Journal of Engineering Science and Technology
Vol. 9, No. 4 (2014) 463 - 476

HYDRAULIC BEHAVIOUR OF HIGLEIG-PORTSUDAN PIPELINE AT OPERATION AND SHUTDOWN CONDITIONS

MYSARA EISSA MOHYALDINN

College of Petroleum Engineering and Technology, Sudan University of Science and Technology, Eastern Diem, P. O. Box 73, Khartoum, Sudan
E-mail: mysara12002@yahoo.com

Abstract

Experimental measurements were carried out to correlate rheological properties of Nile blend with temperature within temperature ranges at which Nile blend exhibits Newtonian, non-Newtonian, and solidification behaviours. The developed correlations were used to describe the hydraulic conditions within each kilometre length of the pipeline during operation and the pressure difference required for restarting and flushing every kilometre length of the pipeline after specified shutdown time. Pressure losses within every kilometre length of the pipeline at different flow behaviours during the pipeline operation have been studied and analysed. The required restarting pressure of every kilometre length has also been studied taking into consideration the possibility of crude solidification. The pressure head transverse between every two pump stations and the effect of flow rate on the pipeline overall pressure losses during operating conditions were studied. These results have been obtained using numerical software developed by the author.

Keywords: Nile blend, Hydraulic, Operation, Shutdown.

1. Introduction

The hydraulic calculations of any pipeline transporting crude oil highly depend on the rheological properties of the crude and the thermal conditions of the pipeline. These two factors are interacted, as stated by Szilas [1] "any fluid flow through a pipeline creates a particular amount of heat which changes the original heat condition of the pipeline. The rate at which this heat is generated depends on the rheological properties of the crude and it increases with the viscosity increment". In fact this change in heat condition within the pipeline results in changing the viscosity which in turns affects the hydraulic conditions of the fluid.

Nomenclatures

c	Heat capacity of the fluid J/kg.°C
D	Pipe diameter, m
f	Friction factor
G	Mass flow rate of the fluid, kg/s
hg	Hydraulic gradient
k	Fluid consistency (non-Newtonian behaviour)
K_{tot}	Overall heat transfer coefficient W/m^2.°C
L	Pipeline length, m
n	Flow index (non-Newtonian behaviour)
Re	Reynolds number
Re_M	Reed and Mertzner Reynolds number for non-Newtonian fluids
Re_{Newt}	Reynolds number for Newtonian fluids
T_i	Inlet temperature, °C
T_o	Surrounding temperature, °C
V	Fluid velocity, m/s

Greek Symbols

ΔP_f	Pressure difference (pressure loss) due to friction, Pa
ΔP_y	Restarting pressure, Pa
μ	Viscosity, Pa.s
ρ_f	Fluid density kg/m^3
ρ_{20}	Fluid density at 20°C, kg/m^3
τ_y	Yield stress, Pa

The Sudanese crude Nile blend, which is produced from Higleig oil field and transported through Higleig-PortSudan pipeline, is a high wax content crude oil with high pour point. It contains about 25% (wt/wt) wax, and its pour points for different heating treatment temperatures without chemical additives are in the range of 36°C~31.5°C. At a certain temperature above its pour point, Nile blend behaves as a high viscous pseudo plastic non-Newtonian fluid. Unlike Newtonian fluids whose rheological behavior is described by the linear Newton model containing a single rheological parameter called viscosity and denoted μ, pseudo plastic non-Newtonian fluids are described by the power law model which contains two rheological parameters known as fluid consistency (denoted as k) and flow index (denoted, n) [2].

Due to the non-linearity of the relationship between the rheological properties of non-Newtonian fluids and temperature, hydraulic calculations of pipelines carrying non-Newtonian waxy crudes are very complex. As Nile blend exhibits non-Newtonian behavior within certain temperature range, hydraulic calculations of Higleig-Portsudan pipeline should consider the temperature dependency of all rheological properties whether the crude exhibits Newtonian or non-Newtonian behaviour. At very low temperatures (below pour point) Nile blend may solidify and exhibit gel-like behaviour at such conditions, if the pipeline goes for planned or emergency shutdown the restartability could not be achieved unless the available restarting pressure allows the rupture of the gel like structure. The force required to do so is known as yield stress and denoted as τ_y. The yield stress is related to both temperature and shutdown time.

