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Flow behavior of Algerian crude oils from different sources

Ahmed Salah Eddine MEDDOUR[1] and Farid SOUAS[*1,2]

[1]*LEGHYD Laboratory, Faculty of Civil Engineering, University of Science and Technology Houari Boumediene (USTHB), Bab Ezzouar, Alger, Algeria*
[2]*Research Unit Materials, Processes and Environment (UR-MPE), Faculty of Engineering Science, University M'Hamed Bougara, Boumerdes, Algeria*

Abstract. A study of the flow behavior of Algerian crude oils obtained from different fields in the TFT region (Tin Fouye Tabankort/South Algeria) was conducted using the AR2000 rheometer equipped with a Couette geometry. Rheology experiments were carried out at different shear rates and temperatures to predict the transport characteristics of crude oils. The results obtained show that all crude oils studied exhibit non-Newtonian behavior at low shear rates and quasi-Newtonian behavior at high values of the shear rate gradient. The analysis of the obtained rheological data revealed that the increase in temperature had a positive effect on the flow behavior of crude oils in pipelines.

Keywords**:** flow behavior; light crude oil; rheology; temperature; viscosity.

1. Introduction

Crude oil flow is an unavoidable factor in oil production and refining technology, at least because of the distance between oil fields and consuming companies. This poses the major problem of crude oil transportation that requires a correct description of its properties, which is the central task of crude oil rheology as any fluid with a complex composition and structure [1]. The behavior of crude oil can change from Newtonian at high temperatures to non-Newtonian at low temperatures, due to the existence of different amounts of components such as aromatics, resins, waxes, asphaltenes, etc. As crude oil obtained from different origins has different composition, it is necessary to measure the rheological properties. The flow of crude oil in pipelines is a source of serious problems with deposits of heavy substances on the wall surfaces that can lead to blockage of the lines. It is therefore necessary to obtain information about the flow of crude oil at different temperatures using a modern rheometer which can be used to predict the transport properties of crude oil [2]. Measuring the rheological properties of crude oil helps to reduce energy consumption, ensure the safety and profitability of pipeline transportation, and is of great importance for the design of pipelines and pumping stations [3]. The rheological behavior of fluids is classified according to the relationship between shear stress and shear rate. This relationship is obtained by curve fitting from experimental rheological data. If this relationship is linear, the fluid is considered Newtonian and if the relationship is non-linear, the fluid is considered non-Newtonian [4-5]. According to Banerjee et al. [6], most crude oils behave like a Newtonian fluid at high temperatures. At a sufficiently low temperature, the waxes begin to precipitate as crystals and the flow changes to a complex non-Newtonian fluid. The viscosity behavior over a wide range of shear rates and temperature shows larger magnitude differences at lower shear rates compared to higher shear rates. Ilyin and Strelets [7] studied the rheology of eight crude oils of different classes (light, heavy, waxy, and extra-heavy crude oils) using the RheoStress 600 rotational rheometer. They showed how the viscosity of a crude oil depends on its nature, temperature, and applied stress. They concluded that the nature of crude oils determines their rheological behavior. Olanrewaju et al. [8] studied the rheology of three samples of light crude oil and fuel oil by Haake RheoStress 6000 rheometer. They also determined the physicochemical characterization of the samples and the dependence of their density on temperature. They found that one crude oil sample exhibited Newtonian behavior, while the other crude oils and fuel oil followed the Herschel-Bulkley model. In this paper, the rheology of five Algerian crude oils from different locations is studied in order to obtain more information about the flow behavior in pipelines.

