Component-based control of oil-gas-water mixture composition in pipelines

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Abstract. The article theoretically proves the method for measuring the changes in content of oil, gas and water in pipelines; also the measurement system design for implementation thereof is discussed. An assessment is presented in connection with random and systemic errors for the future system, and recommendations for optimization thereof are presented.

1. Introduction

When technological processes and equipment for extraction, collection, preparation and transportation of oil as the liquid power resource are developed, the actual phase and component composition, and certain specific features of multiphase and multicomponent media moving along the pipelines are often not accounted for in a proper manner. Oil flows are generally considered as uniform. Yet, in a number of situations, such assumption results in unfavourable consequences [1]:

1. Additional errors of oil commercial accounting.
2. The latest information updates on oil wells daily performance individually for oil, gas and water being missing.
3. Shorter lifespan of pipelines and higher risks of accidents, including those related to oil wells drilling and operation.
4. Atmosphere pollution by the oil gas accompanying.

Methods and devices are known for controlling and monitoring the commodity oil flow right in pipelines, such as those using the ultrasound, acoustic vibration, turbine etc., yet none of those would work with oil-gas-water mixture.

The research undertaken in terms of this work relates to solving the task of multiphase non-separated measurement of oil wells performance, individually for oil, water and free gas, remaining complicated and not solved fully until now.

2. Method description

The presented work is based on the radioisotope measurement method using the effects of Compton scattering and gamma rays photoelectric absorption by the pipeline walls material and substances forming the crude oil.

The basic idea of the method includes the following: it is assumed that a multichannel gamma ray emission block and the radiation receivers in form of detection blocks should be installed upon the pipeline outer surface, without breaking-in physically.
The collimated gamma ray from Cs137 radioisotope penetrates through the pipeline wall to interact with the limited amount of the monitored liquid. Passing the gamma ray through the substance transforms the gamma-quantum power via elementary actions of their interaction with atoms and electrons of the medium[2].

The signal attenuation degree and pulsation nature within specific energy spectrum allows assessing the medium parameter measured, with the medium being the radiation absorber. Gamma quanta interacting with the substance within the energy range 400-800keV give the emission attenuation in the narrow beam of the gamma-radiation measured, as it passes through the substance, due to photoelectric absorption of gamma quanta leaving the narrow beam with the Compton effect taken into account [3].

As a result, in addition to the direct radiation beams being reduced, some scattered radiation appears to be dispersed within the medium in all directions. Therefore, the information about the monitored medium comes from both the direct and the scattered radiations [4].

In accordance with the Beer–Lambert law, a narrow gamma ray direct the beam passing through the medium with properties constant in time, thickness d (m), is defined with the expression:

\[ N_d = N_{0d} \cdot \exp(-\mu_0 d) = N_{0d} \cdot \exp(-\mu \cdot \rho_{mix} \cdot d) \]  

(1)

where \( N_{0d}, N_d \) are the intensities or mathematical expectations of the number of gamma quanta to be registered by the detection block in absence and in presence of the medium to monitor, correspondingly; \( \mu_0, \mu \) are the linear and the weight coefficient of attenuation, m\(^{-1}\), m\(^2\)/kg; \( \rho_{mix} \) is the density of the mixture, kg/m\(^3\).

By selecting the energy of the primary quantum, mutual position and direction (collimation) diagrams of the radiation source and detector (scattering angle and the distance between the scattering region and the detector), one can obtain the linear correlation between the radiation scattered at a specific angle, and the density of the dispensing medium:

\[ N_s = N_{0s} \cdot (1 - \mu d \rho_s) \]  

(2)

The secondary gamma radiation has a wide energy spectrum. The soft and the hard portions of the spectrum are separated during the detection to form independent signals of the measurement information, i.e. \( N_d \) and \( N_s \) corresponds to the hard portion of the spectrum, while \( N_s \) corresponds to the soft one. Then the information arrives to the information control and processing block, where the required parameters are to be calculated using the relevant math expressions. The mixture density shall be calculated in accordance with the following expression:

\[ \rho_{mix} = \frac{\ln \left( \frac{N_{0s}}{N_s} \right) - b \times \ln \left( \frac{N_{0d}}{N_d} \right)}{a} \]  

(3)

where \( N_{0d}, N_{0s}, a, b \) are the calibration factors.

The volume part of water in the crude oil shall be calculated in accordance with the following expression:

\[ W = \left[ \frac{\ln \left( \frac{N_{0d}}{N_d} \right)}{\ln \left( \frac{N_{0s}}{N_s} \right)} - k_2 \left( \frac{\ln \left( \frac{N_{0d}}{N_d} \right)}{\ln \left( \frac{N_{0s}}{N_s} \right)} \right) \right] \times \left[ \frac{k_3 - k_4 \times \ln \left( \frac{N_{0d}}{N_d} \right)}{\ln \left( \frac{N_{0s}}{N_s} \right)} \right] \]  

(4)

where \( k_1, k_2, k_3, k_4 \) are the calibration factors.

