice

Sound engineering judgement must be applied throughout different stages of production and operations especially in matters that are related to occupational health and safety, control, routine checks, repairs, maintenance, instrumentation, constructions, and upgrade (Malins, 1977). This can be successfully achieved particularly for a waxy oil reservoir, through proper pre-start-up safety review (PSSR), planning, and enforcement of regulations.

4) Safety and environmental impact assessment

This is another bedrock of the oil industry within which life and livelihood could be of utmost value. For instance, the Piper Alpha disaster in the North Sea in July 1988 is attributed to unprofessional practices related to unaddressed failure in Safety and environmental considerations. It was reported that gas leakage from plant led to the world greatest oil industry disaster where 167 people lost their lives (Macleod and Richardson, 2018). Similarly, the ethical issues that would ensure the successful flow of waxy crude oil includes.

5) Accuracy of experimental data

Usually, fluid analysis is carried out to determine the fraction of crude oil including wax content. Furthermore, wax deposition models are used for field prediction and hence for design of prevention and mitigation measures, which sorely depend on the experimental results. The experimentation could be through fluid characterisation that defines the oil fraction (e.g., wax, saturate, aromatic, resin and asphaltene) using standard analytical methods and through pipeline flow loop studies pilot plant or laboratory scale level (Paso *et al.*, 2014). The experiment is complex and requires careful study of the developed data obtained through repetitive experimental runs.

6) Social responsibility towards host community

It is crucial for oil and gas company to maintain their real value to the society. This will surely provide enabling and safe environment for the company to carry out their production, transportation, and process activities. Hence, it serves as a powerful tool for creating more meaningful and lasting relationships with key stakeholders and environment (Kanji and Chopra, 2010).

7) Environmental degradation and oil spillage control

Appropriate measure need to be implemented and maintained to ensure the prevention of activities that results in environmental degradation and oil spillage. Wax remediation activities could result to corrosion, unsolicited clearing of vegetation, oil spillage, and acid sulphate leaching. Therefore, the use of inhibitors that are harmful to environment during wax treatment must be avoided at all costs (Alamri, 2020; Chen et al., 2019).

II. MATERIALS AND METHODS

The crude oil sample used in this study was supplied by Roemex Oilfield Service Company, UK. The sample is naturally waxy crude from a well in the North Sea with unknown properties. The sample is characterised (Table 3) to obtain some definite fundamental properties. Figure 1 presents a laboratory flow rig designed in accordance with the best professional and ethical practices that allow a smooth flow of hydrocarbon. However, where the standard operating procedure is not strictly followed, the deposition of wax occurs on the pipe wall, which demonstrates the consequence of non-adherence to professional practices. The laboratory scale facility comprises a jacketed pipe-in-pipe (test section) that is made up of copper material of 15 mm inner pipe and 22 mm outer pipe. The coolant fluid (glycol and water) flow in the outer pipe connected to a chiller while the crude oil flow in the inner pipe.

Four thermocouples are used to monitor the temperature variation within the test section. These includes type K self-adhesive patch and exposed tip thermocouples connected at the inlet and outlet of the pipe. The exposed tip thermocouples are used to monitor crude oil temperatures (T1 and T4). Whereas the exposed tip thermocouples are used to monitor the coolant fluid temperature (T2 and T3) Figure1. Two GC35 pressure sensors (P1 and P2, inlet and outlet) were used to monitor pressure drop across the test section. GC35 has a range between 0 to 75 psi (0 -5 bar). The full experimental procedure is reported in a study by Makwashi (2020).

One of the fundamental and initial practices when dealing with the waxy oil reservoir is fluid characterisation prior to actual production. Therefore, in this study, oil characterisation was done using different standard methods. Similarly, complete characterisation of this oil sample is reported by Makwashi (2020). A shear-controlled Rheometer (Bohlin Gemini II) was used to study rheological properties of the waxy crude oil (such as viscosity, WAT, and PP) which are vital for the calibration of flow loop. The same method was employed by El-Dalatony et al. (2019) and Adeyanju and Oyekunle (2013).

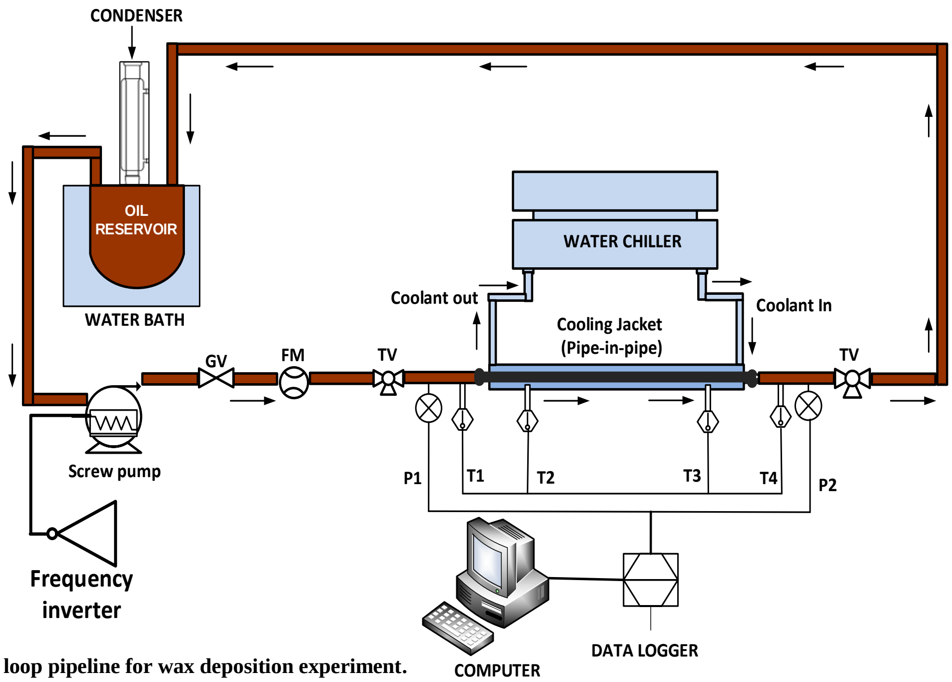

Figure 1: Flow loop pipeline for wax deposition experiment.

