Hindawi
Journal of Engineering
Volume 2024, Article ID 6877306, 8 pages
https://doi.org/10.1155/2024/6877306

Research Article

New Viscometers for Measuring the Viscosity of Liquids

Jamshidbek Shamuratov,[1] **Oybek Mustafayev**,[1] **and Islom Kadirov**[2]

[1]*Department of the Metrology, Technical Regulation, Standardization and Certification, Tashkent State Technical University Named after Islam Karimov, Tashkent, Uzbekistan*
[2]*Department of Transport Systems, Urgench State University, Urgench, Uzbekistan*

Correspondence should be addressed to Jamshidbek Shamuratov; jamshid.shamuratov.phd2022@gmail.com

Received 30 October 2023; Revised 15 January 2024; Accepted 2 February 2024; Published 15 February 2024

Academic Editor: Natt Makul

This article's goal is to present a viscometer that makes use of a novel viscometry measurement technique. The post will also suggest brand-new vibration viscometers. The development of new viscometers has allowed for the continuous and instantaneous measurement of liquid viscosity. The viscosity can be precisely measured automatically using these viscometers, which are made for industrial application. These viscosity measurement tools can currently be applied to a number of different tasks, including the research of recently developed oil products, the choice of the best flow characteristics for different transfer situations, and the advancement and refinement of fuel preparation techniques.

1. Introduction

It has been possible to create a vibration viscometer that can measure the viscosities of liquids and solutions in both moving and stationary fluids and solutions over a short period of time continuously. Following the completion of the construction element assembly process, experiments were conducted to assess the material's metrological properties and ascertain the mathematical model for the vibration viscometer's viscosity measurement [1].

The viscosity calculation formula, or theoretical formula, has been established. It should be mentioned, nevertheless, that a number of experiments are carried out before the viscosity calculation formula—which is displayed below—is determined. It is difficult to quantify viscosity in a method that satisfies all of these experiments, even with modern equipment.

Therefore, it is important to consider the assumptions used in deriving the formula and the potential issues that may arise from them when measuring viscosity.

It is preferable to correct or, depending on the purpose of the measurement, to obtain an empirical formula based on the theoretically obtained viscosity calculation formula in order to measure and obtain the viscosity under the conditions; in some cases, this may be convenient in terms of measurement accuracy [2].

1.1. History and Development of Viscosity Measurement. Viscosity measures have a long history; it is thought to have started when the US automotive industry first emerged and people started gauging the viscosities of engine oils. In order to keep engines operating at peak efficiency, engine oil viscosities have to be managed in the United States. Engine oil viscosities are still specified nowadays (e.g., 5W-30) for both high and low temperatures. The engine is thought to burn out if the oil's viscosity drops below 2.6 cp (purified water's viscosity at 20°C is around 1 cp = 1 MPa·s: 1 milliPascal second). In the process of creating engine oils that use less energy and increase fuel economy, this has lately gained importance [3].

In addition, there has been a growing need for viscosity measurements in the realm of cutting-edge technology in order to preserve quality. This is partly because viscosity-related applications are finding new markets. These include resist inks for liquid crystals, semiconductor abrasives, glass coating materials, powder particle size distribution, polymeric emulsion, and surface-active agent cloud point measurement.

Furthermore, measuring the viscosity of human blood has been discussed recently. High blood viscosity raises the risk of sudden mortality from circulatory system-related disorders, according to studies. It is generally accepted that the viscosity of human blood ranges from around 3 to 10 MPa·s, depending on the technique of measurement [4].

This study examined the relationship—that is, the deviation from the assumptions—between the vibration viscometer prototype that the authors developed and the assumptions that were used to determine the viscosity calculation formula. An oscillating viscometer was designed with an experimental research incorporated. It is thought that there are issues unique to the prototype viscometer, even if many of the measurement values for each hypothesis are broadly characterized. Thus, from the perspective of metrology, experimental study is crucial [5].

