Chapter

Challenges during Operation and Shutdown of Waxy Crude Pipelines

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Abstract

Transportation of waxy crude oil faces great challenges due to shear and temperature dependency. At high temperatures, waxy crude exhibits low viscous Newtonian behavior where the resistance to flow due to friction is low, and hence low pumping pressure is required to transport it. At low temperatures, however, the crude exhibits shear thinning non-Newtonian behavior where its apparent viscosity becomes shear-dependent. In such cases, the operated pipeline needs to maintain a high pressure to guarantee a continuous flow. Moreover, due to heat transfer between the internal pipeline and surroundings, oil temperature declines along the pipeline. It follows that the crude viscosity and, hence, frictional resistance increase. If the flow is interrupted for any reason, i.e., emergency or planned shutdown, then the restartability of the pipeline becomes a challenge because of the nonexistence of heating generated from friction. In this chapter, the challenges normally facing transportation of waxy crude oil will be discussed. The chapter will introduce the rheological properties of waxy crude oil and explain and describe how these properties can affect the pressure losses inside the pipeline during its operation and shutdown. The measures that need to be considered when designing a waxy crude pipeline will be discussed.

Keywords: waxy crude, rheology, pipeline, oil transportation

1. Introduction

Flow assurance is one of the major technical challenges in oil and gas production operations. The formation of gas hydrate, wax, halite, asphaltenes, mineral scales, and naphthenic acids can all result in serious operational and economic concerns. The industry needs novel and innovative techniques to reduce the costs associated with flow assurance and to improve the overall operation performance. Nowadays, with the decrease in conventional oil reserves, oil companies are improving unconventional oil fields where the reserved hydrocarbons are heavy and possess complex properties. The most important consequence of these ultraheavy hydrocarbons is that they hinder the flow through different production and transportation systems. In particular, for oil transportation through pipelines, we have to consider the complexity of the fluid rheology as an important factor that needs to be fully controlled in order to generate a smooth transportation.

The crude oil that possesses a high amount of wax, known as waxy crude oil, can cause many operational obstacles during production, storage, and transportation. It is considered that the most important obstacle is the crystallization and sedimentation of wax in the crude oil in the pipes during transportation. While waxy crude oil is flowing through the pipeline, and due to continuous cooling of the oil caused by heat transfer toward surroundings, crystals of wax form and grow in size to form partial to total blockage of the pipe cross-sectional area. This process continues with shutdown time, and farther the distance from the pipeline inlet, the faster is the wax deposition on the pipe internal wall and the higher tendency of the wax crystals to enlarge in size. This results in a continuous decrease in the pipe internal diameter, and, as the frictional loss is inversely proportional to the pipe diameter, higher frictional pressure loss will occur. Because of that, the pumping pressure needs to be increased in order to preserve the desired flow rate. However, knowing the mobility of the flow is an important issue for effective and frugal process of a pipeline framework. The main concern of waxy crude oil is the stream restart after delay in planned or emergency shutting down of the flow process for any reason.

Wax precipitation and deposition also contribute significantly in changing the original rheology of the oil. While wax crystals are precipitated and deposited, viscosity of the crude oil rises to convert it to a high viscous fluid that adhered to the internal pipe wall to decrease the effective cross-sectional area of the pipe. A solution to this issue can be achieved by applying various methods to lower the viscosity and pour point. The most common methods extensively implemented are heating of the transported crude, dilution with lighter fluid, and adding chemical additives, known as flow improvers/modifiers, to the flow stream. Each one of the three methods has its own advantages and disadvantages; however, generally speaking, chemical additives stay the most commonly recognized solution as compared to the other choices.

Usually the waxy crude oil is pumped at temperatures above its wax appearing temperature (WAT) in order to prevent forming of wax on the wall of the pipes. The pressure pumped should be high enough to hold the stability of the fluid. When temperature gets lower due to heat transfer, the crude becomes more viscous. And if the temperature lowers enough to initiate wax deposition, then there will be a double effect that results in higher frictional pressure, viz., higher viscosity and smaller pipe diameter.

