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In-line measurement of multiphase flow viscosity

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ABSTRACT

The transportation modes depend entirely on the viscosity of the oil. To date, none of the viscometric methods are able to provide measurements to meet all the requirements of oil flow, features of main oil pipelines, and trends in the oil industry, such as decarbonization and digitalization. The method of inline viscosity measurement of multiphase flow through a metal pipeline can be based on direct gamma ray measurement. It is stipulated by the ability of gamma-radiation to penetrate through the pipeline material without destroying it, as well as by the ability to work with flows containing free gas and the high capability to be introduced into automatic control systems. The authors consider the physical forces acting on the gas inclusions in the oil flow. They determine the physical dependence between the parameters determined by the radioisotope method and the viscosity of oil in the three-phase flow. These studies show good agreement with the work of other scientists. The prospect of further research will be to clarify the mathematical model of gas-oil flow, to increase the accuracy by reducing the number of assumptions made.

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1. INTRODUCTION

The current standard in the petroleum industry is to make viscosity measurements in the laboratory or with contact sensors that automatically take a fluid sample and analyze its characteristics [1]. The most commonly used viscometry methods are the capillary flow method, the rotary method, and the Stokes method. The research and modernization of these methods are characterized by high accuracy but are limited to the area of contact measurements, which precludes their application to inline measurements over the entire volume of oil flow [2]. Many scientists are developing a new generation of viscometers with improved characteristics. The principles of such devices, provide continuity and high speed of measurements, in many of them there is no contact between the sensor and the fluid being monitored, and the viscosity analysis is made on the whole volume.

A number of studies have focused on in-line flow viscosity measurement by a combination of ultrasonic velocity profiling (UPV) with a new non-contact ultrasonic transducer and pressure drop (PD) method [3]. This work [4] is the first to apply two methods in parallel: planar laser-induced fluorescence (PLIF) and particle image velocity (PIV) to measure the viscosity of moving fluid in a reservoir. In the aerohydrodynamic method [5], the authors propose to apply a pulsating air jet to the liquid surface and measure the viscosity by analyzing the parameters of the waves generated on the surface. Litvinenko *et al.* [6] suggests using observation of the parameters of the gas inclusion and its motion to measure viscosity. Suhantoro and

Yulianti [7] propose an affordable device of extremely lightweight design and experimentally prove the possibility of measuring viscosity by the degree of light scattering in the controlled liquid.

There are also several contact methods of measurement, which are capable of inline measurements. Research by Huang *et al.* [8] place a wave guide in the fluid under test and propose to measure two oil flow parameters based on a single ultrasonic wave: the degree of attenuation characterizes the viscosity, the speed of propagation characterizes the temperature of the fluid. Nour *et al.* [9] describes a capacitive pressure sensor consisting of 3 condensers, the clouds of which are located on different sides of the microchannel, and derives the relationship between the capacitance of the condenser and oil viscosity. Duan *et al.* [10] identified the relationship between the viscosity of the oil flow and the deformation of the sensing element created directly on the surface of the polyimide pipeline. Research by Bista *et al.* [11] makes viscosity measurements using a modification of the Coriolis flowmeter.

Let's analyze the classical and the most recent techniques of viscometry for compliance with the properties of the oil flow, pipeline parameters and trends in the development of the oil industry. List of the requirements: i) produce inline measurements; ii) perform non-contact flow measurements in steel pipelines up to 1420 mm in diameter; iii) suitable for monitoring three-phase flow; iv) functional on non-transparent flows; v) full volume flow control; vi) control flow with highly variable chemical composition; vii) make measurements in turbulent flow conditions; viii) correctly operate at fluctuating filling levels in the oil pipeline; ix) measure other parameters in addition to viscosity.

