Measurement of phase flow in water, oil and gas media using infrared radiation

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Abstract. This paper analyzes the problem of multiphase flow metering in the oil and gas industry. The main types of multiphase flow meters, their advantages and disadvantages are considered. A schematic diagram of a multiphase flow meter is proposed, which includes a mixture homogenizer, a Coriolis flow meter, an IR fraction meter and is based on the concept of intelligent measuring systems. An experimental pouring stand has been developed for conducting studies of the absorption of near-infrared radiation in a gas-liquid mixture stream. Studies have been carried out on the absorption of near-infrared radiation in a multiphase flow for a volumetric gas content of 5 and 10% in the range of liquid moisture content from 10 to 90% in increments of 20%. Based on the results of the study, a generalized correlation dependence is obtained. A computational and experimental method is proposed for determining the volumetric ratio of phases in a flow using the parameters of absorption of near-infrared radiation, which can be applied to various ranges of gas content.

1. Introduction
The task of measuring the flow rate of phases of well products is one of the urgent problems of oil and gas production. There are two main types of multiphase flow meters (MFMs): separating and non-separating. At the initial stage of accounting for well production, separating MFMs, the so-called automated group metering units (AGMU) [1-3], were used, since separating the multiphase flow into liquid and gas and measuring the flow rates of these fluids separately is the easiest way to account for produced hydrocarbons from the point of view of the principle of action. However, separating MFMs have such disadvantages as large dimensions, high metal consumption, a significant number of moving parts, and significant maintenance costs. Due to this and scientific and technological development, since the 90s of the last century, non-separating MFMs have been actively developed, based on various physical principles of action, which make it possible to measure the flow of oil, gas and water in a gas-liquid mixture flow (GLM) without their separation. Currently, compact non-separating MFMs are produced [4-7], which have satisfactory metrological characteristics. However, these units are quite complex in their principle of operation and have a high cost, and some of them use unsafe radioactive radiation sources. [8]

In existing non-separating measuring systems, in most cases, a Venturi tube is used, which allows determining the flow rate of the entire GLM flow at a known mixture density from the measured pressure drop with the required accuracy, which was discussed in [9-12]. The need for preliminary data on the density of the mixture to determine the flow rate is the main disadvantage of the Venturi tube. In this
regard, the use of Coriolis flow meters, which make it possible to carry out independent measurements of mass flow and mixture density, seems more promising for this purpose. The vast majority of existing commercial Coriolis flow meters are designed for measuring single-phase media. The difficulties in measuring multiphase media with such devices are due to the bubble effect, resonator effects, attenuation, etc. [13]

However, the development of a Coriolis flow meter for measuring the flow rate of a multiphase mixture is known [14,15]. These developments allow us to consider the development of flow metering as a promising area - improving the accuracy of measuring the parameters of a multiphase mixture using Coriolis flow meters.

In [16], the concept of intelligent measuring systems was proposed, in accordance with which the method of physical and mathematical modelling is used in conjunction with measurements of the necessary indirect parameters. The intelligent system, which includes measuring blocks of signals from sensors, digital processing, multiphase hydrodynamics ratios, and specially developed algorithm and program code, allows you to determine the desired parameters of a multiphase mixture (phase composition and phase flow). This paper proposes and substantiates the concept of a multiphase flow meter that implements this approach, including a Coriolis flow meter and a method for determining the phase flow in a stream using the parameters of absorption of near-infrared (NIR) radiation.

The basics of NIR spectroscopy, and in particular the absorption of infrared radiation, are currently widely used to determine the moisture content of various substances, including liquids. For example, the use of NIR spectroscopy for determining moisture content in a biodiesel emulsion is described in [17]. And in [18], the NIR spectroscopy method was used to determine the proportion of water in crude oil in the moisture content range from 0 to 5%. Currently, there is a flow meter for oil and oil products - Red Eye Multiphase [19,20], based on the principle of absorption NIR spectroscopy. This moisture meter has high accuracy but provided that the gas content in the stream should not exceed 10%, and the structure of the oil and gas stream should be homogeneous since water cut measurements are carried out at only one point.

