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AN INSIGHT INTO WAXY CRUDE OILS FLOW CURVES USING SHEAR-ROTARY RHEOMETRIC EXPERIMENTS AND POWER LAW MODEL

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Abstract

The rheological behavior of crude oil is highly dependent on paraffin content, shear stress, shear rate, and temperature. To study the influences of these parameters on the rheology of the fluid, the flow curves for various paraffinic crude oils with 7 and 25 wt.% paraffin contents were generated using a digital rheometer of Anton Paar MCR 302 with a Parallel-plate diameter of 30 mm at a rotation torque of 100 nNm and the changes in the curves were tracked. In this regard, the shear-rotary tests were performed in a shear rate range of 100 to 600s^{-1} at 26 and 22°C. Since the Psaudoplastic fluid models are used to describe the non-Newtonian crude oils behaviors, by fitting the flow curves generated from the shear-rotary tests to the Power law model, the model indices for each of the paraffinic crude oils were successfully approximated.

***Keywords**: Rheometer; Paraffinic crude oil; Power law; Shear rate; Shear stress; Flow curve.*

1. Introduction

The study of rheological properties of crude oil began about three decades ago. The collective agreement in all studies carried out through shear-rotary rheometry tests indicates that the crude oil is non-Newtonian at temperatures below wax appearance temperature (WAT) [1-6]. Many researchers have tried to provide models for predicting the crude oil rheological behavior in recent years. In these studies, it has been attempted to provide models for predicting rheological properties of paraffinic crude oils [7-8], and the indices of the models are determined using a number of experimental data [9]. In another study, a rheological binomial equation was proposed to consider the dependence of rheological parameters of paraffinic crude oils on the temperature [9]. A model was proposed to predict the yield stress in terms of the difference between the desired temperature and the formation temperature of the gel and the density of the oil sample, which is consistent with the experimental data [10].

Several studies indicate that decrease of temperature and increase of paraffin content, increase non-Newtonian properties of crude oil [11-13].

For the flow curves approximation and the experimental data matching, the equations of Pseudoplastic fluids, such as Power law, Herschel–Bulkley, Bingham plastic, *etc.* are used. In some cases, different equations are used to describe the different parts of the flow curve, in which the concept of shear stress is used. Generally, the model of Power-law is the most widely used equation in the resources and more suitable for modeling in engineering calculations [14-16].

One of the characteristics of fluid rheological behavior is the relationship between shear stresses and shear rates. In this sense, in order to analyze the fluid rheological behavior, we need to obtain the flow curve at different amounts of shear rate (shear stress-shear rate diagram). To acheive this purpose, various rheometers are used, each of which, according to conditions, is limited to a specific range of shear rates. Generally, a rheometer is a laboratory device used to measure the way in which a liquid or suspension flows in response to applied forces.

In this study, we report the flow curves for various paraffinic crude oils and changes in the curves are investigated. We report novel experimental data, and the capability of the Power law model to correlate the data is investigated.

2. Equipment and method

2.1. Materials

The crude oils consisting of 7 and 25 wt. % paraffin contents were considered whose physicochemical properties including API gravity, density, viscosity, paraffin content, sulfur content, water content, pour point and nitrogen content are presented in Table 1. Any kind of crude oil with at least 5 wt. % paraffin content is referred to as paraffin oil [17]. The reference crude oils greatly vary in their characteristics/properties and compositions. They vary in color from black to light brown, and density from 0.872 to 0.896 g/cm^3 at 26°C. The pour points vary between 10 and 12°C. The water content in all the reference crude oils is insignificant (less than 0.05 vol. %). The API gravity ranges from 22.30 to 38.50. The crude oils were not pre-treated before using.