Correspondence of viscosimetry methods to requirements of the main oil pipeline are shown in Table 1. The evaluation is made exactly of those measuring principles, to which references are given. The study of the table clearly shows that at present, none of the viscometric methods is able to provide measurements in accordance with all requirements of oil flow as an object of control. The authors see the direction for research, which could solve the identified problem of lack of viscometric methods applicable to multiphase flows-global theoretical and experimental research of gas-pneumatic method. Its modernization for turbulent non-transparent flow, by studying the motion of gas inclusions in turbulent flow of high viscosity, refusing to inject additional gas inclusions into the flow and building the method on the observation of inclusions already present in the flow, and replacing the light waves, by waves capable of penetrating through the steel walls of the pipeline and control the non-transparent flow. The purpose of this article will be a theoretical study of the possibility of using radioisotope radiation to modernize the gas-pneumatic method of measuring viscosity. For this purpose, the author will investigate the dependences of gas inclusions motion on viscosity, justified experimentally, will give experimental data on the capabilities of radioisotope measurement method and theoretically justify the reality of scaling the capabilities of radioisotope sensor to control the viscosity of the oil flow. The analysis of 127 sources of the literature, made by the authors, proves the absence of similar researches by other scientists.

Table 1. Analysis of viscometric methods regarding suitability for oil flow control conditions

No of requirement / Method	1	2	3	4	5	6	7	8	9
Classic methods [1]	-	-	+	+	-	+	+	+	-
UPV + PD [3]	+	+	NS	+	+	-	-	-	+
PLIF + PIV [4]	+	-	+	-	+	+	+	+	+
Aerohydrodynamic method [5]	+	-	+	+	-	+	+	+	-
Pneumatic bubble method [6]	+	-	NS	-	+	+	NS	+	+
Optical method [7]	+	-	+	-	+	-	NS	NS	-
Ultrasonic method [8]	+	-	-	+	+	-	+	-	+
Capacitive pressure sensor [9]	+	-	-	+	+	+	NS	-	+
3D tubular sensor system [10]	+	-	-	+	+	+	NS	-	+
Coriolis flowmeter [11]	+	-	-	+	+	+	+	-	+

*NS is not studied

2. METHOD

2.1. Research consistency

To create a new method of multiphase flow viscometry, the authors analyze existing developments and choose the most promising direction for research. In the case of control of multiphase flows of oil transported through metal pipelines, the radioisotope method has the highest capability for implementation. It is stipulated by the ability of gamma-radiation to penetrate through the pipeline material without destroying it, as well as by the ability to work with flows containing free gas and the high capability to be introduced into automatic control systems.

The authors consider the physical forces acting on the gas inclusions in the oil flow. And determine the physical dependence between the parameters determined by the radioisotope method and the viscosity of oil in the three-phase flow. In addition, the authors analyze the risks that can lead to inaccurate viscosity determination. The authors' hypothesis that the viscosity of multiphase flow can be determined by the parameters of gas inclusions in it is consistent with the latest scientific developments. However, the authors are the first to suggest using the radioisotope method to determine the parameters of gas inclusions and provide formulas for this purpose.

The research also addresses the topic of regulations for the operation of radioisotope measuring devices, which must be observed in order to ensure the safety of plant personnel. Finally, the authors define a direction for further research and consider the benefits of the method for industry and science.

2.2. Radioisotope measuring method

The measurement method that underlies the development of the viscometer has been completely described in [12]. The main idea of the method is that gamma rays interacting with the controlled matter are absorbed and scattered. The number of gamma rays that have passed through the oil stream without any change indicates the state of the controlled system. It can be calculated as shown in (1)

$$I = I_0 \exp(-\mu\rho d) \tag{1}$$

where μ is mass attenuation coefficient of radiation by the medium, d is linear size of the controlled medium, I_0 and I are the intensities of gamma radiation initial and after passing through the controlled medium.

Measurements performed by the radioisotope sensor are based on the principle of attenuation of ionizing radiation by the oil stream flowing between the radiation and detection units. The ionizing radiation results from the radionuclide Cs 137 decaying and emitting photons with an average energy of 661 keV. The emitted photons, passing through a narrow opening in the radiation unit, penetrate the pipeline with the oil flow, undergoing photoelectronic absorption and Compton scattering. As a result, the detection unit detects a smaller number of photons with a lower average energy. The detection unit calculates the number of photons that have passed through the pipeline with the oil flow, preserving their original energy, the so-called direct emission. The composition of the measuring device and location of the sensor in relation to the controlled pipeline is schematically shown in Figure 1.

