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THERMAL PROPERTIES

OSCILLATORY VISCOMETER FOR MEASURING THE VISCOSITY OF LIQUIDS

P. M. Matyakubova, P. R. Ismatullaev, and Zh. U. Shamuratov UDC 532.137

Viscosity values of liquids are important for prediction of liquid flow in many oil and gas and chemical product processes. In this paper, a description is given of a number of methods used for measuring the viscosity of liquids, including the capillary, rotational, oscillatory, and sonic viscometries. A description is also given of a number of models used for assessing the viscosity of elements, the dependence of viscosity on temperature, and the viscosity of multicomponent systems, including the Arrhenius equation. The scatter in the data to be found in the literature is emphasized by comparison of two data reviews on elements.

Keywords: *physical model, flow, moisture content, liquid material, thermosensitive element, heating element, pipeline, heat transfer.*

Introduction. Determination of a viscosity value is key in all areas of oil industry. For example, in transportation of oil and oil products, viscosity is one of the main indicators of quality of the oil being pumped. This indicator is also considered in planning the optimal operating conditions for oil pumping stations, in particular, oil-transfer systems. Therefore, it is necessary to exercise in-process operation control of such a parameter as viscosity. To carry out real time monitoring, instruments capable of performing this task are required. Such instruments include viscosimeters, or viscometers (viscosity converters, or meters).

The velocities of layers are not identical and gradually decrease in approaching the lower plate. This is due to the presence of internal friction in the liquid. This phenomenon is described with the help of the Newton law:

$$\tau = \eta \frac{du}{dn} . \qquad (1)$$

The viscometer is an instrument or a device measuring viscosity. Classification of viscometers is conducted by a number of indicators [1, 2]:

1) by the accuracy of measurements: working and reference ones;
2) by the area of application: laboratory, industrial, and medical ones;
3) by the properties of the investigated viscous medium: universal and special ones;
4) by the viscometry method: capillary, rotational, oscillatory, ultrasonic, and falling-sphere viscometers;
5) by the temperature and pressure of the investigated medium: in the range of normal, higher, and extreme values.

Literature Review. At present-day oil and gas production and processing facilities, chemical and pharmaceutical factories, many scientists have been engaged in scientific investigations of viscosities for measuring the viscosity of liquids and gas.

Viscosity is the property of liquid or gas to resist the motion of certain of its particles with respect to others in motion or the force of resistance to the displacement of one layer of liquid with respect to another one. This properly is also called internal friction of liquid (G. M. Panchenkov). The viscosity and density of well fluids are very important properties since their values can determine the economic efficiency of an oil reservoir. A vibrating wire viscometer with an electroinsulating recoil mechanism (stretching device) was developed (Mohamed Kandil).

Islam Karimov Tashkent State Technical University, 2 Universitetskaya Str., Tashkent, 100095, Uzbekistan; email: tgtu_mss@rambler.ru, iprtstu@mail.ru, jamshid.shamuratov.phd2022@gmail.com. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 97, No. 1, pp. 136–143, January–February, 2024. Original article submitted Mach 1, 2023.

The 19th and 20th centuries were the most advanced periods in the science of measuring viscosity of liquids. Liquids with higher viscosity have lower velocities due to higher damping. Analytical equations are provided relating viscous damping of a dynamic system to viscosity of liquids. The viscosities obtained under the proposed method have a good agreement with viscosities obtained from standard rotational viscometry with the use of the cone and plate geometry (Behic Mert, Hartono Sumali, and Osvaldo Campanella).

Investigations by domestic scientists and their influence on the modernization process in present-day conditions have gained significant momentum since the 90s of the 20th century. G. A. Rakhmatulin, O. M. Arifdzhanov, K. T. Rakhimov, A. K. Khodzhiev and others have made a contribution to the study of problems of viscosity of liquids. The authors consider this problem from different standpoints and propose their new conclusions.

Principal Part. The selection of a viscometer for measurement is basically determined by the goal and objectives of the investigation. At present, we know quite a few viscometer designs but most of them are based on four most common viscometry methods:

1) capillary method;
2) falling-sphere method;
3) rotational method;
4) vibration (oscillatory method).

