Ethiopian International Journal of Multidisciplinary Research

pISSN:2349-5707 Volume:13,Issue 4, April -2026 eISSN:2349-5715

ARCHITECTURE AND ALGORITHMIC MODEL OF THE ULTRASONIC VISCOSITY AND DENSITY METER

Yusupbekov Nodirbek Rustambekovich

Ergasheva Kamola Nasriddinovna

Tashkent State Technical University

Abstract. The article provides an analytical review of modern approaches and technologies for measuring the viscosity and density of liquid media. Classical and innovative techniques are analyzed, including capillary, vibrational, ultrasonic, optical, and hybrid methods. Special attention is paid to high-frequency acoustic systems and intelligent data-processing algorithms based on wavelet analysis and neural networks. The study highlights the principles of next-generation instruments that ensure high-accuracy measurements in in situ mode. Integration of networks sensor with digital platforms and Industry 4.0 technologies significantly enhances the effectiveness of liquid property monitoring. Comparative characteristics of sensitivity, measurement range, and metrological performance of existing instruments are presented.

Keywords: viscosity, density, ultrasonic measurement, vibrational sensors, neural networks, measurement systems.

Аннотация. В статье представлен аналитический обзор современных методов и технологий измерения вязкости и плотности жидких сред. Рассмотрены классические и инновационные подходы, включая капиллярные, вибрационные, ультразвуковые, оптические и комбинированные методы. Особое внимание уделено высокочастотным акустическим системам и интеллектуальным алгоритмам обработки данных, основанным на вейвлет-анализе и нейросетевых моделях. Проанализированы принципы работы приборов нового поколения, обеспечивающих высокую точность измерений в режиме in situ. Отмечено, что интеграция сенсорных систем с цифровыми платформами и технологиями Индустрии 4.0 позволяет существенно повысить эффективность контроля физических свойств жидкостей. Представлены сравнительные данные по чувствительности, диапазону измерений и метрологическим характеристикам существующих приборов.

Ключевые слова: вязкость, плотность, ультразвуковые методы, вибрационные сенсоры, нейросетевые алгоритмы, измерительные системы.

INTRODUCTION: Devices for comprehensive viscosity and density measurements of liquids with adaptive control, unlike traditional viscosity meters, are equipped with additional algorithmic procedures that enable specialized measurement modes. Specifically, the device provides highly accurate recording of the attenuation coefficient of Lamb wave zero-point symmetric modes and horizontally polarized normal waves (HPNW), as well as measurement of the propagation velocity and absorption coefficient of longitudinal waves in the liquid being measured. Simultaneous monitoring of the ambient temperature is also possible [1-3].

In terms of measurement methodology, all algorithms operate on a single principle: an electrical pulse is generated, exciting the corresponding transducer. The elastic signal is then emitted into the medium under study, received as an echo signal, converted into electrical form, and then its arrival time delays and amplitude parameters are recorded. To improve accuracy, the device design incorporates a method of comparative measurements on two acoustic baselines of different lengths, significantly reducing the influence of random errors. Based on the obtained data, wave propagation velocities and attenuation coefficients are calculated, which are then used to determine the physical properties of the liquid medium.

$$\alpha_i = \frac{1}{2(L_{i2} - L_{i1})} ln \frac{A_{i2}}{A_{i1}}, \; c_i = \frac{2(L_{i2} - L_{i1})}{t_{i2} - t_{i1}}. \qquad (1)$$

In this case, the index i (where $i = 1...3$) corresponds to the number of the parameter being measured, and therefore to the channel number. For the i-th channel, two sounding bases are used – L_{i1} and L_{i2} – and the echo signal amplitudes A_{i1} and A_{i2} are recorded. It should be emphasized that three channels are sufficient to implement the entire set of measurements, since the propagation velocity and absorption coefficient of longitudinal waves in the test liquid can be determined within a single channel [4-7].

