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Dynamic method for controlling dynamic viscosity of liquid

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Abstract. The purpose and objectives of the work are to develop scientific and technical bases and experimental testing of the dynamic method of control of the dynamic viscosity of liquids located directly in the pipeline on the basis of angular accelerations of the body immersed in the liquid. The developed method of control of the dynamic viscosity of liquids allows to take into account the uneven supply of mechanical energy from the drive motor of the rotary viscometer based on the assessment of the dynamics of the motion of the body immersed in the liquid. The developed method of control of dynamic viscosity of liquids is based on the proven positions of theoretical mechanics, dynamics of rotational motion, the theory of machine parts and is a logical continuation of the development of rotational methods of control of viscosity of liquids. The results of experimental testing of the developed dynamic method of control of the dynamic viscosity of liquids suggest the adequacy of the developed approaches. As a result of experimental studies of motor oil G-Energy 10w-60 on the basis of the developed dynamic method revealed the ratio of dynamic viscosities at temperatures of 100 ° C and 40 ° C, which was 6,7. Application of existing methods of control of viscosity of G-Energy oil at temperatures of 100 ° C and 40 ° C gives the ratio of dynamic viscosities 6,8. The discrepancy between the results of the dynamic method of control of the dynamic viscosity of the liquid and the control results obtained by known methods of control of the dynamic viscosity of liquids is about 1%.

Further improvement of the metrological characteristics of viscometers, as well as the maximum degree of automation of measurements, is associated with the application of new physical principles for the development of new methods for controlling the dynamic viscosity of liquids [1-6].

To control the dynamic viscosity of liquids, a method was developed that represents a variation of the well-known rotational method, but implemented on a new physical principle.

Consider the dynamic method of control of the dynamic viscosity of the liquid in a simplified viscometer model. Viscometer consists of an ellipsoid with pointed ends, laminar flow shaper, flanges, bearing supports, shaft. In the gap between the pipe and the ellipse is the test liquid. Scheme viscometer for controlling dynamic viscosity of liquid is shown in figure 1.

The developed dynamic method of control of dynamic viscosity of the liquid is based on the previously developed dynamic methods of control of mechanical parameters of systems of rotational action [7, 8] and is implemented as follows.

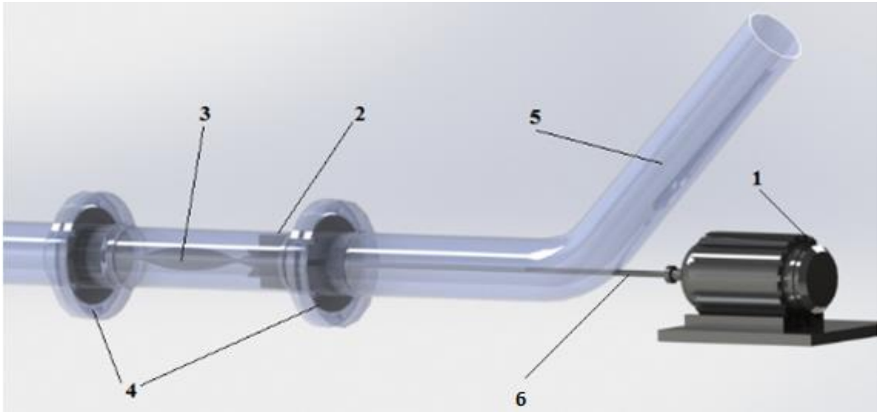

Figure 1. Scheme viscometer, implementing a dynamic method for controlling dynamic viscosity of liquid: 1-single-phase motor, 2-laminar flow shaper, 3-ellipsoid with pointed ends, 4-coupling, 5-pipe outlet, 6 - connecting shaft.