The free gas volume part in the crude oil shall be calculated in accordance with the following expression:
where $\rho_w$, $\rho_{oil}$ are the densities of water and oil, correspondingly.

The area-speed method is the basis of oil and gas flow rates measurement. The method suggests the flow rate for each component in the multicomponent flow to be defined as the average flow rate being multiplied by the area of the part of the cross-flow occupied by the component. At the same time, volumetric gas discharge $T_{avg}$ averaged by time shall be defined in accordance with the following expression:

$$Q_{g,avg} = S \cdot (\varphi \cdot v_g)_{avg}$$  \hspace{1cm} (6)

where $S$ is the area of the pipeline cross section; $Q_{g,avg}$ is the volumetric gas discharge averaged by time $T_{avg}$; $\varphi$ is the share of the part in the pipeline cross section occupied by gas; $v_g$ is the gas flow rate; $(\varphi \cdot v_g)_{avg}$ is the $\varphi$ multiplied by $v_g$ averaged by time $T_{avg}$.

The averaged discharge by weight of the crude oil shall be defined in accordance with the following expression:

$$Q_{m,avg} = S \cdot (\rho \cdot v_{liq})_{avg}$$  \hspace{1cm} (7)

where $Q_{m,avg}$ is the crude oil weight discharge averaged by time $T_{avg}$; $\rho$ is the crude oil density; $v_{liq}$ is the liquid flow rate; $(\rho \cdot v_{liq})_{avg}$ is the $v_{liq}$ multiplied by $\rho$, averaged by time $T_{avg}$.

The following expression shall define the averaged weight discharge of oil:

$$Q_{m,oil,avg} = Q_{m,avg} \cdot (1 - W_{avg})$$  \hspace{1cm} (8)

where $Q_{m,oil,avg}$ is the weight discharge of oil averaged by time $T_{avg}$; $W_{avg}$ is the volume part of water in oil averaged by time $T_{avg}$.

The weight of liquid $m_{liq}$, the weight of oil $m_{oil}$ and the volume of gas $V_g$ shall be defined in accordance with the following expressions [5]:

$$V_g = T_{avg} \cdot Q_{g,avg}$$  \hspace{1cm} (9)

$$m_{liq} = T_{avg} \cdot Q_{m,avg}$$  \hspace{1cm} (10)

$$m_{oil} = T_{avg} \cdot Q_{m,oil,avg}$$  \hspace{1cm} (11)

Figure 1 shows how the detection block output signal is changed as the substance density and composition within the pipeline change.

Signal fluctuations of the secondary convertor output upon filling the pipelines with gas (empty pipe) and with liquid (water) are caused by random nature of the radioisotope convertor output signal.

Signal fluctuations of the detection block output on oil-gas-water mixture moving along the pipeline are caused by the random nature of changes in the content of gas in the mixture.
Figure 1. Detection block output signal changes upon the substance density and composition changes in the pipeline.

Liquid and gas flow rates in the crude oil flow shall be measured using the mark method, with free gas bubbles within the liquid being the natural marks in the flow. Figure 2 shows the portion of the pipe with two radioisotope-measuring convertors.

\[ S_1 \] is the cross section of the pipeline controlled by the first radioisotope measuring convertor; \[ S_2 \] is the cross section of the pipeline controlled by the second radioisotope measuring convertor; \( L \) is the distance between the \( S_1 \) and \( S_2 \) cross sections.

With no free gas bubbles in the flow (i.e. the flow is single phase and uniform), the output signals on both radioisotope measuring convertors shall be the same. Should a free gas bubble appear within the uniform medium flow, the bubble shall have to pass the \( S_1 \) cross section first, and then cross section \( S_2 \), too; the output signals for the first and the second radioisotope convertors shall look like those presented in figure 3. The speed of bubble in figure 3 (device 1) is twice as high as the same in figure 3 (device 2).
Figure 3. Radioisotope measuring convertor 1 and radioisotope measuring convertor 2 output signals on the bubble passing cross sections $S_1$ and $S_2$.