The device operates in such a way that measurements in each channel are performed sequentially, and the results are recorded and stored in the device's built-in memory. Before the main experiment, a mandatory calibration procedure is performed: in this mode, the device performs trial measurements in one or more reference liquids with predetermined physical parameters. The resulting numerical data is stored in memory and subsequently used in the implementation of computational algorithms. Upon completion of the measurement cycle for all channels, the software automatically calculates the desired characteristics of the test fluid based on embedded mathematical signal processing models. In the extended configuration, the measurement chamber contains up to six acoustic channels, as well as an additional channel for measuring the temperature of the test medium. The general diagram of the chamber is shown in Fig.1 (the temperature sensor is not shown in the drawing).

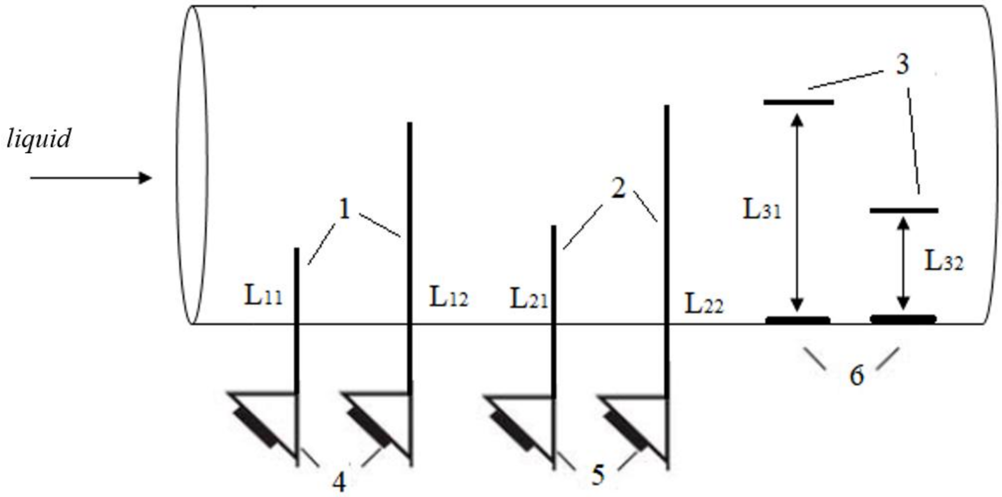

Fig.1. Design of a measuring chamber for complex control of viscosity and density of liquids: 1 - waveguide of symmetric Lamb wave mode; 2 - waveguide of horizontally polarized normal wave (HPNW); 3 - reflectors of longitudinal waves in the studied medium; 4-converter of symmetric Lamb wave mode; 5 - HPNW converter; 6 - longitudinal wave converter.

Fig.2 shows algorithmic sequence of operation of a device for complex measurement of viscosity and density of liquids.

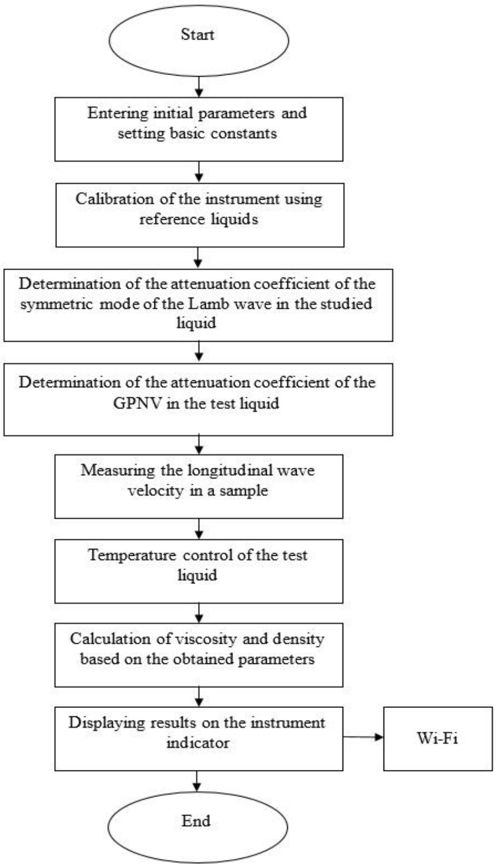

Fig.2. Algorithmic sequence of operation of the device for complex measurement of viscosity and density of liquids.