2. Schematic diagram of a multiphase flow meter
The schematic diagram of the proposed non-separating flow meter is presented in Figure 1. A homogenizer (mixer) is installed to create a uniformly mixed flow. The mixer also serves to equalize the speed of the phases in the flow. The design of the homogenizer should ensure high-quality homogenization of the flow on the one hand and a low pressure drop on the other. After the mixer, a representative sample is taken, which passes through the NIR fraction meter and returns to the general flow. The NIR fraction meter measures the optical density at two wavelengths of NIR radiation over the entire cross-section of a representative sample using the patented technology. [21]

Next, a Coriolis mass meter is installed, designed to measure the total mass flow rate and density of the mixture. To control the thermobaric parameters, pressure and temperature meters are installed.
3. Study of the absorption of NIR radiation in a gas-liquid mixture flow

*Experimental installation (pouring stand) and experimental technique.* The installation diagram is shown in Figure 2. The principle of operation of the stand is as follows. By means of a pump 3, a gas-liquid flow with a gas content of \( \alpha_g \leq 10\% \) is circulated in a closed circuit having a certain volume \( V \). To homogenize the flow, a mixer 2 is used, which is a pipe section in which spiral-shaped flow bodies are installed. After the mixer, the flow passes through a measuring IR cell, where the optical density of the mixture is measured at wavelengths of 880 and 1660 nm. The thickness of the translucent layer is 2.5 mm and can be adjusted. IR LEDs are used as a source of NIR radiation, IR photodiodes are used as detectors.
The components in the gas-liquid flow were water, exxsol D100 (oil simulator) and air. The required ratio of these components in the flow was set by installing the corresponding volumes of oil simulator and water on the stand. The required volumes were set through the formula for the connection of mass and density using high-precision scales. The optical density measurements were based on measurements of the zero signal (when filling the measuring IR cell with air) and the signal when the NIR radiation passed through the studied flow. It should be noted that the installation in question is a prototype installation where a mixture of oil, water and associated petroleum gas can be studied.

Experiment results. The experiments were carried out for a volumetric gas content of 5 and 10% in the range of the liquid moisture content from 10 to 90% in increments of 20%. The results are shown in Figure 3, which shows graphs of the dependence of the difference in optical density $\Delta D = D^g - D^a$ on the liquid moisture content $\alpha_{wl}$.

![Figure 3](image)

Figure 3. Dependence of the difference in optical density $\Delta D$ on the liquid moisture content $\alpha_{wl}$:

a) $\alpha_g = 0,05$; b) $\alpha_g = 0,1$.

The obtained experimental data are approximated by second-order polynomials:
for $\alpha_g = 0.05$ \[ \Delta D = -0.00005 \alpha_w^2 + 0.01081 \alpha_u + 0.01809 \] (1)

for $\alpha_g = 0.1$ \[ \Delta D = -0.000025 \alpha_w^2 + 0.00906 \alpha_u + 0.02860 \] (2)

Expressing from here the quantity $\alpha_w$, we obtain:

for $\alpha_g = 0.05$ \[ \alpha_w = 108.06 - \sqrt{12038.8 - 20000 \Delta D} \] (3)

for $\alpha_g = 0.1$ \[ \alpha_w = 181.28 - \sqrt{34006.2 - 40000 \Delta D} \] (4)

According to these formulas, the moisture content was calculated, and the calculated values were compared with the true ones (Figure 4). Quality estimates of models (1) and (2) are presented in Table 1.