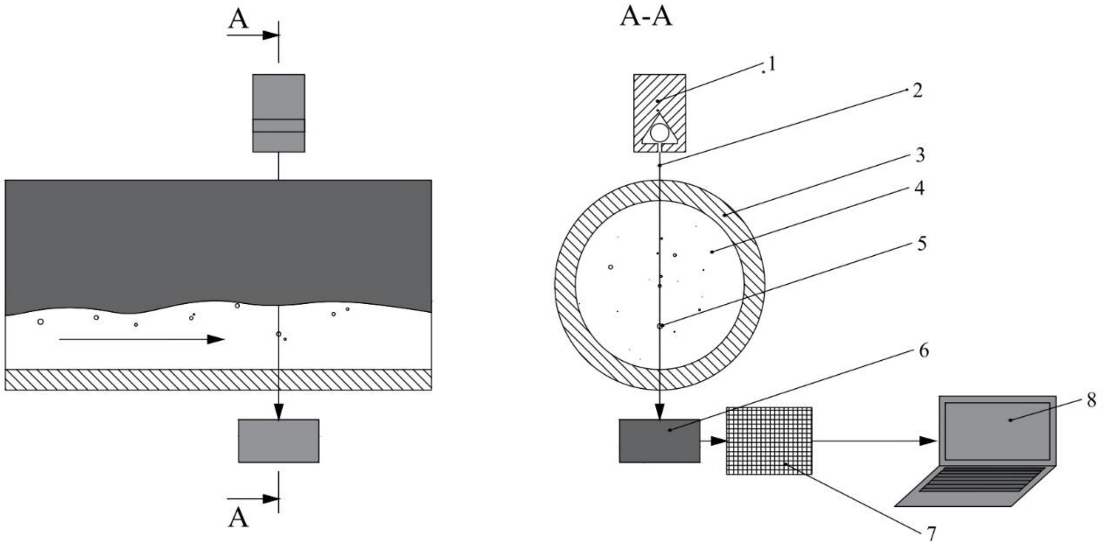

Figure 1. The composition of the measuring device; 1 is gamma ray emitter, 2 is direct gamma radiation, 3 is pipeline wall, 4 is multiphase flow, 5 is gas bubbles, 6 is detection unit, 7 is system of processing and accumulation of information, and 8 is personal computer

3. RESULTS AND DISCUSSION

3.1. Theoretical foundation of the new method

The newly extracted "crude" oil, characterized by high content of water, mechanical and chemical impurities and free gases, goes through several stages of purification, and the so-called "commercial" oil containing up to 1 percent of water and up to 0.05 percent of mechanical impurities is delivered to the main oil pipeline. In the transported flow there is also an unknown share of free gas, which is always present in commercial oil and the content of which increases during transportation. This gas, has a negative impact on most methods of measurement, introducing into them an error [13], but causes the possibility of measuring the viscosity by the analysis of the movement of gas inclusions in the oil flow.

Being in the oil pipeline under the same pressure, the liquid and gas components move with considerable difference in speeds, it is caused by multiple excess of density of liquid over density of gas and existence of dependence between density and necessary pressure to create the same speed [14]. Application of radioisotope technology for oil flow control allows to determine the density and velocity of each phase with high accuracy. Moreover, radioisotope radiation makes it possible to determine the linear size and velocity of each bubble passing through the monitored area.

However, a strong velocity difference is observed only for gas inclusions of relatively large diameter, while small bubbles move inseparably from the liquid flow. Such a phenomenon is caused by frictional forces between air bubbles and the oil flow, which, by slowing down all air bubbles, does not allow bubbles with a diameter smaller than the critical one to outpace the liquid flow. Moreover, the term "critical diameter" of the gas inclusion in this article means exactly the boundary size of the bubble at which the friction force is capable of slowing down the bubble velocity to that of the liquid flow; this diameter differs greatly for oils of different viscosities, and therefore the friction force cannot be calculated from this equality. At the same time, this critical diameter varies within certain limits, which makes it possible to judge the velocity of the liquid flow from bubbles smaller than the range of critical diameters, and to judge their own velocity from bubbles with a diameter greater than the range.

