Experimental Investigations of Rheological Properties of Nile Blend Waxy Crude

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Abstract: In this paper, laboratory work has been carried out using samples of Sudanese crude (Nile blend) in order to describe its rheological behavior at different flow and thermal conditions, and hence, identifying the temperature dependency of these properties. The rheological properties of Nile blend have been measured using a reliable viscometer connected to a water bath to allow simulating of the pipeline flow temperature. The rheological properties of Nile blend have been correlated with temperatures at different heating treatment conditions. The developed correlations can be utilized in prediction of pressure profiles along Higlig-PortSudan pipeline during its operation condition. The outcome of this paper is useful in performing hydraulic calculations of Higlieg-PortSudan pipeline under non-isothermal operation.

Keywords: *Nile blend, rheological properties, Newtonian*

المستخلص: في هذه الورقة تم إجراء تجارب معملية على الخام السوداني مزيج النيل من أجل وصف سلوكه الإنسيابي عند مختلف الظروف الحرارية والجريانية وبالتالي معرفة إعتمادية هذه الخواص على درجة الحرارة. الطريقة التي أتبعت في القياسات المعمليه هي استخدام جهاز قياس اللزوجه (فسكوميتر) موصل بحمام مائي من اجل تسليط درجة حرارة مماثله للخام أثناء جريانه خلال خط الانابيب. تم خلق علاقات ارتباط بين الخواص الانسيابية ودرجة الحرارة عند مختلف ظروف المعالجات الحرارية. هذه العلاقات يمكن الاستفاده منها في التنبؤ بتوزيع الضغط على طول خط انابيب هجليج-بورتسودان أثناء التشغيل. نتائج هذه الورقه يمكن الاستفاده منها في إجراء الحسابات الهيدرولوكية لخط أنابيب هجليج-بورتسودان عند الجريان غير متساوي الحرارة.

Introduction:

Compared with wax-free crude oils, waxy crude oils possess very complicated rheological behavior that entails special considerations to be taken in order to achieve safe transportation within technical and commercial capabilities. This fact makes transportation of waxy crude oils through long distance pipelines a subject of study for many decades to introduce new measures for solving problems resulting from the presence of wax. The key factor of determining the optimum transportation scenario of a waxy crude pipeline is to define the challenges by which the pipeline is faced. These challenges may include wax deposition, high pour point, high viscosity and pressure drop at temperatures below the cloud point, and high re-start pressure for gelled oil in the pipeline at temperatures below the pour point (1).