1.2. Viscosity Definition. The relative motion between two boards positioned opposite each other in a sample liquid is used to define viscosity. When the velocity gradient (shear rate), which is determined by dividing the relative displacement speed by the distance between the two boards, and the interactive force (shear stress) per unit area generated in the planar direction between the opposing two boards are proportionate, the result is viscosity. This definition indicates that the shear stress and the shear rate are proportionately related. If viscosity is represented as a constant, stable value and shear stress and shear rate are proportionate, the fluid is referred to as a Newtonian fluid. On the other hand, all such fluids are collectively referred to as non-Newtonian fluids if the proportional relationship with the shear stress deteriorates due to changes in the shear rate or if the proportional relationship is lost due to temporal changes (a fixed viscosity value cannot be determined for the liquid due to the measurement conditions). Although viscosity is easily defined, as was previously shown, there are numerous structural issues with the instruments used to perform actual measurements. For example, for methods like the cup type, which measures the time it takes for the sample liquid to flow from the opening of a specific sample cup, the falling-sphere type, which measures the viscosity by the time it takes for a rigid body to fall within the sample liquid, and the capillary type, which measures the time it takes for the sample liquid to flow inside a capillary, it is important to stabilize the measuring environments, such as keeping the measuring temperature constant. For the rotation type, a rotor's rotation must be controlled at a steady pace, and the torque needed for the rotation must be measured consistently. On the other hand, technology to consistently vibrate the oscillator at the natural frequency is crucial for the vibration type, which determines the viscosity from the power to drive an oscillator submerged in a sample liquid. The underlying theory of the measurement principle, which has evolved into the modeling formula (modeling equation), and the "uncertainties" inherent in the measurements have been demonstrated with the capillary, rotation, and vibration types of viscosity measurements based on the aforementioned measurement principles [6].

2. Materials and Methods

2.1. Physical Quantity Determined by Every Method of Measurement

2.1.1. Type of Capillary. Gravity causes a liquid that is filling a vessel to flow to a lower position, and the liquid's viscous behavior is determined by the flow time. The flow time of globally standardized water is used as a reference to measure the time taken by the liquid for movement and convert it to a viscosity value. According to this concept of measurement, the physical quantity to be measured—that is, time—is inversely related to density but proportionate to viscosity. Consequently, this physical quantity is known as the "kinematic viscosity" and can be expressed as "viscosity/density" [7].

2.1.2. Type of Rotation. A rotor that is submerged in a liquid rotates continuously. The torque required to rotate anything is proportionate to its viscosity. The physical amount that is measured is called "viscosity" [8].

2.1.3. Type of Vibration. A liquid-immersed oscillator vibrates at a constant displacement magnitude. Viscosity in a liquid is determined by measuring the power required to cause vibration. "Viscosity × density" is the expression for the physical quantity that needs to be measured [9].

2.2. First Vibration Viscometer

2.2.1. Measuring Principle. A thin, flat plate can sense the viscous resistance of a liquid by vibrating it while submerged in it (Figure 1). The oscillations' amplitude can be used to calculate a liquid's viscosity. Viscosity can be measured with a vibrating plate viscometer, which has a vibrating plate that vibrates at a resonance frequency. In this instance, the following formula yields the product of viscosity and liquid density (viscosity × density):

$$\begin{aligned}\rho\mu &= \frac{R_M^2}{\pi f A^2}\left(\frac{f_a}{f}\frac{E_a}{E}-1\right)^2 \\ &= K\cdot\Lambda_0,\end{aligned} \tag{1}$$

where

$$\begin{aligned}K &= \frac{R_M^2}{\pi f A^2} \\ \Lambda_0 &= \left(\frac{f_a}{f}\frac{E_a}{E}-1\right)^2,\end{aligned} \tag{2}$$

where ρ is the density of the liquid sample, kg/m^3; μ is fluid sample viscosity, Pa $*$ s; E_a is the vibration plate in the air, m; E is the amplitude of fluctuations in the liquid sample, m; R_M is the viscometer-specific mechanical impedance factor, N/m^2; f_a is the resonance frequency in the air, Hz; f is the resonance frequency in a liquid sample, Hz; A is the area on both sides of the vibrating plate, m^2.

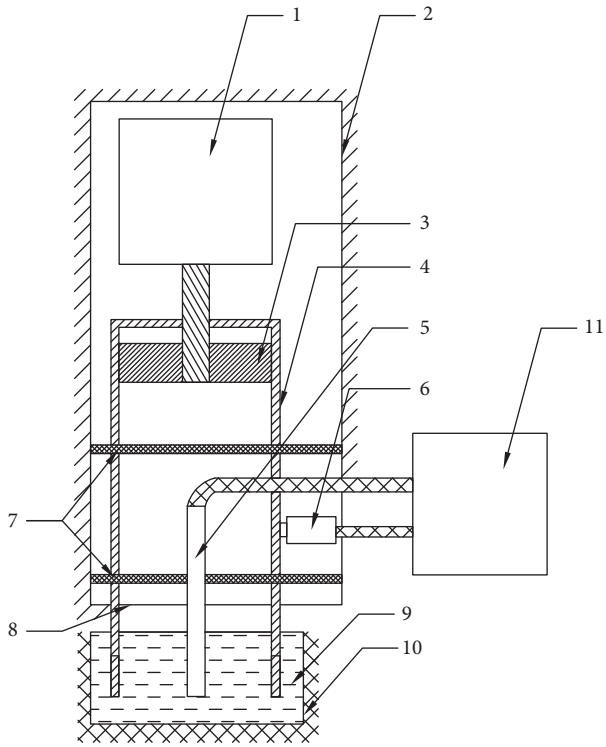

Figure 1: Schematic view of the oscillation viscometer.