To more easily understand the principle of viscosity determination proposed in this paper, we should present a mathematical model of gas-oil flow reduced to the velocity of the liquid component, which will be determined with high accuracy from bubbles smaller than the critical range in diameter. As a result, all bubbles can be represented by moving in a stationary liquid medium with a velocity equal to the difference of their own and the velocity of the liquid component, or the "reduced" velocity. Then two forces will act on the bubbles of linear sizes exceeding the range of critical ones, directed along the bubble motion line in opposite directions: the reduced pressure force and friction force of the bubble surface against the oil flow. As we know from Newton's second law, the difference of these forces will accelerate or decelerate the bubble motion up to a certain velocity value, at which the vector sum of these forces becomes equal to zero.

Since the change of the size of a gas bubble, resulting from the merging of several or crushing one, is relatively rare; the reduced bubble velocity is so slow, that the frictional force along the course of the oil bubble movement in different sections of the liquid changes smoothly and at small values; as a result of averaging the viscosity determined for the whole set of bubbles monitored, the error caused by measuring the set of bubbles moving with acceleration will be balanced by the error caused by monitoring the bubbles moving with acceleration. Formula description of the considered forces together with the parameters of the oil flow measured by radioisotope method will allow to calculate the value of viscosity of the oil flow.

As mentioned earlier, the occurrence of velocity difference is a consequence of the action of the same value of pressure on the gas-water flow phases having different densities. In the general case, the total pressure in the oil pipeline is the sum of the static and dynamic components, and the static pressure component acts in all directions equally, and therefore can not be considered in the calculations for the developed method of measurement. The dynamic component is velocity-directed and can be calculated by (2):

$$P = \frac{\rho\vartheta^2}{2} \tag{2}$$

where ρ and ϑ are the density and velocity of the substance in question.

Considering a small volume of the liquid component of the oil flow equal to the volume of the gas inclusion and moving in the same section of the same pipeline, we can equate the head forces acting on them:

$$\frac{\rho_g\vartheta_g^2\pi r_g^2}{2} = \frac{\rho_l\vartheta_l^2\pi r_g^2}{2} \tag{3}$$

where r_g is the radius of the cross-sectional area of the considered gas bubble, ρ_g and ρ_l are the densities of gas and liquid, ϑ_g and ϑ_l are the velocities of gas and liquid.

At the same time, friction forces due to the viscosity of the oil affect the liquid and gas components. Since the value of friction force is directly proportional to the velocity of interacting layers, and the difference of velocities of liquid and gas component significantly exceeds the difference of velocities of two bordering liquid layers, at this stage of research the viscosity force between liquid layers can be neglected. In most cases, the relative velocity of the gas inclusion is small and characterized by small Reynolds numbers; hence, we can apply Stokes' law to the relative motion of the gas inclusion in a resting oil flow, which determines the friction force acting on spherical objects with small Reynolds numbers. Considering the friction force acting on the gas inclusion, the balance of forces acting on the air bubble at small Reynolds numbers for the reduced velocity of the gas bubble will be

$$\frac{\rho_g \vartheta_g^2}{2} \cdot \pi r_g^2 - 6\pi \eta_l r_g (\vartheta_g - \vartheta_l) = \frac{\rho_l \vartheta_l^2}{2} \cdot \pi r_g^2 \tag{4}$$

$$I = I_0 \exp(-\mu_l \rho_l d_l - \mu_g \rho_g d_g - \mu_p \rho_p d_p) \tag{5}$$

where η_l is the dynamic viscosity of the liquid component of the oil flow.

In the given formula the only unknown quantity is viscosity, the other parameters can be determined with the help of radioisotope sensor. For this purpose, the processing unit records the readings of the radioisotope sensor and processes all the obtained data. The radioisotope sensor is a combination of a radiation unit, a detection unit, and a secondary information processing unit. The radiation unit acts as a receptacle for the radionuclide and forms a narrow beam of ionizing radiation, the detection unit converts the energy of the gamma radiation that has passed through the monitored area of the oil stream into an electrical signal proportional to it, and the secondary instrument calculates the values of densities and velocities of the liquid and gas components of the oil stream.

As the gas bubbles pass through the monitored section, the detector records bursts of radioisotope radiation intensity. In order to determine the phase velocities of the oil flow, the processing unit analyzes bursts of gamma ray intensity. The burst height in the autocorrelation function characterizes the linear size and density of an air bubble, and its width at a known linear size determines the velocity of a given bubble. Determining the velocity of bubbles with a diameter smaller than the critical one provides information about the oil flow velocity. The density of the liquid component of the oil stream is determined with high precision in the gas-free intervals on the basis of the known initial radiation intensity and the measured attenuated intensity from the Bouguer-Lambert-Beer law.