Practically, in order to demonstrate the consequence and the severity of unprofessional practices on wax deposition using the pipeline flow loop – a total of 26 test matrix was designed (Table 1 and 2). A standard operating procedure was designed to avoid wax deposition following the methods used by Makwashi (2020). The cooling temperature was varied at 10, 15, 20, 25, 30, and 35℃ and the influence of both laminar and turbulent flow was examined at 5 l/min and 9 l/min. Overall, the experiment is conducted at a constant experimental period of 2 hrs. It worth noting that the wax crystals remained dissolved in the crude oil matrix as the oil temperature is maintained at or above WAT and the flow rate at 9 l/min.

Wax thickness in the pipeline can be quantified using different techniques; (1) gauging using Vanier caliper (Rittirong et al., 2017), (2) pressure drop correlation Eq. (1) (Chen et al., 1997), (3) volume and (4) weight correlations Eqs. (2) and (3) (Hoffmann and Amundsen, 2010; Makwashi et al., 2019). The four techniques were comparatively used as shown in section III. However, pressure drop method has proven to give better result with minimum errors (Makwashi et al. 2019; Chi et al., 2017; and Rittirong et al., 2017). Full details of these methods is reported by Makwashi (2020).

$$\delta_w = \frac{di - \left[\left(\frac{1}{\Delta P}\right)\left[(128Q\mu)\left(\frac{\theta R_b}{180}\right) + \frac{8Q^2 k_b\, \rho}{\pi^2}\right]\right]^{\frac{1}{4}}}{2} \qquad (1)$$

where δ_w is the average thickness of the wax deposit, *di* is the inside diameter of the pipe and μ is the apparent viscosity of the crude oil.

$$\delta_w = R - \sqrt{R^2 - \frac{M_{dep}}{L\,\pi\rho_{dep}}} - \delta_o \qquad (2)$$

where R represent the inner pipe radius, and M_{dep} is the deposit weight, whereas L is the length of the pipeline test section, and δ_0 is the excess oil layer due to residual oil and ρ_{dep} is the density of deposit.

$$\delta_w = \sqrt{\frac{V_{wax}}{\pi L}} \qquad (3)$$

where V_{wax} represent the volume of wax that drops out of the system.

On the other hand, crude oil can be classified as light or heavy oil. A crude oil with API gravities > 33°API is regarded as light crude with lower density. Whereas those with lower API gravity value < 28°API are the heavier crudes usually consisting of more asphaltenes fractions and a small quantity of dissolved gases (Sifferman, 1979). The API of crude oil sample used in this study is 35°API with density of 835 kg/m3. Usually, API of a crude oil is determined using Eq. (4).

$$^{o}\mathrm{API} = \frac{141.5}{\gamma} - 131.5 \qquad (4)$$

where γ is the specific gravity (density of oil/density of water).

Table 1: Test matrix - pipeline flow rig experiment "effect of varied cooling temperature".

No. of Tests	Objective	Pipe Wall Temperature	Variable Conditions	Ageing Period	Crude Oil Temperature
2	Effect of ΔT	$T_{cool}=15^{O}C$	Qo;5&9 l/m	t = 2 hr	T_{oil} = WAT + $15^{O}C$
2	Effect of ΔT	$T_{cool}=20^{O}C$	Qo;5&9 l/m	t = 2 hr	T_{oil} = WAT + $15^{O}C$
2	Effect of ΔT	$T_{cool}=25^{O}C$	Qo;5&9 l/m	t = 2 hr	T_{oil} = WAT + $15^{O}C$
2	Effect of ΔT	$T_{cool}=30^{O}C$	Qo;5&9 l/m	t = 2 hr	T_{oil} = WAT + $15^{O}C$
2	Effect of ΔT	$T_{cool}=35^{O}C$	Qo;5&9 l/m	t = 2 hr	T_{oil} = WAT + $15^{O}C$
2	Effect of ΔT	$T_{cool}=40^{O}C$	Qo;5&9 l/m	t = 2 hr	T_{oil} = WAT + $15^{O}C$

Table 2: Test matrix - pipeline flow rig experiment "effect of varied flow rate".

No. of Tests	Objective	Oil Flow Rate (l/min)	Coolant Temperature	Ageing Period	Crude Oil Temperature (T_{oil})
2	Effect of Q	2	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$
2	Effect of Q	3	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$
2	Effect of Q	4	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$
2	Effect of Q	5	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$
2	Effect of Q	7	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$
2	Effect of Q	9	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$
2	Effect of Q	11	15 & $30^{O}C$	2 hr	WAT + $15^{O}C$

III. RESULTS AND DISCUSSION

Generally, the reliability of flow rig experimental results lies in the crude oil properties and the conditions within which the flow rig is configured. This implies that an accurate crude oil characterization is necessary to guarantee smooth crude oil production. Therefore, characterization of crude oil should be carried out prior to the installation of the main production facilities. This allows the field engineers to identify the flow assurance challenges and design appropriate prevention and mitigation methods. The flow rig study carried out in this study was used to develop better understanding of the ethical and professional practices with regards to the wax deposition (prevention and mitigation strategies). Initially, the properties that define the sample crude oil as waxy were measured, these include the API gravity, wax appearance temperature, wax content, and viscosity. Table 3 summarised the properties obtained in this work. It should be noted that the full oil characterization procedure is reported in our previous paper (Makwashi et al., 2021). However, brief descriptions of each standard procedure are given in this study.

Wax content is another parameter that indicate the depositional tendency of a samples. Wax content of the crude oil is obtained through modified UOP46-64 method, also called acetone precipitation method (Hoffmann and Amundsen, 2010; Coto et al, 2011). A study by Holder and Winkler (1965) revealed that a crude oil containing small amount of wax (2% by mass of wax) could cause deposition problem. The crude oil wax content is found to be 19.7 wt.%, which implies that the crude oil highly waxy. Similar results was reported by Makwashi et al, 2021).