At the initial stage, in the absence of filling the pipeline with liquid, the moment of inertia of all rotating masses (ellipsoid, elements in the bearing assemblies, the connecting shaft, the rotating masses of the asynchronous electric motor) is determined taking into account the coefficient of mechanical losses: the asynchronous electric motor (hereinafter the motor) is started and the average value of the angular acceleration of the output shaft of the electric motor in the selected speed range, which can be in the range from zero to the nominal angular velocity of the motor rotor is determined. The minimum value of the speed range depends on the measuring instruments, the maximum value can be equal to the nominal value of the angular velocity of the motor rotor:

$$\varepsilon_1 = d\omega / dt_1 \tag{1}$$

where dω is the change in angular velocity at the selected range, rad/s, dt_1 – time for which the change in angular velocity dω occurred at the selected speed range at the first start of the motor, s.

If it is necessary to determine the average value of the angular acceleration during acceleration of the motor shaft in the range from zero to the nominal value of the angular velocity expression (1) takes the form:

$$\varepsilon_1 = \omega_{nom} / t_1 \tag{2}$$

where ω_{nom} - the nominal angular velocity of the motor shaft, rad/s, t_1-the acceleration time of the motor shaft in the range from zero to the nominal value of the angular velocity at the first start, s.

Determination of the angular acceleration of the motor rotor is carried out by means of an incremental encoder, the average torque M, which develops a system of rotating masses of the motor, is defined as:

$$M = k_{loss} \cdot J_{r.m.m} \cdot \varepsilon_1 \tag{3}$$

where k_{loss} - coefficient characterizing the mechanical and additional losses in the rotor of the electric motor, $J_{r.m.m.}$ - the moment of inertia of the rotating masses of the electric motor, reduced to the axis of rotation of the rotor, kg m^2.

Next, the motor 1 is stopped. Then, using the fastening elements, the connecting shaft 6 is connected to it with the ellipsoid 3, the moment of inertia of which is known (determined by the method of torsional vibrations or by the calculation method) J_e. The electric motor starts and determines the value of the angular acceleration of the system of rotating masses «the moment of inertia of the rotating masses of the electric motor, ellipsoid and connecting shaft», at the selected speed range:

$$\varepsilon_2 = d\omega / dt_2 \tag{4}$$

If it is necessary to determine the average value of the angular acceleration during acceleration of the motor rotor from zero to the nominal value, the expression (4) takes the form:

$$\varepsilon_2 = \omega_{nom} / t_2 \tag{5}$$

where t_2 - time of acceleration of the motor rotor from zero to the nominal value of the angular velocity at the second start of the motor, s.

The average value of the torque *M*, which develops a system of rotating masses «moment of inertia of the rotating masses of the motor, the ellipsoid and the connecting shaft», is defined as:

$$M = (k_{loss} \cdot J_{r.m.m.} + J_e) \cdot \varepsilon_2 . \tag{6}$$

Since at the first and second start the losses in the stator and rotor of the electric motor remain unchanged (since the voltage does not change, the frequency of the supply network and the temperature of the electric motor (the resistance of the stator windings)), therefore, according to the energy diagram of the electric motor, the mechanical characteristic of the electric motor does not change. Therefore, the right parts of the expression (3) and (6) can be equated and determine the moment of inertia of the rotating masses of the motor, taking into account the loss factor:

$$k_{loss} \cdot J_{r.m.m} = J_e \cdot \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2} \tag{7}$$

If we consider the acceleration interval for two starts of the motor 1 from zero to the nominal value, $d\omega_1 = d\omega_2 = \omega_{ном}$ and $dt = t$, then the dependence (7) can be expressed in terms of:

$$k_{loss} \cdot J_{r.m.m} = J_e \cdot \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2} = J_e \cdot \frac{\frac{d\omega_2}{dt_2}}{\frac{d\omega_1}{dt_1} - \frac{d\omega_2}{dt_2}} = J_e \cdot \frac{t_1}{t_2 - t_1} \tag{8}$$

where t_1 - time during which there has been a change in the angular speed of the rotor of the electric motor $d\omega_1$, s, t_2 - time during which there has been a change in the angular speed of the motor $d\omega_2$, s.

