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MODERN INTELLIGENT AND DIGITAL APPROACHES TO VISCOSITY MEASUREMENT

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Abstract
This article explores modern intelligent and digital approaches to measuring viscosity and density of liquid media, along with methods for self-monitoring and fault tolerance in flow measurement transducers. It highlights the transition from traditional laboratory-based techniques to integrated cyber-physical systems that enable continuous monitoring and control of industrial processes. Special attention is given to the application of artificial intelligence, machine learning, and digital signal processing for improving measurement accuracy and predictive capabilities. The study examines various density measurement methods, including static, hydrostatic, vibrational, acoustic, radiation, and digital techniques, outlining their advantages and limitations. It also discusses the role of Industry 4.0 technologies, sensor networks, and digital twins in enhancing measurement performance.

Keywords: Viscosity measurement, density measurement, intelligent sensors, self-monitoring, fault tolerance, flow transducers, measurement reliability, artificial intelligence, Industry 4.0, digital signal processing, self-diagnostics, sensor networks.

Introduction

Аннотация
В данной статье рассматриваются современные интеллектуальные и цифровые подходы к измерению вязкости и плотности жидких сред, а также методы самоконтроля и отказоустойчивости измерительных преобразователей расхода. Освещается переход от традиционных лабораторных методов к киберфизическим системам, обеспечивающим непрерывный мониторинг и управление технологическими процессами. Показана роль методов искусственного интеллекта, машинного обучения и цифровой обработки сигналов в повышении точности измерений и расширении возможностей прогнозирования. В целом внедрение интеллектуальных измерительных систем способствует снижению затрат на техническое обслуживание, повышению надежности систем и развитию современных промышленных технологий.

Ключевые слова: Измерение вязкости, измерение плотности, интеллектуальные датчики, самоконтроль, отказоустойчивость, расходомеры, надежность измерений, искусственный интеллект, Индустрия 4.0, цифровая обработка сигналов.

Viscosity is one of the most significant physical properties of liquids and semi-liquid materials, describing their internal resistance to flow and deformation under applied force. Accurate viscosity measurement plays a critical role in numerous industrial sectors, including chemical manufacturing, food processing, petroleum refining, pharmaceuticals, cosmetics, biotechnology, and lubricant production. Traditional viscosity measurement methods, while widely used, often suffer from limitations such as manual operation, delayed analysis, low adaptability, and inability to provide real-time process monitoring. In response to increasing industrial automation demands, modern intelligent and digital technologies have revolutionized viscosity measurement systems, introducing advanced sensors, smart algorithms, artificial intelligence (AI), Internet of Things (IoT), cloud analytics, and digital twins into viscosity monitoring processes [1-4].

The integration of digital and intelligent approaches enhances measurement precision, automation, predictive diagnostics, and remote monitoring capabilities. These advancements support Industry 4.0 initiatives by enabling smart manufacturing systems that can autonomously optimize process parameters based on real-time viscosity data.

The rapid development of computing technology, sensor technologies, and automated control systems over the past two decades has led to the emergence of a new stage in the development of methods for measuring the viscosity of liquid media. While classical methods (capillary, rotational, and vibrational) were primarily focused on laboratory studies, modern intelligent systems enable the integration of measurements into cyber-physical production complexes, ensuring continuous monitoring and control of technological processes.

Modern approaches involve not only obtaining experimental data but also their comprehensive processing using artificial intelligence (AI) and machine learning methods. Automatically identifying patterns in viscosity changes depending on temperature, pressure, and composition, predicting the behavior of liquids under changing technological conditions.

Adapting signal processing algorithms in real time, minimizing measurement errors. In the works of international researchers (MIT, Technical University of Munich, University of Cambridge), models based on a hybrid of molecular dynamics and machine learning are actively being developed. These models make it possible to predict the viscosity of new materials and biofluids without the need for lengthy experiments.

An important direction is the integration of measuring instruments into Industry 4.0 platforms. This is achieved by connecting sensors into networks, transmitting data to cloud systems, and further analysis using Big Data and digital twins.

Companies such as Siemens, ABB, Honeywell, and Rheonics are implementing intelligent density-viscometers operating on vibrational and ultrasonic principles, capable of functioning in in-line mode (without sampling). These devices not only measure viscosity and density but also generate predictive models of product quality, which is especially in demand in the oil and gas and chemical industries [5,6].

