Field oil viscometer and methods for calculating viscosity of water-cut fluids

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Abstract. A field oil viscometer is developed and certified for measuring the viscosity of water-cut oil sampled from a well manifold line or a field pipeline. A method is proposed for calculating oil viscosity differing in standard water-cut based on a single well measurement, regardless of the water-cut of a fluid and its temperature. The viscosity of standard water-cut oil is measured when a sampled dry crude oil is degassed to atmospheric value.

1. Introduction
One of the major contributing factors for the profitability of oil fields developed is the viscosity of a fluid [1–8].

First production of high-viscosity oil fields in the Ural-Volga region and other regions of the Russian Federation requires reliable evidence on wellhead oil viscosity and that in various sections of oil collection and commercial oil production systems.

Both water-free and water-cut viscosity measurements are used to design mechanized well operations, to construct and operate field pipelines and other oil production facilities.

There are few tools for measuring the viscosity of a fluid in the fields. Viscometers (Reotests) available measure the viscosity at atmospheric pressure in laboratory settings in the long term after sampling.

2. Methods and materials
Therefore, making a viscometer able to measure the viscosity of a pressurized fluid at a sampling point with the smallest temperature change has long required a solution. To measure the viscosity, a gauge was made able to measure the rolling time of a ball in a calibrated tube (Höppler device), pre-tated with a reference fluid [9]. The viscometer is used to quickly monitor well production beyond the State Control for Measurement Uniformity Assurance.
The measurement procedures were developed in accordance with the provisions of GOST R 8.563, GOST R ISO 5725-2. The viscometer is certified (accreditation certificate No. RA.RU/310652; state registration No. FR.1.31.2019.32427).

A metal ball rolls down an inclined calibrated tube. The running time of the ball is fixed and measured by a timer (stopwatch). It measures the rolling time of the ball between two magnets on the outer side of the tube using reed switches also mounted on the outer side of the tube in the same section as the magnets.

A technique to measure oil viscosity in the field implies extracting a pressurized fluid from a pipeline or a production vessel with a flexible high-pressure hose. Then, a pipeline valve and an inlet valve of the device are gradually opened. When the cavity of the viscometer is filled with the target liquid with partially open inlet valves, the free gas is vented into the atmosphere under pressure through an outlet valve of the device. To equalize the temperature in the pipeline and in the viscometer housing, when the outlet valve is partially closed, the liquid is drained from the device at a rate of three times the replaced volume of the viscometer cavity. Next, the gas is finally bled out through the outlet valve, both valves (inlet and outlet) and the pipeline valve are completely shut off, the device, together with the hose, is completely disconnected, transferred to a mobile laboratory and installed on a stand for measurements. A calibrated tube is placed inside the housing. The said calibrated tube is axially rotated in the housing with a drain plug downwards and is cut off by a locking element in the expansion part of the device once the liquid has been collected and the free gas has been removed. The rolling time of the ball in the calibrated tube is measured at various angles the viscometer body is inclined to the vertical. The body of the device and the calibrated tube are made of non-magnetic material.

The dynamic viscosity of a liquid is calculated from the source data on ball and liquid density differences, the coefficient for each tilt angle of the gauge, and the time the ball travels from one sensor to another.

The device is calibrated on a reference liquid at different tilt angles to obtain constant coefficients that are put into the scheme for calculating the viscosity. An assembly drawing of the viscometer is shown in Fig. 1.

Through valve 12 and flexible high pressure hose 17 viscometer 1 is hermetically connected to sampling valve 11 installed in well manifold line 5. Valve 13 remains closed during this period. Then, valve 11 is opened and inlet valve 12 begin to slowly open. As soon as manometer 14 reaches its maximum value, outlet valve 13 begins to slowly open. With the liquid starting to pour out of valve 13 under pressure, thus indicating that the cavity of the device is filled, it continues blowing off for some time with a threefold change in the volume of the cavity of the device. The procedure is performed to equalize the temperature of the liquid in manifold 10 and in the cavity of the device. Thereafter, free petroleum gas is released from the viscometer cavity under pressure as well. Further, outlet valve 13 is closed. Then valves 12 and 11 are closed, and hose 17 is disconnected from valve 11.

The gauge is then brought into a mobile laboratory outside the explosive zone and installed on a vertical stand enabling to rotate and fix it at various tilt angles to the vertical. The vessel is shaken repeatedly to homogenize collected oil samples. Electronic cartridge 9 is connected to the viscometer.

Once mounted on the stand, the device is repeatedly turned around to stir the water-oil mixture, after which rod 16 with a shut-off valve closes capillary tube 2.

The viscometer is installed obliquely at an angle of 30° or 45° or 60°. In the shortest possible time, the vessel is turned through an angle of 180°, causing ball 3 to roll down tube 2 and pass through permanent magnets 5 and 6 during which magnetic field (pulse) changes, and the timer fixes a time interval between the two pulses when the ball passes from magnet 5 to magnet 6. The timer records the time the ball passes from one magnet to another.