Problems related to the operation of pipelines carrying waxy crude have been discussed previously by many researchers. A. Uhde and Kopp (2) have studied the operation of handling waxy crude pipeline. G. King [3] has represented an equation for temperature calculation in a variety of pipelines in both tropical and arctic environments. White [4] discussed the utilization of the data obtained from viscometers and loops test in providing safe pumpability for waxy oils. Dafan and Zheming [5] have found a good agreement between field tests and laboratory experiments carried out on the Chinese Daqing field waxy crude. Wardhaugh *et al.* [6] have studied on ways of measurement of waxy crude rheology using different devices; in their study they concentrated on non-Newtonian behavior. Majeed *et al.* [7] have proposed a model for wax deposition calculation applied in an offshore crude-oil pipeline. Wardhaugh and Boger [8] have done comprehensive study for handling waxy crude oils through pipelines. In their research they have developed reproducible laboratory rheometers and provided an understanding of the waxy oil rheology that is applicable to the design and operation of waxy oil pipelines. Sanjary *et al.* [9] have discussed in details the waxy oils problems in oil production and transportation concentrating on the problems resulting from wax deposition and the factors affecting it. Chen *et al.* [10] have studied handling Chinese waxy crude by different treatments techniques including oil-heating and adding pour point depressants (PPD) techniques. D.S. Svetlichnyy et al. [11] have studied heating treatment efficiency as a measure for solving the problems facing a waxy crude transportation through a Kazakhstan pipeline. In their study they focus on the effect of cooling rate and the kinetics of wax crystallization on Higlig - Port Sudan pipeline is a long-distance pipeline handling the Sudanese waxy crude (Nile blend) from Higlieg oil field in south western Sudan to refineries in Elobied and Khartoum and then to Port Sudan for exporting. The line has a total length of 1504 km, along which there are six pump stations working alternatively and arranged at different locations to provide the required energy for delivering the crude [12]. Table 1 shows the elevation of every pump station along Higlig - Port Sudan pipeline and the distance between the pipeline inlet and every pump station. Due to the short history of Sudan oil production, the available literature related to Nile blend is limited. Nile blend was classified by Amel A Nimer and her coworkers as sweet crude with wax content of 25.8 wt% [13]. The pour point of the crude is 36° C [14], which considered as a high pour point. These properties necessitate applying special treatment measures to guarantee continuous flow, from one hand, and to overcome pressure losses due to the wax precipitation and deposition on the pipe wall, from the other hand. Nowadays the used method for this purpose is the chemical treatment done by adding PPD. The effect of PPD will enhance the crude properties by reducing both pour point and viscosity. The surrounding conditions of the pipeline also affect the crude property. The soil temperature, in particular, may fluctuate within short or long term which cause increase or decrease in the rheological properties, and hence, pressure losses. In addition, Newtonian and non-Newtonian flow behaviors may occur at higher and lower ranges of temperature, respectively. Newtonian and non-Newtonian behaviors can be identified from comparing the pipeline flow temperature with a temperature value known as abnormal temperature. Below the abnormal temperature waxy crude oils exhibit non-Newtonian flow, most probably, pseudo-plastic in which the Rheological behavior is describe by two parameters, namely fluid consistency and flow index. At temperatures higher than the abnormal temperature waxy crude oils exhibit Newtonian flow with rheological behavior described by the fluid viscosity. All the above necessitates studying temperature-dependency of Nile blend rheological properties to be able to accurately predict these properties, and hence, predict the friction losses under any soil temperature.

Research Methodology:

Different equations are used to describe rheological properties of Nile blend and similar waxy crude oils at d ranges of temperature within which the crude behaves as Newtonian and non-Newtonian. The first task of this work was, therefore, to identify the abnormal temperature. To identify the abnormal temperature, the pour point was firstly measure by the conventional method using a test jar. The abnormal temperature was then estimated using the rule of thumb (abnormal temperature=pour point + 12) [15]. To get the viscosity of Nile blend when it behaves as Newtonian, the measurement temperature is always set at values greater than the abnormal temperature using a water bath while measuring the shear stresses at different shear rates. The viscosity is taken as the slope of the relationship between shear stress and shear rate. The viscosity was then correlated with the measurement temperature. The same procedure was followed when the crude behaves as non-Newtonian. The relationship between shear stress and shear rate, however, is nonlinear following the power law equation which contains two rheological properties (fluid consistency and flow index). Fluid consistency and flow index were also correlated with the measurement temperature.

The test device and conditions:

The device used to measure the rheological properties of the crude is the viscometer VT500 with a HAAKE phoenix P2 circulator. This device is a viscometer (VT) with a power supply VS500. In the measurements VT500 has been connected to DOS-based software in one side and to a phoenix P2 circulator in the other side, and the measurements have been carried out at different thermal and shear conditions.

The conditions which considered during the measurements are:

1. Heating treatment temperature: the heating treatment temperature affects the rheological behavior of the crude and its potential properties (pour point and cloud point). During the measurements, heating treatment temperatures of 60°, 70°, 75° and 95° C were considered. From the pipeline optimization point of view, the optimum heating treatment temperature has to be identified to guarantee a good economical efficiency considering the pumping, chemical additives, and intermediate heating stations construction costs.

2. Cooling rate: The cooling rate of the pipeline, normally, is in the range of

0.01-0.05°C/min. In the current work, however, the applied cooling rate is 0.1°C/min which is the minimum cooling rate that can be applied by VT500 viscosmeter. This cooling rate has been used for some measurements (within non-Newtonian temperature ranges).

3. Shear rates: the effect of shear rates on waxy crude viscosity is obvious at lower temperature degrees at which the flow is non-Newtonian, the change of shear rates at low temperatures at which the crude is, in most cases, laminar, represents the pipeline shear rates at different position in radial direction. At these measurement temperatures the apparent viscosities at equilibrium shear stresses have been measured at different shear rates.
4. The injection rate of PPD: PPD amount of 50 ppm was added to the crude to determine its effect on the rheological properties.