In this paper, experimental measurements have been carried out to describe the rheological behavior of Nile blend. Rheological models of Nile blend were developed at temperature ranges within which Nile blend exhibits Newtonian, non-Newtonian, and solidified behaviours. These models were then used to simulate pressure transverse between pump stations during the pipeline operation under specified conditions. The models also are used to predict restarting pressure after various shutdown times.

2. Research Methodology

The study of hydraulic behavior of Higlieg-Portsudan pipeline has been achieved in two steps:

• **The first step: experimental measurements**
In this step samples of Nile blend were subject to shear using the viscometer HAAKE VT 150. Different heating treatment temperatures and measurement temperatures have been controlled using a water bath. The heating treatment temperature is a temperature to which the crude is heated before the measurement in order to revert the sample to its original properties (to erase history effect) whereas the measurement temperature is the temperature at which a desired rheological property is measured. In the pipeline large scale, the heating temperature simulates the treatment temperature of the transported crude whereas the measurement temperature simulates the environment surrounding temperature (the soil temperature for buried pipelines).

• **The second step is numerical and computational modeling**
This step is achieved by employing published mathematical models (*Appendix A*) to develop a computational tool. The models used are discussed below.

2.1. Pressure difference

Consider a horizontal pipeline as illustrated in Fig. 1. The minimum pressure difference that makes the fluid flow from the inlet to the outlet of the pipeline must be greater than the resistance force resulting from the friction effect. So to evaluate the flow efficiency of a pipeline that equipped with a specific energy generation units, or to identify the energy consumption by flow, the friction pressure prediction is an essential.

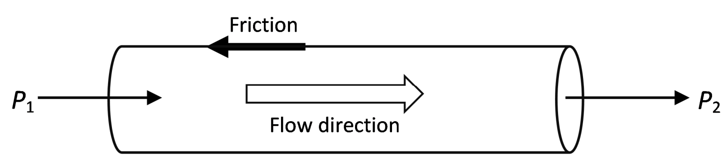


Fig. 1. Direction of Flow and Friction in a Pipe Segment.

The friction pressure can be calculated using the following equation [3]:

$$\Delta P_f = f\,\frac{\rho L V^2}{2d} \tag{1}$$

In case of non-isothermal transportation, both ρ and f in Eq. (1) are temperature-dependent. Different models are used to describe the temperature dependency of density. The model used in this study considers the crude density at 20°C as a reference density to obtain the density at any temperature T [3]:

$$\rho(T) = \rho_{20} - (1.825 - .001315\rho_{20})(T - 20) \tag{2}$$

The friction factor f for different flow regimes (laminar or turbulent) changes with temperature, mainly, due to temperature effects on rheological parameters within which crude behaves as Newtonian or non-Newtonian fluid. All equations that used to calculate the friction factor f depend on the relationship $f = f(\mathrm{Re})$, where Re is the Newtonian Reynolds number or non-Newtonian Reed and Metzner Reynolds number which can be obtained from the following equations:

$$\mathrm{Re}_{(Newt)}(T) = \frac{\rho(T)Dv}{\mu(T)} \tag{3}$$

$$\mathrm{Re}_{M}(T) = \frac{D^{n(T)}v^{-2-n(T)}\rho(T)}{8^{n(T)-1}\left(\dfrac{3n(T)+1}{4n(T)}\right)k(T)} \tag{4}$$

Due to the variation in rheological properties along the pipeline, different points along the pipeline have different Reynolds numbers; accordingly, assuming a constant flow rate, friction factor is obviously varied within Newtonian and non-Newtonian ranges of temperature. Laminar and turbulent regimes have also been considered, and Kemlowski equations were employed for friction factor calculation when crude follow turbulent regime due to high flow velocity [4].

2.2. Hydraulic calculations of Higlieg-Portsudan pipeline during operation condition

The total normal-force-curve slope of nose-cylinder-boattail body is determined by the summation of the normal-force-curve slopes of the nose (with the effect of cylindrical part) and afterbody.

Considering the pressure-temperature dependency, Eq. (1) has been applied to obtain the pressure difference (for each kilometer length) variation along the pipeline.

The hydraulic gradient between two points can be calculated from the following equation:

$$hg = \frac{\Delta P_{1-2}}{\rho g \Delta L} + \frac{\Delta h_{1-2}}{\Delta L} \tag{5}$$

where $\Delta P, \Delta h$, and ΔL are pressure, elevation, and distance difference respectively between point 1 and 2.

