METHOD AND INSTRUMENTS TO MEASURE DYNAMIC VISCOSITY OF OIL PRODUCTS IN PIPELINE

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Abstract. The purpose of this paper is to develop a new method to determine the dynamic viscosity of oil products in a pipeline. Its main difference in comparison with the existing methods is that the viscosity can be determined directly in the pipeline, which allows excluding the human factor that occurs, when using the existing methods and measuring instruments, and improving the accuracy of measuring the dynamic viscosity of oil products due to taking into account the cavitation processes inside a pipeline. The gist of a new method lies in the fact that the rotating element – an ellipse that has the form of a spindle – is placed inside a pipeline in a horizontal position and set in motion by an asynchronous electric motor. Determination of the dynamic viscosity of oil products is carried out by measuring the moment of fluid resistance against the motion of an asynchronous electric motor: the higher the dynamic viscosity, the greater the moment of resistance is developed when the ellipse rotates. The main criteria for estimating the dynamic viscosity of oil products are the moment of inertia of the rotating masses of the drive mechanism and their angular accelerations. The developed hardware-software complex with a rotation angle sensor allows registering and processing the measured parameters. The experimental data obtained in the course of the study demonstrated sufficient convergence of the dynamic viscosity values obtained by the developed method and by the existing methods. In future, it is planned to obtain the dependences of the moments of resistance of various types of oil products on the angular velocity of an asynchronous electric motor and, based on the results obtained, determine the range of speeds, at which the greatest measurement accuracy is achieved.

Keywords: dynamic viscosity, rotor-spindle, pipeline, asynchronous electric motor.

Introduction

The use of viscosimeters in oil and gas industry plays an important role in determining the quality of oil and oil products, as well as the cost of their transportation. At the same time, the existing methods do not allow determining the viscosity of oil directly in the pipeline, which complicates control of its quality and cavitation conditions in the pipeline and, as a result, leads to unpredictable losses in oil transportation capacity. At present, depending on the method of measurement, the following types of viscometers are used: capillary, ball, vibration and rotational ones [1-8]. Modern capillary viscometers have a number of disadvantages, which include a long duration of measurements, large overall dimensions, as well as the difficulty of automating the measurement of viscosity [9]. Ball viscosimeters are mainly used for viscosity measurements at high temperatures of the liquid being studied. When opacity of the liquid being investigated, it is necessary to use devices for measuring the speed of falling of the ball, which increases the complexity and cost of the measurement. The use of ball viscometers for automatic measurements has a number of difficulties and requires a special measuring chamber, to which the test liquid must be delivered. Viscometers working on the basis of the vibrational method have a narrow range of measured values. In addition, they cannot be used at high-temperature due to the high relative error that arises in high-temperature viscometry.

In turn, rotational viscometers have become more widespread. Their main advantage over the other ones lies in the ability to carry out continuous measurements in the ease of their automation. However, the existing types of rotational viscometers have a limited lower value of the measured viscosity and a high measurement error due to the inability to take into account the flow of the fluid at the end of the movable cylinder [10-14].

Analysis of the methods for determining the dynamic viscosity of oil and oil products has shown that for further increase of the automation level, vibration and rotational control methods are the most preferable for use. However, the existing ones do not allow high-precision measurements of the dynamic viscosity of oil and oil products directly in the pipeline. The method developed in this article allows determining it with sufficient accuracy due to taking into account the processes of cavitation taking place in the pipeline.

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Materials and methods

The method developed in this article makes it possible to determine the dynamic viscosity of oil and oil products directly in the pipeline and to study their rheological parameters in a wide range of electric motor velocity gradients.

To explain the developed method, we have built a simplified model of a developed viscometer that consists of an ellipse with sharpened ends, a laminar flow maker, flanges, bearing supports, a shaft and an asynchronous electric motor (hereinafter referred to as an electric motor). In the gap between the pipe and the ellipse, the investigated liquid is the oil product. The scheme of the viscometer being developed is shown in Figure 1.