The test procedure:

- The selected sample was heated externally to the heating temperature to make the sample back to its original state and assure that all separated wax is de-melted. The standing time at this temperature was chosen according to measurement temperature. For measurement temperature at which the crude is expected to behave as Newtonian fluid this time was 15 min; whereas it was 20-30 min for low measurement temperatures.
- After the standing time elapsed the sample was cooled down from the heating treatment temperature to 50°C to avoid the escape of the light-end components during pouring it to the measuring device. At this temperature the crude was poured instantly into the measuring device and then the temperature has been declined or elevated to the measurement temperature.
- At the measurement temperature aging time of 20-35 min has elapsed before the measurement is carried out.

Results and Discussion:

Controlling the measurement conditions, the following results are obtained:

1. Flow curves: The flow curves are illustrated for both Newtonian and non-Newtonian flow for different heating temperatures.
2. Newtonian kinematic viscosity: above the abnormal temperature crude viscosities have a unique value at any measurement temperature regardless of the range of applied shear. The viscosity values were measured and their variations with temperature were obtained within Newtonian ranges of temperature.
3. Non - Newtonian rheological parameters: the psedoplastic non-Newtonian parameters includes the flow consistency k and the flow index n. these parameters have been measured below the abnormal temperatures within non-Newtonian ranges of temperature, then the variations of these parameters with temperature have been obtained for different heating temperatures.
4. The effect of Chemical modifier (PPD) on the rheological properties of the crude: 50 ppm of PPD has been added to the samples to know its effect on the Newtonian flow and non-Newtonian flow rheological parameters.

Flow Curves:

The flow curve is obtained by plotting shear stresses versus shear rates at any measurement temperature. The types of the flow curves are different at different range of temperature, and for a waxy crude oil the flow curve at any measurement temperature depends on the physical properties of that crude and the heat treatment temperature. Generally waxy oil exhibits Newtonian and non-Newtonian (Pseudoplastic or yield-Peudoplastic) at different temperature measurements and by using different heat treatment temperature. The measurements carried out on Nile blend result in different types of flow curves that can be classified as follows:

Newtonian flow:

The characteristics based on which a fluid can be classified as Newtonian fluid are [(15)]:

1. At the measurement temperature, the relative error between the viscosity at any shear rate and the arithmetic mean value result from viscosities that measured at all measurement shear rates must be within 3%.
2. $\mu_1 \approx \mu_2 \approx \mu_3 \approx .... \approx \mu_N$, Where N is the number of shear rates at which viscosities are measured.
3. Plotting $\lg\tau \sim \lg\dot{\gamma}$ results in a straight line.

Figure 1 is an example of Newtonian flow curve of Nile blend sample preheated to 60°C. The Newtonian behavior is indicated by linear relationships between shear stress and shear rate. As the viscosity is the slope of the shear stress-shear rate curve, it is clear from the figure that viscosity is temperature-dependant.

Non-Newtonian flow:

For waxy oils that behave as non-Newtonian fluids, the apparent viscosity is affected not only by oil composition and measurement temperature, but also by thermal history, shear history, shear rate, and shear action time. Moreover the effects of these factors increase with the temperature declination. The abnormal temperature below which the Nile blend behave as non-Newtonian (abnoramal temperature) was found to be 40 to 42°C. Below this temperature, it has been found that, the apparent viscosity is shear-dependant, but the shear time does not affect its value. So Nile blend can be classified as shear-thinning crude.

The shear rates-dependence of Nile blend apparent viscosity within low temperatures in Figure 2 represents the variation of the apparent viscosity with temperature at different shear rates. Figure 2 shows that the relationship between viscosity and temperature depends on shear stress and this dependency is more significant at lower shear rates. This is a strong indicator of the non-Newtonian behavior of Nile blend at this condition.