Modern research in the field of microelectromechanical systems (MEMS) contributes to the development of miniature viscosity sensors used in medicine and biotechnology. For example, micro-vibrational and cone-and-plate microviscometers are used for analyzing blood, biological fluids, and nanomaterials. The advantages of such sensors include: ultra-small sample volume (down to microliters); high sensitivity; the possibility of integration into portable diagnostic devices.

One of the most promising directions is the application of wavelet analysis for processing signals obtained from vibrational and ultrasonic sensors. This approach allows useful signal components to be extracted even under strong noise conditions and improves measurement accuracy in complex flow regimes.

In Uzbekistan, research related to the digitalization and intellectualization of viscosity measurement methods is actively developing. At Tashkent State Technical University named after I. Karimov and Tashkent University of Information Technologies, developments include: intelligent sensor networks combining ultrasonic and vibrational sensors into a unified monitoring platform; digital twins of technological processes for predicting changes in rheological properties of liquids; adaptive control systems based on the integration of sensors into industrial controllers and SCADA systems.

Thus, modern intelligent and digital approaches to viscosity measurement enable the transition from individual laboratory measurements to comprehensive monitoring and control systems. Key trends include: integration of sensors into IoT and cyber-physical systems; use of machine learning algorithms for predicting liquid properties; miniaturization of devices based on MEMS technologies; application of wavelet analysis and digital signal filtering; development of intelligent monitoring platforms within Industry 4.0.

The contribution of Uzbek scientists in this field lies in adapting intelligent methods to the specifics of national industries (oil and gas, chemical, and energy sectors), ensuring the practical significance of research and its alignment with the strategic development goals of the republic.

Review of Methods for Measuring Liquid Density

Measuring the density of liquid media is one of the key tasks in physical chemistry, hydrodynamics, and engineering sciences. This parameter characterizes the mass of a substance per unit volume and is closely related to the thermodynamic and rheological properties of liquids. Accurate density data are essential for designing technological processes, quality control, studying phase transitions, and developing new materials [7-11].

Over the past decades, a significant number of density measurement methods have been proposed and implemented. They can be conditionally classified into static, dynamic, acoustic, vibrational, radiation, and digital methods. Let us consider them in more detail.

Static Methods

The simplest and historically earliest method is the pycnometer method, where a vessel of known volume is filled with liquid and its mass is determined. Despite its simplicity and high accuracy, this approach is poorly suited for automation and rapid analysis. In modern practice, static methods are mainly used in laboratories for calibration and reference measurements.

Hydrostatic Methods

These are based on Archimedes' principle, according to which the force acting on an immersed body depends on the density of the displaced liquid. Measurement is carried out by determining the difference in weight of a body in air and in the test liquid. This method is widely used in analytical chemistry and biological studies.

Oscillatory (Vibrational) Methods
Among the most accurate and widely used methods are those based on recording the oscillation frequency of a solid element (for example, a U-shaped tube) filled with liquid. The frequency depends on mass and, consequently, on the density of the medium. Such instruments are produced by leading global companies like Anton Paar (Austria), Rheonics (Switzerland), and Endress+Hauser (Germany), and are used in petrochemical, pharmaceutical, and food industries.

Acoustic Methods
These methods are based on the dependence of ultrasonic wave velocity on the density and compressibility of the medium. Such devices allow in situ measurements, including under extreme conditions (high pressure and temperature). Their advantage lies in the ability to simultaneously determine several physical parameters (e.g., density and viscosity).

Radiation Methods
These are used when working with aggressive, toxic, or high-temperature liquids makes conventional instruments impractical. The method is based on measuring the attenuation of gamma or X-ray radiation passing through the medium. Such densitometers are used in nuclear energy and petrochemicals.

Digital and Intelligent Methods
Modern trends are associated with the digitalization of measurement processes. Vibrational and acoustic sensors are increasingly equipped with built-in microprocessors, enabling automatic correction of results considering temperature, pressure, and external disturbances. In several international projects, Industry 4.0-based systems have been implemented, where densitometers are integrated into intelligent sensor networks with remote monitoring and predictive analytics capabilities.