The viscometric analysis was carried out using a rheometer at shear rate of 10, 60 and 120 1/s, varied cooling temperature (0 – 50℃) and at a cooling rate of 1.0 ℃/min. Parameters such oil viscosity, WAT and pour point were measured. Figure 2 show a complete circle of a single experiment captured on a computer. The red line represents the oil viscosity while the varied cooling temperature is represented by green line and the constant shear rate by blue line. Whereas the blue line represents the constant shear rate. As intersection of a baseline drawn from the Newtonian region and a tangent that fitted to the inflexion point represent the WAT of oil, any point of inflexion following the WAT point define the pour point of the crude oil.

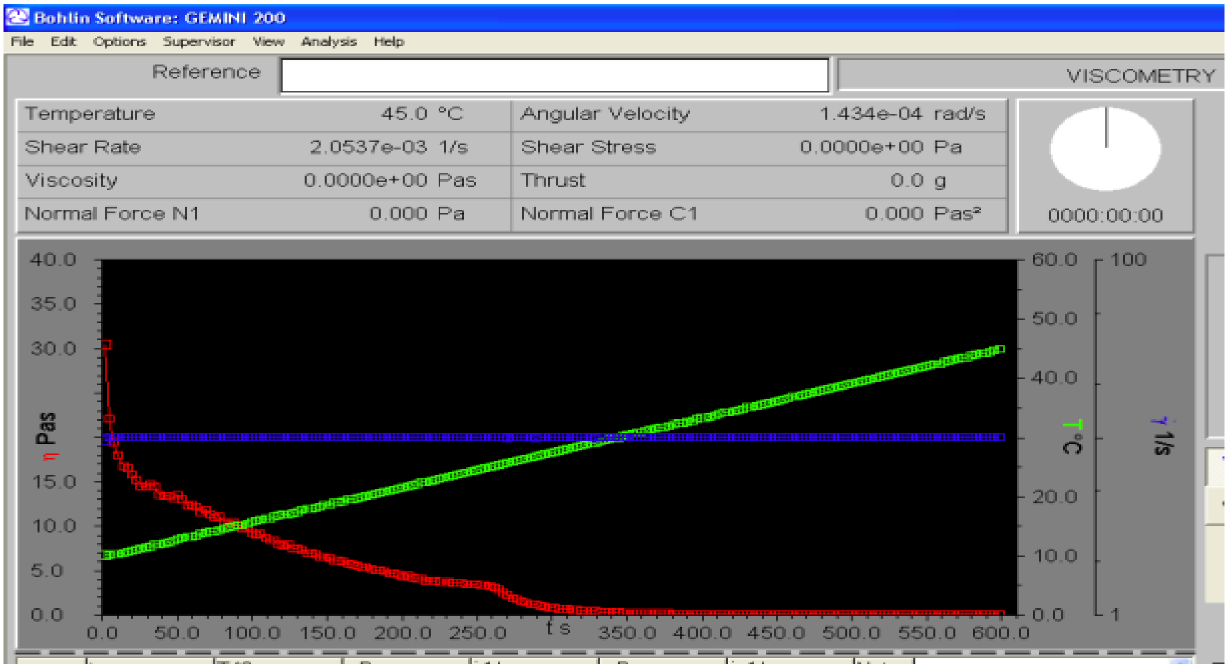

Figure 2: Viscometry analysis using Bohlin II Rheometer.

Figure 3 and Table 3 showed the analysis of result which describe the viscosity of crude oil that varies inversely with shear rate (10, 60 and 120 1/s) and cooling temperature (0 – 50°C). It is found that increase in oil viscosity due to a decrease in cooling temperature produces the formation of a gel structure in crude oil. This transformation produces the higher risk of wax precipitation and deposition in the oil pipeline. Roughly, equal wax appearance temperature (35°C) was observed at 10, and 60 1/s whereas at 120 1/s the WAT measured is lower (30°C). This implies that the viscosity of oil drops with increase in shear rate, this causes a decrease in the WAT value because of the decrease in the intermolecular attraction of the wax molecules towards the colder surface.

Therefore, to avoid deposition of wax on the pipeline surface the crude oil temperature must be maintained around 30°C or higher, particularly at the laminar flow regime. Consequently, any temperature below this condition could potentially cause wax deposition problem, although this depends on the oil flow rate. Hence, during oil and gas production the field and operation engineers are responsible for making proper design and operating the system based on the oil characteristic and other criteria, otherwise, wax deposition problem occurs.