Capillary viscometry method. The method of capillary viscometry is based on Poiseuille′s law. According to the law, the flow of viscous incompressible liquid through a thin cylindrical tube is described by the equation [3]:

$$\eta = \frac{\pi d^4 \Delta p}{128 l Q}. \tag{2}$$

Figure 1 shows a schematic diagram of a capillary viscometer. The method of capillary viscometry is usually classified under high-accuracy methods of measuring viscosity due to a relatively low error of measurement that fluctuates in fractions of a percent. The value of an error basically depends on two parameters: the correctness of fabricating an instrument and the accuracy of chronometration.

Falling-sphere viscometry method. This method is based on the Stokes law according to which the free-fall velocity of a solid sphere in a viscous infinite medium is described by the equation [4]:

$$\eta = \frac{2r^2(\rho_b - \rho_{liq})g}{9v} \tag{3}$$

It should be pointed out that Eq. (3) is only true in the case when the sphere fall velocity is quite low, and also, the following relation is observed:

$$r \le \frac{6\eta}{\rho_b v}. \tag{4}$$

Figure 2 is a schematic diagram of a viscometer based on the falling-sphere method.

In using this method, it is necessary to consider the obtained corrections for the finite dimensions of the vessel with the investigated liquid (L, liquid height in the vessel; R, vessel radius; r, falling-sphere radius). Furthermore, the relationship $r/R < 0.1$ should be fulfilled, then the equation assumes the form

$$\eta = \frac{2r^2(\rho_b - \rho_{liq})g}{9v(1 + 2.4r/R)}. \tag{5}$$

Based on this method, a great number of viscometer models have been created, however, not all of them can perform measurements in a flow regime, which is relevant for a system of measuring the amount of oil. One of falling-sphere viscometers that meets this requirement is a Japanese JSW viscometer.

Rotational viscometry method. In rotational viscometers, the investigated liquid is placed in the gap between two coaxial cylinders. One of them (rotor) revolves, and the other one (stator) is immobile. In this case, the force-measuring element can be both a rotor and a stator [5]:

$$\eta = \frac{k\varphi}{w}. \tag{6}$$

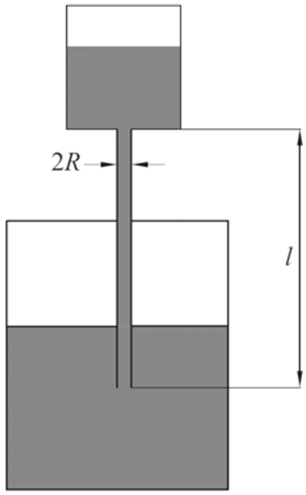


Fig. 1. Schematic diagram of a capillary viscometer.

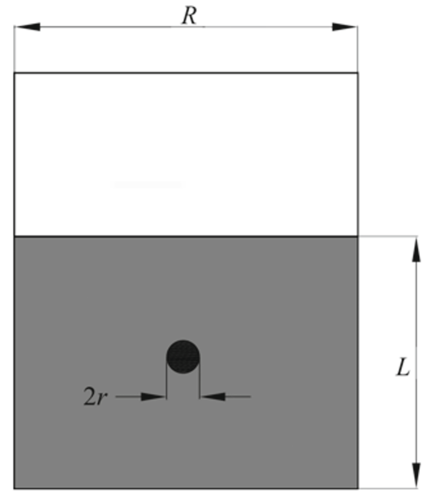


Fig. 2. Schematic diagram of a falling-sphere viscometer.

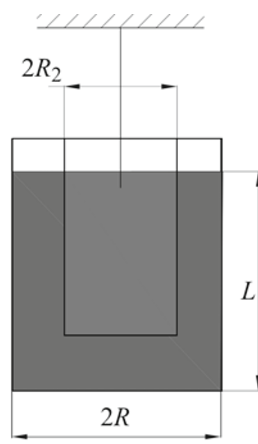


Fig. 3. Diagram of a rotational viscometer.

Let us consider an inverse model, i.e., the external coaxial cylinder performs a revolution, and the internal cylinder is fixed, and a rotating torque is imparted to it. A scheme of a rotational viscometer is shown in Fig. 3.

