Effect of pressure, temperature and gas phase composition on the rheological properties of heavy crude oil

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Abstract. Influence of pressure, temperature and the nature of gas on the viscosity of heavy crude oil from the Tatarstan field was studied using rheology method (rheometer MCR 302). The effect of temperature from 25 to 125 °C and pressure from 0.1 to 12.5 MPa on crude oil viscosity was investigated. It was found that an increase in temperature of 125 °C leads to a decrease of viscosity by 8 times. At the same time, an increase of pressure up to 10 MPa leads to an increase in viscosity by 38% at low temperatures. Also the influence of the nature of gas (nitrogen, argon and air) on the viscosity of crude oil at different temperatures and pressures was analyzed. It is shown that crude oil viscosities depend on gas composition. On the other hand, the influence of the composition of binary gas mixtures in a wide range of temperatures and pressures on the viscosity of heavy oil has been studied. The activation energies of flow are calculated for two types of gas mixture. It is shown that the gas phase at different ratios of the components does not significantly affect the rheological parameters of crude oil.

1. Introduction.

The recovery of heavy crude oil across the world grows due to the severe depletion of traditional light oil reserves. Heavy crude oils and bitumens present about a quarter of total hydrocarbon resources [1, 2]. Russia along with Venezuela and Canada own largest discovered deposits of heavy crude oil in the world [3]. A third part of heavy crude oil and bitumen reserves of Russia is located in Tatarstan. The production of hydrocarbons from heavy oil fields is limited by high viscosity of crude oils and bitumens, which does not allow using conventional methods of recovery. Therefore, methods and technologies, which can help to reduce viscosity inside the reservoir, have great practical interest. In order to increase
The efficiency of heavy oil recovery different technologies can be used like gas injection [4–6], thermal treatment [7] and chemical flooding [8, 9].

A viscosity is important parameter which determines possibility of the extraction of heavy crude oils by these methods. On the other hand, it is known that the viscosity of crude oil substantially depends on the gas phase. Therefore, the aim of the work was to study the effect of the gas phase on the viscosity of heavy crude oils at different pressures and temperatures. The influence of the nature and composition of gas mixtures on the rheological characteristics is analyzed and the activation energy of flow is estimated. The influence of nature of gas in mixture on viscosity is discussed.

2. Experimental part.

2.1 Physical-chemical properties of crude oil.

Measurements of viscosity, density and API-gravity (American Petroleum Institute Gravity) of oil samples were carried out on Anton Paar SVM 3000 Stabinger viscometer at 20 °C. Crude oil was thoroughly stirred before measuring. Water content determined by Karl Fischer titration was shown not to exceed 0.05 wt%. Dynamic viscosity of crude oil from one of the Tatarstan oilfields was measured to be 2480 mPa·s. Density and API-gravity was measured to be 0.9617 and 15.2 correspondingly [10].

2.2 Viscosity of crude oil at reservoir temperature and pressure

Viscosities of heavy crude oil samples at simulated reservoir conditions (high pressure and high temperature) were measured using Physica MCR302 rheometer (Anton Paar, Austria) equipped with pressure cell up to 150 bar with two measuring geometries. Sample volume of CC25/PR concentric cylinders geometry was 15 ml. The rheometer was checked at different pressures and temperatures on reference fluid squalane (C₃₀H₆₂), which was purchased from Sigma-Aldrich (purity over 99 wt%). A good agreement between obtained experimental and literature values is observed [11–15]. The apparatus and experimental procedures have been described in detail in our previous publication [10].

3. Results and discussion
3.1. Influence of pressure and gas nature on the viscosity of heavy crude oils.

The effect of pressure and temperature on the viscosity of crude oil in a nitrogen atmosphere was studied. Measurements were carried out in a wide range of temperatures from 25 to 125 °C and pressures from 0.1 to 10 MPa, Table 1.

| Pressure, MPa | \( \eta_{25} \) | \( \eta_{50} \) | \( \eta_{75} \) | \( \eta_{100} \) | \( \eta_{125} \) |
|---------------|----------------|----------------|----------------|----------------|----------------|
| 0.1           | 1600           | 225            | 69             | 32             | 23             |
| 2.5           | 1757           | 234            | 74             | 34             | 23             |
| 5.0           | 1896           | 249            | 81             | 37             | 24             |
| 7.5           | 2054           | 266            | 87             | 38             | 23             |
| 10.0          | 2214           | 283            | 91             | 40             | 22             |