1.1 Definition of waxy crude oil

Waxy crude oil can be defined as the crude oil that contains high amount of long-chain paraffin wax (alkanes) components, making the crude to possess a high pour point and, may be, a low API gravity. A waxy crude oil is distinguished by the fact that it exhibits non-Newtonian rheological behavior at low range of temperature (i.e., about 20 F above the pour point). For such non-Newtonian behaved crude oils, the effective viscosity is not only temperature dependent but also a function of the effective rate of shear in the pipeline. At reservoir conditions, due to high pressure and temperature, wax molecules are normally dissolved in the crude oil to form a single continuous hydrocarbon liquid phase. While flowing through pipelines, especially in sub-sea environments, due to cooling down, wax crystals may start to precipitate from this continuous phase, and eventually the fluid may lose its liquidity behavior. This change of flow behavior normally starts to occur when the crude temperature becomes lower than its cloud point or WAT [1].

1.2 Wax chemical compound formation and properties

The wax existing in crude oil mostly contains paraffin hydrocarbon (C18-C36) recognized as paraffin wax and naphthenic hydrocarbon (C30-C60). The hydrocarbon element of wax is able to present in several phases, i.e., gas, liquid, and particles (solids), relying on the flow conditions, i.e., pressure and temperature. When the temperature of wax decreases, the agglomerates and the wax crystals from paraffin wax are recognized as microcrystalline or naphthenic hydrocarbon [2]. Chemical flow modifiers can be used to enhance the crude flowability at flow conditions where crystallization or gelling is expected. These flow modifiers can delay the crude crystallization by reducing its pour point and viscosity. According to [3], the temperature of the waxy crude oil at the time of injecting the chemical additives is an important factor to determine their efficiency. If the temperature is very low, surely some amount of wax will be formed, and this accumulated wax will affect the rendering of chemicals. It has been observed that a high molecular weight wax chemical flow modifier has better performance for lowering waxy crude pour point. The crystal growth development rate of the lower-molecular-weight wax inhibitor is much slower than that of the higher molecular weight wax inhibitor.

1.3 Wax appearance temperature or cloud point

Wax appearance temperature is the temperature below which wax starts to appear in a waxy crude liquid. When a heated waxy crude is cooled down to a temperature lower than WAT, the wax molecules form clusters of aligned chains. Once these nuclei reach a critical size, they become stable, and further attachment of molecules leads to growth of the crystal. Formation of these nuclei causes the fluid to take on a cloudy appearance, hence the name cloud point. This also is referred to as the wax crystallization temperature or WAT. If the WAT of a produced or transported waxy crude oil is found significantly higher than the temperatures expected to be encountered during production or transportation, then wax deposition problems should be expected, and precaution measures are to be taken to avoid the problem and lessen the consequences arisen from.

1.4 Factors controlling wax deposition

Wax deposition along the pipeline is affected by several factors that include temperature, pressure, wax molecular weight, and the other crude oil components. For a proper design, operation, and optimization of a waxy crude production and transportation system, the effect of each of these factors is to be investigated carefully following documented experimental procedures and standards.

Wax deposition onto the production system generally requires a nucleating agent, such as asphaltenes and inorganic solids. The wax deposits vary in consistency from a soft mush to a hard brittle material. Paraffin deposits will be harder if longer-chain n-paraffin is present. Paraffin deposits can also contain other materials such as asphaltenes, resins, gums, fine sand, silt, clays, salt, and water. High-molecular-weight waxes can deposit even in the higher-temperature sections of a well, while lower-molecular-weight fractions tend to deposit in lower-temperature regions. Prior to solidification, the solid wax crystals in the liquid oil change the flow properties from a Newtonian low viscosity fluid to a high viscous non-Newtonian shear-dependent fluid. With further temperature reduction, the oil may eventually turn into a very-complex-flow behavior gel with yield stress (i.e., becomes yield-pseudoplastic or yield-plastic non-Newtonian fluid). Regardless of the rheological behavior the oil is exhibiting, oil viscosity is always inversely proportional to the oil temperature. As the temperature of oil increases, the oil viscosity decreases and vice versa.

The wax solubility is also directly proportional to process temperature. According to Sadeghazad and Christiansen [4], when water is present in the crude, wax deposition tends to reduce. This is because the water decreases the oil's temperature drop keeping the solution above the pour point temperature. They stated that water is able to maintain the oil temperature because oil has only half the specific heat as compared to that of water.

The second factor that affects the wax deposition is the pressure. The wax present in oil has a positive divergence, i.e., the solubility of the wax present in the solution decreases with the increase in applied pressure. This is because of the intermolecular forces between molecules [4].