Fig.3 shows a block diagram of the operating algorithm of a device for the complex measurement of viscosity and density of liquids, demonstrating the step-by-step organization of the measurement process and the processing of the obtained data.

Table 1. Distribution of functions of measuring channels of a device for complex measurement of viscosity and density of liquids

Channel number	*Measured parameter*	*Measurement principle*	*Note*
1	Attenuation coefficient of symmetric modes of Lamb waves	Analysis of echo signal amplitude at different sounding bases	Used for basic control
2	The attenuation coefficient of antisymmetric modes of Lamb waves	Comparison of signal amplitudes at different frequencies	Hypersensitivity
3	Velocity of propagation of longitudinal waves	Measuring time intervals of signal arrival	Related to the density of the environment
4	Longitudinal wave absorption coefficient	Analysis of signal amplitude reduction	Allows to take into account bulk viscosity
5	Complex acoustic parameters (backup channel)	Used for advanced computing	Can be adapted to the tasks
6	Temperature of the liquid	Temperature	-

	being tested	sensor	

Each measurement cycle, which provides the initial data for subsequent calculation of the density and viscosity of the fluid being studied, is implemented using its own algorithm. The methods for recording the attenuation of symmetric Lamb wave modes and horizontally polarized normal waves have the same implementation structure [8,9].

In this regard, Fig.3 presents a generalized algorithm for carrying out measurements, applicable immediately to both of the indicated types of elastic waves.

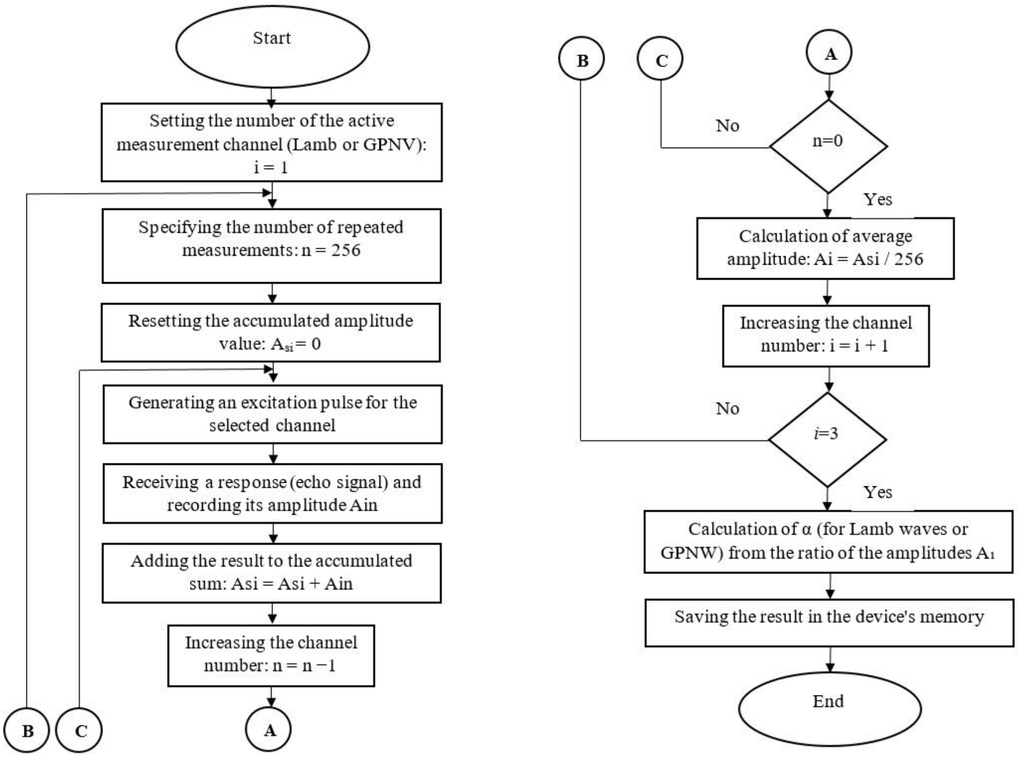

Fig.3. Algorithm for calculating attenuation parameters for symmetric Lamb waves and GPNW in the studied liquid.