After determining the design, materials, and dimensions of the vibration system, K in equation (1) becomes a constant value (viscometer constant). After defining $\rho\mu$ the density and viscosity of the liquid sample, it is possible to calculate the kinematic viscosity of the sample η.

We investigate the measurement process of a vibratory viscometer based on the following assumptions [10]:

(i) There is no turbulence from vibrating plates

(ii) There is no slippage between the liquid, the vibrating plate, and the surface

(iii) The sample is a Newtonian fluid

(iv) The vibrating plate's size is sufficient in relation to the vibration's wavelength, so the impact of the vibrating arm's end can be disregarded and the wave is thought to be a plane wave

(v) The sample container is large, so the impact of the wall's reflected wave can be disregarded

The above assumptions apply to the properties of the fluid. As with Iida et al., a Newtonian fluid is assumed. The standard cold viscosity fluid (hydrocarbon oil) used for calibration is a Newtonian fluid [2].

Iida et al. and this work use the same characteristic equation:

$$\rho\mu = K \cdot \Lambda_0. \tag{3}$$

2.2.2. Measurement Equipment Configuration. The following components and pieces are part of the oscillation viscometer (Figure 2): plate 1 is submerged in container 2, which holds the liquid that is being studied. In order to stop vibrations in plate 1, pusher 5 rotates when engine 9 is started. The lower wall 6 is securely fastened to the wall of body 10. To take the test liquid's temperature, a thermometer 7 is positioned in the space between the plate's two U-shaped branches. In order to measure the vibration amplitude of the plate in both the test liquid and the air, an additional inductive sensitive element 8 is attached. To guarantee the plate's vertical position, a thin elastic element 4 in the shape of a thread is employed. The gadget is connected to data processing unit 11, which calculates the viscosity value based on the test liquid's temperature and the magnitude of vibrations produced when the device is started [2].

2.3. Second Oscillating Viscometer. A coil of wire wrapped around a ceramic cylinder is attached to the base of the tuning fork. When voltage is applied to the coil of wire, the electromotive force (EMF) generated in it causes the vibration of the tuning fork (generating a frequency of 128 Hz) to deform the parts of the tuning fork immersed in the studied liquid [11], as a result of which the viscosity of the liquid depends on the deformation of the tuning-fork branches (Figure 3).

The tuning fork is surrounded by an external wall to reduce heat exchange and external influences, and the wall allows ignoring of external influences on the tuning fork and the amount of EMF generated in the coil of wire. The forks of the tuning fork are immersed in the studied liquid up to the specified amount, while the vessel containing the studied liquid is placed on a lifting table [12]. The tuning forks are oscillated by an electromagnetic excitation system, and the electromagnetic voltage that drives the tuning forks is adjusted by a coil of wire. Since the voltage of the coil providing the electromagnetic force is constant, the vibration amplitude of the tuning fork is determined by the forces of mechanical resistance of the liquid (internal frictional resistance of the liquid), which characterizes the viscosity of the studied liquid [13].

However, the viscometer proposed as the new viscometer has several disadvantages: the viscometer is a laboratory-type device, which does not allow it to be portable and directly used in the production process. The presence of a sensitive element in only one branch of the tuning fork increases its mechanical imbalance, thereby reducing the accuracy of the instrument's readings. It is an electromagnetic voltage that creates tuning forks, as a result of which the device is sensitive to changes in ambient temperature (the device must be thermostated). In addition, the calibration of the device is very complicated and requires a highly qualified specialist, which does not allow automation of the measurement process [14].

2.3.1. Measurement Equipment Configuration. As a new viscometer, the proposed viscometer consists of the following parts: plate holding base 1, coil with wire winding 2, tuning fork 3, piezoelectric sensor 4, viscometer outer wall 5, sample liquid under investigation 6, sample container for liquid 7, control and calculation unit 8, resistance for balancing the circuit 9, and capacitor 10 for forming EMF.