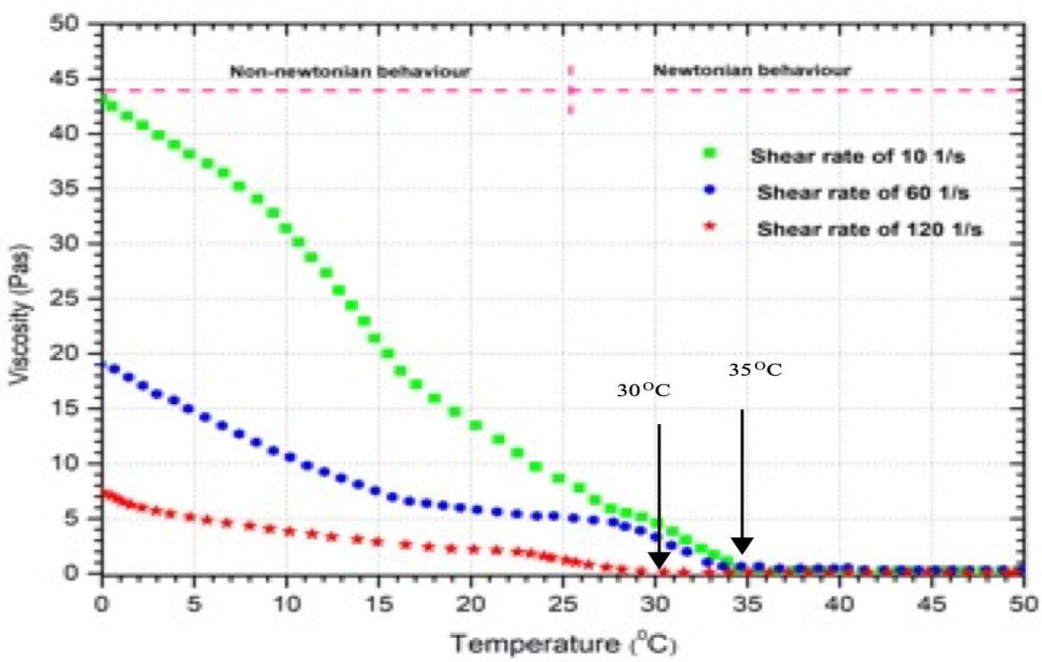

Figure 3: Effect of a shear rate of 10, 60 and 120 1/s at varied cooling temperature on crude oil viscosity, pour point and wax appearance temperature.

Table 3: Properties of the crude oil sample.

Properties	Unit	Sample	Method
Appearance		Brown	Visual
Density	kg/m3 (15℃)	835	Measurement
Sp. Gravity	60°F/60°F	0.835	Calculated
API Gravity	–	35	API Method
Wax Content	wt%	19.7	Modified UOP 46-64
Pour Point	℃	25.5	Rheometry
WAT at 120 1/s	℃	30	Rheometry
WAT at 10 1/s	℃	35	Rheometry
Viscosity	Pa.s (at 45℃ >WAT)	0.0056	Rheometry
Viscosity	Pa.s (at 15℃ <WAT)	3.89	Rheometry

A. Flow Rig Study: Effect of Coolant Temperature and Flow Rate on Wax Deposition

Figure 1 (pipeline flow rig) allows the crude oil sample to be transported without deposition under both laminar and turbulent flows (5 and 9 l/min), particularly if the cooling temperature (pipe wall) is kept above or equal to WAT (30 °C) of the sample. The results of experiments shown in (Figure 4 and 5) were run at a constant oil temperature of WAT + 15°C (45°C) and different cooling temperatures of 15, 20, 25, 30, 35 and 40 °C. It is observed that wax deposition measured in wax thickness (mm) increased with a decrease in cooling temperature and it reaches the maximum as the temperature drops to 15°C. This implies as the pipe wall temperature drops the crude oil temperature to decreases because of the decrease in the radial temperature gradient. zero wax thickness (i.e., at 35 nd 40°C, $\delta_{wax} \approx$ 0mm). Therefore, maintaining the wall temperature above WAT will eliminate any precipitation process of wax crystals. The increase in wax thickness as coolant temperature decreased leads to the formation of a thicker wax layers on the pipe wall thereby reduces the effective pipe diameter.

At a constant lower cooling temperature (15°C) i.e., below the WAT, wax deposition occurs even at a higher flow rate (9 and 11 l/min) (Figure 6, Table 4). The results showed that wax thickness of 1.3 and 1.5 mm was measured at 9 and 11 l/min respectively. This is because a mass transfer of the wax molecules is created towards the cold surface due to increase in radial temperature gradient and the concentration gradient.

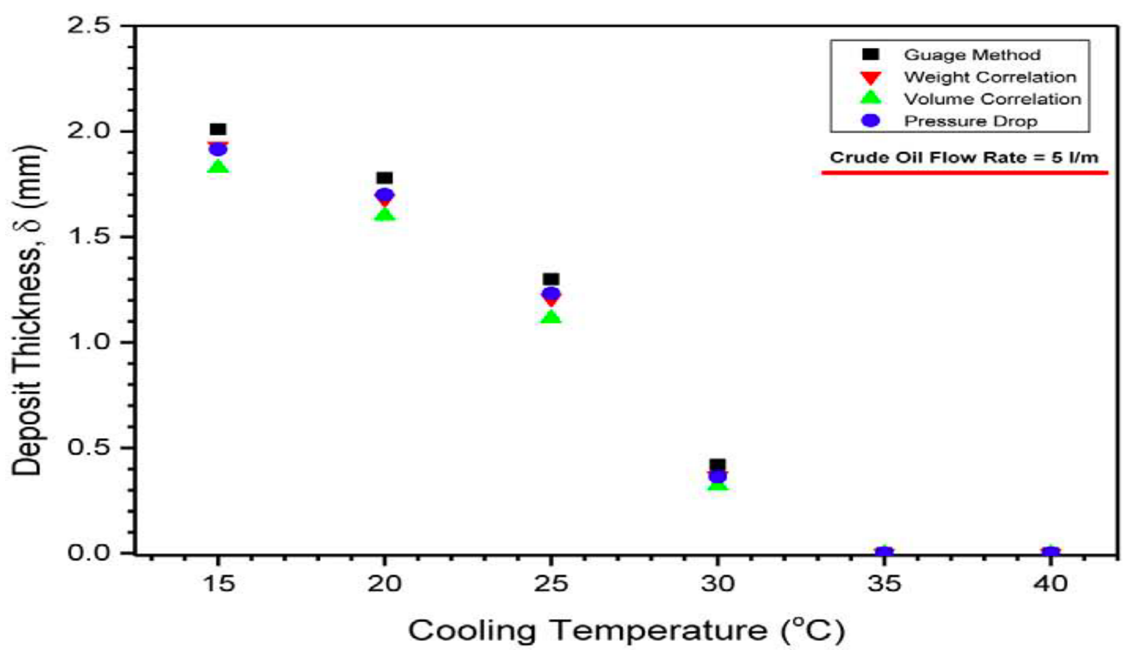

Figure 4: Effect of cooling temperature (15, 20, 25, 30, 35 and 40°C) on wax deposition at a constant flowrate of 5 l/min.