Basically, rotational viscometers represent a high-accuracy measurement method. However, they require the use of several types of rotors to ensure measurements in a broad range. The measurement range of one rotor is narrow, hence, the replacement of rotors causes interruption in measurements and a loss of time. Furthermore, the accuracy of measurements is only guaranteed for a full scale, and that means that in measurements of a low viscosity range, measurement errors are inevitable. In the worst-case scenario, the viscosity value cannot be obtained since viscosity varies in the case of a constant rise in the specimen temperature after the start of measurements both in the low and high viscosity ranges. This occurs because in the low viscosity range, a larger rotor is required for detecting a torque exceeding a certain level. In the high viscosity range, the rotor is exposed to a higher kinetic force caused by a high friction force.

Oscillatory viscometry method. The essence of the oscillatory viscometer method consists in the following: a flat thin plate (fork, sphere, cylinder, or another body) is dipped into the investigated liquid and is set in oscilative motion due to an external harmonic force. The oscillation parameters, viz., amplitude, frequency, and phase shift in vibrations of the body and fluctuations of an external force causing oscillations, will depend on the viscosity of the investigated liquid [6].

Different versions of implementing the oscillatory viscometer method, viz., its amplitude, frequency, and phase versions, are also possible. The choice depends on the viscosity measurement range. Thus, for example, to determine the viscosity of liquids with average viscosity, use is most often made of the frequency–phase method. In this case, the calculation formula is as follows:

$$\eta = \frac{m_0^2 (w_0^2 - w^2)^2}{8S^2 w^3 \rho}, \quad (7)$$

where m_0 is the mass of a vibrating element, kg; w_0 is the frequency of the harmonic exciting force in the air, 1/s; w is the frequency of the harmonic excitation force in the investigated liquid, 1/s; S is the area of the surface of a vibrating element, m^2; ρ is the density of the investigated liquid, kg/m^3.

The frequency–phase variant of the oscillatory viscometer method is used for very viscous liquids. In this case, a measurement is taken of the frequency of oscillations of the viscometer probe, first, of a nonsubmerged one (w_0) and then, of a probe submerged (w) in a liquid at a phase shift:

$$\varphi = \frac{\pi}{2}. \quad (8)$$

The amplitude–resonance variant of the oscillatory viscometer method is suitable for measuring the viscosity of less viscous media. In this case, the amplitude of fluctuations is the highest. Hence, the measured parameter is the amplitude of the viscometer probe oscillations. Thus, for low viscosity values, we have [7]:

$$\sqrt{\eta\rho} = \frac{F_0}{w^{3/2} S \sqrt{10A}}, \quad (9)$$

where F_0 is the exciting force in the liquid, N; A is the amplitude of the vibrating element, mm.

Comparison of the Viscometry Methods. The comparison was conducted in accordance with the most widely used viscometry methods described earlier. Table 1 shows a comparative table for the main viscometry methods.

Having made a comparative analysis of the viscometry methods, we confirmed the correctness of the choice of the viscometry method for developing a viscometry converter (viscometer). This choice is due to a number of advantages of the oscillatory viscometer method compared to other ones considered above.

Patent Review. The object of the patent review is on-line automatic instruments (devices) for measuring viscosity that correspond to oscillatory viscometers to a fuller extent.

The subject-specific search for information was conducted in the following databases:

1) full texts of RF patent documents for the period of 1994–05.2015;
2) full texts of utility models for the period of 1994–05.2015;
3) utility model abstracts (abridgements of utility model specification) for the period of 1994–05.2015;
4) abstracts of claim for Russian inventions as of 05.2015;
5) database of the Eurasian Patent Agency EAPATIS (Eurasian Patent Information System) as of 05.2015;
6) full texts of USA patents as of 05.2015.

In the course of the patent review we identified a group of patent documents characterizing the state of the art in the area of viscometers (viscosity converters). In selecting the documents, priority was given to flow-through (flow-type) instruments for continuous determination of liquid viscosity. The result of considering the patents is shown in Table 2.