Figures 3 and 4 are examples of Nile blend non-Newtonian flow curves in Cartesian and logarithmic forms. Figure 3 shows the flow curves of Nile blend at different temperatures below abnormal temperature. It is clear that for the same shear rate, shear stresses increases with the decrease of temperature. At temperature values 30°, 32°, and 34° C the relationship is clearly exponential following the power law of pseudoplastic fluids. At temperatures 36° and 38 °C the relationship is semi-linear which indicates that the crude starts to behave as Newtonian fluid.

Viscosity-temperature relationship for Newtonian Nile blend:

Table 2 shows the relationship of kinematic viscosity with measurement temperatures for Nile blend without PPD considering the heating treatment.

Non-Newtonian crude parameters:

Table 3 shows the relationship of flow consistency and flow index with measurement temperatures for pseudoplastic Nile blend without PPD considering the heating treatment.

3.4 The effect of PPD:

To describe the effect of the chemical modifier pour point depressant (PPD) on Nile blend behavior, 50 ppm of PPD was added to Nile blend samples. From Figure 5, it should be noted that, PPD has more significant effect on crude rheology at lower degrees of temperature than at higher temperature.

Conclusions:

Nile blend has different flow behavior within different ranges of temperature. The crude behaves as Newtonian fluid at high temperatures, always above their abnormal temperatures and behaves as non-Newtonian, mostly pseudoplastic, at particular temperature ranges below their abnormal temperature. The rheological properties of Nile blend have been correlated with temperature within their Newtonian and non-Newtonian ranges of temperature. The formulated correlations assist in accurate prediction of pressure losses within the pipeline.

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Table 1: Higlieg-PortSudan pipeline pump 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	817.0	413
PS# 5	1085.7	377
PS# 6	1313.0	646
Terminal (in PortSudan)	1504.1	9

Table 2: Nile blend Newtonian flow kinematic Viscosity-Temperature relationship

H.T Temperature ^{o}C	$\mu - T$ Equation	Correlation coefficient	Temperature Range ^{o}C
60 (cooling rate=0.1^{o}C/min)	$\mu(T) = 2.5655 - 0.0235T$	0.9733	43~60
70	$\mu(T) = 2.2534 - 0.0175T$	0.9562	41~70
75 (cooling rate=.5 ^{o}C/min)	$\mu(T) = 2.3564 - 0.0201T$	0.9475	40~60
95	$\mu(T) = 2.3279 - 0.0206T$	0.9776	38~60

Table 3: The variation of *K* and *n* with temperature considering heating treatment

H. T. Temperature ^{o}C	Measurement temperature ^{o}C	$k(mpa.s^n)$	n	Correlation coefficients
60 (cooling rate=0.1^{o}C/min)	30	3916.2	0.4288	0.9993
	32	3985.2	0.4039	0.9962
	34	1115.6	0.6016	0.9984
	36	205.98	0.8116	0.9982
	38	172.03	0.8439	0.9981
70	30	10116	0.3671	0.9884
	34	3274	0.4410	0.9975
	36	398.38	0.7435	0.9999
	40	100.93	0.9055	0.9055
75 (cooling rate=0.5 ^{o}C/min)	30	22773	0.2180	0.9700
	32	2838.9	0.5113	0.9961
	34	2162.7	0.5232	0.9967
	36	464.11	0.7008	0.9984
95	30	1277.4	0.5648	0.9960
	32	433.95	0.6097	0.9982
	34	246.78	0.7495	0.9964