Table 1. Physicochemical properties of reference crude oils*

Reference crude oils	A	B
Density @ 26°C (g/cm^3)	0.872	0.896
API Gravity	38.50	22.30
Paraffin content (wt.%)	7	25
Sulfur content (wt.%)	0.41	4.25
Water content (vol.%)	<0.025	<0.05
Pour point (°C)	12	10
Nitrogen content (wt.%)	0.08	0.12

**More information about the crude oils is available upon request to the authors*

2.2. Apparatus

The rheometer used in this study is Anton Paar MCR 302, which is a product of Anton Paar Company (France). This device is primarily utilized to perform a variety of rheological tests, such as rotational and oscillatory as well as the combination of both. MCR 302 can be used to determine the rheological behaviors of fluids, gels or solids. It is equipped with Peltier temperature control for heating/cooling and an UV curing system for photosensitive samples. The Peltier temperature system (P-PTD 200) allows temperature sweep experiments in the range of –40 up to 200°C with high heating and cooling rates. The UV curing system (Delolux 80) allows the investigation of UV-initiated curing reactions, following materials development from their original to their fully cured state (Table 2).

Table 2. MCR 302 specifications

Technical Data	Rheometer MCR 302
Parallel-plate geometry	20 and 40 mm
Peltier temperature rang	-20…200 °C
UV curing system (356nm)	0…>1000 mW/cm^2
Min. torque, rotation	10 nNm
Min. torque, oscillation	2 nNm
Torque resolution	0.1 nNm
Angular velocity	10-9…314 rad/s
Normal force range	0.005…50 N
Normal force resolution	0.5 N

The tasks performed by MCR 302 are as follows:

- Drawing flow curves and studying the flow behavior of materials (melt and soluble).
- Scan curve of viscosity and other linear viscoelastic properties as a function of frequency.

- Temperature scan curve
- Time scan curve
- Strain scan curve
- Creep curve and stress depletion
- Relaxation time distribution function curve
- Hysteresis curve
- Checking the temperature and time of gelation

2.3. Experimental procedure

MCR 302 is a rheometer that utilizes an EC motor technique, low friction bearing, and an optimized normal force sensor in order to optimize its performance. By using the Anton Paar Rheo Compass software, control of the measuring system and generating reports are performed.

After assuring that the compressed air pressure is 90 psi (or higher), it is initialized through the Anton Paar Rheo Compass software. The measurement tool is connected to the quick connector coupling and line up the alignment marks (Figure 1). Thereafter, the sample is loaded onto the mount. If there is too much of the sample, the sample will be reduced with a spatula also if the sample sticks to the measuring plate, the Base mount will unscrew to insert the disposable Metal pan + Fixture (Figure 1).