A New Measuring Instrument is Proposed. The invention comes under the notion of measuring liquid viscosity (viscometry) and can be used for determining the viscosity of chemical solutions, oil products, alcohols, and other low-viscosity liquids in various areas of technology and production.

There are capillary-type viscometers whose principle of operation is based on determination of the time of discharge of a certain amount of liquid through narrow capillary tubes. The disadvantages of capillary viscometers are a relatively low efficiency of control and the impossibility of forming continuous measurements.

An oscillatory viscometer based on measuring the maximum amplitude of oscillation by an object under control (a thin plate) submerged in the tested liquid is the closest to the proposed invention in terms of technical essence and the obtained result [8].

The new device includes a U-shaped thin plate submerged in the investigated liquid, a system of linear elastic elements in the form of elongated fibers fastened firmly to the casing, the plate, and the casing walls, and a thermosensitive element determining the plate′s distance in the air and in the test fluid. There is an inductive measuring element, a vibration exciter (vibratory motor) and a data-processing unit.

TABLE 1. Comparison of the Main Viscometry Methods

Criteria	Capillary viscometer	Falling-sphere viscometer	Rotational viscometer	Oscillatory viscometer
Suitable for gases	Yes	No	Yes	Yes
Measures density	No	No	Yes	Yes
Direct measurement	No	Yes	Yes	Нет
Moving parts	No	Yes	Yes	No
Measurement range	Narrow	Narrow	Wide	Wide
Possibility of continuous operation	No	No	Yes	Yes
Construction size for on-line measurements	–	Large	Large	Medium

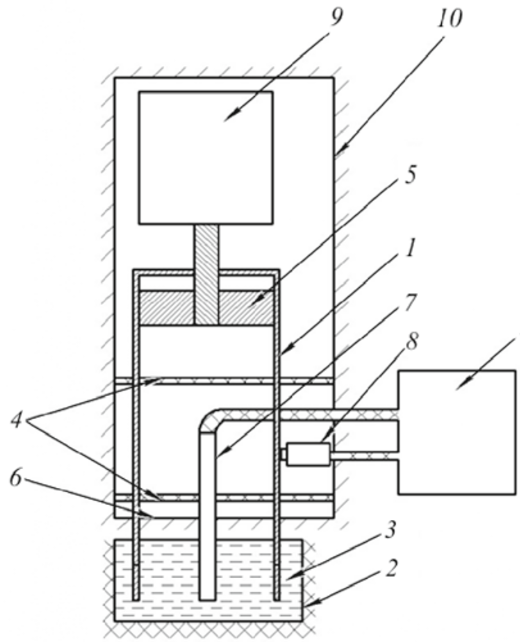
TABLE 2. Patents Consideration Results

Patent grating country, type and number of protective documents, class number	Applicant for a patent, patent owner	Date of application and publication	Title of invention (utility model or design)	Status as of 05.2020
RF Patent for an invention No. 2277706 G01N11/16	Endress + Hauser Flowtech	Date of application: 17.08.2002 Date of publication: 06.10.2006	Viscometer (options) and methods of determination of the viscosity of a medium	Relevant
USA Patent No. 5323638 G01N11/16; G01N29/024; G01N33/03; G01N9/00	Marconi GEC (General Electric Company), Ltd	Date of application: 04.10.1992 Date of publication: 28.06.1994	Sensory apparatus	Undetermined
EPO Patent for an invention EP0282251B2 G01L9/00; G01N11/16; G01N9/00	Schlumberger Electron	Date of application: 03.07.1988 Date of publication: 13.12.2000	Liquid sensor	Undetermined
RF Patent for an invention No. 2393456 G01N9/00; G01N11/00	Schlumberger technology	Date of submission of documents: 24.02.2006 Date of publication: 04.10.2009	Density and viscosity sensor	Relevant

During the operation of the viscometer, its vibration system (for example, for measuring the vibration exciter frequency) is determined by measuring the viscosity in terms of the maximum amplitude of oscillations of the plate submerged in the investigated liquid.

The disadvantage of the newly proposed viscometer is the low sensitivity of the measuring device.