2. Experimental

In this study, five different samples of light crude oil were used from different oil fields in Algeria. These samples were recognized by identifying them with the numbers 1, 2, 3, 4 and 5. At a temperature of 20 °C, the important factors for crude oil classification are specific gravity (°API), density (d: kg/m^3), freezing point (fp: °C) and sulfur content (S). According to their respective average values (i.e. 36 < API < 44, 0.806 < d < 0,830, -30 < fp < -35, and 0.05 < %S < 0.1), Algerian crude oil is classified as light. The flow behavior of the five crude oil samples was performed using the AR-2000 rheometer [9-12] with a Couette geometry (14 mm diameter) at different temperatures (10, 20, 30 and 40°C). Software (Rheology Advantage Data Analysis Program, TA Instruments) was used to control the test procedure and analyze the data. Initially, all samples are

[*]Corresponding author. *E-mail address*: farid.souas@usthb.edu.dz (Farid Souas)

pre-sheared for 60 s with a shear rate of 0.15 $s^{-1}$for proper sample homogenization [13]. The samples are then allowed to settle for 1 min before starting the data acquisition procedure. The range of the applied shear rate varies from 0.1 s^{-1} to 700 s^{-1}.

3. Results and discussion

3.1. Rheological model

Three rheological models, namely the Herschel and Bulkley model, the Bingham model and the power law model (Equations 1-3 respectively) were used to determine the flow behavior of crude oil samples at different temperatures.

$$\tau = \tau_0 + K\dot{\gamma}^n \qquad (1)$$

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad (2)$$

$$\tau = K\dot{\gamma}^n \qquad (3)$$

where: τ is the shear stress (Pa), τ_0 is the yield stress (Pa), K is the consistency index ($Pa \cdot s^n$), $\dot{\gamma}$ is the shear rate (s^{-1}), n is the flow behavior index and μ is the apparent viscosity (Pa·s).

The reliability of each rheological model was evaluated on the basis of the standard error, which is expressed as follows:

$$SE = \left[\frac{\left[\frac{\sum_{i=1}^{n}(x_m - x_c)^2}{n-2}\right]^{\frac{1}{2}}}{X_m^{max} - X_m^{min}}\right] \times 1000 \qquad (4)$$

where: x_m is the measured value, x_c is the calculated value and n is the number of data points.

The results of fitting the experimental data are shown in Figures 1-5. These figures show that the Herschel and Bulkley model best describes the flow behavior of crude oils over the given range of shear rates and temperatures. This means that crude oils are non-Newtonian fluids, i.e. with increasing shear rate, the viscosity decreases. This is also confirmed by the lowest values of the standard error in Table 1.

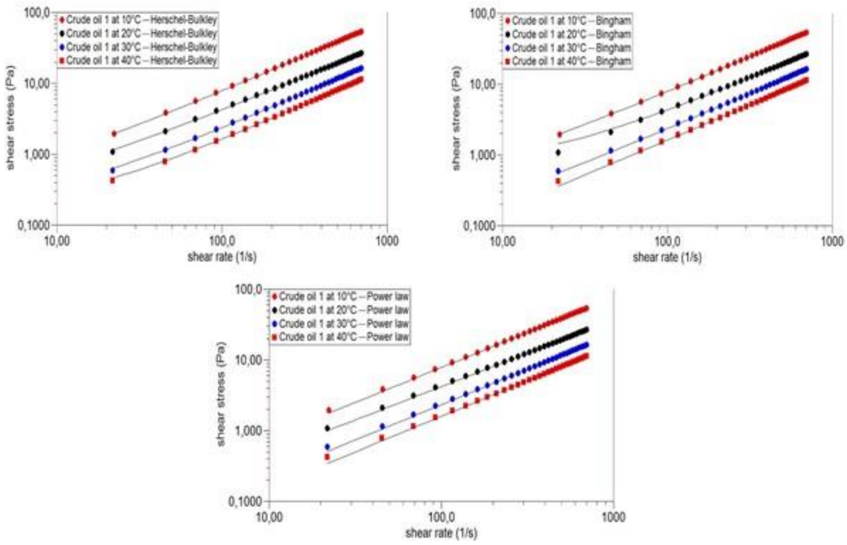

Figure 1. Modeling the flow behavior of crude oil 1 at different temperatures.