Table 1 shows the elevation of every pump station along Higleig-Portsudan pipeline and the distance between the pipeline inlet and every pump station.

Table 1. Sudan Pipeline Pumps Stations Locations and Elevations.

Station No.	Distance (km)	Elevation (m)
PS# 1 (in Higlig)	0	394
PS# 2	236.1	721
PS# 3	576.5	426
PS# 4	817	413
PS# 5	1085.7	377
PS# 6	1313.06	646
Terminal (in port Sudan)	1504.1	9

2.3. Hydraulic calculations of Higlieg-Portsudan pipeline during shutdown condition

Restarting pressure is calculated considering all flow behaviours (Newtonian, non-Newtonian, and solidification) of the crude. The restarting pressure for the solidification-absent condition is simply predicted using Eq. (1) considering the temperature distribution at any time after shutdown, and neglecting the transient pressure resulting from the acoustic wave propagation.

If the pipeline is shutdown for long period of time, the temperature of crude may drop to below the crude solidification temperature. In this case, additional pressure is required to exceed the yield stress before crude flows smoothly.

For solidified pipelines, the restarting pressure, which is equivalent to the yield pressure plus the friction pressure, strongly increases with shutdown time due to the temperature drop. The yield pressure is related to the yield stress by the following equation:

$$\Delta P_y = \frac{4\tau_y(T)\Delta l}{D} \tag{6}$$

3. Results and Discussion

3.1. Experimental results

The solidification point of the crude was found to be 29°C when the crude was preheated to 60°C. The solidification temperature is considered as an approximated value used to distinguish between the Newtonian and non-Newtonian ranges of temperature. If the temperature is 12°C above the solidification point, the crude is assumed to be Newtonian. The heating temperature is a simulated value of the pipeline inlet temperature. Using this value, the experiments result in the following rheological equations

$$\mu(T) = 1\times 10^9 T^{-4.508} \tag{7}$$

$$k(T) = 6\times 10^9 e^{-.4606} \tag{8}$$

$$n(T) = .0022T^2 - .092T + 1.1109 \tag{9}$$

Equations (7), (8), and (9) describe the temperature dependency of viscosity (for Newtonian flow), fluid consistency, and flow index (for non-Newtonian fluid). These equations are utilized to describe the hydraulic conditions along the pipeline

Below the solidification temperature, the crude yield stress is found to be related to temperature as follows:

$$\tau_y(T) = 236.27 - 5.6371T \tag{10}$$

Equation (10) is used to predict restarting pressure of the pipeline after various shutdown times by introducing the yield stress to Eq. (6).

Williams [5] have obtained a linear relationship between the waxy crude yield stress and the time. Their relationship was emphasized by Fig. 2 which is obtained from experimental measurements carried out by the author. The only difference between the two results is that, shorter standing times have been chosen in the present measurements.

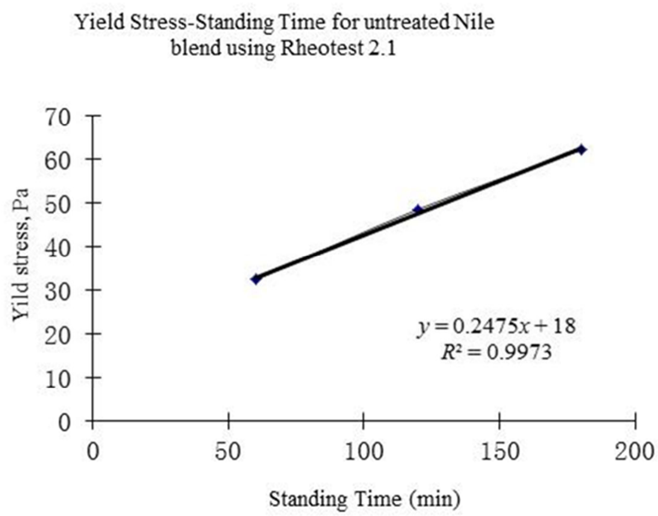


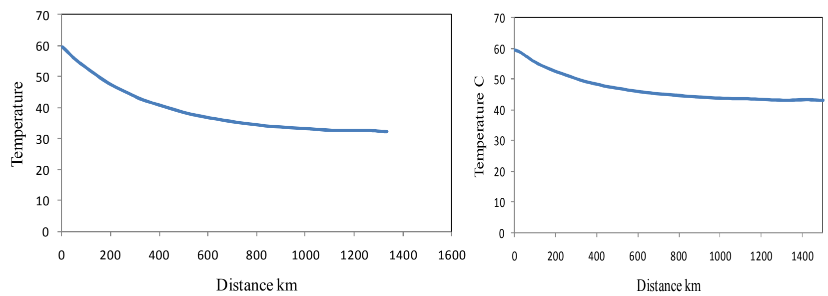
Fig. 2. The Relationship between Yield Strength and Standing Time.