3.2. Experimental justification

In recent years, scientists have been actively observing the behavior of gas inclusions in liquids. Their experimental studies prove the dependence between viscosity and the character of their motion. Fan *et al.* [15] investigate the patterns of gas bubble formation and motion in liquids of different viscosities. A precise measurement of the bubble formation process is performed using a helium-neon laser as a light source using beam expansion and light amplification techniques. According to Muilwijk and Van den Akker [16] increasing fluid viscosity reduces the speed and acceleration of bubble rise. Research by Zähringer and Kováts [17] also note the relationship between bubble shape, bubble size, and liquid density and suggest that increasing viscosity or decreasing surface tension leads to much narrower bubble size distributions. In addition, as surface tension decreases, the average bubble diameter decreases significantly, while the average bubble size increases with increasing viscosity. Due to the relatively high resolution of the image in the work [18], the uncertainty in the recognized bubble sizes and the calculated bubble velocities is less than 5%.

Certification of radioisotope sensors similar in construction and type of used radionuclide showed the maximum fixed dose rate of equivalent radiation at 1 m distance equal to 0.1 μSv/h, which is 200 times less than established by sanitary rules of radiation protection for measuring instruments. Moreover, operation of the radioisotope measuring installation is fully automated and requires absolutely no presence of people nearby, the equipment itself is placed in a protective box, which surface is marked for radioactive danger, and penetration into which is impossible without a special key. Based on the above information, it can be concluded that the measuring system does not cause any harm to the health of the plant personnel if they follow the safety regulations.

3.3. Implementation prospects

Oil viscosity is one of the key physical quantities for pipeline transport, characterizing the friction force between fluid layers during its movement. Flow measurement of viscosity during oil transportation will provide the ability to accurately calculate the necessary pressure in the oil pipeline, select the most suitable oil pumping equipment, to determine the mode and in particular the speed of transportation to ensure the least frictional head loss. In addition, in-line viscosity measurement will be the basis for the selection of measures to be applied to reduce viscosity or special transportation methods, which also affect the energy intensity of the transport itself and the cost of oil. Therefore, in order to reduce the energy costs of oil production and transportation, it is necessary to determine the viscosity as accurately as possible throughout its volume [19].

In addition to reducing energy costs (decarbonization trend), the introduction of inline viscometers corresponds to the trend towards digitalization. Companies that do not invest in big data, machine learning, and forecasting systems lose their competitiveness over time [20]. Gazpromneft, one of the largest Russian oil companies, is actively introducing big data analysis, but experts note a lack of usable data. They need readings from instruments that collect information at high frequency. The more such devices are available, the more accurate the forecasting systems will be. An inline viscosity sensor, one of the key characteristics of oil, could become such a device and ensure the company's competitiveness in the long run.

The proposed method can be used in many areas of industry. Viscosity control of liquids is necessary, for example, in chemical, food, glass, paint and other industries [21]–[24]. Viscosity is used to judge about the quality of semi-finished and finished products, about those physical and chemical changes in the material that occur during the technological process. In many processes related to surface coating, the viscosity of the applied substance must be maintained within a specified range.

Of particular value is the data that will be obtained from the implementation of the method in trunk oil pipelines. These data and their analysis will expand scientists' knowledge about the nature of multiphase motion laws, confirm or deny previously put forward theoretical laws, and possibly solve questions that scientists have been facing for decades, such as predicting the start of turbulence and the behavior of turbulent flow [25]–[32].

4. CONCLUSION

In light of the research outlined in the article, the following conclusions can be made that none of existing viscometry methods is capable to provide measurements according to the properties of the oil flow, pipeline parameters and trends in the development of the oil industry. Furthermore, the method of inline viscosity measurement of multiphase flow through a metal pipeline can be based on direct gamma ray measurement. In addition, this study shows good agreement with the work of other scientists. The recommendation for further study such as include elaborating on the gas-oil flow mathematical model in order to improve the accuracy by limiting the number of presumptions.

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