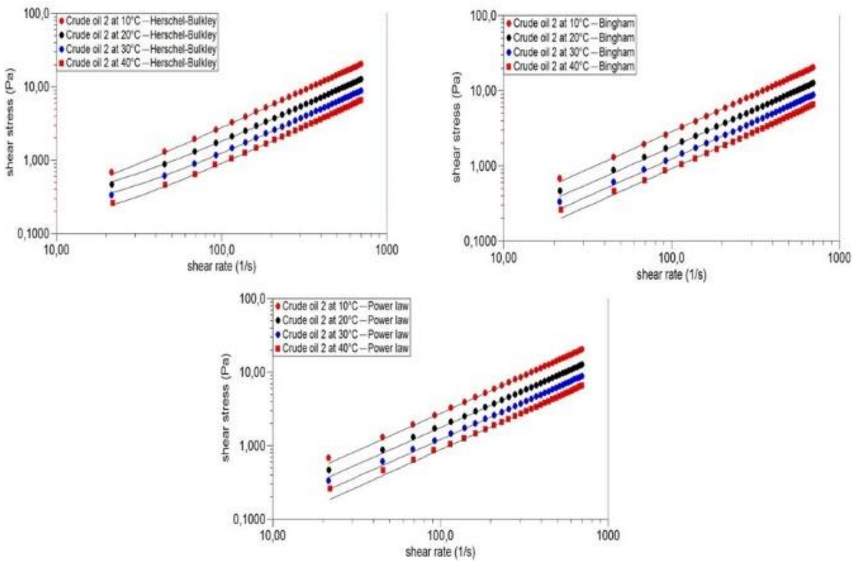

Figure 2. Modeling the flow behavior of crude oil 2 at different temperatures.

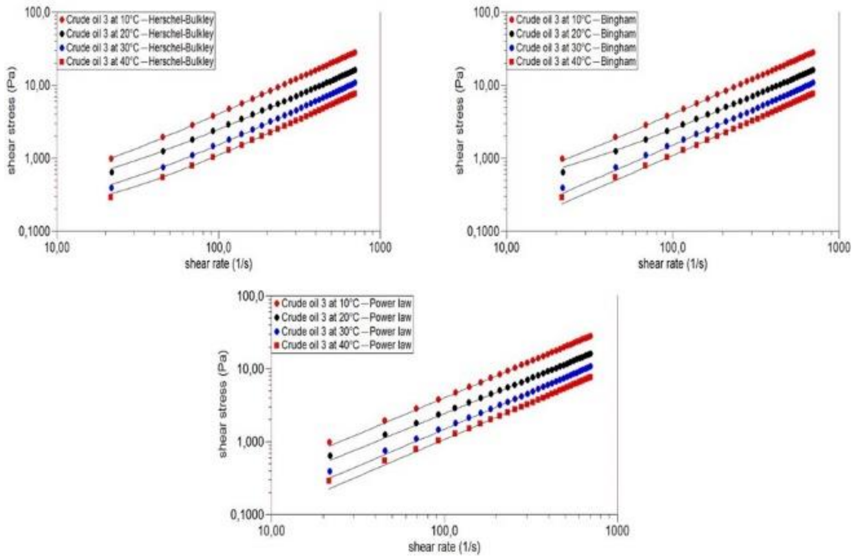

Figure 3. Modeling the flow behavior of crude oil 3 at different temperatures.

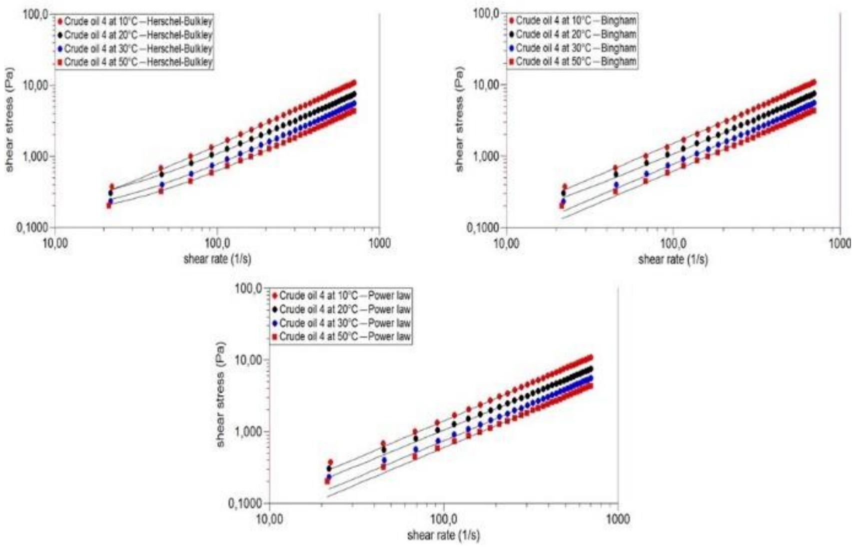

Figure 4. Modeling the flow behavior of crude oil 4 at different temperatures.