The algorithm shown in Figure 1.4 illustrates the order of calculations required to determine the attenuation coefficient of symmetric Lamb waves and GPNW in a liquid medium [10].

The method is based on the comparison of the amplitudes of echo signals recorded during the passage of elastic waves through two different sounding bases:

$A1$= short base echo signal amplitude;

$A2$= long base echo signal amplitude.

The attenuation coefficient α is defined as a logarithmic function of the amplitude ratio:

$$\alpha = \frac{1}{2(L_2 - L_1)} ln \frac{A_1}{A_2}, \qquad (2)$$

where L_1 and L_2 are the lengths of the sounding bases.

This approach allows us to exclude the influence of hardware factors and systematic errors, since a relative comparison of signals is used, rather than their absolute values.

To improve the accuracy of calculations, the amplitudes are averaged over the results of multiple measurements:

$$\bar{A} = \frac{1}{N} \sum_{n=1}^{N} A_n , \qquad (3)$$

where N is the number of experiment repetitions, A_n is the amplitude value at the n-th measurement.

At the final stage, the averaged values are substituted into formula (1), after which the calculated value of the attenuation coefficient is automatically saved in the internal memory of the device.

The presented algorithm is universal: it is equally applicable to both symmetric Lamb wave modes and GPNW. This allows it to be used in integrated ultrasonic systems for rapid viscosity and density testing of liquid media [11-13].

The presented algorithm (Fig.4) illustrates the process of recording the time of passage of acoustic pulses through a liquid medium and the subsequent calculation of the velocity of longitudinal waves.

The method is based on sequential measurement of signal arrival times over two acoustic baselines of different lengths. Let t_1 and t_2 be the average signal arrival times for the short (L_1) and long (L_2) baselines, respectively. Then the longitudinal wave velocity in the liquid is determined by the expression:

$$C_l = \frac{2(L_2 - L_1)}{t_2 - t_1}. \tag{4}$$

Here the coefficient 2 takes into account the double path of signal propagation (from the emitter to the reflector and back).

To minimize random errors, each measurement of the signal arrival time is performed multiple times, after which the average value is calculated:

$$\bar{t}_i = \frac{1}{N}\sum_{n=1}^{N} t_{in}, \ (i = 1,2), \tag{5}$$

where N is the number of repetitions, tin is the signal recording time at the n-th measurement.

The algorithm automatically records the received data into the device's internal memory, eliminating the need for manual recording of values and increasing the reliability of measurements.

Based on this, this scheme ensures an accurate determination of the velocity of longitudinal waves in the studied liquid, and its use in conjunction with algorithms for calculating the attenuation coefficient allows for a comprehensive assessment of the viscosity, density, and other physical parameters of liquid media.

Fig.5 shows a generalized block diagram of a device designed for the comprehensive determination of viscosity and density of liquid media. The system's architecture is modular, with the difference between channels determined solely by the type of elastic waves excited. This approach ensures the device's versatility and allows for an expanded range of functions.

The key element of the circuit is the processor (1), which performs control tasks, processes incoming signals, and implements built-in algorithms. Control commands are sent to the driver (2), which converts them to operate the multichannel probe pulse generator (3). The generated pulses are sent to the measuring chamber (4), where the acoustic waves interact with the fluid being measured.

The signal from the camera is fed to a multichannel switch (5), amplified by unit (6), and converted to digital form using an ADC (7). A DAC (8) is used to close the measuring circuit, returning the processed signal to the measuring chamber.