The third factor controlling wax deposition is the wax molecular weight. The higher the molecular weight of the wax, the lesser its solubility because of its melting point increasing with the increase in the molecular weight [4, 5]. Al-Shafey and his co-workers stated that the solution composition greatly affects the wax deposition as well [6]. A set of experiments conducted by Sadeghazad and Christiansen reveals that the cloud point decreases for a wax solution with a lighter composition, i.e., it would take longer time for the wax to deposit [4].

1.5 Wax deposition mechanism

The problem of paraffin wax may be described as a situation in which a predominantly organic deposit hampers the production of crude oil. The loss of the crude production from a well depends on the severity and location of the deposition. In a pioneering work, Burger and others [7] investigated four wax deposition mechanisms, namely, molecular diffusion of wax molecules, shear dispersion of wax crystallites, Brownian diffusion of wax crystallites, and gravity settling. Gravity settling of paraffin crystals in flow line conditions is negligible, because it's dominated by shear dispersion. These four wax deposition mechanisms are discussed in the following subsections:

1.5.1 Molecular diffusion

Molecular diffusion is the deposition mechanism prevalent in well tubing. To avoid the deposition in flowing well, the flowing oil temperature needs to be maintained above the cloud point throughout the flow journey until the oil reaches the wellhead [8, 9]. Deposition is enhanced as a result of radial heat transfer from the tubing core toward the surroundings. Due to wax deposition, a concentration gradient is formed in the oil as a result of temperature gradient profile, due to increasing solubility of waxes with increasing temperature. The concentration difference causes waxes in the solution to diffuse from the warmer oil, which has a greater concentration of dissolved waxes, to the colder oil, which has a lower concentration, resulting in molecular diffusion of the paraffin crystals toward the surface wall. The wax concentration gradient is triggered as the differential temperature at a cross section causes the particles near to the cold walls to start the deposition from the oil solution and develop an initial layer of deposit [10]. As the layer is deposited, a concentration gradient occurs between the bulk fluid and the wall causing more wax to be trapped and oil flowing through the wax as a porous media away from the wall, thus thickening the wax concentration. This mechanism is the common mechanism observed for wax deposition.

1.5.2 Shear dispersion

At low temperatures, shear dispersion is believed to be the most occurring mechanism. It deals most with particles that are settling on the surface of a cold pipe due to the grooved or rough surface as well as the intermolecular forces [11]. Yet it was concluded that the shear dispersion is not significant based on field operating experience as well as experimental investigations.

When wax particles are moving along while transporting oil through a pipeline on an average speed, shear dispersion occurs as a shearing effect near the wall. The speed of the flowing fluid is less near the wall due to the shearing and friction causing a shear dispersion. Thus the crystalized precipitates move toward the wall due to its higher weight and away from the turbulent flow of the crude. Once reaching the wall, such precipitates form an initial layer of deposition or get trapped in the matrix made by the molecular diffusion caused earlier [12]. Shear dispersion is most effective when the temperature of the turbulent flow is below the WAT, thus causing high wax precipitation. A shear dispersion coefficient expressed by Burger and his co-workers [7] is:

$$D_s = \frac{a^2 \gamma C_w^*}{10} \tag{1}$$

where D_s is the shear dispersion coefficient (m^2/s); a is the particle diameter, m; C_w is the wax volume fraction concentration excluding the wall, fraction; and γ is the oil shear rate on the wall, s^{-1}.

1.5.3 Brownian diffusion

When tiny solid crystals are suspended within the oil, they collide frequently with thermally vibrant molecules. Due to such collision, a Brownian movement is initiated. At a concentration differential of these particles, the motion will cause diffusion. Coefficient of the Brownian diffusion is expressed as:

$$D_b = \frac{RT}{6\pi\mu a N} \tag{2}$$

where R is the gas constant (J/mol.K); Ta is the absolute temperature (K); U is the viscosity (Pa.s); a is the particle diameter (μm); and N is the Avogadro's number (mol).

Yet as referred by Burger et al. [7], the Brownian diffusion can be ignored.

1.5.4 Gravity settling

As the waxy crystals are denser than the oil particles, they tend to settle down and deposit. However, according to some results, it is believed that the gravitational deposition is insignificant toward the wax deposition. The turbulent flow or the shear dispersion would disperse the settling particles thus eliminating the gravity settling.