Further, to control the dynamic viscosity of the test liquid, completely fill the pipeline outlet 5 with the test liquid and start the electric motor 1. When the ellipsoid rotates, a friction force between it and the liquid under study will be created, which will create a friction moment directed in the opposite direction to the rotation of the ellipsoid. Then the average torque M, which develops a system of rotating masses, is defined as:

$$M = (k_{loss} \cdot J_{r.m.m.} + J_e) \cdot \varepsilon_3 - M_{f \cdot f} \tag{9}$$

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where $M_{f \cdot f} = J_{f \cdot f} \cdot \varepsilon_3$ - the moment of friction caused by the viscosity of the fluid under study, where $J_{f.f}$ is the moment of inertia of the friction forces generated by the viscosity of the fluid under study.

Equate (6) and (9) and replace with (7) $k_{loss} \cdot J_{r.m.m.}$ at $J_{э} \cdot \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2}$, and get:

$$M = (k_{loss} \cdot J_{r.m.m.} + J_e) \cdot \varepsilon_3 + M_{f \cdot f} \tag{10}$$

$$(J_e \cdot \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2} + J_e) \cdot \varepsilon_2 = (J_e \cdot \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2} + J_e) \cdot \varepsilon_3 + J_{f \cdot f} \cdot \varepsilon_3 \tag{11}$$

Of (11) taking into account (7), and considering that $d\omega_1 = d\omega_2 = d\omega_3 = \omega_{НОМ}$, $dt_1 = t_1$, $dt_2 = t_2$, $dt_3 = t_3$:

$$J_{f \cdot f} = J_e \cdot \frac{t_3 - t_2}{t_2 - t_1} \tag{12}$$

Of (12) the friction torque caused by the viscosity of the liquid:

$$M_{f \cdot f} = J_e \cdot \frac{t_3 - t_2}{t_2 - t_1} \cdot \varepsilon_3 = J_e \cdot \frac{t_3 - t_2}{t_2 - t_1} \cdot \frac{\omega_{nom}}{t_3} \tag{13}$$

Knowing the dynamic viscosity of the test liquid μ_1 at a temperature T_1, we determine the acceleration time of the drive motor from zero to the nominal angular velocity t_{3_1} and calculate the friction moment $M_{f \cdot f_1}$:

$$M_{f \cdot f_1} = J_e \cdot \frac{t_{3_1} - t_2}{t_2 - t_1} \cdot \frac{\omega_{nom}}{t_{3_1}} \tag{14}$$

Determine the acceleration time of the drive motor from zero to the nominal angular velocity t_{3_2} at the temperature of the test fluid T_2 and calculate the friction moment $M_{f \cdot f_2}$:

$$M_{f \cdot f_2} = J_e \cdot \frac{t_{3_2} - t_2}{t_2 - t_1} \cdot \frac{\omega_{nom}}{t_{3_2}} \tag{15}$$

The ratio of the dynamic viscosities of the fluid under study μ_2 and μ_1 at temperatures T_1 and T_2 in proportion to the ratio of torques $M_{f \cdot f_2}$ and $M_{f \cdot f_1}$:

$$\frac{\mu_2}{\mu_1} \approx \frac{M_{f \cdot f_2}}{M_{f \cdot f_1}} = \frac{t_{3_2} - t_2}{t_{3_1} - t_2} \cdot \frac{t_{3_1}}{t_{3_2}} \tag{16}$$

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Select from (16) the required ratio of the dynamic viscosity μ_2 at a temperature T_2 of:

$$\mu_2 = \mu_1 \cdot \frac{t_{3_1}}{t_{3_2}} \cdot \frac{t_{3_2} - t_2}{t_{3_1} - t_2} \tag{17}$$

Thus, knowing the values given to the axis of rotation of the rotor moments of inertia of the ellipsoid with the connecting shaft, we can control only one parameter, namely the acceleration time to the nominal angular velocity at the first, second (they are measured only once during installation) and the third start of the motor 1. Knowing the ratio of acceleration time and viscosity of the test liquid at the initial temperature of the liquid, it is possible to control the viscosity of the test liquid.