Below WAT, the crude oil experiences a gel transition, therefore, wax deposition thicknesses are observed to be lower at relatively higher cooling temperature at a low flow rate (e.g., at 30°C and 5 l/m, $\delta_{wax} \approx$ 0.4mm). It is observed that above the WAT, both the laminar (5 l/m) (Figure 3a) and the turbulent (9 l/m) (Figure 5) flow produces zero wax

On the other hand, Figure 7 demonstrated that maintaining the crude oil flow at high cooling rate particularly at above or equal to WAT could lower the severity of the deposition. Therefore, as seen in Figure 7 the flow rate was varied from 2 to 11 l/min and at constant cooling temperature of 30°C. The results showed that there is no-wax deposition ($\delta_{wax} \approx 0mm$) at 9 and 11 l/min (tubular flow conditions). However, under laminar condition (e.g., 2 l/min) wax thickness is 2 mm at 15°C and 0.85 mm at 30°C. This implies that at high temperature the solubility of the wax crystals is very high. Whereas, the high flow rate is related to the shear stripping i.e., shear removal effect and short residence time. Researchers, such as Kang et al. (2019) has represented this effect and proved that there are reduction rate of deposit formation caused by shear forces.

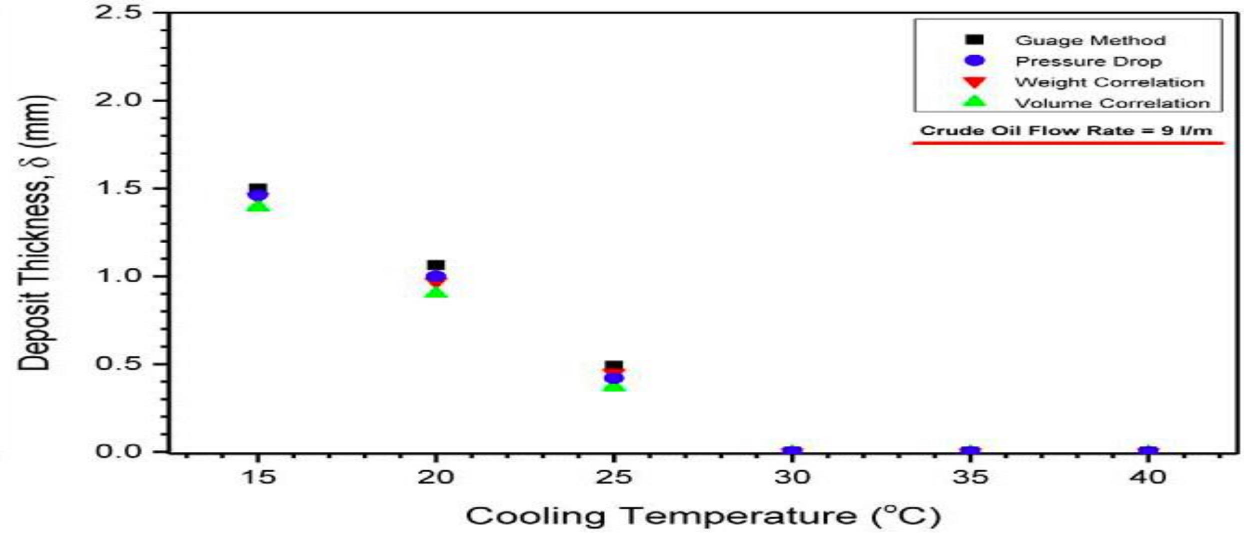

Figure 1: Effect of cooling temperature (15, 20, 25, 30, 35 and 40°C) on wax deposition at a constant flowrate of 9 l/min.

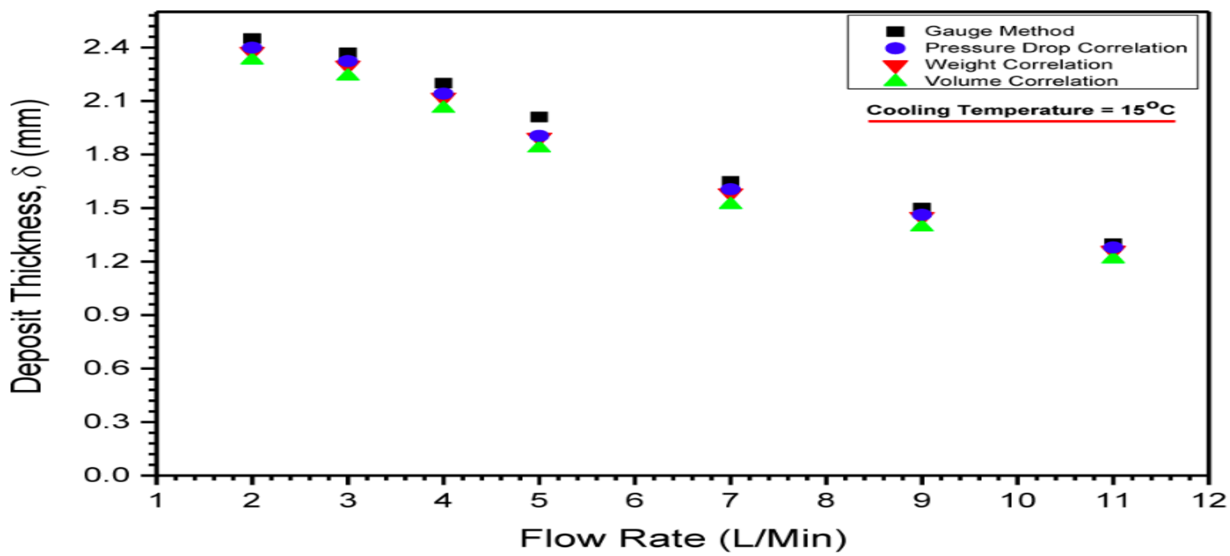

Figure 6: Effect of varied crude oil flow rate on wax deposit thickness at constant cooling temperatures of 15°C.