To improve calculation accuracy, a temperature control unit (9) is included, allowing for the thermal conditions of the experiment to be taken into account. Intermediate results and calibration data are stored in the memory module (10). Final values are displayed on the display (12), ensuring operator convenience.

An additional element of the circuit is a Wi-Fi module (11), which enables the transmission of measurement results to a local network or remote servers. This enables remote monitoring.

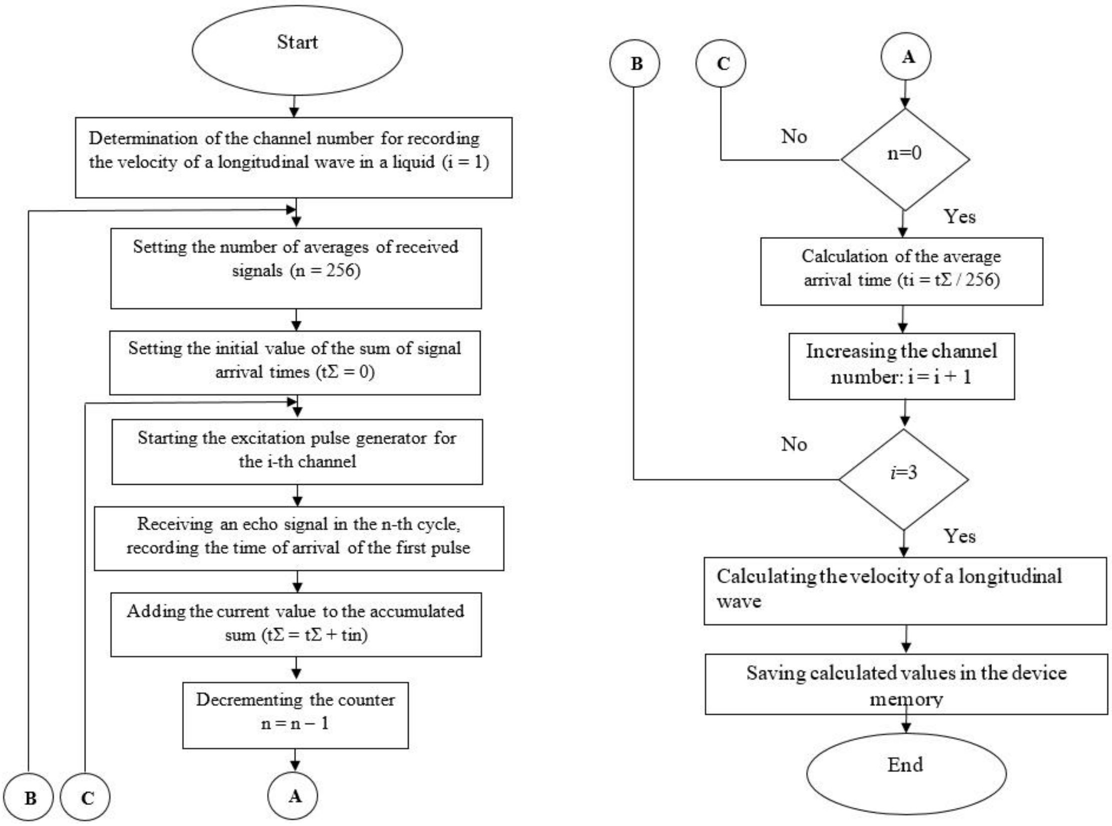

Fig.4. Block diagram of signal arrival time measurements for calculating longitudinal wave velocity.

Integration of the device into industrial automation systems and expands its functionality in the context of the Industry 4.0 concept.

Based on this, the proposed architecture combines high accuracy and reproducibility of measurements with modern data transmission means, which allows the device to be used both in laboratory research and in real production conditions.