1.6 Waxy crude rheology

The most commonly used parameter to describe fluids' rheology is the viscosity, defined as the amount of resistance exhibited by the fluid to start the deformation process once shear stress is applied. As the waxes are precipitating, the fluid changes into a non-Newtonian fluid. This generally occurs when the process temperature decreases below the WAT [13]. Moreover, the waxy crude oils possess high yield stresses when the temperature further declines to values below the pour-point temperature. When the temperature is lower than the pour-point temperature, the oil loses its total mobility and turns into a gel-like structure that would require critical value of stress to flow, known as yield stress value of the gel. At low temperatures (below WAT), waxy crude oils generally exhibit non-Newtonian flow behavior (namely, pseudoplastic fluids). The main feature of the pseudoplastic non-Newtonian fluid is the dependency of viscosity on shear rate (while it is constant for Newtonian fluids). **Figure 1** shows typical flow curves of fluids exhibiting different types of rheological behavior as proposed by Wardhaugh and others [3]. The upper curve (a) shows the variation of applied shear stress and shear rate as measured by a viscometer. The lower curve (b) shows the variation of fluid viscosity with shear rate. It is clear that the viscosity of Newtonian fluid is independent of shear rate, while the viscosity of non-Newtonian fluids decreases with increasing shear rate. Viscosity is the amount of resistance exhibited by the fluid to start the deformation process once shear stress is applied. Different correlations are used to derive viscosity as per the case. The value of viscosity of crude oil depends on many factors including the composition of oil, temperature, amount of gas dissolved, and pressure or stress. The viscosity can be calculated as the ratio of shear stress (Pa) to shear rate (s^{-1}); hence, the SI unit of viscosity is Pa·s.

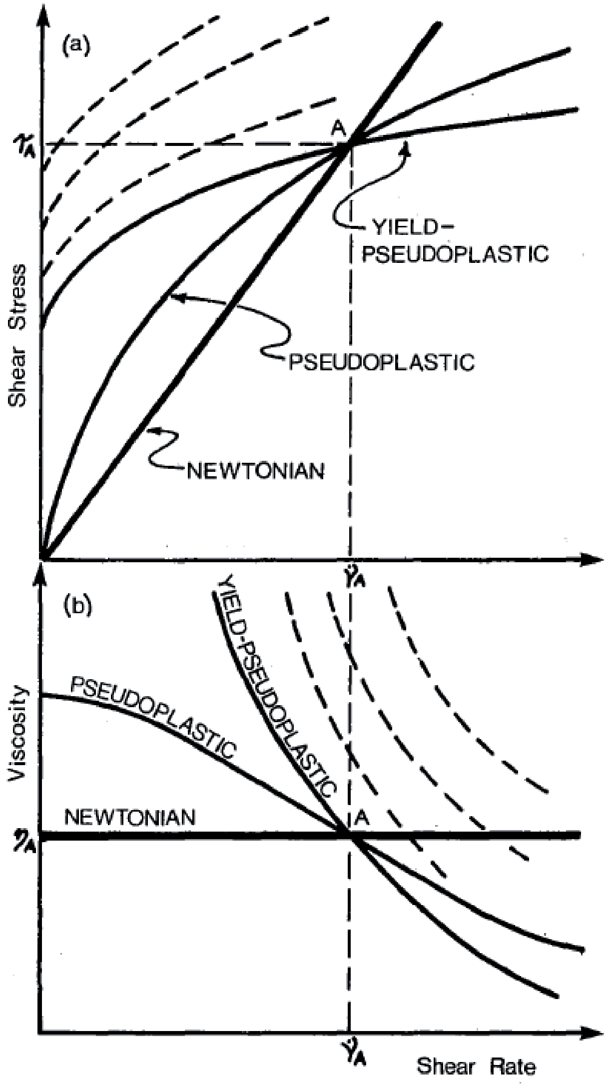

Figure 1.
Typical flow curves of fluids exhibiting different types of rheological behaviors [3].

As the fluid flows through a pipeline, it starts a deformation due to the slippage action occurring. Shear stress is a force that is acting parallel to the flow propagation of the fluid. The main cause of the shear stress is the friction exerted between the particles, which is proportionally related to the viscosity of the fluid. Mathematically, the shear stress is the force applied on a surface divided by the surface area, i.e., $\tau = \frac{F}{A}$, where τ is the shear stress in N/m^2 (or Pascal), F is the applied force in N, and A is the cross-sectional area of the fluid parallel to the applied force in m^2.