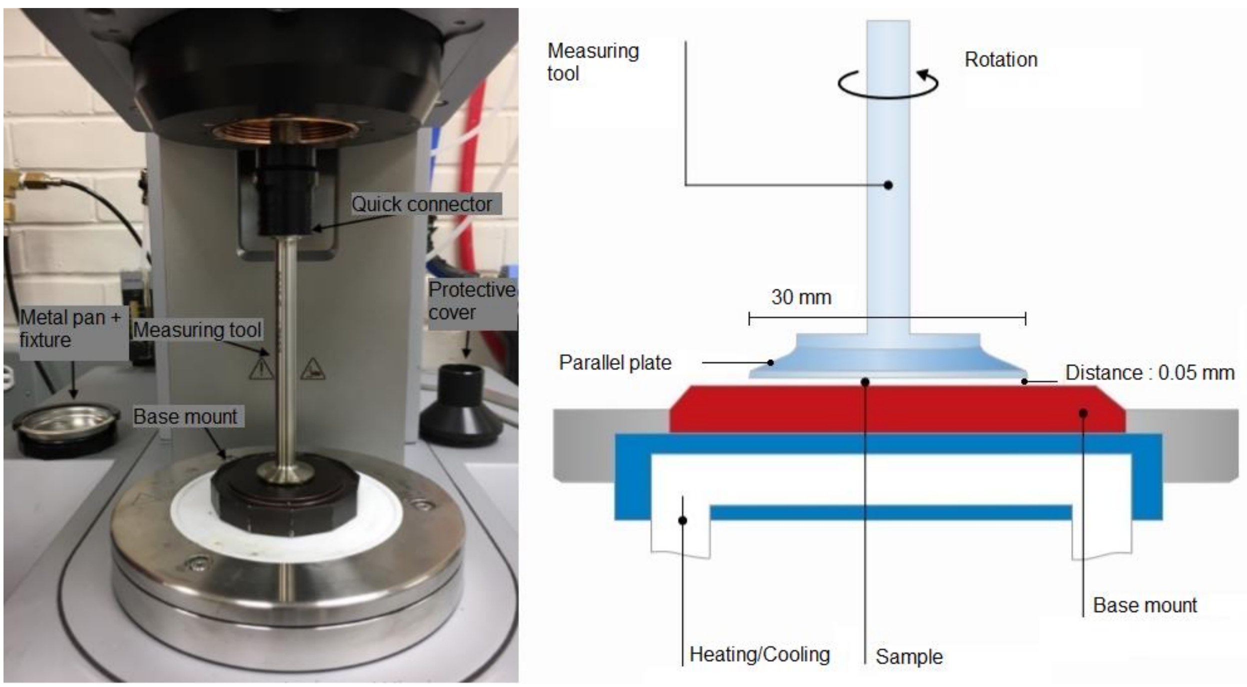

Figure 1. Physical components and schematic view of Peltier temperature control

When using MCR 302, there are two measuring methods available: shear-rotary tests and oscillatory tests. For data gathering, the desired measuring method is the shear-rotary test, in which the measuring device turns in only one direction (Figure 1), and the shear rate profile, made up of different rotational speeds is set to determine the shear rate. Using this profile, the rheometer is able to determine the required shear stress according to the viscosity law. For each of samples of the reference crude oils, shear-rotary test is carried out. In order to carry out the test, the desired heating/cooling temperature at 26°C is set and maintained the system at:

- Parallel-plate diameter: 30 mm.
- Distance between Parallel plate and Base mount: 0.05 mm (an appropriate gap for our samples).

- Rotation torque: 100 nNm.
- Shear rate range 100 to 600s^{-1}.

After the settings above, the system can be started to collect data and generate a report (table of data and diagrams) by Rheo Compass software. After data collecting and report generating at 26°C, the heating/cooling temperature is set at 22°C and the above settings are adjusted again and another test is run at the same temperature.

3. Results and discussion

Depending on the characteristics of reference crude oils, various results can be obtained from rheological measurements. The experimental outputs (Tables 3 and 4) and flow curves (Figures (2-*a*), (2-*b*), (2-c) and (2-d)) were generated using the Rheo Compass software.

Table 3. Experimental flow curves data for reference crude oils at 26°C

Shear rate (s^{-1})	Shear stress (Pa)		Shear rate (s^{-1})	Shear stress (Pa)	
	7%	25%		7%	25%
100	0.411	63.214	250	1.023	100.954
120	0.492	69.386	300	1.226	110.81
140	0.574	75.071	380	1.552	125.034
170	0.696	82.90	450	1.836	136.315
200	0.819	90.077	600	2.445	157.897

Table 4. Experimental flow curves data for reference crude oils at 22°C

Shear rate (s^{-1})	Shear stress (Pa)		Shear rate (s^{-1})	Shear stress (Pa)	
	7%	25%		7%	25%
100	0.643	89.132	220	1.395	132.231
110	0.701	93.481	260	1.642	143.762
118	0.752	96.834	295	1.860	153.143
125	0.790	99.660	330	2.081	161.970
140	0.891	105.471	385	2.432	174.962
155	0.983	110.983	435	2.740	185.981
168	1.074	115.551	510	3.214	201.393
189	1.201	122.560	600	3.772	218.450