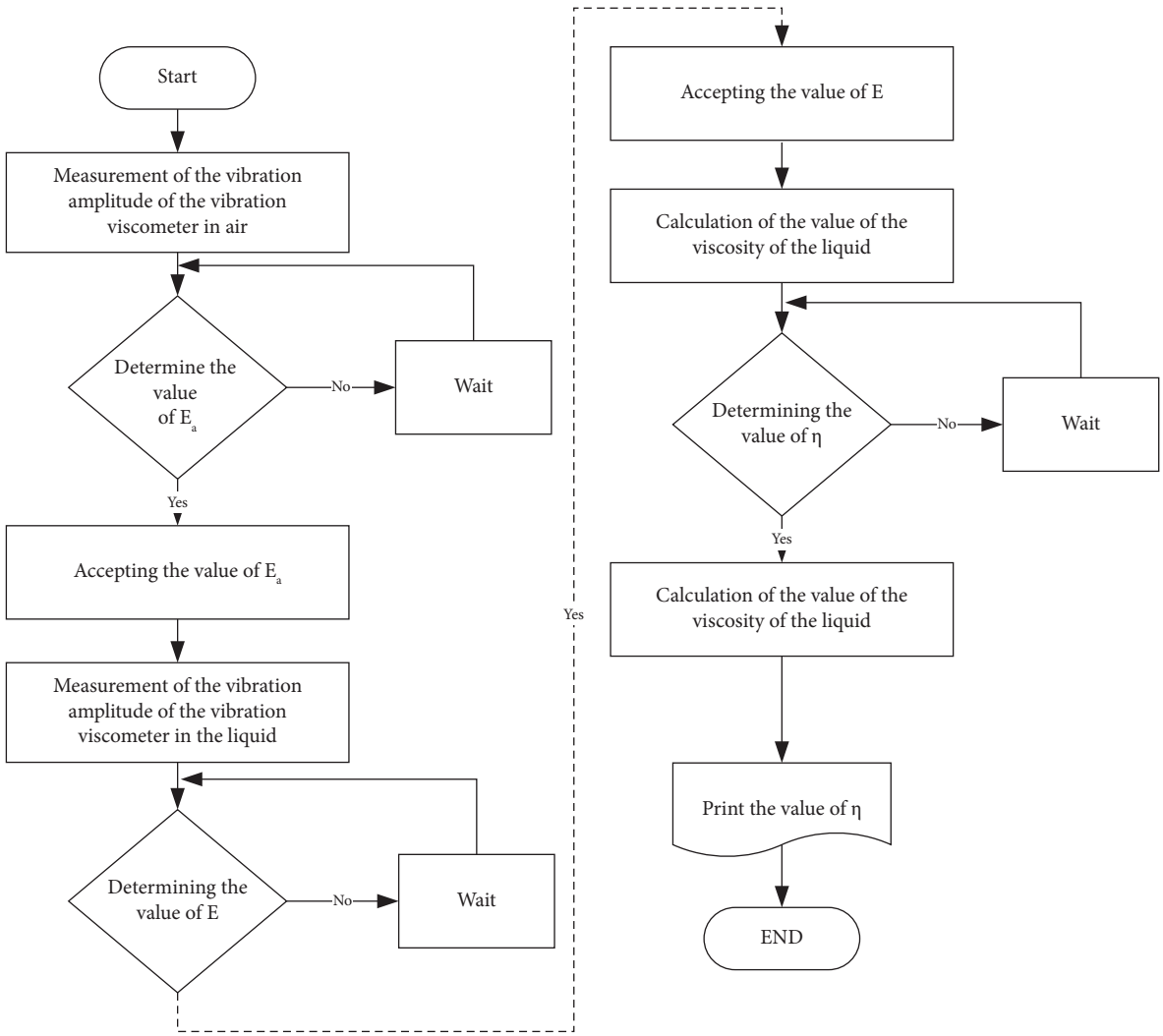

Figure 2: Schematic diagram of the measuring system of the viscometer with an oscillating plate [2].

As a new viscometer, the proposed viscometer works as follows: when the viscometer starts, the wire-wound coil 2 acts on the tuning fork 3 in the horizontal direction with a constant and constant force F_1. The tuning fork 3 vibrates in the horizontal direction inside the sample fluid 6 under investigation. The second end of the tuning fork 3 inside the investigated sample liquid 6 vibrates with the frequency f_2 under the influence of the force F_2. The frequency and amplitude of tuning fork 3 Δx are measured using a piezoelectric sensor 4.

Based on the fact that the wire-wound coil 2 acts on the tuning fork 3 with a constant and constant force F_1, a force F_2 is generated on the inside end of the sample liquid 6 of the tuning fork 3 and begins to oscillate (Figure 4). Based on the resulting F_2 force η, the dynamic viscosity value of the liquid is determined as follows [15]:

$$\eta = \frac{k}{\Delta x}, \tag{4}$$

where η is the dynamic viscosity of the liquid, MPa·s; k is the vibrational viscometer constant; Δx is the amplitude of the part of the tuning fork in the sample liquid, mm.