3.2. Numerical results

3.2.1. Operation conditions

Figures 3(a) and (b) show examples of temperature distribution along the pipeline. This distribution is at flow rate of 0.33 m^3/s (equivalent to 180000 bbl/day), inlet temperature 60°C and soil temperature 32°C and 43°C respectively.

Experimental results indicate that the abnormal temperature (the temperature below which the crude flow changes from Newtonian flow to non-Newtonian flow) of Nile blend is 40°C. Figure 3(a) shows that the abnormal temperature is reached at the distance 600 km while Fig. 3(b) shows that the temperature is higher than the abnormal temperature throughout the pipeline length because soil temperature is higher the abnormal temperature.

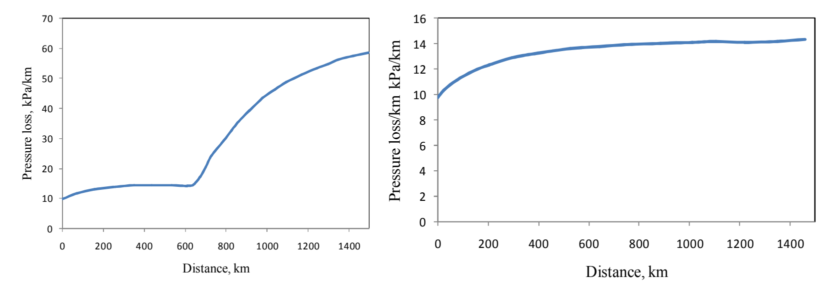


(a) Soil Temperature 32°C. **(b) Soil Temperature 43°C.**

Fig. 3. Temperature Distributions along Higleig-Portsudan Pipeline (Inlet Temperature 60°C and Flow Rate 0.33 m^3/s).

The pressure temperature dependence is illustrated in Figs. 4(a) and (b) in which the distribution of every kilometer pressure difference (pressure loss) is obtained. The boundary between Newtonian and non-Newtonian behavior is illustrated in Fig. 4(a) while Fig. 4(b) indicates that the crude behaves as Newtonian fluid throughout the pipeline length.

Figure 4(a) shows a sudden increase of pressure loss after more than 500 km. This sudden increase of pressure loss is due to temperature declination at this point to the abnormal temperature (as indicated Fig. 3). In other words, from the pipeline inlet to the sudden elevation point the crude behaves as Newtonian, whereas after the sudden elevation point it behaves as non-Newtonian.



(a) Soil Temperature 32°C. **(b) Soil Temperature 43°C.**

Fig. 4. 1-km Pressure Losses Distribution along Higleig-Portsudan Pipeline (Inlet Temperature 60°C and Flow Rate 0.33 m^3/s).

Pressure transverse between every two pump stations is normally illustrated by a straight line with slope equals to the hydraulic gradients between these stations. The pressure difference is the friction pressure of the pipeline segment that joins these two stations.

Figures 5 and 6 illustrate the pressure head transverse between every two pump stations using the same input data that result in Figs. 3 and 4 respectively. In Fig. 5 non-Newtonian flow appeared after 350 km Newtonian flow (as illustrated in Fig. 3), whereas there is no non-Newtonian flow in Fig. 6. The elevation of every pump station has been indicated by writing the station number at its specified location on the pipeline profile.

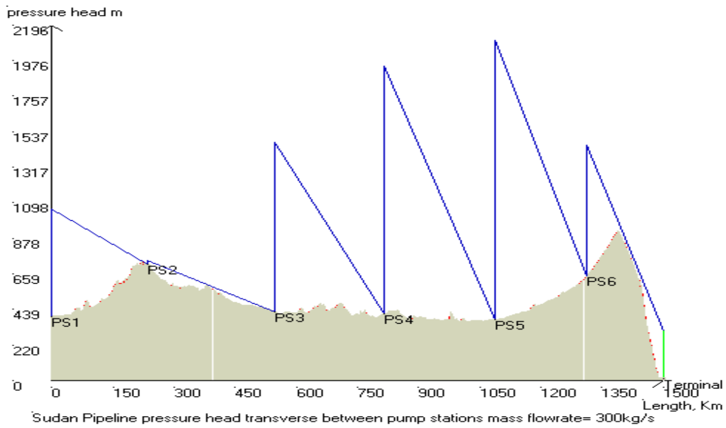


Fig. 5. Pressure Transverse between Pump Stations of Higleig-Portsudan Pipeline (Inlet Temperature 60°C, Soil Temperature 32°C, Flow Rate 0.33 m^3/s).