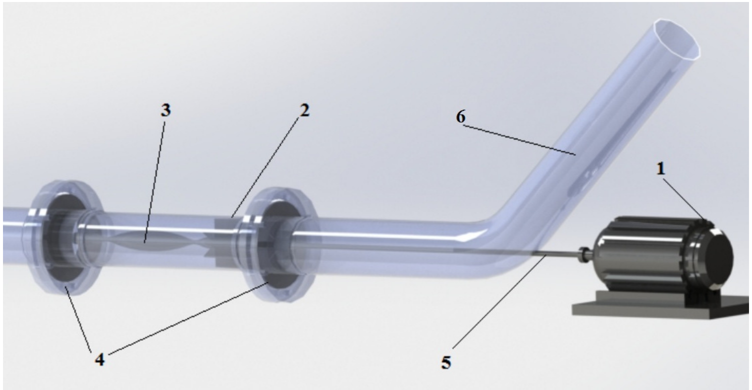

Fig. 1. **Scheme of viscometer being developed:** 1 – asynchronous electric motor; 2 – laminar flow maker; 3 – ellipse with sharpened ends; 4 – couplings, 5 – connecting shaft; 6 – pipeline outlet

The scheme of a rotating ellipse 3 with forces and torques acting on it is shown in Fig. 2.

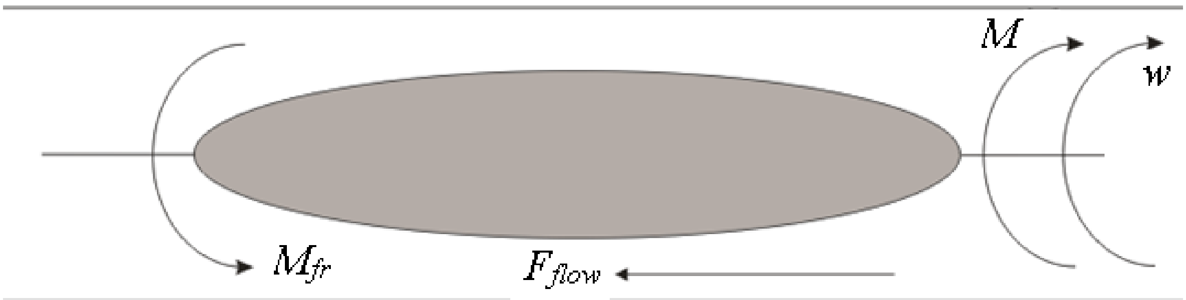

Fig. 2. **Scheme of rotating ellipse with forces and moments acting on it:** M_{fr} – friction torque created by the viscosity of the liquid being studied, kg·m^2; F_{flow} – force of the flow inside the pipeline, N; M – torque developed by an electric motor connected to the ellipse, kg·m^2; ω – angular velocity of the ellipse, rad·s^{-1}

The developed method for determining the dynamic viscosity of oil products is implemented as follows. First, the moment of inertia of all rotating masses (ellipse, elements in bearing supports, connecting shaft, rotating masses of electric motor) is determined taking into account the loss coefficient. The average value of the angular acceleration of the output shaft of the electric motor, ε1, is determined within the selected speed range, which can be in the range from zero to the rated value of the angular velocity. The selection of the speed range depends on the instruments for measuring the angular velocity. Determination of the angular acceleration of the rotor of the electric motor is carried out with the help of an incremental encoder and a hardware and software complex, while the average value of the torque, M, which is developed by the system of rotating masses of the electric motor, is defined as follows:

$$M = (k_{loss} \cdot J_{rmem}) \cdot \varepsilon_1 , \quad (1)$$

where k – coefficient characterizing the mechanical and additional losses in the electric motor;

J_{rmem} – moment of inertia of the rotating masses of the electric motor reduced to the rotation axis of the rotor, kg·m^2;
ε_1 – average value of the angular acceleration of the output shaft of the electric motor at the selected speed range at the first start, rad·s^{-2}.