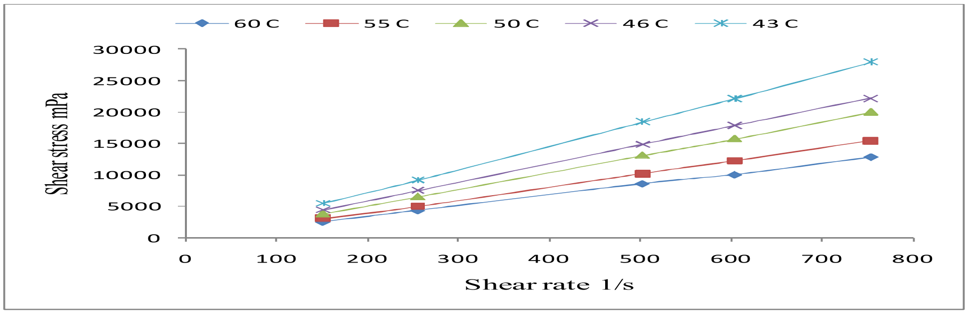

Figure 1: Flow curves of untreated Nile blend preheated to 60^o C

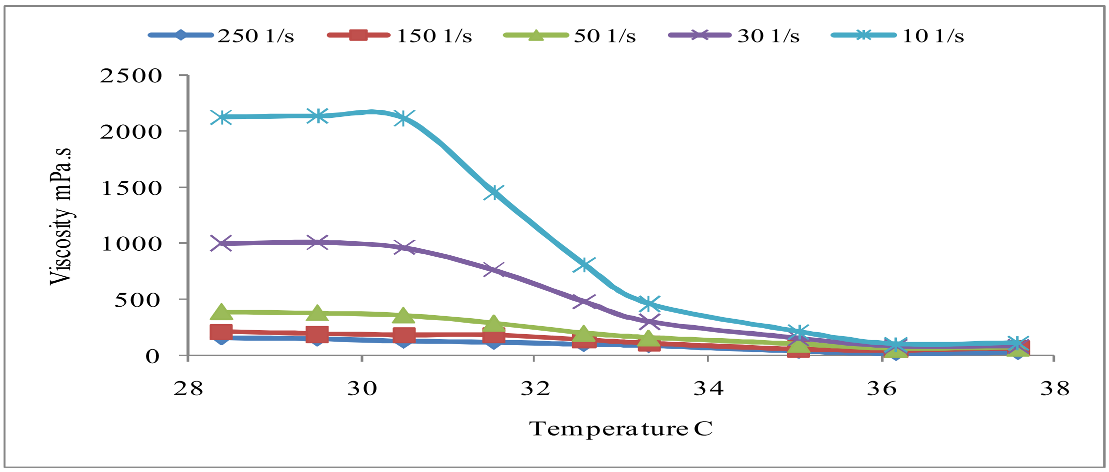

Figure 2: Variation of non-Newtonian Nile blend apparent viscosity with temperature (chemically untreated samples preheated to 60^o C)

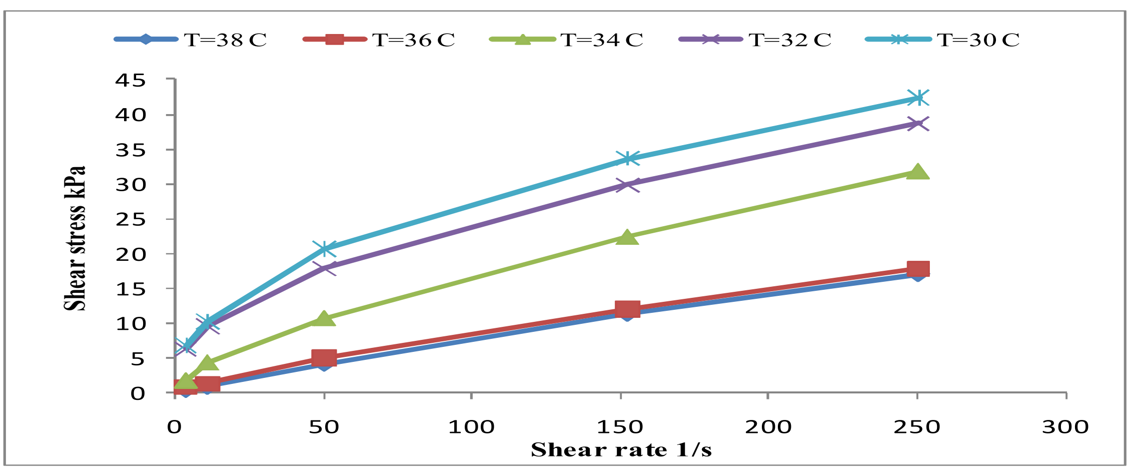

Figure 3: Flow curve of untreated non-Newtonian Nile blend preheated to 60^o C (Cartesian form)