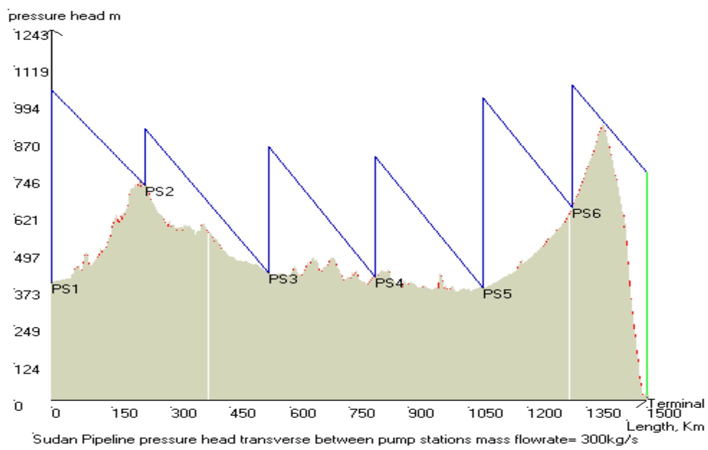


Fig. 6. Pressure Transverse between Pump Stations of Higleig-Portsudan Pipeline (Inlet Temperature 60°C, Soil Temperature 42°C, Flow Rate 0.33 m^3/s).

Effect of flow rate on overall pressure difference (pressure loss)

The effects of flow rate on the overall pressure difference for Nile blend flow were obtained for different soil temperatures as shown in Table 2. The table shows that for mass flow rates of more than 300 kg/s pressure losses highly increase, so very high flow rates are not recommended. If increasing flow rate is a must, measures should be taken to decrease pressure losses. This can be achieved by heating the crude or injecting flow modifiers to decrease viscosity and hence decrease pressure losses.

Table 2. The Overall Pressure Difference Variation with Mass Flow Rate at Different Soil Temperatures.

Soil Temperature °C / Mass Flow Rate kg/s	45	42	35	31
	The pipeline overall pressure drop, kPa			
100	2949	3053	4154.8	9030.7
200	9719.5	10000	13148	29073
300	19373	20001	22390	48521
400	31468.6	32446	23948.5	60573
500	46312.7	47530	143615	144375

3.2.2. Shutdown conditions

Figures 7 to 12 show the temperature and restarting pressure difference distribution along the pipeline every 12 hrs after shutdown. Newtonian, non-Newtonian, and solidified lengths of the pipeline have been indicated by different colored lines. At soil temperature of 42°C which is greatly higher the solidification point, the crude is exhibits Newtonian flow no matter how long the flow is stopped and hence it is easy to restart the pipeline. At soil temperature 32°C the crude initially exhibits Newtonian flow at earlier shutdown times within near distances from the pipeline inlet. For longer shutdown times, the distance within which the crude exhibits Newtonian flow becomes shorter until reach the time when the crude exhibits non-Newtonian for all the length of the pipeline and hence restarting pressure increases. At soil temperature 27°C, which is lower than the solidification temperature, the crude will exhibit non-Newtonian flow few hours after the shutdown and then solidify. In this case, very high restarting pressure is required which may exceed the pump stations capability.