The viscometer (Fig. 4) includes the following components and elements: the plate 1 (Figs. 4 and 5) is submerged in the vessel 2 in which the tested liquid 3 is placed. The lower wall 6 (from a ferromagnetic material) is firmly fastened to the casing wall 10, and, at the start of the motor 9, the propelling screw 5 revolves and finds itself on the plate 1 to prevent the occurrence of vibrations. A thermometer 7 for measuring the temperature of the tested liquid is placed between two U-shaped plate extensions. An inductive sensing element 8 is also set up to measure the amplitude of plate oscillations in



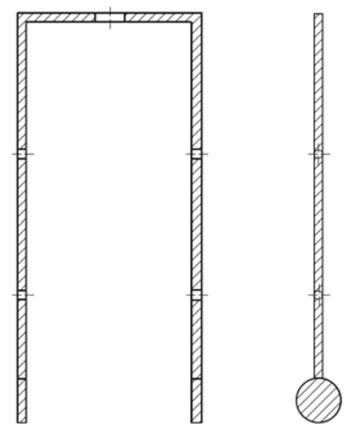


Fig. 4. Schematic view of the proposed oscillatory viscometer.

Fig. 5. Schematic diagram of the plate of an oscillatory viscometer.

the air and in the investigated liquid. A thin elastic element in the form of a thread 4 serves to ensure a vertical position of the plate. The device is connected to the unit 11 (Fig. 4).

The viscometer works in the following way: this method is based on the vibration of a flat plate in the liquid with a constant driving force. The motion amplitude will depend on the liquid viscosity. A measurement is taken of the amplitude of plate oscillations in the air and in the liquid, and the following dependences are derived:

$$\rho\eta = \frac{R_{\mathrm{M}}^2}{\pi f A^2}\left(\frac{f_{\mathrm{a}} E_{\mathrm{a}}}{fE} - 1\right)^2 , \tag{10}$$

where ρ is the density; E_{a} and E are the amplitude of fluctuations in the air and liquid respectively; f_{a} and f are the fluctuation frequencies in the air and liquid; A is the plate area; R_{M} is the actual component of mechanical impedance.

In using the method, the following assumptions were made:

1) the liquid is a Newtonian liquid;
2) no turbulent flow occurs;
3) there is no slip between the plate and the liquid;
4) the size of the fluctuating plate should exceed one length of the oscillatory wave and be flat;
5) the plate′s end influence on the amplitude decay is insignificant;
6) the dimensions of the vessel are large enough for the effects of the waves reflected from the walls to be insignificant.

It has been shown that the resonance frequency in the air and liquid can be considered identical for all practical purposes so that

$$\rho\eta = \frac{R_{\mathrm{M}}^2}{\pi f A^2}\left(\frac{E_{\mathrm{a}}}{E} - 1\right)^2 = K\theta , \tag{11}$$

where $\theta = \frac{R_{\mathrm{M}}^2}{\pi f A^2}$ is the damping coefficient, and $K = \frac{E_{\mathrm{a}}}{E} - 1$ is determined experimentally using reference viscosity materials. Recent comparisons of this method with the rotating-cylinder technique for slaggy systems have shown good agreement, usually within ±7%.