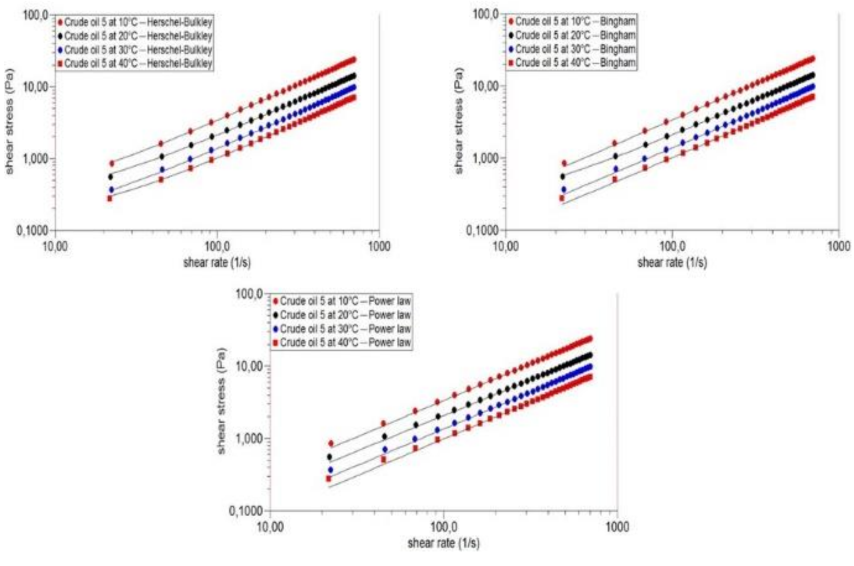

Figure 5. Modeling the flow behavior of crude oil 5 at different temperatures.

Table 1. Standard error values for rheological models

Crude oil	Temperature, °C	Herschel–Bulkley	Bingham	Power law
Crude oil 1	10	0.962	1.004	1.396
	20	2.770	3.894	3.762
	30	1.484	2.454	2.856
	40	1.648	3.753	3.639
Crude oil 2	10	0.867	4.792	1.673
	20	1.705	3.959	3.769
	30	1.840	5.353	4.178
	40	2.966	7.111	5.221
Crude oil 3	10	0.664	1.313	1.603
	20	2.543	2.648	4.178
	30	2.262	4.779	4.297
	40	2.015	5.025	4.464
Crude oil 4	10	1.391	8.723	2.460
	20	2.425	4.771	5.223
	30	2.392	7.478	5.824
	40	3.266	8.275	6.981
Crude oil 5	10	1.308	2.877	2.361
	20	1.679	2.141	3.569
	30	2.106	4.586	3.878
	40	1.778	5.359	4.400

3.2. Steady flow behavior

The results obtained from the rheological tests for the crude oil samples are presented in Figures 6-9. These figures show comparatively the evolution of viscosity and shear stress as a function of shear rate for the selected temperatures (10 °C- 40 °C). Table 2 shows the asphaltene and paraffin content in crude oil samples. It is observed that these are lighter crude oils with different asphaltene contents. The asphaltene content of crude 1 is (1.5%) higher than that of crude 4 (0.15%), which influences their flow behavior. In addition, the paraffin or wax content of these crude oils varies from 1.05% to 2.85%, which affects the pour point and rheological behavior [14].

The shear stress versus shear rate curves clearly show the non-Newtonian pseudoplastic character of the crude oils for the chosen temperatures. In fact, the curves indicate the existence of a yield point above which flow can occur, followed by a linear relationship between shear stress and shear rate. It was also observed that the yield stress and shear stress of the five crude oil samples decrease with increasing temperature due to weakening of intermolecular forces under continuous heating [15].