Then the motor stops and, with the help of fastening elements, a connecting shaft 6 is attached to an ellipse 3, the sum of the moments of inertia of which is known (determined by the method of torsional oscillations or by the calculation method). In this case, the investigated liquid does not flow in the pipeline. The electric motor is started and the value of the angular acceleration, ε_2, of the system of rotating masses "electric motor, ellipse and connecting shaft" is determined within the selected speed range. The average value of the torque, M, which is developed by this system of rotating masses, is calculated as follows:

$$M = (k_{loss} \cdot J_{rmem} + J_r) \cdot \varepsilon_2, \tag{2}$$

where J_r – sum of the moments of inertia of the rotating masses of the connecting shaft and ellipse reduced to the axis of rotation of the rotor of the electric motor, kg·m^2;
ε_2 – average value of the angular acceleration of the output shaft of the electric motor at the selected speed range at the second start, rad·s^{-2}.

Since the losses in the stator and rotor of the electric motor remain unchanged at the first and second starts (since the voltage, the frequency of the mains and the temperature of the electric motor (the resistance of the stator windings) do not change), therefore, the speed-torque characteristic of the electric motor does not change and the right-hand sides of Eq. 1 and Eq. 2 can be equated. Therefore, the moment of inertia of the rotating masses of the electric motor taking into account the loss factor can be calculated as follows:

$$k_{loss} \cdot J_{rmem} = J_r \cdot \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2} \tag{3}$$

In order to determine the viscosity, we fill the pipeline with the test liquid (oil product). When the ellipse rotates, a frictional force will be created between it and the liquid to be studied, which will create a friction torque headed in the opposite direction to the rotation of the ellipse. Then the average value of the torque *M*, which is developed by the system of rotating masses, is calculated as follows:

$$M = (k_{loss} \cdot J_{rmem} + J_r) \cdot \varepsilon_3 - M_{a\kappa}, \tag{4}$$

where M_{fr} – friction torque created by the viscosity of the liquid being studied, kg m^2.

Taking into account Eq. 2 and Eq. 4, the friction torque can be calculated as follows:

$$M_{fr} = J_r \cdot \frac{\varepsilon_1 \cdot (\varepsilon_3 + \varepsilon_2)}{\varepsilon_1 - \varepsilon_2}, \tag{5}$$

Thus, knowing the values of the moments of inertia of the ellipse with the connecting shaft reduced to the axis of rotation of the rotor, it becomes possible to measure only one parameter, namely, the angular acceleration. Determining the friction torque and the area of the parts rotating in the liquid, we can determine its viscosity. Only the third start is supposed to be carried out constantly and, the indications obtained is to be compared with the indications of the first and second starts, which is to be registered by the hardware-software complex of the viscometer.

To implement the developed method, a laboratory bench was created to determine the viscosity of the liquid (Fig. 3).

The test bench consists of an asynchronous single-phase electric motor with a power of 450 W, an encoder characterized by 100 pulses per revolution, a hardware-software complex (HSC), a section of a laminator and a viscometer (pipe diameter is 108 mm), and a drain cock. All of the above elements were installed on a single frame. In the laminator section, an ellipse is mounted on two bearing supports; an asynchronous motor is connected to an ellipse by means of a connecting shaft. The laminator section is needed to fill the test liquid and to create a laminated flow for future experiments. The connecting shaft passes through the laminator section.