Table 1. Comparison of common rheometric geometries for viscosity measurement.

Coaxial cylinders method	Advantages	Limitations	Applications
Cone–plate	High accuracy, uniform velocity field, wide range of liquids	Sensitive to gap size, requires careful calibration	Oil and gas, lubricants, polymers
Plate–plate	Small sample volume, uniform shear, high accuracy	Cannot be used for liquids with large particles (large inclusions)	Pharmaceuticals, biofluids, nanomaterials
Coaxial cylinders method	Suitable for highly viscous and non-Newtonian fluids	Edge effects, need for corrections	Polymer pastes, concentrates, suspensions

An analysis of liquid density measurement methods shows that each has both advantages and certain limitations. Traditional static methods using pycnometers are highly accurate and still used in laboratory conditions; however, due to their labor intensity and lack of automation, they are gradually being replaced by more advanced approaches. Hydrostatic methods retain importance in educational and analytical practice due to their simplicity, although their accuracy largely depends on the quality of weighing equipment and experimental stability.

Vibrational densitometers have become the most widespread in recent decades. They are characterized by high accuracy, the ability to work with small sample volumes, and integration into automated process control systems, making them highly востребован in petrochemical, pharmaceutical, and food industries. However, they require regular calibration and cleanliness of the measured medium.

Acoustic methods enable measurements under extreme temperature and pressure conditions and allow simultaneous determination of multiple parameters, including viscosity. However, they require complex hardware implementation. Radiation methods are used in specialized cases where direct interaction with the medium is impossible, such as with aggressive or radioactive substances. Despite their versatility, their use is limited by high equipment cost and strict radiation safety requirements.

Modern trends are associated with the development of digital and intelligent systems that combine the advantages of vibrational and acoustic methods, supplemented by adaptive signal processing and integration into Industry 4.0 digital platforms. Such systems allow not only real-time measurement but also prediction of changes in liquid properties, significantly expanding their industrial applications.

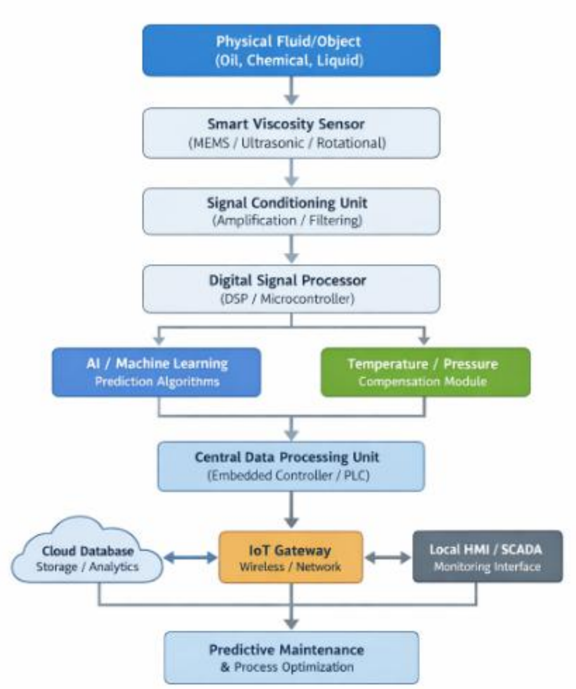

Fig.1. Architecture of a modern intelligent and digital viscosity measurement system integrating smart sensors, AI algorithms, IoT communication, and predictive analytics modules.

This scheme represents the general architecture of a modern intelligent and digital viscosity measurement system. At the first stage of the system, the controlled process fluid or product appears as a physical medium. Intelligent viscometric sensors (MEMS, ultrasonic, or rotary sensors) installed in this medium determine the viscosity parameters of the liquid in real time.

The analog signals received from the sensors are transmitted to the signal conditioning unit, where they are amplified, filtered, and cleared of noise. At the next stage, signals are digitized using a digital signal processor or a microcontroller, followed by preliminary processing.

Digitized data is sent to artificial intelligence and machine learning algorithms. These algorithms allow for predicting viscosity, identifying trends, and anticipating anomalies. At the same time, the temperature and pressure compensation module takes environmental influences into account, thereby increasing measurement accuracy.

All data is transmitted to the central control unit (PLC or embedded controller). This control unit exercises general control over the system, makes necessary decisions, and automatically adjusts the process [12-14].