Table 2. Asphaltene and paraffin content in crude oil samples

Characteristic(s)	Method	Sample				
		1	2	3	4	5
Asphaltene content, wt %	ASTM D6560	1.5	0.50	0.75	0.15	0.60
Paraffin content, wt %	UOP 46-64	2.85	1.20	1.88	1.05	1.40

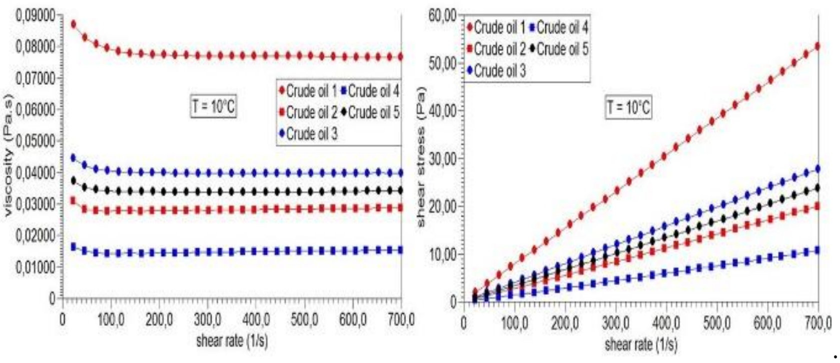

Figure 6. Flow curves of crude oils at a temperature of 10 °C

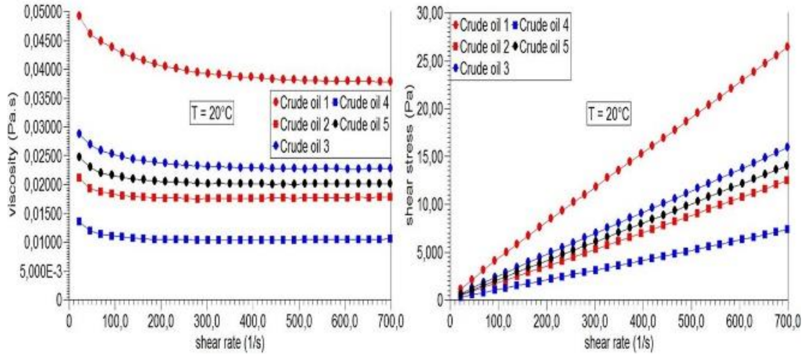

Figure 7. Flow curves of crude oils at a temperature of 20 °C.

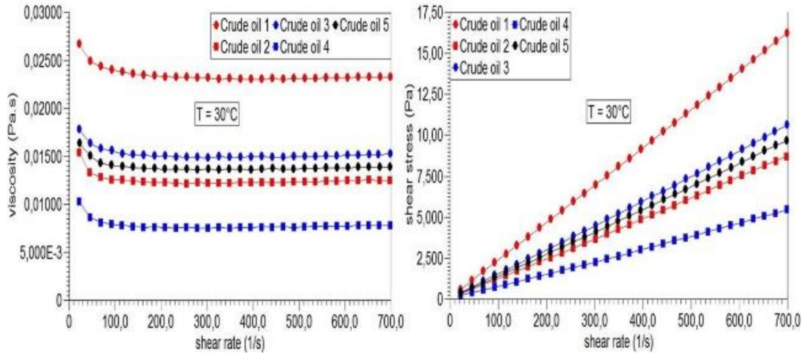

Figure 8. Flow curves of crude oils at a temperature of 30 °C.

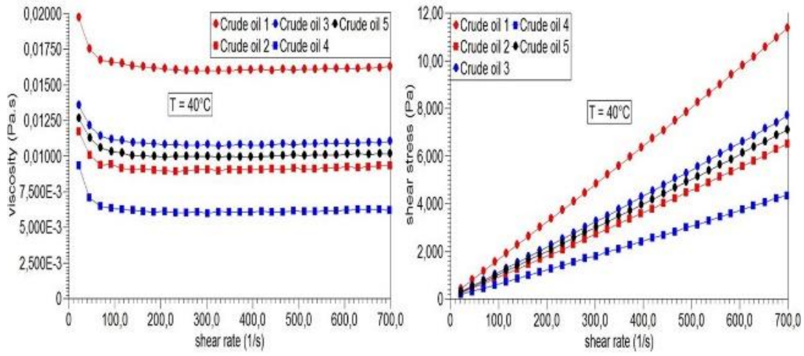

Figure 9. Flow curves of crude oils at a temperature of 40 °C.