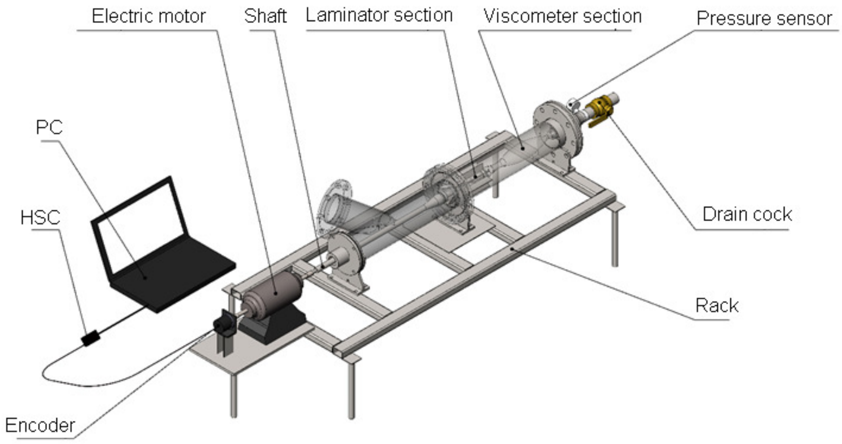

Fig. 3. **Test bench for determining viscosity of liquid**

For statistical processing of the experimental data, the technique of determining the minimum required number of measurements using the Student's t-distribution was used [15]. As a result of experiments and calculations according to this technique, for the determination of the torque with the accuracy of 0.5 %, there were performed two series of experiments, consisting of 10 measurements of the angular acceleration each.

Results and discussion

To confirm the validity of the developed theory, the following experiment was carried out on the basis of the developed test bench.

As it is known, the viscosity of a liquid depends on its temperature [3; 10; 11]. For the study, a liquid with known rheological properties was selected, which is G-Energy 10w-60 oil. The kinematic viscosity of G-Energy 10w at 40 ºC is 60 154 $mm^2 \cdot s^{-1}$.

In the application of the developed method we determined the minimum required number of measurements needed to satisfy the accuracy of 0.5 % [15], and, as a result, 12 measurements were carried out, blunders were eliminated, the average friction torque values were found, and the relative random error values, which were in the range of 0.59 % - 0.75 %, were determined.

With the help of HSC, we carried out 12 starts of an asynchronous electric motor and determined the average value of the angular acceleration of the output shaft of the electric motor at the first start, ε_1.

In the next stage, we determined the moments of inertia of all rotating masses: the moment of inertia of the rotating masses of the electric motor, which was 0.0045 $kg \cdot m^2$; the moment of inertia of the rotating masses of the ellipse and the connecting shaft, which was determined by calculation and was 0.00133 $kg \cdot m^2$; the sum of the moments of inertia of the rotating masses of the entire viscometer, which was 0.00178 $kg \cdot m^2$.

In the next step, we connected the motor to the connecting shaft and conducted a second series of 12 starts of the electric motor (from zero to the rated speed equal to 3,000 rpm), and with the help of HSC we determined the average value of the angular acceleration of the system of rotating masses "rotating masses of the motor, ellipse and connecting shaft" during the second start, ε_2.

Then, we poured 10 liters of G-Energy 10w-60 oil heated to 47 ºC into a test bench through the laminator section. When the oil was cooled to 40 ºC, 12 starts of the electric motor were made and with the help of HSC the average value of the angular acceleration of the system of rotating masses "rotating masses of the electric motor, ellipse and connecting shaft" at the third start, ε_3, was registered. The obtained results are presented in Table 1.

Substituting the values obtained with Eq. 5, we determined the friction torque and the moment of inertia of the viscosity of the liquid under investigation: M_{fr} = 1.6 N·m.

Table 1

Average values of acceleration of a single-phase electric motor and the sum of the moments of inertia of the rotating masses of the viscometer

J_r, kg·m^2	ε_1, rad·s^{-2}	ε_2, rad·s^{-2}	ε_3, rad·s^{-2}
0.00178	1,767	523.6	110.4

Conclusions

On the basis of the obtained results, it can be concluded that the developed method for determining the dynamic viscosity of oil products makes it possible to measure the friction torque created by the viscosity of the liquid under investigation by measuring the angular accelerations of a single-phase electric motor. The method improves the accuracy of viscosity measurement in comparison with other existing methods by taking into account cavitation processes in the pipeline. The developed viscometer, consisting of PC software, hardware-software complex, encoder, single-phase electric motor, ellipse and connecting shaft, allows measuring the dynamic viscosity of oil products directly in the pipeline.