Dynamic viscosity values of low-viscosity liquids are determined using the vibration viscometer proposed by the expression [16].

2.4. Third Vibration Viscometer. The viscometer proposed as a new viscometer also belongs to the type of vibration viscometers. As a new viscometer, the proposed viscometer can be used to determine the viscosity of transparent liquids [17].

The viscometer proposed as a new viscometer (Figure 5) consists of the following parts: plate holding base 1, multilayer ceramic piezoelectric actuator 2, thin plate 3, sample liquid under investigation 4, sample liquid container 5, and laser vibrometer 6.

2.4.1. Measurement Equipment Configuration. When the viscometer starts, the multilayer ceramic piezoelectric actuator 2 acts on the thin plate 3 in the horizontal direction with a constant and constant force F_1. A thin plate 3 oscillates in the horizontal direction with a specific frequency

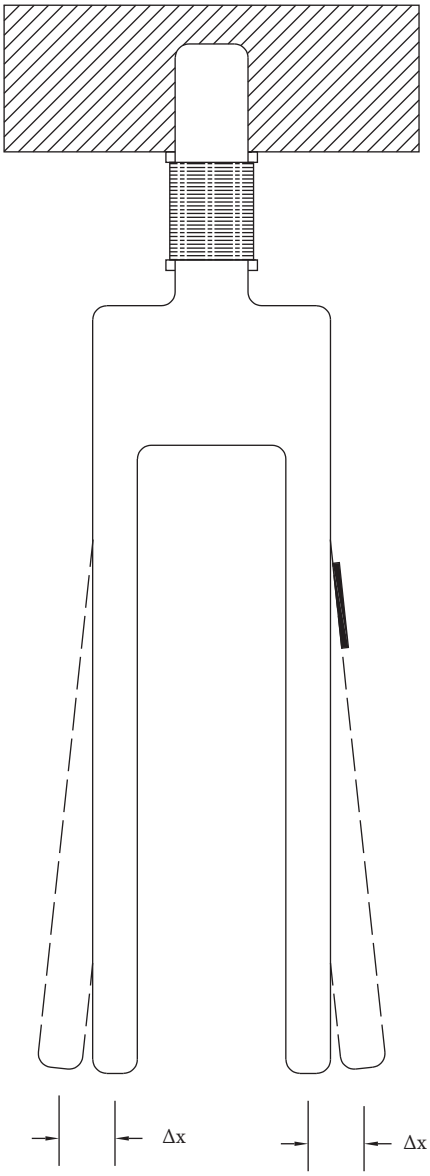

Figure 3: The scheme of the amplitudes of the tuning fork in the process of oscillation.

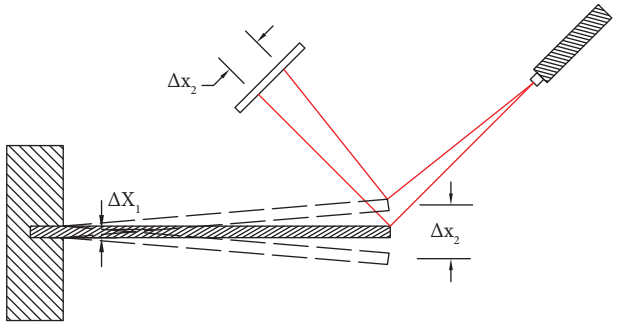

Figure 4: The scheme of the amplitudes of the thin plate in the process of vibration.

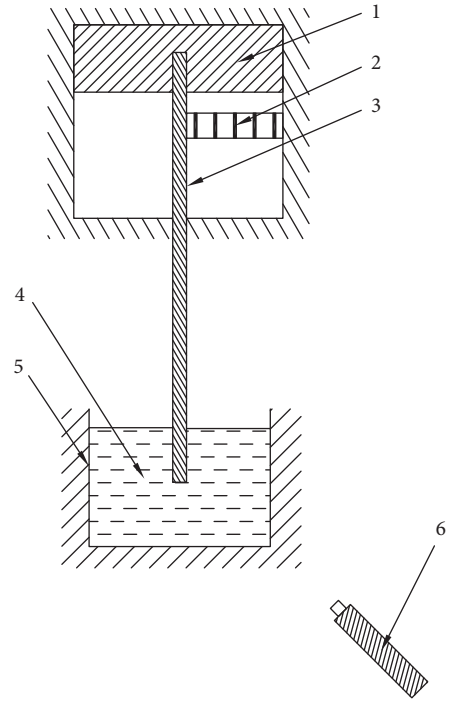

Figure 5: The structure of the vibration viscometer.

f_1 and amplitude Δx_1. The thin plate 3 oscillates in the horizontal direction inside the sample fluid 4 under investigation. The second end of the thin plate 3 inside the sample liquid 4 under investigation vibrates with the frequency f_2 under the influence of the force F_2. The frequency and amplitude of the thin plate 3 are measured using the Δx_2 laser vibrometer 6 (Figure 4).