The shear rate is the rate at which the deformation caused by the shear stress is taking place. In Newtonian fluids, the shear rate increases as the flow rate increases. As in the case of flow through pipelines, the shear rate is the gradient of change in velocity across the radius of the pipe assuming that the top and bottom flows are not in similar velocities. Assuming two parallel plates with one moving while the other is stationary, the shear rate can be defined as $\frac{v1 - v2}{h}$ where $v1$ is the velocity at the top plane, $v2$ is the velocity at the bottom plane, and h is the gap between the plates. This radial velocity and shear distribution are similar to what happens during oil flow through pipelines. While flow velocity is constant along the pipeline (since the pipe diameter is constant), there is a radial velocity variation along the cross-sectional area due to the effect of shear. At the pipe wall, where the shear stress is maximum, velocity is zero, whereas the maximum velocity occurs at the center of the pipe. **Figure 2** shows an example of the radial velocity distribution at three values of flow rates [3], where A is the highest flow rate and C is the lowest flow rate as indicated by radial velocity distribution showing a turbulent flow and laminar flow, respectively.

1.7 Transportation of waxy crude through pipelines

Significant percentage of pipelines worldwide transport waxy crude oils with different amounts of wax contents and, hence, wide range of rheology complexity. In China, for instance, more than 80% of the produced oils are classified as waxy crude [14] with total annual production of over 100 million tons and total annual storage of more than 70 million tons [15]. Worldwide, half of the recoverable oil reserve is classified as heavy crude [16] with the waxy crude contributing about 20% to the total hydrocarbons reserve [17]. There was a noticeable increase in the production of waxy crude recently. The daily total production rate worldwide has increased from 1 million BOPD in 1960 to almost 24 folds (contributing to one third of the total world oil production) in 2009 [1].

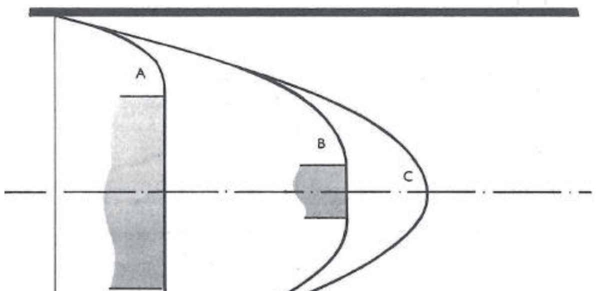

Figure 2.
Radial velocity distribution in the pipeline at three values of flow rate ($V_A > V_B > V_C$) *[3].*

Since pipelines are the main transportation methods of waxy crude oils, proper precautions and measures should be adopted to ensure a safe and smooth flow at various operating conditions. For long-distance pipelines, in particular, the temperature variation along the pipeline causes axial change of the rheological behavior which results in complexity of prediction of pressure losses at different segments along the pipeline.

Two cases need to be considered of a waxy crude pipeline, operating conditions and shutdown conditions.

2. Waxy crude pipeline operations

During operation, the flow of the transported waxy crude tends to facilitate the pipeline operation due to continuous shear of the fluid, from one hand, and the heat generation due to friction, from the other hand. The former causes reduction of the crude viscosity, which results in the decreasing of the generated frictional pressure losses, and hence, less pumping pressure is required. The latter adds a significant heating to the transported fluid, which can compensate part of the heat losses resulting from the heat transfer due to temperature difference between

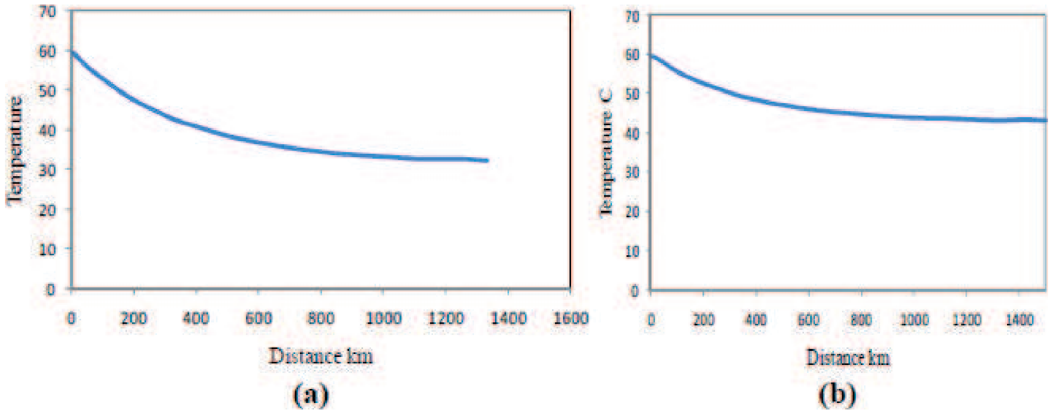

Figure 3.
Temperature distributions along Higleig-Portsudan pipeline (inlet temperature 60°C and flow rate 0.33 m³/s) [18].