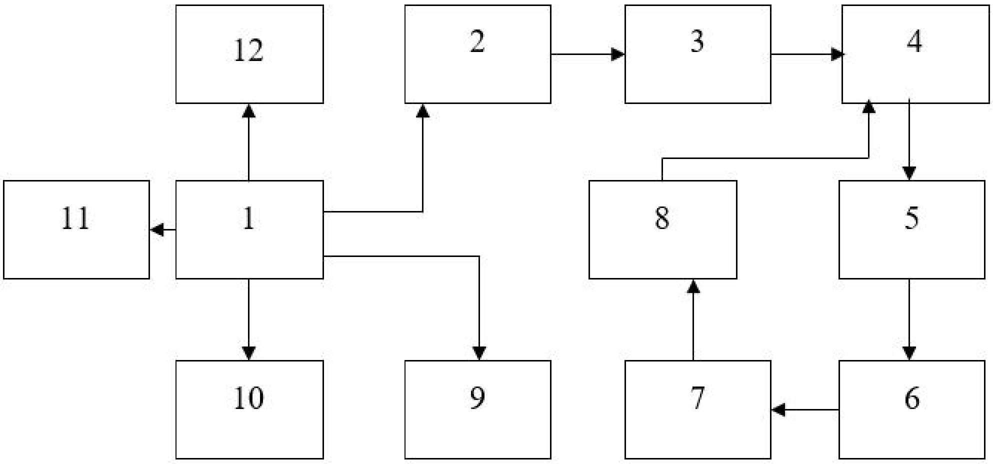

Fig.5. Block diagramdevices for complex measurement of viscosity and density of liquids.

A detailed diagram of the measuring chamber is shown in Fig.6. Structurally, it consists of two angle-beam transducers (13) mounted on plates (14), which are rigidly connected to each other using clamps (15) and immersed in a reservoir containing the liquid being measured (16). A temperature sensor (17) is installed between the waveguides; its mounting location is not shown in the diagram.

The camera operates as follows. When the appropriate function is selected on the keyboard (11), the processor (1) initiates the first measurement cycle, including the driver (2) and the first channel of the probe pulse generator (3). The probe pulse generator generates a sequence of radio pulses with a narrow, nearly monochromatic spectrum, which are fed to the first transducer (13). The transducer, activated by the signal, excites a normal wave propagating across the plate (14). The wave is reflected from the edge of the plate and returns to the transducer, where it is converted into an electrical echo signal.

The generated signal is fed through the first channel of the switch (5) to the amplifier (6), then converted into digital code using the ADC (7) and transmitted to the processor via the memory unit (10) for further processing. The gain is controlled using the DAC (8), which generates a control signal whose value is set during the instrument calibration process.

In the second cycle, the procedure is repeated for the other sounding base, i.e., for the second transducer (13). After this, the processor, using the data on the arrival times and amplitudes of the echo signals, calculates the zero-mode attenuation coefficient (e.g., GPNV) using formula (1), stores the obtained values along with information from the temperature control unit (9), and activates the next channel. The final results are automatically displayed on the display (12).

The accuracy of attenuation coefficient determination depends significantly on the accuracy of signal amplitude measurements and the length of the wave's contact with the liquid medium. Adherence to the conditions established in the derivation of the theoretical relationships between the attenuation coefficient and the liquid parameters is also a significant factor. As practice has shown, the issue of matching the waveform in a plate to a flat model is particularly important. Since experimental verification of this condition is technically difficult, a calibration procedure is used.

Calibration is performed as follows: the plates are immersed in a reference fluid with known parameters (density, viscosity, and sound velocity). Based on the measurement results, the desired characteristics are calculated and then compared with reference data. Based on this, a correction factor is calculated and taken into account in subsequent measurements. It is important that the contact length between the wave and the fluid remains the same during calibration and in actual operation [14,15].

Implementing this requirement presents certain technical challenges, as the use of long plates makes the acoustic unit bulky and complicates its integration into industrial equipment. To address this issue, the plates can be manufactured in a combination of straight and curved sections.