Table 4: Wax deposition under varied flow rate after 2 hrs at 15°C cooling temperature

Varied Parameter	Average thickness correlation (mm)			
Flow Rate (l/min)	Wet Gauge/ Vernier Calliper	Volume	Weight	Pressure drop
2	2.48	2.31	2.4	2.4
3	2.38	2.29	2.31	2.31
4	2.22	2.00	2.18	2.18
5	2.01	1.87	1.94	1.94
7	1.67	1.60	1.62	1.62
9	1.52	1.47	1.50	1.50
11	1.38	1.28	1.33	1.32

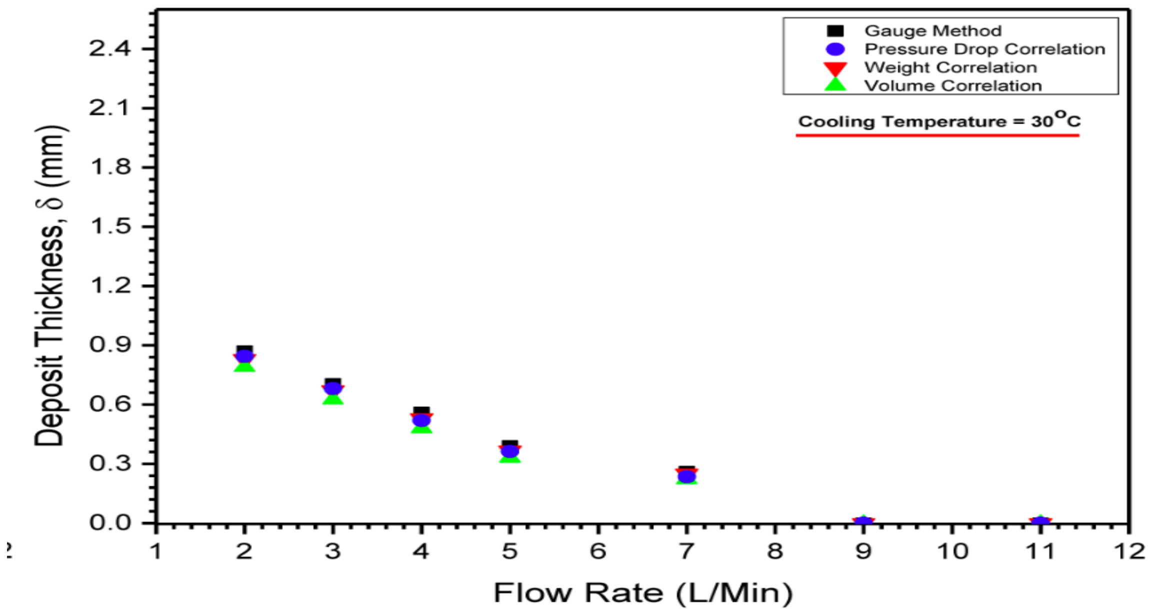

Figure 7: Effect of varied crude oil flow rate on thickness of wax at constant cooling temperatures of 30°C.

Maintaining the crude oil temperature above wax appearance temperature and at a relatively high flow rate provides a safe and uninterrupted production of waxy crude oil (without deposition). Figure 8(a) below shows a cross-sectional view of wax deposited in a pipeline. The deposited wax is measured after 2 hours of ageing and at constant cooling temperature and flow rate of 20°C (below WAT) and 7 l/min (laminar flow) respectively. In comparison, Figure 8(b) shows an empty pipe after pigging operation. The deposition is as a result of non-adherence to the standard operational parameters, such as operating the pipeline outside the WAT envelope. As shown in Figure 3, to avoid wax deposition based on the temperature envelops the oil temperature need to be maintained at 30°C or higher, although depending on the crude oil flow rate.

IV. CONCLUSION

The sample crude oil was successfully characterized and evaluated using both established techniques and modified approaches. Similarly, the waxy crude oil was experimentally studied using a pipeline flow loop, which was designed and fabricated in the laboratory. Following the experimental analysis and theoretical studies, the essential factors necessary for the uninterrupted production of waxy crude oil were addressed, while addressing the uncertainties and complexity associated with the deposition problem. The study revealed the unethical practices that could possibly lead to the deposition of wax molecules in the pipeline. It has been shown that addressing unprofessional behaviours along with improvement in advancement in technologies could prevent

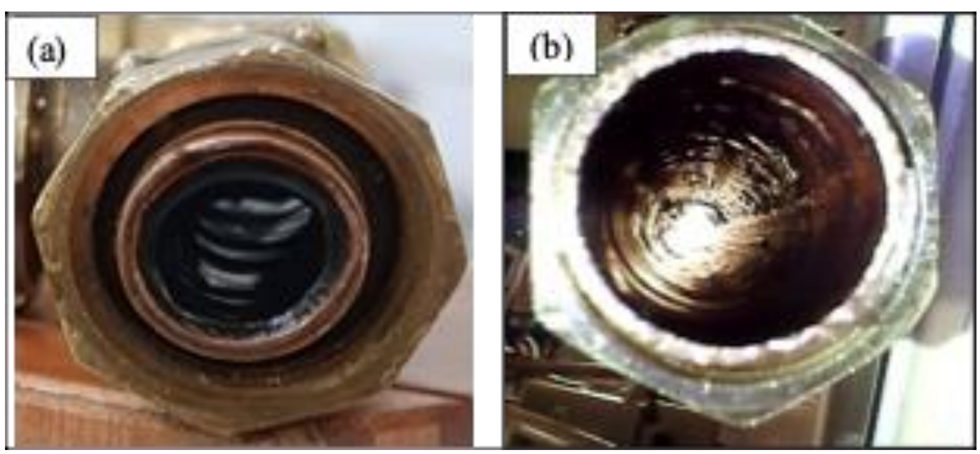

Figure 8: A cross section of the pipeline showing a) Pipe with deposited wax after 2-hour experiment. (b) Empty pipe after pigging operation.

the costly problem of wax crystals in the production system. On the other hand, the laboratory case study has revealed that the standard operating conditions and crude oil properties need to be measured accurately and continuously updated throughout the entire production life cycle.