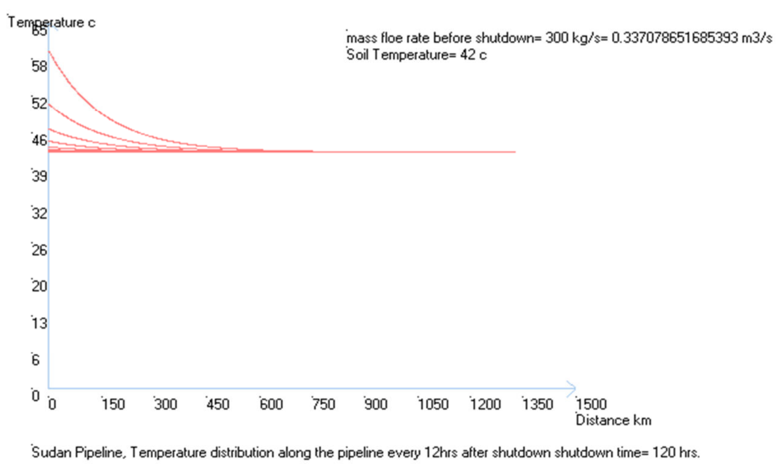


Fig. 7. Transient Temperature Distribution along the Pipeline every 12 Hours after Shutdown. (Inlet Temperature 60°C, Soil Temperature 42°C, Flow Rate 0.33 m^3/s).

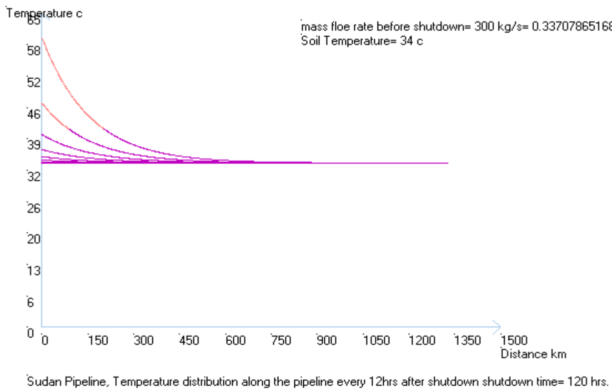


Fig. 8. Transient Temperature Distribution along the Pipeline every 12 Hours after Shutdown. (Inlet Temperature 60°C, Soil Temperature 32°C, Flow Rate 0.33 m^3/s).

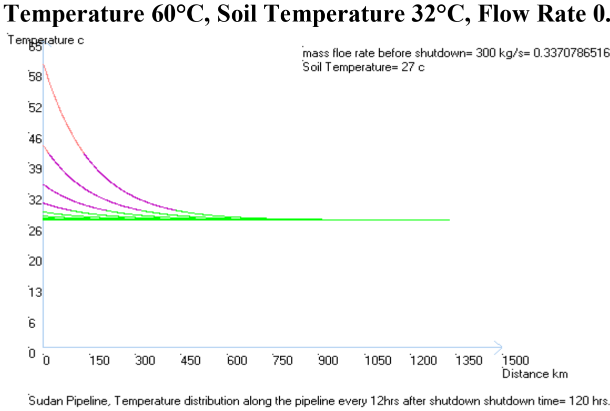


Fig. 9. Transient Temperature Distribution along the Pipeline every 12 Hours after Shutdown. (Inlet Temperature 60°C, Soil Temperature 27°C, Flow Rate 0.33 m^3/s).

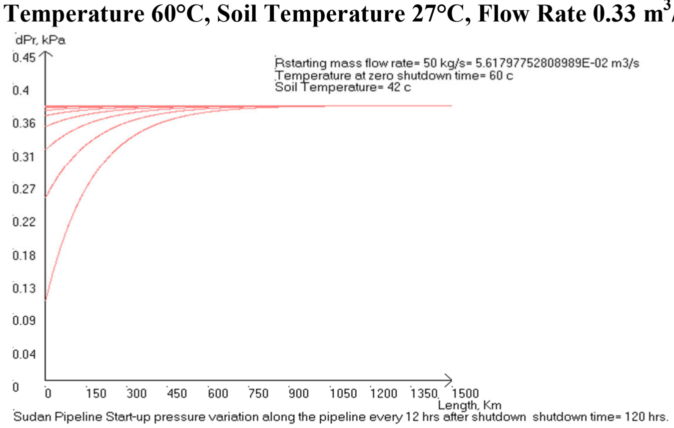


Fig. 10. 1-km Transient Restarting Pressure Distribution along the Pipeline every 12 Hours after Shutdown. (Inlet Temperature 60°C, Soil Temperature 42°C, Flow Rate 0.33 m^3/s).