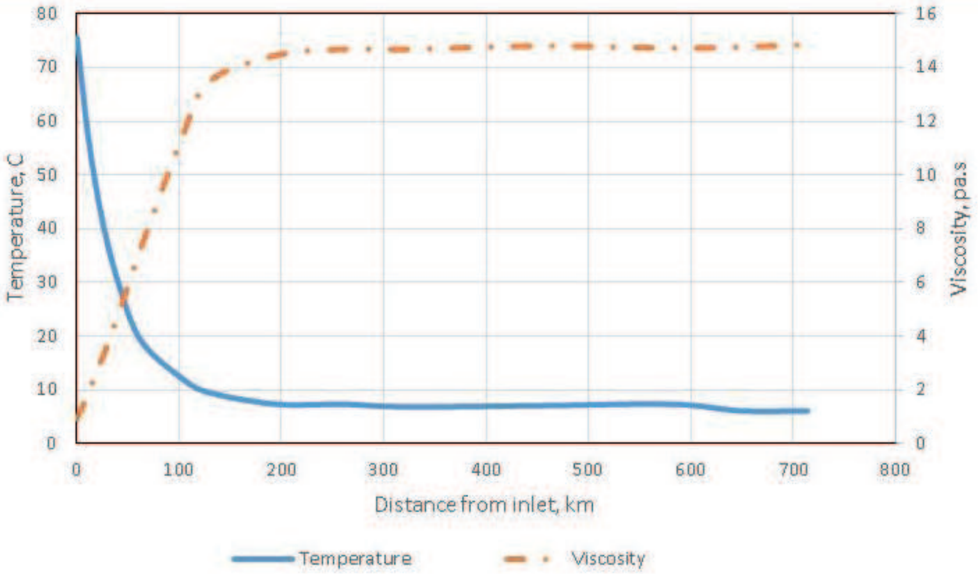

Figure 4.
Variation of temperature and viscosity along pipelines [19].

the fluid and surroundings. As a result, the temperature along the pipeline can be maintained to be always above the WAT. **Figure 3** is an example of temperature distribution along the Sudanese Higleig-Portsudan pipeline assuming two values of soil temperature [18]. The figure indicates that the shear action due to flow can maintain the temperature and delay the distance at which the temperature falls down to surrounding (soil) temperature. This distance is directly proportional to the fluid flow rate.

Figure 4 shows a typical variation of temperature and viscosity along a waxy crude pipeline [19]. As we go far from the inlet, temperature declines due to heat transfer between the fluid and the pipeline surroundings. The temperature