Then, the vessel is turned through an angle of 180° to restore the ball to its starting position. By switching cartridge 9, it is possible to measure in the opposite direction. As soon as the ball passes through both magnets, the indicator of block 9 displays the viscosity of the measured medium.
Fig. 1. Viscometer: 1 – housing; 2 – calibrated tube; 3 – ball; 4 – drain plug; 5, 6 – permanent magnets; 7, 8 – reed switches; 9 – electronic cartridge; 10 – well manifold; 11 – sampling valve; 12, 13 – inlet and outlet valves; 14 – manometer; 15 – thermometer; 16 – rod with shutoff valve; 17 – flexible high pressure hose

Figures 2 and 3 show the arrangement of magnets and reed switches in the device.

Fig. 2. The principle of measuring the rolling time of a ball in a calibrated tube
The stainless steel housing has permanent magnets mounted on one side and reed switches on the other side. When the steel ball passes through the first reference point, the magnetic field generated by the permanent magnet is transmitted to the reed switch through the steel ball, and it closes, thereby sending a pulse signal to start the stopwatch. When passing the second checkpoint, a signal is sent to stop the stopwatch. The measurement result is displayed on the stopwatch screen.

The dynamic viscosity of oil ($\mu_i$, mPa·s) measured by the viscometer in the i-th sample taken with a 0° inclination of the tube is calculated by the formula

$$\mu_i = T_{av} \cdot (\rho_b - \rho_o) \cdot F,$$

where $T_{av}$ is the time the ball travels from one magnet to the other, s; $\rho_b$ is the density of the ball, kg/m$^3$, taken equal to 7,839 kg/m$^3$; $\rho_o$ is oil density measured by a liquid density measuring instrument, at a sampling temperature, kg/m$^3$; $C$ is the constant (factor) of the viscometer, set when calibrating the viscometer, given in the Table.

### Table 1. Values of constants

| Viscometer tilt angle | 30°     | 45°     | 60°     |
|-----------------------|---------|---------|---------|
| C (device factor)     | 0.000039170 | 0.000055026 | 0.000067380 |
The result of viscosity measurements ($\mu$, mPa·s) is the arithmetic mean value for five measurements of viscosity

$$\mu = \frac{\mu_1 + \mu_2 + \mu_3 + \mu_4 + \mu_5}{n},$$

where $\mu_1$, $\mu_2$, $\mu_3$, $\mu_4$, $\mu_5$ are measured viscosity values, mPa·s; $n$ is the number of measurements equal to 5. Cartridge 9 calculates the average viscosity from five measured values.

When taking a fluid sample from the manifold line of the well or from the reservoir, the temperature of the fluid inside the tube is simultaneously recorded by measuring the rolling time of the ball.

There are two methods for measuring the viscosity of well fluids in an oil field. The first involves measuring the viscosity of water-cut oil having residual pressurized gas at a sampling point. To do this, a sample is taken and released from free gas by venting it into the atmosphere under pressure during the sampling process. In winter, the viscometer is brought into a mobile laboratory for measurements directly near the well. The measured viscosity will correspond to these specific values of water cut, pressure and fluid temperature for subsequent use in calculations.

The other method implies obtaining the values of the water-cut oil viscosity under standard conditions, i.e. at $T = 20 \degree C$ and pressure $P = 0.101$ MPa. Thus, this method involves degassing the sample to atmospheric value following a gas release from oil samples in the instrument into the atmosphere. The calculations should also involve the water-cut of oil, which significantly affects its viscosity. As a result, it is required to predict the viscosity at different temperature and water-cut values against the measured value of the viscosity at some arbitrary point.

Let us dwell on this method.

The studies [10] indicate that the effect of oil water cut on its viscosity can be calculated using the Richardson formula:

$$\mu = A \exp (CB),$$

where $\mu$ is the viscosity of water-free oil mPa·s; $A$, $C$ are the experimental factors depending on physical and chemical properties of oil; $B$ is the oil water cut, unit fraction.

The value of the factor “$C$” for each oil field is determined experimentally. Moreover, this coefficient depends on the oil temperature. A combined effect of temperature and oil water cut must be investigated in laboratory settings to derive a universal dependence of the fluid viscosity on these parameters.

The studies are based on the idea that logarithmic viscosity-temperature relation is invariant against the water cut of a liquid. In other words, on the graph temperature-viscosity dependences at different water cut are lines with approximately the same inclination to the axes.

Studying emulsions, water-free oil can be taken as a reference fluid. When the viscosity of water-cut oil is studied, the invariance is supposedly caused by the constancy of physical and chemical properties that a continuous phase (oil) has in “water-in-oil” reverse emulsions varying in water cut. When oil water-cut values are more than 0.65–0.70, the phases get inverted and the described approach to calculations becomes impossible. As for a range of fluid temperature variation, 55 °C is taken as its maximum value. On the one hand, the wellhead oil temperature in most of the RF fields does not exceed this value, on the other hand, at temperatures above 55 °C, the viscosity of emulsions is decreased, due to partial melting and a reduced thickness of the armor shells of water droplets in emulsions. This increases the coalescence of drops, their enlargement and separation of the phases of the emulsion.

The minimum temperature value in the research corresponded to 15 °C and was achieved on a laboratory setup by thermostating.