The five crude oil samples show similar rheological behavior for different temperatures. It is worth mentioning that sample 1 is characterized by its high viscosity and shear stress compared to samples 3, 5, 2 and 4, respectively. This showed that there is a correlation between the main rheological parameters of the crude oils and their composition. The viscosity of crude oils depends on the concentration of light hydrocarbons in the crude oil and its temperature. The presence of paraffin wax in the crude oil causes a strong dependence of its viscosity on temperature [16]. At low temperatures, the flow curves change to higher stress levels, indicating an increase in the strength of the internal fluid structure. In fact, this structure depends on a strong gel network in the crude oil, which is responsible for the change in the rheological behavior of crude oil. Under these conditions, the rheological behavior of crude oil is also characterized by a complex dependence on its shear rate [17]. For example, crude oil 1 has a relatively higher asphaltene and wax content than the others, which accounts for its high viscosity at low temperatures. After increasing the temperature to 40 °C, the crude oil becomes more fluid due to the decrease in viscosity.

The viscosity versus shear rate curves for all crude oils show the presence of two different regions: the first is at low shear rate where the viscosity decreases with the increase in the shear rate, indicating shear thinning behavior. The second is at high shear rate where the viscosity stabilizes and remains constant, indicating a quasi-Newtonian behavior due to the permanent dissipation of the heavier components [18]. It should be noted that the impact of temperature on viscosity becomes more significant. Indeed, the viscosity of crude oils decreases exponentially in the test temperature range from 10 to 40 °C. This is due firstly to the major effects of temperature on the viscosity of the heavy components present in crude oils. Secondly, high temperatures destroy the ordered chemical structure of the heavy components in the phase of crude oils, which reduces the viscosity [19].

3.3. Yield stress

The yield stress of a given substance, τ_0, is defined as the minimum shear stress required to initiate its flow as a liquid. Below this stress level, the sample behaves like a solid with an elastic property. But when the applied stress exceeds the yield stress, permanent deformation causes the sample to start flowing [20]. The modeling analysis was performed numerically by the rheometer using the Herschel Bulkley model to determine the yield stress for each sample at different temperatures and the results are presented in Table 3. It was observed that the apparent yield stress decreases significantly with increasing temperature, which means that the energy required to make the crude oils flow is lower. This suggests that increasing temperature reduces the internal friction that prevents liquid movement of crude oil samples.

Table 3. Apparent yield stress measurement

Temperature, °C	Yield stress, Pa				
	Crude oil 1	Crude oil 2	Crude oil 3	Crude oil 4	Crude oil 5
10	1.932	0.668	0.963	0.368	0.835
20	1.074	0.458	0.630	0.298	0.544
30	0.581	0.331	0.388	0.227	0.365
40	0.428	0.258	0.292	0.201	0.275
% reduction	78	61.4	70	45.4	67

4. Conclusion

The analysis of the rheological data obtained for five different light crude oils from the oil fields in southern Algeria allows us to conclude that the studied crude oils behave as a pseudoplastic fluid (Herschel-Bulkley) with a yield stress for flow at all tested temperatures. All five crude oil samples show similar rheological behavior for different temperatures, expressed by the change in flow behavior from non-Newtonian to quasi-Newtonian at high shear rates. Crude oil 1 has the highest apparent viscosity and yield stress compared to the four pseudoplastic crudes 3, 5, 2, and 4, respectively, because it has a relatively higher content of heavy components such as wax and asphaltenes than the other four. The results of rheological property measurements are highly dependent on crude oil composition, temperature and shear rate. The viscosity of all crude oils decreased significantly with temperature over the range of 10, 20, 30 and 40 °C. The increase in temperature had positive effects on the flow characteristics of crude oils in pipelines, as it significantly reduced viscosity, shear stress, and yield stress.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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