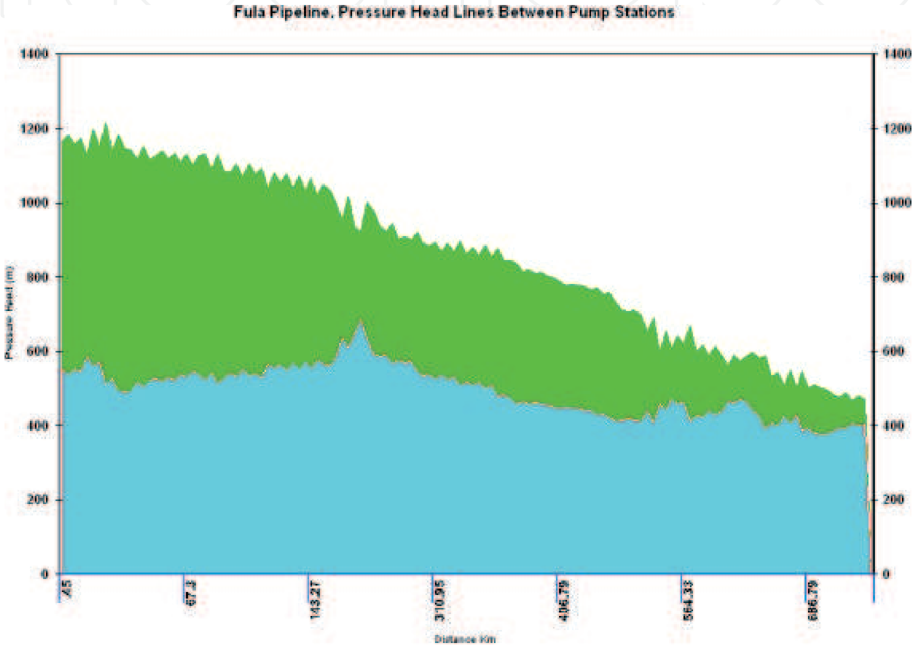

Figure 5.
Fula pipeline profile and pressure transverse between initial and terminal pump stations [20].

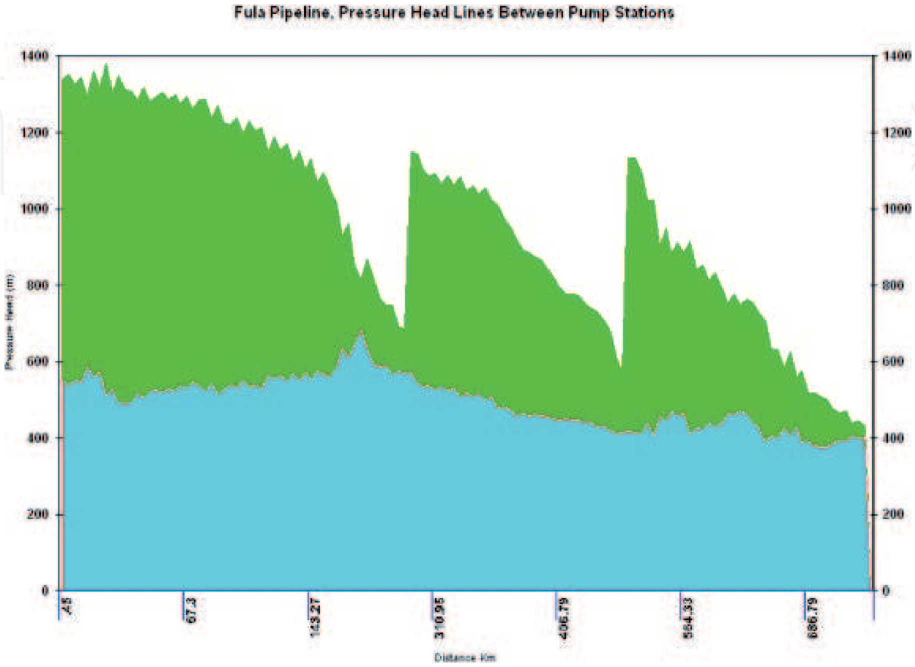

Figure 6.
Fula pipeline profile and pressure transverse between pump stations (3 pump stations) [20].

reduction leads to increase in viscosity, which eventually results in increase in frictional pressure loss per unit of length. The trend of the variation of pressure loss per kilometer length follows the same trend of viscosity variation.

To maintain a smooth operation of the pipeline, the total pressure losses due to elevation difference and friction (which is highly affected by the crude rheology) needs to be balanced by operating one or more pump stations. To facilitate the crude pumping, the crude rheology can be enhanced by heating or injection of chemical flow modifiers. **Figures 5** and **6** show the pressure traverse between pump stations of another Sudanese pipeline (Fula pipeline) assuming one and three pump stations, respectively [20]. The figures indicate that the inlet pumping pressure gradually declines along the pipeline to reach the next pump station at a specific terminal pressure, which may serve as a suction pressure to the successive pump station. This pressure profile is affected by flow rheology and wax precipitation inside the pipeline both of which are highly temperature dependent.

