Considerations Regarding Rheological Behavior of Some Crude Oils

MARIA STOICESCU*, DORU STOIANOVICI†, ION ONUTU†, GEORGETA STOIANOVICI‡

1Petroleum-Gas University of Ploiesti, 39 Bucuresti Blv., 100680, Ploiesti, Romania
2ICPE-CA, Bucuresti, 313 Splaiul Unirii, 030138, Bucharest, Romania

The paper presents the experimental research results which the Romanian crude oils type B were subjected to. Tests conducted in laboratory environment aimed determination of crude oils rheological parameters and also identification of rheological behaviour models. Experiments, conducted at different temperatures, led to rheological behaviour models characteristic of non-Newtonian fluids. The established rheological relations help to better understanding of tested fluids so we can know either their behaviour or how we could impose their behaviour according to our needs.

Keywords: crude oil, rheological model, viscosity, shear stress, Bingham plastic fluid, fluid model

In practice, knowledge materials behaviour subjected to external mechanical stresses is of particular interest, from which fluid flow is of a special importance for oil industry. Flow is a process of fluid deformation whose quantitative description is based on the equation linking the stresses which the fluid is subjected to by its properties and the size of the induced effects - constitutive or rheological equation, respectively. Similar to the equation of state, the rheological equation is specific to a class of fluids or even to a single fluid because the material coefficients of these equations depend on its nature and they are experimentally established [1].

It is known that crude oils are complex mixtures of aliphatic and aromatic hydrocarbons, oxygen, nitrogen and sulphur, which can also include resins and asphaltenes. Crude oils considerably vary depending on their chemical composition, each of them being an unique mixture of different compounds. With a density of approx. 830 kg/m³ and a content of approx. 0.2% sulphur, crude oils analysed in this paper are considered to be of good quality on international markets. In table 1 is presented their composition [2].

![Fig. 1. Rheotest 2](image)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>B TYPE CRUDE OIL COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td><strong>Concentration, %</strong></td>
</tr>
<tr>
<td>Saturated hydrocarbons</td>
<td>38 ± 20</td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td>27.5 ± 15</td>
</tr>
<tr>
<td>Resins</td>
<td>12 ± 5</td>
</tr>
<tr>
<td>Asphaltenes</td>
<td>3.5 ± 1.5</td>
</tr>
</tbody>
</table>

Components of these crude oils evaporate, a crude oil of Class C or D could result [3]. Table 2 presents the main physico-chemical characteristics of the analysed crude oils.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>PHYSICO-CHEMICAL CHARACTERISTICS OF THE CRUDE OILS TYPE B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
<td><strong>Values</strong></td>
</tr>
<tr>
<td>Density at 20 °C, kg/m³</td>
<td>830 ± 30</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>&lt; 23</td>
</tr>
<tr>
<td>Pour point, °C</td>
<td>-15 ± 22</td>
</tr>
<tr>
<td>Kinematic viscosity at 20 °C, m²/s x 10⁴</td>
<td>2.1 ± 10.7</td>
</tr>
<tr>
<td>Total sulphur content, mass %</td>
<td>0.20 ± 0.15</td>
</tr>
</tbody>
</table>

Experimental part

Crude oils samples of 10 mL each were used to establish the behaviour laws for each fluid whose physico-chemical characteristics were presented in table 2. The experiments were conducted within the General Hydraulics Laboratory of Petroleum-Gas University of Ploiesti using a RHEOTEST 2 viscometer (fig. 1).

* email: stoicescu.maria@yahoo.co
It was used the measurement system corresponding to the device with two coaxial cylinders, the test substance being placed in the annulus space [4-6]. Tangential tension, \( \tau \), shearing rate, \( \frac{dv}{dy} \) and dynamic viscosity, \( \mu \), were determined based on the records achieved during tests [7, 8].

**Results and discussions**

**Rheological behaviour in terms of shear stress and shear rate**

Figures 2, 3, 4 illustrate the rheograms of the three crude oils samples at temperatures between 0 and 20°C. The obtained results indicate a linear behaviour corresponding to a Bingham linear equation [4, 8-11] that relates tangential tension on the shear rate, \( \tau = f\left(\frac{dv}{dy}\right) \), respectively,

\[
\tau = \tau_0 + \eta \frac{dv}{dy}, \text{ dyn/cm}^2
\]

where \( \tau_0 \) is the shear stress threshold and \( \eta \) is the plastic viscosity; these represent the rheological constants of the model.

An exception is the Z1 crude oil behavior at temperatures of 15.2 and 19.5 °C, when it corresponds to Ostwald de Waele model (power law) [5, 11],

\[
\tau = K \left(\frac{dv}{dy}\right)^n, \text{ dyn/cm}^2
\]

where \( K \) is the consistency index having an average value \( K_0 = 37 \) and \( n \) is the behaviour index having an average value \( n_m = 0.73 \), indicating a pseudo-plastic behaviour.

Having fairly close values, average values of the two behaviour indices have been calculated.

Table 3 presents the average values of the rheological constants corresponding to the Bingham model at test temperatures. Rheological constants values estimated by least squares method both vary from one crude oil to another, and from one temperature to another. \( \tau_0 \) ranges from 745 dyn/cm\(^2\) to 1450 dyn/cm\(^2\) and plastic viscosity ranges from 4 dyn/cm\(^2\) to 10 dyn/cm\(^2\).