That is, during the operation of the dynamic viscometer, only the third start of the electric motor 1 will be constantly carried out and compared with the readings of the first and second starts of the electric motor 1, which will already be in the base of the hardware and software complex of the viscometer immediately after the launch of the viscometer into operation.

To test the developed method, a laboratory bench was created to determine the viscosity of the liquid, figure 2.

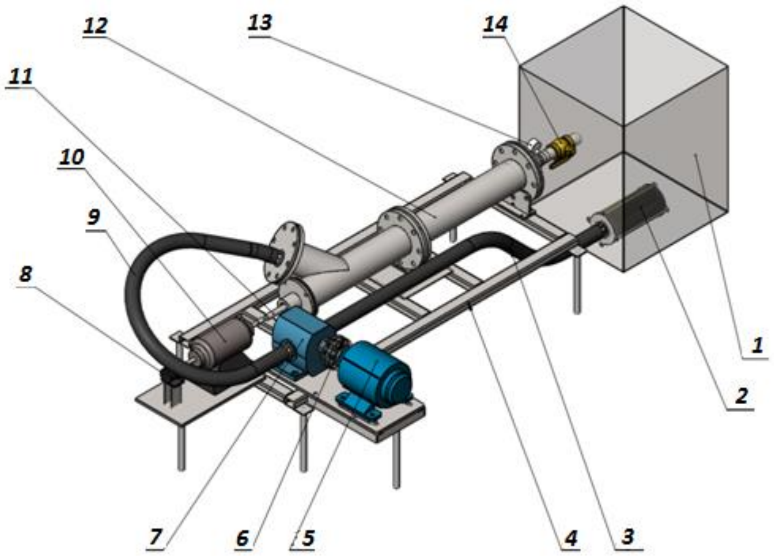

Figure 2. Laboratory stand for dynamic control of dynamic viscosity of liquid: 1-tank, 2-filter, 3-high pressure hose, 4-frame, 5-eldin A100L2 motor, 6-clutch, 7-pump G11-25, 8-encoder, 9-high pressure hose, 10-single-phase motor, 11-shaft, 12-viscometer section, 13-pressure indicator, 14-safety valve.

The tank 1 is filled with about 150 liters of the test liquid, through the filter 2 and the high pressure hose 3 it enters the gear pump 7, which rotates the asynchronous electric motor 5, with frequency control to change the operating modes of the pump. The gear pump 7 generates a pressure of 2 to 3 MPa and a fluid flow rate of up to 100 l/min depending on the speed of the asynchronous electric motor 5. From the gear pump 7, the test liquid along the high pressure hose 9 enters the section of the viscometer 12 where it passes through the flow laminator (figure 2 not shown), and completely fills the cavity of the ellipsoid with built-up ends (figure 2 not shown). The rotation of the ellipsoid occurs by means of a single-phase motor 10 connected to the ellipsoid by a shaft 11. At the other end of the single-phase motor 10, an encoder 8 is installed, which with the help of the developed hardware and software complex determines the acceleration time of the rotor of the single-phase electric motor 10. After the viscometer section 12, the test liquid is discharged back into the tank 1 through the adjustable safety valve 13. To control the fluid pressure in the system, a pressure indicator is installed 13.

To determine the sensitivity of the acceleration time of the system of rotating masses «ellipsoid - shaft - single-phase motor» to change the viscosity of the test liquid in the section of the viscometer 12 on the basis of the developed laboratory bench, a full-scale experiment was conducted.

G-Energy 10W-60 oil with known rheological properties at different temperatures was used as the test liquid. At 40 ° C, the kinematic viscosity and density of the oil are $\nu_1 = 154{\cdot}10^6$ m²/s and $\rho_1 = 887$ kg/m³ , and at 100 ° C $\nu_2 = 24{\cdot}106$ m²/s and $\rho_2 = 840$ kg/m³.