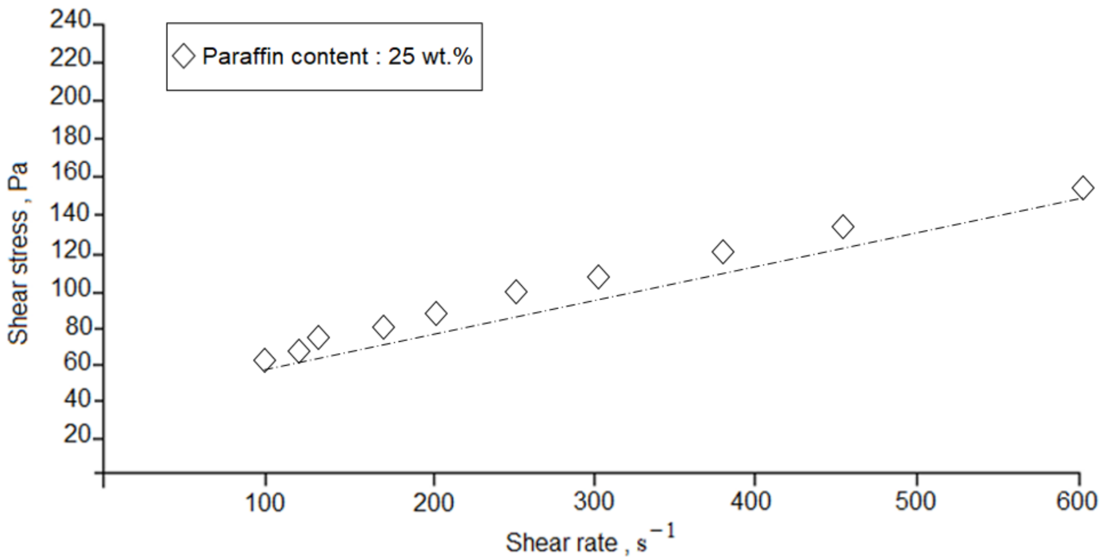

Figure 2-a. Flow curve for reference crude oil with 25 wt. % paraffin content at 26°C