Strong dependence of crude oil viscosity from the temperature was observed. Increasing of temperature from 25 to 50 °C leads to decreasing of viscosity in 8 times (Table 1). Increasing of pressure from 0.1 to 10.0 MPa leads to increasing of viscosity by 38% at 25 °C. It should be pointed out that crude oil viscosity does not depend on pressure at 125 °C (Table 1). Since viscosity is highly dependent on pressure, it is necessary to investigate the effect of the gaseous medium on the physical-chemical properties of heavy crude oils. Thus, we analyzed the influence of the gaseous medium (argon, nitrogen and air) on the viscosity of crude oils at 25 °C, Table 2. The viscosity in nitrogen and air atmosphere was found to be close, in contrast to argon medium.

| Pressure, MPa | \( \eta_{N_2} \) | \( \eta_{Ar} \) | \( \eta_{Air} \) |
|---------------|----------------|----------------|----------------|
| 2.5           | 1674           | 1704           | 1686           |
| 5.0           | 1809           | 1826           | 1836           |
| 7.5           | 1958           | 1973           | 1985           |
3.2. Effect of gas mixture composition on crude oil viscosity. Estimation of the activation energy of flow.

In order to determine the effect of the gas phase composition on the viscosity of crude oil samples, gas mixtures of carbon dioxide (1) with oxygen (with a molar/volume fraction of carbon dioxide $x_1$ in the range from 0.4 to 1) and nitrogen (1) with oxygen (with a molar/volume fraction of nitrogen $x_1$ in the range from 0.6 to 1) were employed. For all gas mixtures, pressures of up to 15 MPa were chosen, with the exception of the atmosphere of pure carbon dioxide, in which the pressure did not exceed 6 MPa, due to the transition of the gas into the liquid phase. Results are presented in Tables 3, 4 and in Figures 1, 2.

**Table 3.** The dependence of crude oil viscosity (mPa·s) from the composition of the gas mixture CO$_2$(1) – O$_2$.

| $x_1$ | 0.4 | 0.6 | 0.8 | 1 |
| --- | --- | --- | --- | --- |
| Pressure, MPa | 3 | 9 | 15 | 3 | 9 | 15 | 3 | 9 | 15 | 3 | 6 |
| Temperature, °C | | | | | | | | | | | |
| 30 | 1079 | 1302 | 1535 | 1093 | 1314 | 1550 | 1106 | 1328 | 1571 | 1110 | 1197 |
| 45 | 368.9 | 447.4 | 529.3 | 372.5 | 451.8 | 534.5 | 379.0 | 459.5 | 543.5 | 378.3 | 410.1 |
| 60 | 144.0 | 174.5 | 206.5 | 145.4 | 176.2 | 208.5 | 147.8 | 179.2 | 211.9 | 147.7 | 159.9 |
| 75 | 75.1 | 88.7 | 105.0 | 73.8 | 89.6 | 106.0 | 75.1 | 91.1 | 107.8 | 74.9 | 81.3 |
| 90 | 36.3 | 44.0 | 52.0 | 36.6 | 44.4 | 52.5 | 37.2 | 45.2 | 53.4 | 37.2 | 40.3 |
| 105 | 21.0 | 25.5 | 30.1 | 21.2 | 25.7 | 30.4 | 21.6 | 26.1 | 30.9 | 21.6 | 23.3 |
| 120 | 12.8 | 15.0 | 17.3 | 12.5 | 15.2 | 17.4 | 12.5 | 15.5 | 18.4 | 11.9 | 13.1 |
| 135 | 6.9 | 8.4 | 9.9 | 6.9 | 8.4 | 10.0 | 7.1 | 8.6 | 10.2 | 7.1 | 7.7 |
| 150 | 4.1 | 4.8 | 5.8 | 4.2 | 4.8 | 5.8 | 4.2 | 4.9 | 5.9 | 4.2 | 4.6 |
Table 4. The dependence of crude oil viscosity (mPa·s) from the composition of the gas mixture N$_2$(1) – O$_2$.