Based on the fact that the multilayer ceramic piezoelectric actuator 2 acts on the thin plate 3 with a constant and constant force F_1, a force F_2 is generated on the end of the thin plate 3 inside the sample liquid 4 under investigation, and the oscillating movement will come. The resulting force F_2 is determined as follows [18]:

$$F_2 = \eta S \frac{\mathrm{d}v}{\mathrm{d}x}, \tag{5}$$

where η is the dynamic viscosity of liquid, MPa·s, S is the surface area of the thin plate in the sample liquid, mm^2, dv are the velocities of sample fluid layers, mm/s, and dx is the distance of movement of sample liquid layers, mm.

The following expressions can be determined based on the calculation of weights and the laws of conservation of energy [19]:

$$\begin{aligned} F_1 \cdot \Delta x_1 &= F_2 \cdot \Delta x_2, \\ F_1 \cdot \Delta x_1 &= \eta S \frac{dv}{dx} \cdot \Delta x_2, \end{aligned} \tag{6}$$

$\mathrm{dv} = \mathrm{dx} \cdot w_2$ we get the following expression

$$F_1 \cdot \Delta x_1 = \eta S \frac{dv}{dx} \cdot \Delta x_2 \Longrightarrow F_1 \cdot \Delta x_1 = \eta \cdot S \cdot w_2 \cdot \Delta x_2. \tag{7}$$

From (7) η, we find

$$\eta = \frac{F_1 \cdot \Delta x_1}{S \cdot w_2 \cdot \Delta x_2}. \tag{8}$$

Viscosities of transparent liquids are determined using the vibration viscometer proposed by expression (8).

3. Results

3.1. Examples of Static Viscosity Measurement and Its Future Prospects. Here are some real-world examples of measurements. Figures 6 and 7 illustrate certain events that were previously thought to be impossible with traditional viscosity measurements.

(1) Engine oil: the "static viscosity" of the oil is used to measure its temperature properties as it changes [20]

  (i) Converting a liquid into a solid by tracking the curing process of a protein substance (egg albumen) based on changes in its "static viscosity"
  (ii) Examining the components of a liquid: determining the components by calculating changes in alcohol concentration based on changes in its "static viscosity"

(2) Future "static viscosity" measurements may also make the following domains (use is appropriate) [21]:

  (i) Assessing the base material's viscosity, which is required to evaluate the particle size distribution (evaluating Brownian motion)
  (ii) Measuring the cure times and temperature characteristics of functional liquids, such as coating materials and inks
  (iii) Determining the "swallowability" of soft drinks and measuring the physical characteristics of biological objects, such as blood viscosity
  (iv) Determining the molecular weight of a turbid solution by measuring its viscosity [6]

Below are the results of the theoretical calculations of the main technical parameters of vibration viscometers, which are classified in Table 1, and the principles of operation are presented.

4. Discussion

4.1. Advantages and Measurement Principles of the Vibration Viscometers. Vibration viscometers exist in two varieties: the tuning-fork vibration type and the rotating vibration type, which both use the same measurement technique. A thorough explanation of the tuning-fork vibration method is the focus of this section [22].

The produced amplitude in the liquid is continuously measured during the viscosity measurement. Furthermore, measurements are made of the air's amplitude. The liquid in

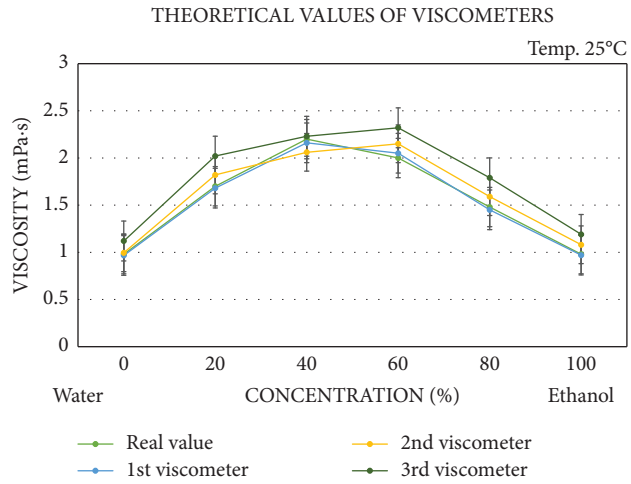

Figure 6: Actual and theoretically calculated viscosities of the water-ethanol mixture in the above viscometers.