Not only will this be critical for assisting the flow assurance of waxy crude oil, but it will also significantly enhance the risk assessment of other crude oil fractions and operational problems. Therefore, this works sheds more light on the need for implementation of sound Engineering practices that would provide the best prevention and management strategies for the solid deposit thereby reduces the associated remediation costs.

AUTHOR CONTRIBUTIONS

Nura Makwashi: Conceptualization, Experimentation, Writing the original draft, Review and Editing. **Stephene Akubo**; Writing the original draft, Review and Editing. **Tariq Ahmed**: Review and Editing. All authors have read and agreed to the published version of the manuscript.

ACRONYMS

WAT = wax appearance temperature
PP = Pour Point
SARA = Saturates, Asphaltenes, Rasins and Aromatics
δw = average thickness of the deposited wax
di = inside diameter of the pipe
μ = apparent viscosity of the crude oil for
NRe = Reynolds Number

REFERENCES

Adeyanju, O. and Oyekunle, L. (2013). Experimental Study of Wax Deposition in a Single Phase Sub-Cooled Oil Pipelines, Nigeria Annual International Conference and Exhibition, Lagos, Nigeria. SPE-167515-MS. https://doi.org/10.2118/167515-MS.

Alamri, A. H. (2020). Localized Corrosion and Mitigation Approach of Steel Materials Used in Oil and Gas Pipelines-An overview. Engineering Failure Analysis. 116: 104735.
https://doi.org/10.1016/j.engfailanal.2020.104735

Bai, Y. and Bai, Q. (2005). Wax and Asphaltenes, Subsea Pipelines and Risers. First edit. Great Britain: Elsevier. DOI:10.1016/B978-008044566-3.50023-3.

Chala, G. T.; S. A. Suleiman and A. Japper-Jaafar. (2018). Flow start-up and transportation of waxy crude oil in pipelines-A review, Journal of Non-Newtonian Fluid Mechanics, 69–87. DOI:10.1016/j.jnnfm.2017.11.008.

Chen, X., Z.; W. Wu; R. Kang; X. He and Y. Miao. (2019). Selection of key indicators for reputation loss in oil Chen and gas pipeline failure event. Engineering failure analysis, 99: 69-84.
https://doi.org/10.1016/j.engfailanal.2019.01.071.

Chen, X. T.; T. Butler; M. Volk and J. P. Brill. (1997). Techniques for Measuring Wax Thickness During Sing and Multiphase Flow, SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers. San Antonio, Texas. SPE-38773-MS DOI:10.2118/38773-MS.

Chi, Y.; N. Daraboina and C. Sarica. (2017). Effect of the Flow Field on the Wax Deposition and Performance of Wax Inhibitors: Cold Finger and Flow Loop Testing, Energy and Fuels, 31(5): 4915–4924.
DOI:10.1021/acs.energyfuels.7b00253.

Coto, B.; J. A. Coutinho; P. Martos; C. Robustillo; M. D. Espada and J. L. Peña. (2011). Assessment and improvement of n -paraffin distribution obtained by HTGC to predict accurately crude oil cold properties, Energy and Fuels, 25(3), 1153–1160. DOI:10.1021/ef101642g.

El-Dalatony, M.; B. H. Jeon; E. S. Salama; M. Eraky; W. Kim and T. Ahn. (2019). Occurrence and Characterization of Paraffin Wax Formed in Developing Wells and Pipelines, Energies, 12(6): 967.
DOI:10.3390/en12060967.

Ershaghi, I. (2019). Ethical Issues Facing Engineers in Oil and Gas Operations. Next-Generation Ethics: Engineering a Better Society. Cambridge University Press, 245-257. DOI: https://doi.org/10.1017/9781108616188.017.

Fan, Y. and Llave, F. M. (1996). Chemical Removal of Formation Damage from Paraffin Deposition Part I - Solubility and Dissolution Rate, in: SPE Formation Damage Control Symposium, Lafayette, Louisiana. Society of Petroleum Engineers.

Gao, S. (2008). Investigation of interactions between gas hydrates and several other flow assurance elements, Energy and Fuels, 22(5), 3150–3153. DOI:10.1021/ef800189k.

Hammami, A. and Ratulowski, J. (2007). Precipitation and Deposition of Asphaltenes in Production Systems: A Flow Assurance Overview, Asphaltenes, Heavy Oils, and Petroleomics, 617–660. DOI:10.1007/0-387-68903-6_23.

Harun, A.; A. B. Lah; H. Husin and Z. Hassan. (2016). An overview of wax crystallization, deposition mechanism and effect of temperature & shear, in: ICIMSA 2016 - 2016 3rd International Conference on Industrial Engineering, Management Science and Applications. eju, Korea (South). 10.1109/ICIMSA.2016.7503992.

Hoffmann, R. and Amundsen, L. (2010). Single-phase wax deposition experiments, Energy and Fuels, 24(2), 1069–1080. DOI:10.1021/ef900920x.

Holder, G. A. and Winkler, J. (1965). Crystal-Growth Poisoning of n-Paraffin Wax By Polymeric Additives and its Relevance to Polymer Crystallization Mechanisms, Nature, 207(4998): 719–721. DOI:10.1038/207719a0.

Huang, Z.; S. Zheng and H. Fogler. (2015). Wax Deposition: Experimental Characterizations, Theoretical Modeling, and Field Practices, CRC Press. DOI:10.1201/b18482.

Kang, P. S.; J. Y. Hwang and J. S. Lim. (2019). Flow Rate Effect on Wax Deposition Behavior in Single-Phase Laminar Flow, Journal of Energy Resources Technology, Transactions of the ASME, 141(3). DOI:10.1115/1.4041525.

Kelland, M. A. (2009). Production chemicals for the oil and gas industry, Production Chemicals for the Oil and Gas Industry. CRC Press. DOI:10.1201/9781420092974.