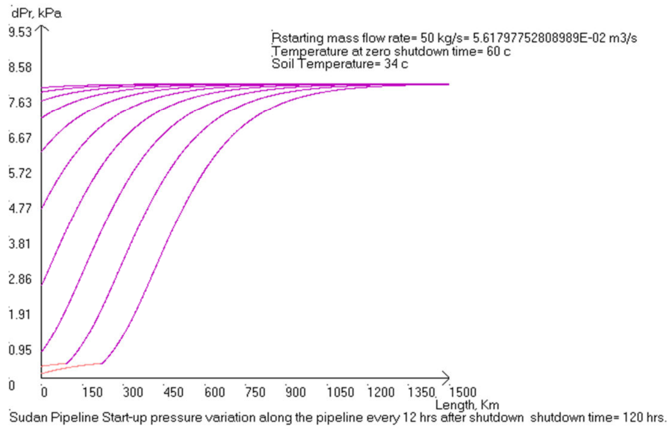


Fig. 11. 1-km Transient Restarting Pressure Distribution along the Pipeline every 12 Hours after Shutdown. (Inlet Temperature 60°C, Soil Temperature 32°C, Flow Rate 0.33 m^3/s).

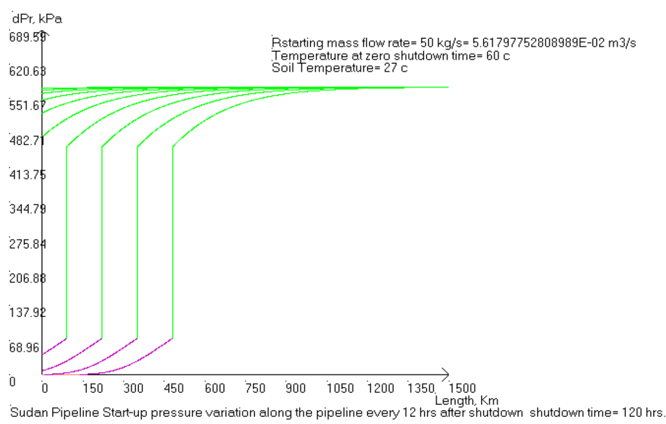


Fig. 12. 1-km Transient Restarting Pressure Distribution along the Pipeline every 12 Hours after Shutdown. (Inlet Temperature 60°C, Soil Temperature 27°C, Flow Rate 0.33 m^3/s).

4. Conclusions

Combining the experimental work with the developed computational tool the following remarks can be concluded:

- Nile blend exhibits different rheological behaviours at different ranges of temperature.
- It is recommended to operate the pipeline at high temperatures at which crude is expected to exhibit Newtonian flow to reduce friction losses and hence save pumping energy.

- The rheological properties of Nile blend are markedly temperature-dependant. This fact should be considered for prediction of hydraulic behavior of Higleig-Portsudan pipeline during operation and shutdown conditions.
- The solidification temperature of Nile blend was found to be 29°C. At temperatures below this value, the crude is expected to form a gel-like structure that hinders restarting of the pipeline.
- Depending on flow and thermal characteristics, Nile blend may exhibits different behaviours within different segments. The far distance from the inlet, the more possibility to exhibit non-Newtonian flow, and hence the more pumping pressure is required to flush a unit length. At the worst condition, the crude may be gelled at temperatures lower than its solidified point.
- It is important to restart the pipeline as quickly as possible when it goes for planned or emergency shutdown to avoid pressure decrease below the solidified point.

References

1. Szilas, A.P. (1986). *Production and transport of oil and gas*. (2nd Ed.), Part B. Elsevier Science Publisher.
2. Wasp, E.J.; Kenny, J.P.; and Ghandi, R.L. (1977). *Solid-liquid flow slurry pipeline transportation*. Trans Tech Pubn.
3. Xiaoheng, Y.; and Gouzhong, Z. (2000). *Oil pipeline design and control*. university of petroleum (China) press, 2000.
4. Bansal, R.K. (2005). *A textbook of fluid mechanics and hydraulic machines*. Laxmi Publications (P) Ltd, New Delhi.
5. Williams, T.M.; Hsu, J.J.C.; and Patterson, H.L. (1996). System developed to predict waxy crude's breakaway yield stress. *Oil and Gas Journal*, 94, 51; 35-39.

Appendix A

Mathematical models in operation condition

Temperature at length L from the inlet can be obtained from Eq. (A-1)

$$T_l = T_0 + (T_{i0} - T_0)\exp\left(-\frac{k_t \pi D l}{G c_o}\right) \tag{A-1}$$

The calculated temperature T_l is then used to calculate the density and viscosity at the length l. The density is calculated from Eq. (A-2) below, whereas the viscosity is calculated from the formulated viscosity-temperature equation.

$$\rho_T = \rho_{20} - (1.825 - 0.001315\rho_{20})(T - 20) \tag{A-2}$$

The flow behavior is identified whether it is Newtonian or non-Newtonian by comparing the temperature with the pour point. Consequently the friction factor is calculated from the following equations for laminar or turbulence regimes.