In the next part of the system, using an IoT gateway, data is transmitted to cloud servers via wireless or network communication. Cloud platforms store large volumes of historical data and perform in-depth analytical analysis.

Operators will have the opportunity to visually monitor the process, control, and adjust parameters through HMI/SCADA interfaces. At the final stage, the predictive maintenance module assesses sensor status, predicts maintenance needs, and optimizes the technological process.

CONCLUSION

Modern intelligent and digital approaches to viscosity measurement have dramatically enhanced the efficiency, precision, and automation of industrial monitoring systems. Through the integration of smart sensors, artificial intelligence, IoT, digital twins, and cloud computing, viscosity measurement has evolved from a simple laboratory procedure into a sophisticated component of smart manufacturing ecosystems. These technologies enable real-time process optimization, predictive maintenance, and adaptive control, contributing significantly to Industry 4.0 transformation. As digital technologies continue to advance, intelligent viscosity measurement systems will become increasingly autonomous, interconnected, and essential across all major industrial sectors.

In conclusion, modern approaches to viscosity and density measurement, combined with intelligent self-monitoring technologies, represent a significant advancement in measurement science and industrial automation. The integration of digital systems, artificial intelligence, and sensor networks enables not only accurate real-time measurements but also predictive analysis and adaptive control of technological processes.

The development of self-monitoring and fault-tolerant flow measurement transducers enhances system reliability, safety, and efficiency, particularly in complex and harsh operating conditions. Techniques such as self-diagnostics, self-calibration, and system reconfiguration allow sensors to maintain functionality and reduce the risk of failure.

Despite considerable progress, challenges remain in improving diagnostic capabilities, especially for differential pressure sensors, and in achieving full integration within Industry 4.0 environments. Future research should focus on developing more advanced algorithms, improving sensor adaptability, and creating unified intelligent monitoring platforms.

Overall, the application of intelligent and digital measurement methods contributes to reduced maintenance costs, increased equipment availability, and improved performance of industrial systems, making them essential for the next generation of engineering solutions.

REFERENCES

1. Yusupbekov N.R., Gulyamov S.M. Smart ultrasonic viscoplotnometers with adaptive control. Measurement, 2022, 196: 111830.
2. Husan Z Igamberdiyev, Azizbek N Yusupbekov, Dinamik modellarda noaniq boshqariladigan ob 'ektlarni adaptiv identifikatsiyalash algoritmlari Toshkent 2017.
3. Advantages of analytic solutions of sentience cloud platform. CTCM YusupbekovN.R., SujithS., AnandN., AbdurasulovF.R.
4. Ergasheva K.N Standartlashtirish sohasidagi zamonaviy o_lchash vositalari Science and innovations, 2023/2, 182-189 pp.
5. Krasilnikov V.A. Acoustic methods for viscosity measurement. Acoustical Physics, 2021, 67(5): 510–519. DOI: 10.1134/S1063771021050121.
6. Anton Paar GmbH. DMA™ 5000 M Density and Viscosity Meter Manual., 2023.
7. Rheonics AG. SRV/SRD Sensor Technical Whitepaper., 2023.
8. Endress+Hauser. LiquiSonic® Sensors and Process Integration., 2023.
9. Siemens AG. SITRANS Process Sensors for Viscosity and Density., 2022.
10. Malvern Panalytical. Ultrasizer II: Ultrasonic Measurement Technology., 2022.
11. Mason W.P. Physical Acoustics: Principles and Methods. Academic Press, 2020. DOI: 10.1016/C2019-0-03218-0.
12. Coussot P. Rheophysics: The Deformation and Flow of Matter. Cambridge Univ. Press, 2014. DOI: 10.1017/CBO9781139027072.
13. Abdurakhmonov K.T., Yusupbekov N.R. Ultrasonic resonant sensors for industrial liquids. Ultrasonics Sonochemistry, 2022, 89: 106047. DOI: 10.1016/j.ultsonch.2022.106047.
14. Gulyamov S.M., Ibragimov Kh.Z. Integration of ultrasonic sensors into SCADA systems. Automation & Remote Control, 2021, 82(12): 2191–2201. DOI: 10.1134/S0005117921120094.