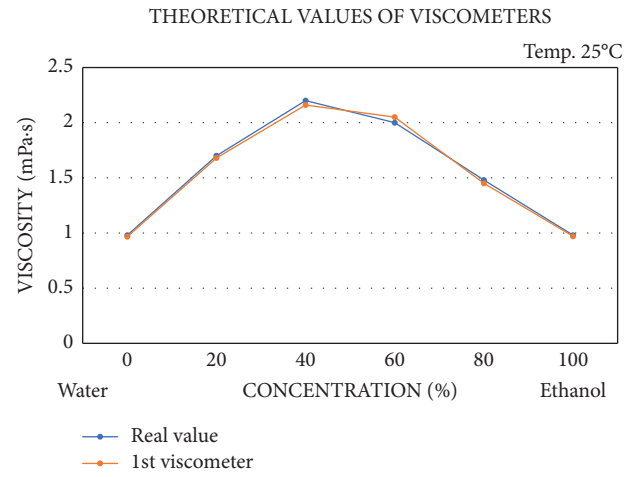

Figure 7: Actual and theoretically calculated viscosities of the water-ethanol mixture in the first viscometer.

which the oscillators are submerged is multiplied by its density to determine the viscosity, which is based on changes in amplitude in the liquid that follows [23]. Because the vibration technique only slightly shifts the sample liquid, very little energy is delivered to it. Additionally, because the oscillator has a low thermal capacity, interference from the measurement to the sample material can be reduced. A quick and stable measurement is made possible by the lack of flowing or churning of the sample liquid, which causes minimal mechanical change to the sample's physical properties even after the measurement begins. A liquid's viscosity varies up to −2 ~−10%/°C depending on its temperature [24]. Therefore, even a tiny amount of interference from the measurement device can be advantageous, for example, by reducing the likelihood that temperature variations would affect the sample's physical characteristics. Furthermore, the viscometer can perform continuous readings at as low as 0.3 MPa·s, or one-third the viscosity of purified water, and as high as 10,000 MPa·s by using a tuning-fork vibration. For

Table 1: Main technical parameters of new viscometers.

Technical parameters	Vibration viscometers		
	First viscometer	Second viscometer	Third viscometer
Vibration frequency (Hz)	30	30	30
Measurement range (MPa·s)	0.3–1000	0.3–1000	0.3–1000
Relative measurement error (%)	±7	±10	±12
Minimum sample volume (ml)	25	35	35
Units of measure	MPa·s, Pa·s, and cP, P	MPa·s, Pa·s, and cP, P	Pa·s, P

*The technical values in the table are determined by the authors through theoretical calculations.

instance, it is possible to track the curing processes of albumen proteins with varying compositions at various temperatures. According to the theoretical formula, the vibration viscometer measures the physical amount that is, in principle, equal to "viscosity × density" [25].

5. Conclusion

With the use of real measurement examples, this article offers a concise description of the characteristics of the new viscosity measurement tools, tuning-fork vibration viscometers. Viscosity × density is the measurement made by vibration viscometers. The "static viscosity" is the result of expressing the "viscosity × density" using water as an example, where the temperature coefficient of the density value is as low as 1/100 of the viscosity value. This has made it possible to easily do continuous measurements of different physical property changes related to viscosity. As the standardized methods for measuring viscosity, a number of viscosity-measuring techniques and their associated uncertainties have previously been confirmed and made available to the public. It is anticipated that further opportunities for accurate viscosity measurements in R&D, production, and quality control across a range of industries would arise as a result of these experiences, significantly advancing their development.

Data Availability

Data supporting this research article are available from the corresponding author or first author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work in this paper was supported by the author.

References

[1] J. G. Woodward, "A vibrating-plate viscometer," *Journal of the Acoustical Society of America*, vol. 25, no. 1, pp. 147–151, 1953.

[2] J. Shamuratov, *New Vibration Viscometer for Measuring the High-Viscosity Liquids Science of Youth- Science of the Future: Collection of Articles of the Iii International Scientific and Practical Conference*, Petrozavodsk: ICNP "New Science", Europe, UK, 2023.

[3] A. N. Solovyov, "Kaplun AB Vibration method for measuring the viscosity of a liquid nauka," *Siberian Branch*, vol. 21, 1967.

[4] House, *Strelkov SP Introduction to the Theory of Vibrations Textbook*, Publishing House Lan, St. Petersburg, PA, USA, 3rd edition, 2005.

[5] J. U. Shamuratov, "Physical quantity measured by a vibration viscometer actual problems of modern science," *Education and Training*, vol. 3, 2023.