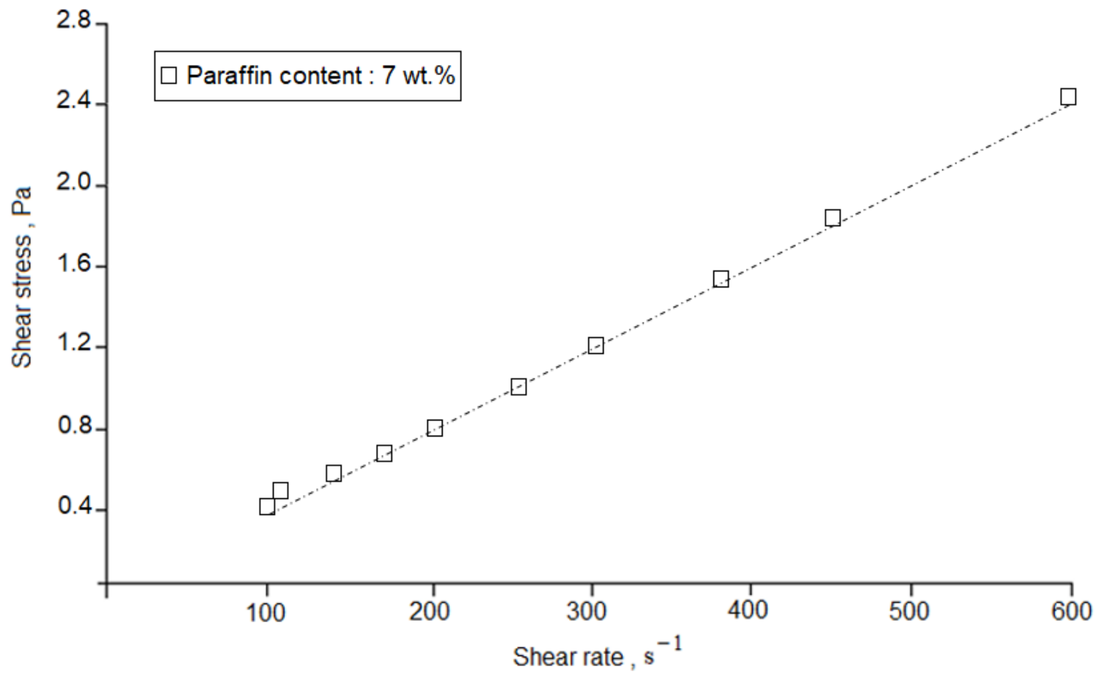

Figure 2-b. Flow curve for reference crude oil with 7 wt. % paraffin content at 26°C

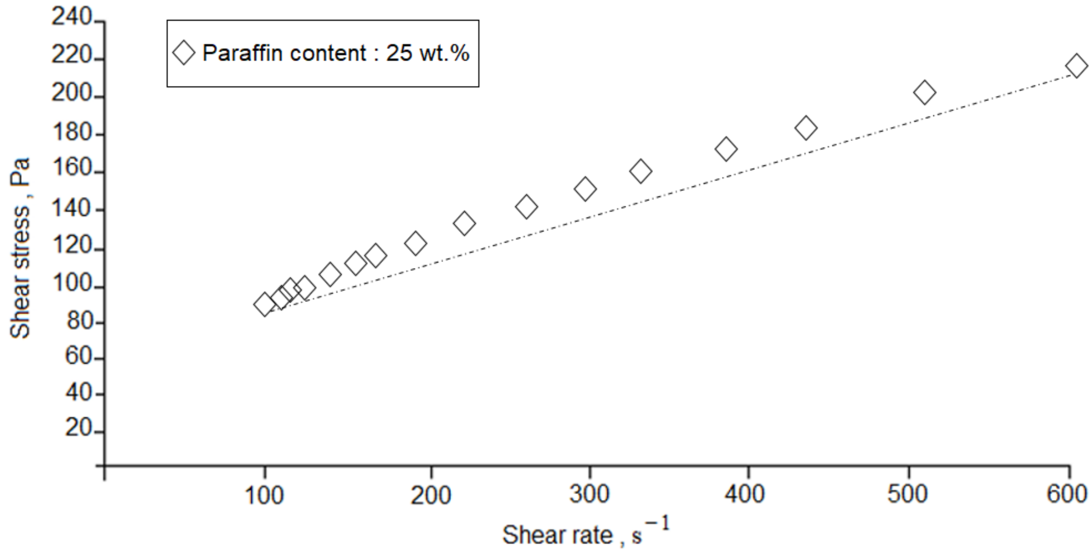

Figure 2-c. Flow curve for reference crude oil with 25 wt. % paraffin content at 22°C

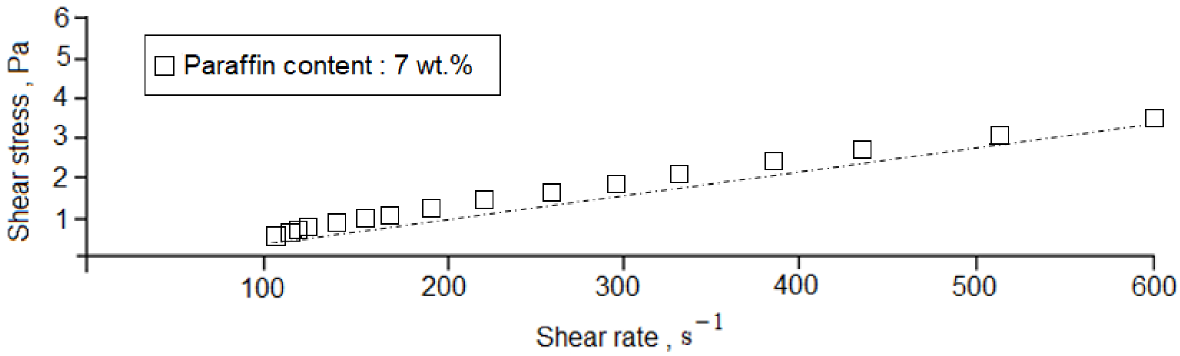

Figure 2-d. Flow curves for reference crude oils with 7 wt. % paraffin content at 22°C