The pressure in the system when measuring the acceleration time of the system of rotating masses «ellipsoid-shaft-single-phase motor» is maintained equal to atmospheric and is controlled by a pressure indicator.

The laboratory bench is filled with oil heated to 115 ° C, its forced movement through the system is carried out, so that all the internal parts of the oil circulation system are warmed up to this temperature. In this case, the oil temperature is measured by means of a thermometer, when the temperature in the tank reaches 100 ° C, the asynchronous electric motor 5 is switched off and 12 starts of the single-phase electric motor 10 are made. According to the results of 12 launches, the average time of acceleration of the system of rotating masses «ellipsoid - shaft - single-phase electric motor» from zero to nominal speed is determined by the developed software complex (figure 2 not shown).

Next, the oil in the tank 1 cools to 42 ° C, the gear pump 7 is started, the oil is run through the system and when its temperature reaches 40 ° C, 12 starts of the single-phase electric motor 10 are made and the acceleration time is determined and the average value is calculated using the software complex. The results of the experiments are recorded in Table 1.

Calculate the dynamic viscosity of the test oil known previously mentioned values at a temperature T_1 = 40 °C, denoting it by μ_1:

$$\mu_1 = \rho_1 \cdot \nu_1 = 136{,}6 \cdot 10^6 \text{ kg/(m·s)} \tag{18}$$

Calculate the dynamic viscosity of the oil under study by known previously mentioned values at the temperature of the T_1 = 100 °C,, denoting it by μ_{2v} :

$$\mu_{2v} = \rho_2 \cdot \nu_2 = 20{,}2 \cdot 10^6 \text{ kg/(m·s)} \tag{19}$$

We use the average values of acceleration $t_{3_1} = 3{,}56\ s$, $t_{3_2} = 0{,}54 s$, $t_2 = 0{,}47\ s$ and the value of the expression (18) $\mu_1 = 136{,}6 \cdot 10^6$ kg/(m·s) determine the value of the dynamic viscosity of the oil at $T_2 = 100$ °C:

$$\mu_2 = \mu_1 \cdot \frac{t_{3_1}}{t_{3_2}} \cdot \frac{t_{3_2} - t_2}{t_{3_1} - t_2} = 136{,}6 \cdot \frac{3{,}56}{0{,}54} \cdot \frac{0{,}54 - 0{,}47}{3{,}56 - 0{,}47} = 20{,}4 \cdot 10^6 \text{ kg/(m·s)} \tag{20}$$

Table 1. Acceleration time of single-phase electric motor at the temperature of the test oil 40 ° C and 100 ° C.

№ experiment's	Acceleration time t_{3_1} single-phase motor to 2700 rpm at an oil temperature equal to 40 °C, s.	Acceleration time t_{3_1} single-phase motor to 2700 rpm at an oil temperature equal to 100 °C, s.	Acceleration time t_2 of single-phase electric motor up to 2700 rpm without oil in the system, s.
1	3,51	0,515	0,449
2	3,62	0,575	0,502
3	3,61	0,600	0,525
4	3,54	0,521	0,454
5	3,64	0,534	0,466
6	3,51	0,542	0,473
7	3,57	0,540	0,471

8	3,51	0,499	0,435
9	3,58	0,534	0,466
10	3,54	0,532	0,464
11	3,61	0,520	0,453
12	3,52	0,511	0,445
Average	3,56	0,54	0,47

Comparing the values of the dynamic viscosity of the engine oil obtained on the basis of known from open sources table values in the expression (19), and the values of the dynamic viscosity determined on the basis of experimental data in the expression (20), we conclude that the discrepancy is about 1%, which confirms the efficiency of the developed method and the adequacy of the approach used:

$$\frac{\mu_2}{\mu_{2v}} = \frac{20{,}4 \cdot 10^6}{20{,}2 \cdot 10^6} = 1{,}01 \tag{21}$$

Based on the comparison, we conclude that the discrepancy is about 1%, which confirms the efficiency of the developed method and the adequacy of the approach used.

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