[6] M. Tokuda, K. Nakajima, T. Yamamoto, H. Nakajima, and K. Kawaguchi, "Development and utilization of a new oscillating-plate type viscometer for casting powder evaluation," *Sumitomo Metals*, vol. 44, p. 368, 1990.

[7] S. Sasahara, S. Inaba, and M. Tomita, "New oscillating plate viscometer for instantaneous measurement of viscosity of molten slag," in *Proceedings of the 4th International Conference On Molten Slags and Fluxes*, Sendai, Japan, June 1992.

[8] K. C. Mills, L. A. Chapman, A. B. Fox, and S. Sridhar, "'Round robin' project on the estimation of slag viscosities," *Scandinavian Journal of Metallurgy*, vol. 30, no. 6, pp. 396–403, 2001.

[9] J. U. Shamuratov, "Method of viscosity measurement using a new oscillating-plate type viscometer for high-temperature," *Material Instruments*, vol. 10, p. 13, 2023.

[10] IUPAC, *Meeting of the Subcommittee on Transport Properties of the Commission I.2: Thermodynamics of IUPAC*, IUPAC, Erlangen, Germany, 1999.

[11] F. J. P. Caetano, J. M. N. A. Fareleira, C. M. B. P. Oliveira, and W. A. Wakeham, "Viscosity of di-isodecylphthalate: a potential standard of moderate viscosity," *International Journal of Thermophysics*, vol. 25, no. 5, pp. 1311–1322, 2004.

[12] T. Retsina, S. M. Richardson, and W. A. Wakeham, "The theory of a vibrating-rod viscometer," *Applied Scientific Research*, vol. 43, no. 4, pp. 325–346, 1987.

[13] J. U. Shamuratov, "The viscosity of liquids, methods for determining viscosity and classification of modern viscometers//"Scientific and technical," *Journal of Namangan institute of Engineering and Technology" Vol*, vol. 7, p. 97, 2022.

[14] A. A. H. Padua, J. M. N. A. Fareleira, J. C. G. Calado, and W. A. Wakeham, "Electromechanical model for vibrating-wire instruments," *Review of Scientific Instruments*, vol. 69, no. 6, pp. 2392–2399, 1998.

[15] J. U. Shamuratov, "Oscillatory viscometers and ways to enhance them," *Science and innovative development*, vol. 252 pages, 2022.

[16] A. A. H. Padua, J. M. N. A. Fareleira, J. C. G. Calado, and W. A. Wakeham, "Validation of an accurate vibrating-wire densimeter: density and viscosity of liquids over wide ranges of temperature and pressure," *International Journal of Thermophysics*, vol. 17, no. 4, pp. 781–802, 1996.

[17] F. J. P. Caetano, J. L. G. Correia da Mata, J. M. N. A. Fareleira, C. M. B. P. Oliveira, and W. A. Wakeham, "Viscosity

measurements of liquid toluene at low temperatures using a dual vibrating-wire technique," *International Journal of Thermophysics*, vol. 25, pp. 1–11, 2004.

[18] Braunschweig, "Viscosity Standard Specimens 100B," *PTB, Bundesalle*, vol. 52, 2004.

[19] D. H. Ferriss, P. N. Quested, L. A. Chapman, and A. P. Day, *The Choice of Equations for the Measurement of Viscosity by the Oscillating cylinder Method Presented at ECTP*, ECTP, London, UK, 2002.

[20] D. Wang and R. A. Overfelt, "Oscillating cup viscosity measurements of aluminum alloys: a201, A319 and A356," *International Journal of Thermophysics*, vol. 23, no. 4, pp. 1063–1076, 2002.

[21] Y. Sato, Y. Kameda, T. Nagasawa et al., "Viscosity of molten silicon and the factors affecting measurement," *Journal of Crystal Growth*, vol. 249, no. 3-4, pp. 404–415, 2003.

[22] T. Iida, T. Tanaka, and M. Koike, "Effect of the reflected wave from the wall of a vessel and end effect of the plate in the oscillating-plate method isij 33 218," *ISIJ International*, vol. 33, 1993.

[23] S. Sasahara, S. Inaba, and M. Tomita, *New Oscillating Plate Viscometer for Instantaneous Measurement of Viscosity of Molten Slag 4th Int. Conf. On Molten Slags and Fluxes Sendai, Japan, 8–11 June 1992 Japan*, Iron and Steel Institute, Washington, DC, USA, 1992.

[24] K. C. Mills, *Recommended Values of Thermophysical Properties for Selected Commercial Alloys*, Woodhead Publishing Ltd, Cambridge, UK, 2002.

[25] R. Wunderlecht, *Presented at 2nd International Symposium on Physical Sciences in Space*, Microgravity Sci. Technol. J. Submitted, Toronto, Canada, 2004.