Figure 4. Comparison of the calculated water cut values with true values:

a) $\alpha_g = 0.05$ ; b) $\alpha_g = 0.1$. 
From formulas (3), (4), we can obtain a generalized dependence for the gas content range from 5 to 10%:

$$\alpha_{wl} = 34.84 + 1464.4\alpha_g - \sqrt{439348 \alpha_g - 9928.6 - 400000 \alpha_g \Delta D} \quad (5)$$

The given error in determining the liquid moisture content by the generalized expression (5) was 8%.

| Model       | Correlation index R | Determination index R² | Mean approximation error ε_mean, % |
|-------------|---------------------|------------------------|-----------------------------------|
| Model 1 (\(\alpha_g = 0.05\)) | 0.987               | 0.974                  | 8.65                              |
| Model 2 (\(\alpha_g = 0.1\))   | 0.993               | 0.986                  | 7.32                              |

4. Computational and experimental method

Thus, a computational and experimental method has been developed for determining the phase composition and phase flow, justified for the gas content range \(\alpha_{gl} \leq \alpha_g \leq \alpha_{g2}\), where in this case \(\alpha_{gl} = 0.05\), \(\alpha_{g2} = 0.1\). The proposed method can be applied for any range of gas content in the flow of water, oil and gas mixture. This method, together with the measurements provided by the proposed multiphase flow meter scheme, and data from laboratory studies (true oil and water densities, component composition of reservoir oil) is reduced to the following calculations.

The volume fraction of phases is determined from the system of equations:

- mixture density

$$\rho_{mix} = \rho_{w}^{(0)} \alpha_{w} + \rho_{o}^{(0)} \alpha_{o} + \rho_{g}^{(0)} \alpha_{g}$$ \quad (6)

where \(\rho_{i}^{(0)} = \frac{m_i}{V_i}\) - true density of the i-th component, \(m_i\) - mass of the i-th component occupying the volume \(V_i\). The true density of the gas is determined by the expression:

$$\rho_{g}^{(0)} = \frac{P}{Z(P,T)RT},$$ \quad (7)

where the gas compressibility factor \(Z(P,T)\) can be determined from the equations of state of para-liquid equilibrium [22].

- a condition of equality of the sum of volume fractions of phases to one:

$$\alpha_{w} + \alpha_{o} + \alpha_{g} = 1 \quad (8)$$

- a volume fraction of water by liquid, determined by the NIR method according to the formula (5):

$$\alpha_{wl} = a(\alpha_g) - \sqrt{b(\alpha_g) - c(\alpha_g) \Delta D},$$ \quad (9)

where \(a(\alpha_g)\), \(b(\alpha_g)\), \(c(\alpha_g)\) coefficients determined by the correlation dependences on gas content.

- a volume fraction of water related to the entire flow:

$$\alpha_{w} = \alpha_{wl} \left(1 - \alpha_{g}\right)$$ \quad (10)
Mass consumption of water, oil and associated gas can be determined by known expressions:

\[ G_w = \frac{G_{mix}}{w} \]
\[ G_o = \frac{G_{mix}}{o} \]
\[ G_g = \frac{G_{mix}}{g} \]

We emphasize that the above methodology for calculating the mass flow rate of phases is applicable under the assumption of equal phase velocities of the water, oil and gas flow.

5. Conclusions

- An intelligent measuring system is proposed - a non-separating multiphase flow meter, which includes the following main components: a gas-liquid flow homogenizer, an infrared fraction meter, a Coriolis flow meter and a physical-mathematical model that relates the phase composition and phase flow to measured parameters.
- An experimental installation has been developed for studying the absorption of NIR radiation in multiphase flows.
- Experimental studies of the absorption of NIR radiation in the flow of GLM (water, oil simulator, air). The dependence of the difference in optical density on the volume fraction of water in the range of the liquid moisture content of 10-90% with a volumetric gas content of the entire stream of 5 and 10% is obtained. The given error in calculating the moisture content according to the generalized correlation equation did not exceed 8%.
- A computational and experimental method is proposed for determining the volume fractions of the phases of oil and gas flows using NIR radiation for various ranges of gas content.

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