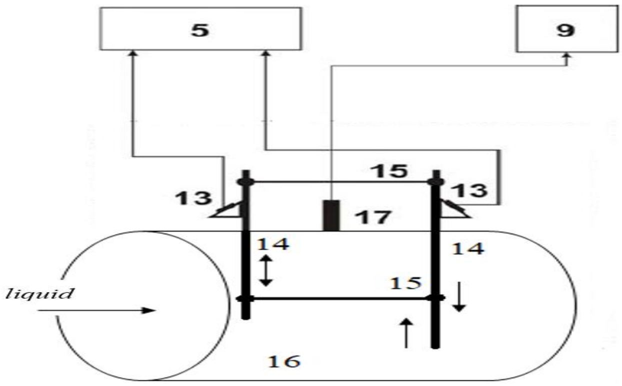

Fig.6. Design of a chamber for recording liquid medium parameters.

Meeting these requirements poses a number of technical challenges. Specifically, the use of elongated plates increases the size of the acoustic unit, significantly limiting its integration into existing process equipment. To overcome this problem, a modular approach to plate construction is proposed: it is formed as a set of sequentially connected straight and curved sections. This implementation method allows for a significant reduction in the acoustic unit's dimensions without compromising its metrological performance. An additional advantage of the modular design is its increased reliability and technological flexibility: individual segments can be replaced or adapted to specific operating conditions, facilitating maintenance and facilitating its integration into various production systems.

This paper presents the architecture and algorithmic model of an ultrasonic viscosity and density meter designed for real-time monitoring of fluid properties. The proposed system is based on ultrasonic wave propagation through a liquid medium, where key parameters such as transit time, attenuation, and frequency response are analyzed. The architecture integrates ultrasonic transducers, signal conditioning modules, data acquisition units, and a digital processing block for parameter estimation.

An algorithmic model is developed to establish the relationship between measured ultrasonic signals and the physical properties of the fluid, including viscosity and density. The model employs calibration functions, temperature compensation, and adaptive filtering techniques to improve measurement accuracy under varying operating conditions. Experimental validation demonstrates that the proposed approach provides high precision, stability, and suitability for industrial process control applications, particularly in environments requiring continuous and non-invasive measurements.

REFERENCES:

1. Yusupbekov NR, Gulyamov SM Smart ultrasonic viscoplotnometers with adaptive control. Measurement, 2022, 196: 111830.
2. Advantages of analytical solutions of sentience cloud platform CTCM Yusupbekov N.R., Sujith S., Anand N., Abdurasulov F.R.
3. Krasilnikov V.A. Acoustic methods for viscosity measurement. Acoustical Physics, 2021, 67(5): 510–519. DOI: 10.1134/S1063771021050121.
4. Uttam K. K, Sayantan SU /An analytical theory for the forced convection condensation of shear-thinning fluids onto isothermal horizontal surfaces.− Applied Mathematics and Computation/Volume 421, 15 May 2022,https://doi.org/10.1016/j.amc.2021.126909
5. Coussot P. Rheometry of Pastes, Suspensions and Granular Materials. – Wiley, 2005.
6. Yusupbekov N.R., Abdurakhmanov H.T., Gulyamov Sh.M. Intelligent methods for measuring physical parameters of liquid systems. – Tashkent: Fan, 2018.
7. Gulyamov Sh.M. Digitalization of measurement processes in chemical-engineering systems. – Tashkent: TSTU, 2020. – 164 p.
8. Mason W. P. Physical Acoustics. – Academic Press, 2018.
9. Barnes H. A. Rheology of Non-Newtonian Fluids. – Oxford: Pergamon Press, 2019.
10. Ferry J.D. Viscoelastic Properties of Polymers. – New York: Wiley, 2010.
11. Macosko C. W. Rheology: Principles, Measurements and Applications. – Wiley-VCH, 2014.
12. Kraynik AM Oscillatory methods for measuring viscosity. – J. Rheology, 2010.
13. Mezger T.G. The Rheology Handbook. – Vincentz Network, 2014.
14. Krasilnikov V.A. Acoustic methods for studying liquids. – M., 2005.
15. Malkin A.Ya. Rheology: concepts, methods, applications. – M.: Chemistry, 2010.