**Table 3**

<table>
<thead>
<tr>
<th>( \Gamma ), °C</th>
<th>( \tau_0 )</th>
<th>( \eta )</th>
<th>( \mu_0 )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1164</td>
<td>8.3</td>
<td>38.33</td>
<td>-0.19</td>
</tr>
<tr>
<td>5</td>
<td>764</td>
<td>7.1</td>
<td>26.67</td>
<td>-0.17</td>
</tr>
<tr>
<td>10</td>
<td>1056</td>
<td>5.5</td>
<td>42.00</td>
<td>-0.27</td>
</tr>
<tr>
<td>15</td>
<td>790</td>
<td>5.1</td>
<td>20.00</td>
<td>-0.18</td>
</tr>
<tr>
<td>20</td>
<td>871</td>
<td>4.5</td>
<td>20.00</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

Table 4 presents tangential tension values at different temperatures established from experimental records, those calculated using the average values of the rheological constants and also the related relative errors. As a rule, the calculated shear stress values were higher than those experimentally determined. However, the experimental value at 15°C is slightly higher than the calculated value. As it can be seen, the errors for \( \tau \) are very small, varying from -0.026 to 3.329 %.

**Rheological behaviour in terms of apparent viscosity and shear rate**

Rheological behaviour of these crude oils was similarly approached in terms of viscosity. Being non-Newtonian fluids, figures 5-7 presents the apparent viscosity variation depending on shear speed, \( \mu = f\left(\frac{dv}{dy}\right) \), for the three crude oils, generally resulting functional relations of power law type,

\[
\mu = \mu_0 \left(\frac{dv}{dy}\right)^m, \text{ cP}
\]

where:

- \( \mu_0 \) and \( m \) represent the power law parameters.
- \( \mu_0 \) ranges from 15 to 60 and \( m \) ranges from -0.28 to -0.12.
Exceptions are the Z1 crude oil behaviour at 15 °C, a linear behaviour of the type:

$$\mu = \mu_0 + m \frac{dv}{dx}, \text{ cP}$$  \hspace{1cm} (4)

and at 19.5 °C, an exponential behaviour of the following type:

$$\mu = \mu_0 e^{n \frac{dv}{dx}}, \text{ cP}$$  \hspace{1cm} (5)

and also the Z3 crude oil behaviour at 10 °C, a 2nd degree polynomial behaviour of the type:

$$\mu = a \left(\frac{dv}{dx}\right)^2 + b \frac{dv}{dx} + c, \text{ cP}$$  \hspace{1cm} (6)

and at 20°C, a linear behaviour of the type shown for Z1 crude oil.

The above table 3 presents the average values of the rheological constants corresponding to the power law model at test temperatures.

Table 4 presents viscosity values at different temperatures established both from experimental records and calculated using the average values of the power law parameters and also the related relative errors. It was found that the calculated viscosity values were higher than those experimentally determined. As it can be seen, the errors for viscosity are also very small, varying from 0.107 to 6.74 %.

### Influence of temperatures on the shear stress and on dynamic viscosity

Figure 8 shows the variations of shear stress and dynamic viscosity with temperature. Test temperatures ranges from 0 to 20 °C in order to avoid light fractions evaporation and their quality modification. Decreased values were recorded for both characteristics with increasing temperature [3-5].

For both analysed parameters, the recorded values correspond to a 2nd degree polynomial trend of the type

$$\tau = AT^2 + BT + C, \text{ dyn/cm}^2$$  \hspace{1cm} (7)
and
\[
\mu = A'T^2 + B'T + C', \text{ dyn/cm}^2 \quad (8)
\]

where \( A, B, C, \) and \( A', B', C' \) respectively, are numerical coefficients that can be experimentally determined.

By numerical treating of the recorded data using least squares method, the constants \( A, B, C, \) and \( A', B', C' \) respectively, and also the standard deviation \( (R^2) \) are indicated in table 5.

It can be seen that, in general, excepting the above mentioned cases, the three samples show similar rheological behaviours for different temperatures. Experimental results shown as rheogramms have clearly established that the analysed crude oils have a non-Newtonian rheological behaviour of Bingham type.

Conclusions

The general objective of this paper is to test rheological properties of the crude oils type B from three different reservoirs and to establish a rheological average behaviour model by which a similar crude oil to be characterized. The rheological model characteristics for the analysed crude oils corresponds to a non-Newtonian fluid with two rheological constants. It is about the rheological model characteristics to a Bingham plastic fluid. Physically, such behaviour could be explained by the presence of very large molecules and/or by the existence of specific interactions between them, creating a poor solid structure whose breaking a particular stress is needed for.

The verification of rheological model corresponding to crude oils type B average behaviour, using experimental established values, indicates a good matching with the calculated values. The registered errors are small, sometimes differences between the calculated and experimental values are sufficiently small to be neglected (e.g. at 15 and 20°C respectively). Higher values of the relative error were registered at low temperatures (e.g. at 0°C).

Also, for the analysed domain, the rheological parameters variation with temperature indicates charts corresponding to 2nd degree polynomial functions.

References

3.*** https://www.epa.gov/emergency-response/types-crude-oil
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Table 5
VALUES OF THE COEFFICIENTS OF SHEAR STRESS AND SHEAR SPEED POLYNOMIAL LAWS

<table>
<thead>
<tr>
<th>Crude oil</th>
<th>( \tau, \text{ dyn/cm}^2 )</th>
<th>( \mu, \text{ cP} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Z1</td>
<td>8.6995</td>
<td>-405.14</td>
</tr>
<tr>
<td>Z2</td>
<td>8.2543</td>
<td>-264.11</td>
</tr>
<tr>
<td>Z3</td>
<td>6.6374</td>
<td>-319.68</td>
</tr>
</tbody>
</table>