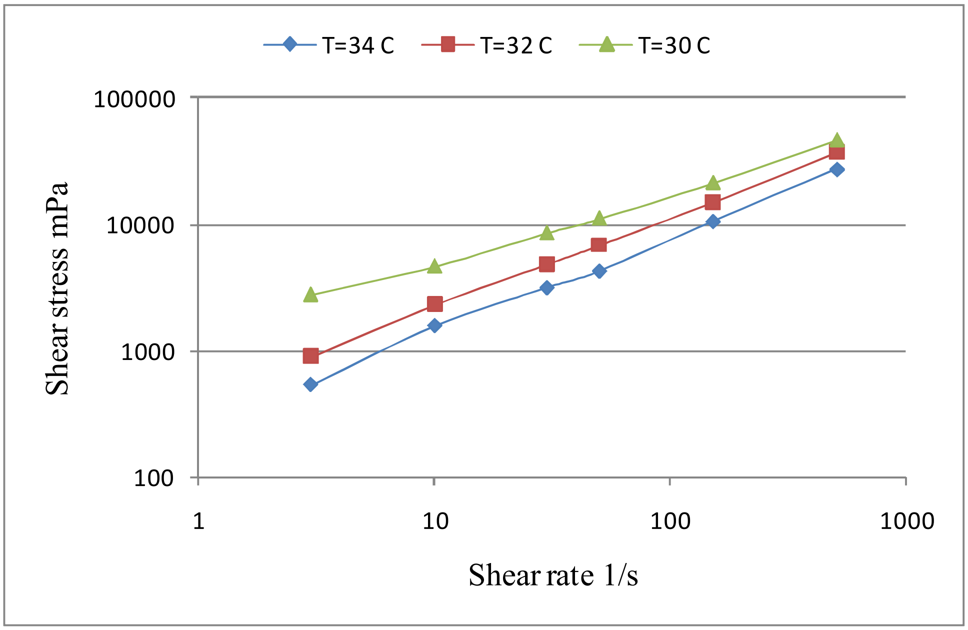

Figure 4: $\lg \tau - \lg \dot{\gamma}$ Flow curve of untreated non-Newtonian Nile blend preheated to 95°C (Logarithmic form)

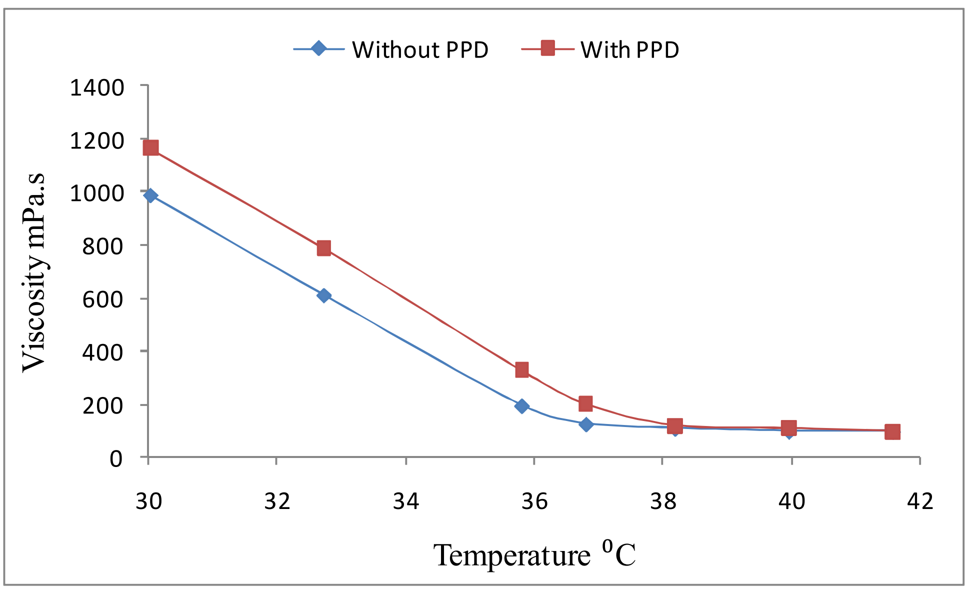

Figure 5: The effect of adding flow improver on the apparent viscosity, Nile blend preheated to 60° C.