Newtonian flow friction factor calculation

$$\mathrm{Re}_{(Newt)}(T) = \frac{\rho(T) D_1 v}{\mu(T)} \tag{A-3}$$

- Laminar regime

$$f(T) = \frac{64}{\mathrm{Re}_{(Newt)}(T)} \tag{A-4}$$

- Turbulent regime

$$f(T) = \begin{cases} \dfrac{.0791}{\mathrm{Re}^{.25}_{(Newt)}(T)} & 2100 < \mathrm{Re}_{(Newt)} \le 100000 \\ .0032 + \dfrac{.221}{\mathrm{Re}^{.237}_{(Newt)}(T)} & \mathrm{Re}_{(Newt)} \ge 100000 \end{cases} \tag{A-5}$$

Non-Newtonian flow friction factor calculation

$$\mathrm{Re}_M(T) = \frac{D^{n(T)} v^{-2-n(T)} \rho(T)}{8^{n(T)-1} \left(\dfrac{3n(T)+1}{4n(T)} \right) k(T)} \tag{A-6}$$

- Laminar regime

$$f\ (T) = \frac{16}{\mathrm{Re}_{MR}(T)} \tag{A-7}$$

Critical Reed and Metzner Reynolds number:

$$\mathrm{Re}_{MRC} = \frac{6464n}{(1+3n)^2 \left(\dfrac{1}{2+n} \right)^{\frac{2+n}{1+n}}} \tag{A-8}$$

- Turbulent regime

$$\begin{aligned} m(T) &= 0.314 n(T)^{2.3} - 0.064 \\ \phi(T) &= \exp\left[\frac{0.572(1-n(T)^{4.2})}{n(T)^{0.435}} \right] \\ E(T) &= 0.0089 \exp(3.572 n(T)^2) \\ f(T) &= E \frac{\phi(T)^{(1000/\mathrm{Re}_{MR}(T))}}{\mathrm{Re}^{m(T)}_{MR}(T)} \end{aligned} \tag{A-9}$$

Friction factor is related to the coefficient factor of flow by this equation:

$$f_i(T) = 4 f(T) \tag{A-10}$$

Friction pressure

$$\Delta P_f(T) = f_i(T)\frac{\rho(T)\Delta L V^2}{2D_1} \tag{A-11}$$

Mathematical models in shutdown conditions

The following equations are used for shutdown calculations. In addition to the distance l, all parameters are functions in time, *t*.

Temperature distribution

$$T(l,t) = T_0 + (T_{inlet0} - T_0)\exp\left(-\frac{k_t \pi D l}{G c_o} - bt\right) \tag{A-12}$$

where

$$b = \frac{k_t D}{\frac{D_1^2}{4} c_o \rho_o + \frac{(D_2^2 - D_1^2)}{4} c_{st} \rho_{st}}$$

Restarting Pressure:

- *Newtonian crude Restarting*

$$\mathrm{Re}_{Newt}(l,t) = \frac{\rho(l,t) D v}{\mu(l,t)} \tag{A-13}$$

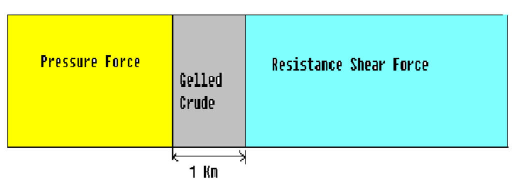
$$f_i(l,t) = \frac{64}{\mathrm{Re}(l,t)} \tag{A-14}$$

- *Non-Newtonian crude restarting*

$$\mathrm{Re}_{MR}(l,t) = \frac{D^{n(l,t)} v^{-2-n(l,t)} \rho(l,t)}{8^{n(l,t)-1}\left(\frac{3n(l,t)+1}{4n(l,t)}\right) k(l,t)} \tag{A-15}$$

$$f_i(l,t) = \frac{64}{\mathrm{Re}(l,t)} \tag{A-16}$$

- *Gelled crude Restarting*



$$\Delta p_y(l,t) = \frac{4000\tau_y(l,t)}{D} \tag{A-17}$$