3. Waxy crude pipeline shutdown and restarting

Unlike operating pipelines, when a pipeline undergoes a planned or emergency shutdown, it loses the positive effects of shearing and heat generation due to continuous flow. The temperature declines steadily from the moment of shutdown until the time at which the temperature at all points along the pipeline reaches the surrounding temperature, which may or may not be above the WAT. Accordingly, the crude oil inside the pipeline exhibits a specific rheological behavior throughout the pipeline length. If the surrounding temperature is significantly higher than the WAT, the crude oil will exhibit a Newtonian flow behavior, where it can easily be restarted after the shutdown period. However, if the surrounding temperature is less than the WAT, then the fluid will exhibit a non-Newtonian behavior, and high restarting pressure is needed. **Figure 7** shows the temperature distribution along Higleig-Portsudan pipeline at the moment of shutdown and after every subsequent 12 h following the shutdown. The figure indicates that the temperature throughout

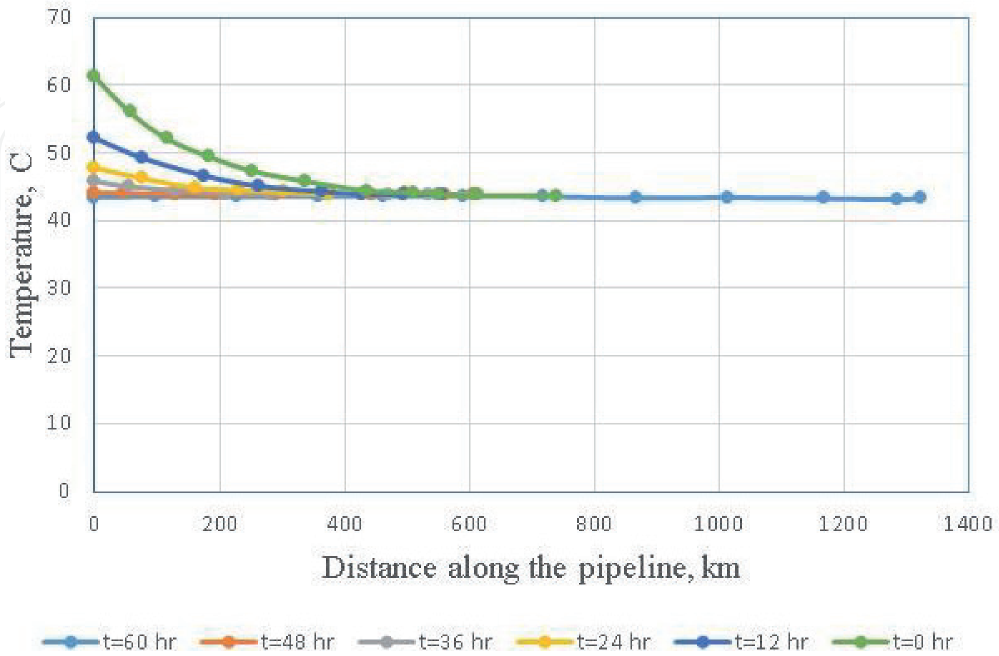

Figure 7.
Transient temperature distribution along the pipeline every 12 h after shutdown (inlet temperature 60°C, soil temperature 42°C, flow rate 0.33 m^3/s) [18].

the pipeline distance reaches the surrounding temperature after 2 days from the shutdown moment.

The most worse shutdown scenario is where the crude temperature drops below pour point and results in the gelling of the crude inside the pipeline. In such complex scenario, the restartability of the pipeline becomes a challenge, and the operator may become unable to restart it. It is, therefore, essential to avoid these complex scenarios by different measures such as heating, chemical additives, dilution of the crude with lighter fluids, and shortening the shutdown periods to ensure that the temperature is always at a value permitting a smooth restarting of the pipeline.

4. Conclusions

Transportation of waxy crude pipeline through pipelines can cause numerous problems that may impose safety, economical, and technical impacts on the pipeline operation. The severity of waxy crude-related problems is highly affected by the complexity of its rheological properties which in turn depends on the operating conditions (mainly temperature). During waxy crude pipeline operation, temperature declines along the axial length due to heat transfer caused by temperature difference between the transported crude and the surroundings. This temperature decline is concurrently encountered by a raise in temperature caused by heat generation due to friction which is proportionally related to the velocity gradients. This temperature variation along the pipeline causes axial variation in the crude rheological properties which results in variation in frictional pressure losses.

During planned and emergency shutdown of waxy crude pipelines, the problems will get worse due the absence of heat generation. The temperature declines steadily from the moment of shutdown until the time at which the temperature at all points along the pipeline reaches the surrounding temperature, which may or may not be above the WAT. Accordingly, the crude oil inside the pipeline exhibits a specific rheological behavior throughout the pipeline length. The problem may get worse when the surrounding temperature is below the WAT or even below pour point. In such case, the pipeline may need to be assisted by putting on some cost-effective measures to facilitate restarting up of the flow.

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