Kanji, G.K. and Chopra, P.K. (2010). Corporate social responsibility in a global economy. Total Quality Management, 21(2): 119-143.

Macleod, F. and Richardson, S. (2018). Piper Alpha: The Disaster in Detail, the Chemical Engineer. Available from: https://www.thechemicalengineer.com/features/piper-alpha-the-disaster-in-detail/

Makwashi, N. (2020). Investigation of wax depositional behaviour in straight and curved pipes: experiments and simulation (Doctoral dissertation, London South Bank University). https://doi.org/10.18744/lsbu.8v4yv.

Makwashi, N.; D. Zhao; M. Abdulkadir; T. Ahmed and I. Muhammad. (2021). Study on waxy crudes characterisation and chemical inhibitor assessment, Journal of Petroleum Science and Engineering, 204:108734. DOI:10.1016/j.petrol.2021.108734.

Makwashi, N.; K. Sarkodie; S. Akubo; D. Zhao and P. Diaz. (2019). Investigation of the severity of wax deposition in bend pipes under subcooled pipelines conditions, in: Society of Petroleum Engineers - SPE Europec Featured at 81st EAGE Conference and Exhibition 2019. Society of Petroleum Engineers

Malins, D. C. (1977). Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms Vol. 1, Nature and Fate of Petroleum., Academic Press, New York. 24– 5.

Mitcham, C. (2020). The Ethics of Technology: From Thinking Big to Small—and Big Again, Axiomathes 30: 589–596. DOI: https://doi.org/10.1007/s10516-020-09505-8.

Ndimele, P. E.; A. O. Saba; D. O. Ojo; C. C. Ndimele; M. A. Anetekhai and E. S. Erondu. (2018). Remediation of crude oil spillage. In the Political Ecology of Oil and Gas Activities in the Nigerian Aquatic Ecosystem, Academic Press. 369–384.

Paso, K.; M. Senra; Y. Yi; A. M. Sastry and H. S. Fogler. (2005). Paraffin polydispersity facilitates mechanical gelation, Industrial and Engineering Chemistry Research, 44 (18), 7242–7254. DOI:10.1021/ie050325u.

Paso, K.G. (2014). Comprehensive treatise on shut-in and restart of waxy oil pipelines. J. Dispersion Sci. Technol. 35(8), 1060–1085. https://doi.org/10.1080/ 01932691.2013.833105.

Pedersen, K. S. and Rønningsen, H. P. (2003). Influence of wax inhibitors on wax appearance temperature, pour point, and viscosity of waxy crude oils, Energy and Fuels, 17(2), 321–328. DOI:10.1021/ef020142+.

Perez, P. E.; K. Boden; A. K. Chichak; L. Gurnon; Hu and J. Lee. (2015). Evaluation of Paraffin Wax Inhibitors: An Experimental Comparison of Bench-Top Test Results and Small-Scale Deposition Rigs for Model Waxy Oils, Offshore Technology Conference, Proceedings, Houston, Texas, USA. 4–7. DOI:10.4043/25927-MS.

Ershaghi, I., M.A. Ershaghi and A., Popa. (2018). April. Data ethics in oil and gas operations. In SPE Western Regional Meeting. Society of Petroleum Engineers.

Rashidi, M.; B. Mombekov and M. Marhamati. (2016) A Study of a Novel Inter Pipe Coating Material for Paraffin Wax Deposition Control and Comparison of the Results with Current Mitigation Technique in Oil and Gas Industry, Offshore Technology Conference, OTC-26695-MS. Society of Petroleum Engineers.

Rittirong, A.; E. Panacharoensawad and C. Sarica. (2017). Experimental study of paraffin deposition under two-phase gas/oil slug flow in horizontal pipes, in: SPE Production and Operations.32: 99–117.

Shahriar, A.; R. Sadiq and S. Tesfamariam. (2012). Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis, Journal of Loss Prevention in the Process Industries, 25(3): 505- 523.

Sharma, R.; N. S. Singh; N. Dhingra and T. Parween. (2020). Bioremediation of Oil-Spills from ShoreLine Environment. In Modern Age Waste-Water Problems, Springer, Cham, 275–291.

Sifferman, T. R. (1979). Flow Properties of Difficult-to-Handle Waxy Crude Oils., JPT, Journal of Petroleum Technology, 31(8), 1042–1050. DOI:10.2118/7409-PA.

Singh, P.; R. Venkatesan; H. S. Fogler and N. Nagarajan. (2000). Formation and aging of incipient thin film wax-oil gels, AIChE Journal, 46(5): 1059–1074. DOI:10.1002/aic.690460517.

Soedarmo, A. A.; N. Daraboina and C. Sarica. (2017). Validation of wax deposition models with recent laboratory scale flow loop experimental data, Journal of Petroleum Science and Engineering, 149. DOI: 10.1016/j.petrol.2016.10.017.

Theyab, M. A. and Diaz, P. (2016). Experimental study of wax deposition in pipeline – effect of inhibitor and spiral flow, International Journal of Smart Grid and Clean Energy, 9(357), 174–181. DOI:10.12720/sgce.5.3.174-181.

Wang, J. F.; L. Zhou; Y. Zhang; E. Huang; L. Yao; F. Zhang; F. Wang and F. Fan. (2019). Experimental study of wax deposition pattern concerning deep condensate gas in Bozi block of Tarim Oilfield and its application, Thermochimica Acta, 671 (2018): 1–9. DOI:10.1016/j.tca.2018.10.024.

Wang. W. and Huang. Q. (2014). Prediction for wax deposition in oil pipelines validated by field pigging, Journal of the Energy Institute, 87(3): 196–207. DOI:10.1016/j.joei.2014.03.013.

White, M.; K. Pierce and T. Acharya. (2018). A review of wax-formation/mitigation technologies in the petroleum industry. SPE Production & Operations, 33(03): 476-485. https://doi.org/10.2118/189447-PA