A series of laboratory experiments was conducted on oils from three different fields in order to obtain a universal dependence for calculating the viscosity at a standard temperature (20 °C) of oil with different water cut and atmospheric pressure ($P = 0.101$ MPa).

The dependences $\ln \ln \mu = f(T)$ are plotted for emulsions with different water content (0-60%) (Fig. 4, 5 and 6) (double logarithmic viscosity-temperature relation. Figures 7 and 8 show the relationship between $\ln \ln \mu = f(T)$ coefficients and the oil water cut, expressed as a percentage.
Fig. 4. $\ln \ln \mu(T)$ relationship for oil No.1

Fig. 5. $\ln \ln \mu(T)$ relationship for oil No.2
Fig. 6. $\ln\ln\mu(T)$ relationship for oil No.3

Consolidated relationships on 3 oils

Fig. 7. Dependences of the slope (factor $B$) of the $\ln\ln\mu(T)$ curve on the water content in emulsions
3. Results

In total, for three oils, the ln(ln(µ)) curves were used to obtain the equation:

$$\mu = \exp(\exp(A_0 - B_0T + 0.004W))$$  \hspace{1cm} (4)

where W is the content of an aqueous phase in the emulsion, %; T is the temperature of the emulsion, °C; µ is the viscosity of the emulsion, mPa·s; A_0 and B_0 are coefficients from the lnln(µ) = f (T) equation for water-free oil.

The values of the factors A_0 and B_0 in equation (4) are determined experimentally by measuring the viscosity of a sample of water-free oil with a viscometer with oil degassed to atmospheric pressure after sampling the liquid at 4–5 values of its temperature. The measurements are made in the field laboratory by thermostating the selected sample. The resulting viscosity dependence in the lnln(µ) - T coordinates can graphically determine the factors A_0 and B_0 for further calculations. Next, the values T=20 °C, A_0, B_0 and W are substituted into formula (4).

Figures 4, 5 and 6 clearly show the invariance of temperature relations with respect to oil water cut. In order to calculate the viscosity of the water-cut oil under standard conditions using equation (4), it is enough to substitute the values of temperature 20 °C and oil water cut percentage into the formula. In other measurements with a residual amount of dissolved gas, a specific measurement value is taken without degassing a liquid sample to atmospheric pressure.

4. Conclusion

A field oil viscometer was developed and certified for measuring the viscosity of water-cut oil taken from a well manifold line or a field pipeline.

A method is proposed for calculating the viscosity of different water-cut oil under standard conditions based on the results of a single measurement of well viscosity, regardless of the water-cut of the product and its temperature.

References

[1] Economides M, Oligney R, and Valko P 2002 *Unified Fracture Design: bridging the gap between theory and practice* (Alvin, Texas: Orsa Press)
[2] Gabzalilova A Kh, Batalov D A, Mukhametshin V Sh and Andreev V E 2021 Geological and technological justification of the parameters of acid-clay treatment of wells *IOP Conference Series: Materials Science and Engineering* **1064** 012058 DOI: 10.1088/1757-899X/1064/1/012058

[3] Mingulov Sh G, Mingulov I Sh, and Mukhametshin V V 2020 Technological features of pumping water into high-viscosity oil injection wells with the bottom hole pump *IOP Conference Series: Materials Science and Engineering* **952** 012058 DOI: 10.1088/1757-899X/952/1/012058

[4] McLachlan G J 2004 *Discriminant Analysis and Statistical Pattern Recognition* Hoboken (New Jersey: John Wiley & Sons)

[5] Khuzin R R, Mukhametshin V Sh, Salikhov D A, Andreev V E, Pepelyaev D V, Stefanovich Yu N 2021 Improving the efficiency of horizontal wells at multilayer facilities *IOP Conference Series: Materials Science and Engineering* **1064** 012066 DOI: 10.1088/1757-899X/1064/1/012066

[6] Batalov D A, Andreev V E, Mukhametshin V V, and Kuleshova L S 2021 Development regulation of oil and gas reservoirs based on effective geological and geophysical information *IOP Conference Series: Materials Science and Engineering* **1064** 012055 DOI: 10.1088/1757-899X/1064/1/012055

[7] Xie X, Weiss W W, Tong Z J, Morrow N R 2008 Improved Oil Recovery from Carbonate Reservoirs by Chemical Stimulation *SPE Journal* **10**(3) DOI: 10.2118/89424-PA

[8] Malyarenko A M, Bogdan V A, Blinov S A, Kotenev Yu A, Mukhametshin V Sh, and Kotenev M Yu 2021 Improving the reliability of determining physical properties of heterogeneous clay reservoir rocks using a set of techniques *Journal of Physics: Conference Series* **1753** 012074 pp. DOI: 10.1088/1742-6596/1753/1/012074

[9] Planovsky A N, Ramm V N, Katan S Z 1962 Processes and apparatuses of chemical technology (Goskhimzavod)

[10] Valeev M D, Leontiev S A, Mayer A V, Mokhov M A 2018 Theory and practice of pumping production of high-viscosity oil from watered wells (Moscow: Gubkin Russian State University)