| $x_1$ | 0.6 | 0.8 | 1   |
|-------|-----|-----|-----|
| Pressure, MPa | 3 | 9 | 15 | 3 | 9 | 15 | 3 | 9 | 15 |
| Temperature, °C | | | | | | | | | |
| 30    | 1103 | 1326 | 1564 | 1104 | 1326 | 1568 | 1101 | 1335 | 1570 |
| 45    | 375.9 | 455.9 | 539.3 | 378.3 | 458.7 | 542.5 | 375.8 | 455.9 | 539.4 |
| 60    | 146.7 | 177.8 | 210.4 | 147.5 | 178.9 | 211.6 | 146.8 | 177.8 | 210.6 |
| 75    | 74.5 | 90.4 | 107.0 | 75.0 | 90.9 | 107.6 | 74.4 | 90.4 | 107.0 |
| 90    | 36.9 | 44.8 | 53.0 | 37.2 | 45.1 | 53.3 | 36.9 | 44.8 | 53.0 |
| 105   | 21.4 | 26.0 | 30.6 | 21.5 | 26.1 | 30.9 | 21.4 | 26.0 | 30.6 |
| 120   | 12.6 | 15.3 | 17.6 | 12.5 | 15.5 | 18.4 | 12.3 | 15.2 | 18.1 |
| 135   | 7.0  | 8.5  | 10.1 | 7.1  | 8.6  | 10.1 | 7.0  | 8.5  | 10.1 |
| 150   | 4.2  | 4.9  | 5.9  | 4.2  | 4.9  | 5.9  | 4.2  | 4.9  | 6.0  |

From Tables 3, 4 and Figures 1, 2 it can be concluded that the composition and nature of the gas phase has little effect on the viscosity of crude oil samples without a catalyst. The main factors affecting viscosity are temperature and pressure.
**Figure 1.** Effect of temperature and pressure on the viscosity of crude oil in the atmosphere CO₂–O₂ (60:40): dashed line – 3 MPa; solid line – 9 MPa; dotted line – 15 MPa.

**Figure 2.** Effect of temperature and pressure on the viscosity of crude oil in the atmosphere N₂–O₂ (60:40): dashed line – 3 MPa; solid line – 9 MPa; dotted line – 15 MPa.

In order to estimate the intermolecular interaction energy of the studied crude oil, the values of the activation energy of flow \( E_{act}^{flow} \) were calculated. The activation energy of flow is usually determined by the Frenkel–Andrade equation

\[
\eta = A e^{\frac{E_{act}^{flow}}{RT}}
\]

where \( \eta \) – viscosity; \( A \) – pre-exponential factor considered independent of temperature; \( R \) – gas constant; \( T \) – absolute temperature, K.

The results of calculation are shown in Table 5.

**Table 5.** Activation energy of flow of crude oil.

| Sample                  | \( E_{act}^{flow} \) · kJ/mol |
|-------------------------|-------------------------------|
| Crude oil               | 20.8                          |
| medium N₂–O₂ (60:40)    | 3 MPa                         |
|                         | 21.0                          |
The activation energy of flow was found to be practically the same in different gas mixtures.

4. Conclusions

The effect of pressure, temperature and gas nature on the viscosity properties of heavy crude oil from the one heavy oil field of Tatarstan has been studied. The influence of temperature from 25 to 125 °C and pressure from 0.1 to 10 MPa on the viscosity of crude oil has been established. It was found that an increase in temperature by 125 °C leads to a decrease in viscosity by 8 times. While an increase in pressure up to 10 MPa leads to an increase in viscosity by 38% at low temperatures. The influence of the nature of gas (nitrogen, argon and air) on the viscosity of crude oil at different temperatures and pressures was analyzed. On the other hand, the influence of the composition of gas mixtures in a wide range of temperatures and pressures on the viscosity of heavy crude oil has been studied. The activation energies of flow state for two gas mixtures are calculated. It is shown that the gas phase at different ratios of components does not significantly affect the rheological parameters of crude oil.

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