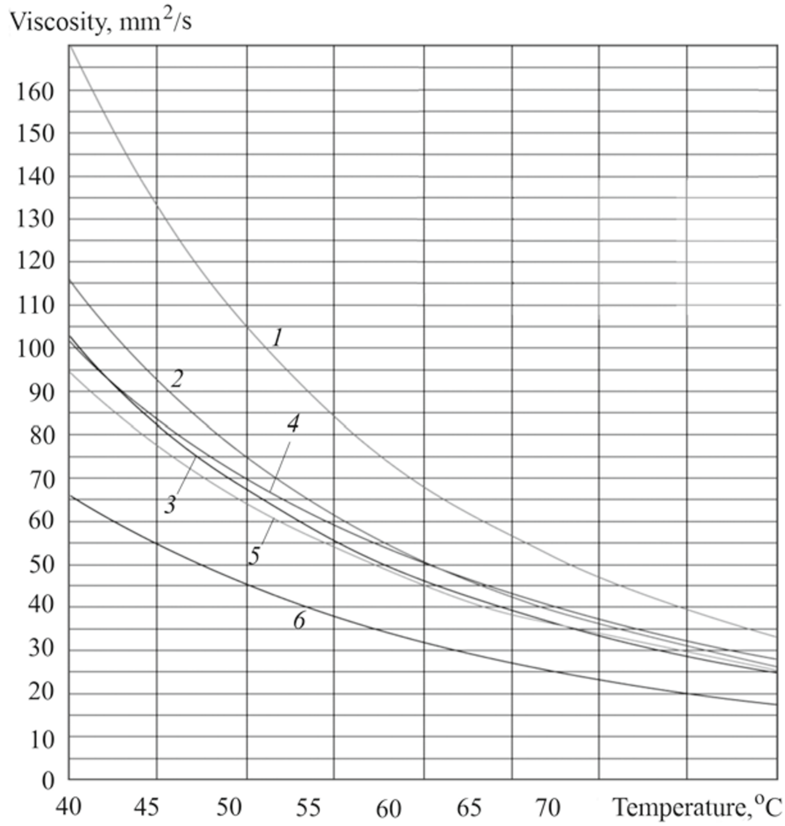


Fig. 6. Motor oil viscosities in dynamics between 40 and 80°C (SAE 20W-50) measured with different viscometers: 1) VPZh viscoplastic fluid viscometer; 2) rotational viscometer-1; 3) rotational viscometer-2; 4) oscillatory viscometer; 5) new viscometer; 6) VPZh-2 viscoplastic fluid viscometer.

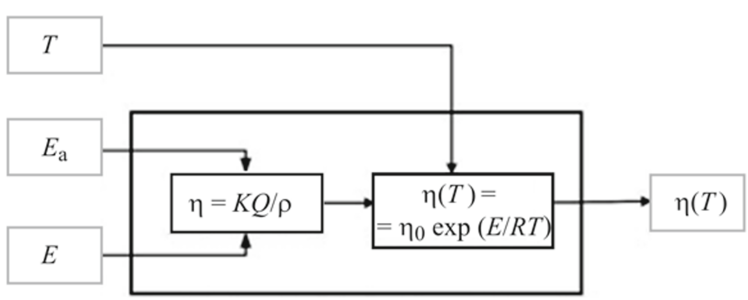


Fig. 7. Flowchart of operation of an oscillatory viscometer.

Comparison of Values of Different Viscometers. Figure 6 shows dependences of motor oil viscosity at a temperature of 40–80°C measured by different viscometers. The temperature dependence of the liquids′ viscosity of the proposed oscillatory viscometer is expressed by the Arrhenius equation in the following way:

$$\eta(T) = \eta_0 \exp(E/RT) , \quad (12)$$

where E is the viscous flow activation energy, and η_0 is the pre-exponential viscosity, both parameters being constants; T is the temperature in K; R is a gas constant equal to 8.3144 $J \cdot mol^{-1} \cdot K^{-1}$ (Fig. 7).

Conclusions. Fabrication of the plate material from aluminum or high-quality steel improves the propagation of the frequency of its fluctuations in the liquid. A plate design also contributes to a reduction in the vibration energy losses in liquid and air.

A data-processing unit also serves for the automation of the proposed oscillatory viscometer and the transmission of values of measurement results to a computer.

Thus, the main technical-economic advantage of the invention is a high dimensional sensitivity, which makes it possible, in the long run, to determine the viscosity of the investigated liquid with high accuracy.

NOTATION

d, capillary diameter, m; du/dn, velocity gradient; g, free-fall acceleration, m/s^2; k, coefficient of the viscometer constant; l, capillary length, m; $p_1 - p_2 = \Delta p$, pressure difference at the ends of the capillary; Q, volumetric flow rate of liquid through a tube capillary, m^3/s; r, sphere radius, m; v, velocity of progressive uniform motion of a sphere, m/s; w, angular velocity, rad/s; ρ_b, density of the sphere material, kg/m^3; ρ_{liq}, liquid density, kg/m^3; τ, shear stress; η, coefficient of dynamic viscosity, Pa·s; φ, rotation angle, deg.

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