As can be seen in Tables 3 and 4 and Figure 2, for a given paraffin content, shear stress increases as shear rate increases. As paraffin content increases, shear stress increases at a given shear rate. As can be observed from Figure 2, changes in paraffin contents of the reference crude oils significantly affect flow curves, i.e., the increase in the paraffin content results in the transfer of the flow curves to higher stress levels. Therefore, indicating an increase in the strength of the internal structure of the fluid with higher content of paraffin. In fact, this structure is dependent on a strong gel network in crude oil, which is responsible for changing the rheological behavior of the fluid. In this situation, the rheological behavior of crude oil is characterised by relative high complexly dependence on its shear rate.

At 26°C, as the paraffin content of reference crude oil decreases, its non-linear flow curve tends into a diagonal line. In other words, the reduction of paraffin content leads to a relatively linear relationship between the shear stress and shear rate and the rheological profile of reference crude oil approaches a Newtonian profile. At this temperature, changes in the paraffin content of the reference crude oils have a significant effect on their rheological behavior.

At 22°C, by increasing the paraffin content, the flow curve moves to higher shear stress levels, indicating an increase in the strength of the paraffinic structure of the fluid. At this temperature, the reference crude oil A has a non-linear flow curve with very low curvature.

As stated earlier, the fluid flow curve can be approximated by the Power law equation. This equation is normally represented by $\tau = k(\gamma)^n$ where k is the coefficient of strength or the fluid consistency index in Pa.s^n, which is numerically equal to the shear stress in the shear rate of 1s^{-1}; also n is known as the fluid behavior index or the Power law index. Both parameters are experimentally determined in a wide range of shear rates and specific temperatures [18]. Accordingly, by fitting the flow curves (Figures (2-*a*), (2-*b*), (2-c) and (2-d)) obtained from the shear-rotary tests, to the Power law equation, the flow equation indices for each of the samples can be obtained. Tables 5 and 6 present the indices.

Table 5. Power-law indices for reference crude oils at 26°C

Paraffin (wt%.)	n	k
7	0.9953	0.0042
25	0.5109	6.012

Table 6. Power-law indices for reference crude oils at 22°C

Paraffin (wt%.)	n	k
7	0.0067	0.9902
25	8.9012	0.5003

As Tables 5 and 6 show, the flow behavior index approaches 0.50 by increasing the paraffin content, indicating an increase in Pseudoplastic profile. Also, the flow behavior index becomes close to unity, by reducing the paraffin content, indicating the rheological behavior of the reference crude oil will be near-Newtonian behavior as well.

4. Conclusion

The reference crude oils with 7 and 25 wt. % of paraffin contents were considered. The flow curve for each of the reference crude oils was successfully reported by performing the shear-rotary tests in a shear rate range of 100 to 600s^{-1} at 22 and 26°C, and changes in the curves were investigated as well. There is a considerable behavioral difference between the reference crude oils; meanwhile, the shear stress increases with increasing paraffin content.

Since the Psaudoplastic models are used to describe the behavior of the non-Newtonian crude oils, therefore by fitting the flow curves obtained from the shear-rotary tests to the Power law model, the model indices for each of the paraffin crude oils were successfully approximated. By applying the obtained indices in the process calculations, it would be possible to analyze the distribution of heat transfer, velocity distribution, flow rate, flow intensity, power consumption and distribution of pressure in different sections of the flow path.

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