The method and instruments presented in the paper are characterized by lower labor-intensity, they do not require taking sampling of the liquid being investigated from the pipeline, exclude errors related to the human factor, and, as a consequence, can be used in companies that pump and process oil and oil products improving their quality control and efficiency of their transportation.

In further studies, it is planned to find a correlation between the obtained measurements (angular acceleration) and the dynamic viscosity of the liquid under investigation.

References

[1] Camas-Anzueto J.L., Camas-Anzueto J., Meza-Gordillo R. etc. Measurement of the viscosity of biodiesel by using an optical viscometer. Flow Measurement and Instrumentation, vol. 54, 2017, pp. 82-87.

[2] Cavicchio A.M, Biazussi J.L., Castro M.S. etc. Experimental study of viscosity effects on heavy crude oil-water core-annular flow pattern. Experimental Thermal and Fluid Science, vol. 92, 2018, pp. 270-285.

[3] Delgadillo M.A., Ibargüengoytia P.H., García U.A. A technique to measure fuel oil viscosity in a fuel power plant. ISA Transactions, vol. 60, 2016, pp. 303-311.

[4] Feja S., Hanzelmann C., Zuber S. PT and viscosity measurements of High-Temperature Ammonia Heat Pump Lubricants. International Journal of Refrigeration, In Press, Accepted Manuscript.

[5] Kornaeva E., Kornaev A., Savin L. Inertial Method of Viscosity Measurement of the Complex Rheology Medium. Procedia Engineering, vol. 150, 2016, pp. 626-634.

[6] Lu X., Hou L., Zhang L. etc. Piezoelectric-excited membrane for liquids viscosity and mass density measurement. Sensors and Actuators A: Physical, vol. 261, 2017, pp. 196-201.

[7] Mendoza de la Cruz J.L., Alvarez-Badillo S., Ramírez-Jaramillo E. etc. Measurements and correlation of Mexican heavy dead crude oil viscosities. Journal of Petroleum Science and Engineering, vol. 110, 2013, pp. 184-192.

[8] Vázquez M., Castaño F.J., Óvári T.-A. etc. New viscosimeter based on the ac field induced rotation of magnetostrictive amorphous wires. Sensors and Actuators A: Physical, vol. 91, 2001, pp. 112-115.

[9] Allmendinger A., Dieu L.H., Fischer S. etc. High-throughput viscosity measurement using capillary electrophoresis instrumentation and its application to protein formulation. Journal of Pharmaceutical and Biomedical Analysis, vol. 99, 2014, pp. 51-58.

[10] Wahren U. Chapter 7 – Effects of Viscosity on Pump Performance. Practical Introduction to Pumping Technology. A basic guide to pumps – from specification to installation and operation Houston: Gulf Professional Publishing, 1997. pp. 55-60.

[11] Sandor M., Cheng Y., Chen S. Improved Correlations for Heavy-Oil Viscosity Prediction with NMR. Journal of Petroleum Science and Engineering, vol. 147, 2016, pp. 416-426.
[12] Kotzakoulakis K., George S.C. A simple and flexible correlation for predicting the viscosity of crude oils. Journal of Petroleum Science and Engineering, vol. 158, 2017, pp. 416-423.
[13] Hamidi H., Mohammadian E., Junin R. A technique for evaluating the oil/heavy-oil viscosity changes under ultrasound in a simulated porous medium. Ultrasonics, vol. 54, 2014, pp. 655-662.
[14] Wen J., Zhang J., Wei M. Effective viscosity prediction of crude oil-water mixtures with high water fraction. Journal of Petroleum Science and Engineering, vol. 147, 2016, pp. 760-770.
[15] Krutov V.I., Grushko I.M., Popov V.V. etc. Fundamentals of Scientific Research (Основы научных исследований). Moscow: «Высшая школа», 1989. 400 p. (In Russian).