One can see from figure 3-2 that the radioisotope measuring convertor output signals comprise surges $n_1$ and $n_2$ as the bubble was passing through. The $n_2$ surge has delay relatively $n_1$ for time $\tau$, which is equal to $(L/V_b)$, where $V_b$ is the bubble motion speed. Therefore, by measuring the delay time ($\tau$) of surge $n_2$ relatively $n_1$, one can calculate the speed of the gas bubble moving:

$$V_b = \frac{L}{\tau}$$

(12)

Because the gas bubble moves together with the liquid flow, one can use the bubble motion speed to assess the local (i.e. where the bubble currently is) speed of the liquid flow. In a real oil and gas mixture flow, not a single bubble, but rather a plurality of bubbles with different sizes move. Therefore, the shape of the radioisotope convertor of output signals shall be more complicated, for example, the one shown in figure 2. Output signal fluctuations of radioisotope measuring convertor 1 shall be repeated at the output of radioisotope measuring convertor 2 with time delay $\tau$. Time $\tau$ may depend on the speeds of all bubbles within the flow (located in different points throughout its cross section), i.e. on the average speed of the gas ($V_g$).

Within the oil-gas flow, larger free gas bubble generally move near the center of the flow, where the local flow speed is higher than the one by the pipeline walls. Smaller bubbles are distributed more or less regularly throughout the entire flow cross section, and their speed characterizes the average liquid flow motion speed. If fluctuations that are caused by smaller bubbles motion were extracted from the entire set of output signals fluctuations of the radioisotope measuring convertor, the delay of those fluctuations at the second radioisotope convertor output relatively those at the first one would characterize the speed of small bubbles motion, i.e., correspondingly, the average liquid flow rate.

With random nature of signals, one signal delay relatively another is generally measured via the mutual correlation method. Measuring the signal delay of the second radioisotope measuring convertor relatively that of the first one suggests the temporal scale (width) of the impulses of signals of radioisotope measuring convertors 1 and 2 (figures 3). With faster motion speed, the radioisotope measuring convertor output signals get compressed along the time axis, while slower speeds expand them. Therefore (provided certain restrictions are imposed on radioisotope measuring convertor output signals), measuring the delay of the signal of radioisotope measuring convertor 2 relatively the one from radioisotope measuring convertor 1 may be substituted with measuring the temporal scale (i.e. the width) of the output signal of radioisotope measuring convertor 1—$\tau$. Normally, the temporal scale (the width) of the output signal is measured by means of the autocorrelation method.
The speed of gas in this case is assessed by the average speed of all bubbles (i.e. those having different sizes). The speed of the liquid flow is assessed by the average speed of bubbles with sizes less than some threshold value, which are the bubbles; therefore, they behave as if they were “frozen” in the liquid, i.e. do not slide relatively the liquid.

The autocorrelation method is used to measure the bubbles speeds. Measuring the liquid flow speed occurs by measuring the width of the autocorrelation function of the crude oil fluctuation function, caused by free gas “small” bubbles motion. Measuring the gas flow speed occurs by autocorrelation function width of crude oil density fluctuation, caused by the motion of all bubbles of the free gas presented within the crude oil flow.

The liquid and gas speeds are calculated in accordance with the following expressions:

\[ V_{liq} = \frac{L_{liq}}{\tau_{liq}} + V_{liq0} \]  
\[ V_g = \frac{L_g}{\tau_g} + V_g0 \]  

where \( L_{liq}, L_g, \) are the calibration factors; \( \tau_{liq} \) is the width of the autocorrelation function, fluctuations caused by the frozen-in bubbles; \( \tau_g \) is the width of the autocorrelation function, fluctuations, caused by all bubbles within the flow.

3. Results of research

The main components of the automated measuring system based on the radioisotope measuring method include a gamma radiation block, a pipeline, a detection block and the measuring information registration, conversion and transmission block. The gamma radiation block, together with the detection block, creates the primary convertor. The secondary convertor is the measuring information registration, conversion and transmission block.

The gamma radiation block is a part of the primary convertor of the system and it creates the radiation beam from the gamma radiation source enclosed in vertical direction and protects the service personnel from the ionizing radiation as the unit operates.

The operating principle of the detection block bases on registering gamma quantum beam using a scintillation detector with a photo-electronic multiplier, spectrometric signal formation with the amplitude proportional to the registered quantum energy, extracting from the registered quantum flow its two components. They correspond to the energies of the quanta, which are within two separate energy ranges, processing the information with a microcontroller in accordance with the algorithm defined [6].

Oil and gas mixture density measurement in a pipeline is a random process. Therefore, gamma radiation intensity attenuation is a random process either. A random process is the process with the value for each fixed \( t=t_0 \) being a random value, too [7, 8].

In this case, the primary convertor output value for oil flows would be the intensity of the registered gamma quanta or random value \( N(t_0) \), the measurement of which in time \( t \) should be described by random function \( N(t) \). The explanation is that the authors work with continuous multicomponent flows that include contaminations. During the measurement, density \( \rho \) fluctuations are observed, caused by dynamics and uncertainty of the component-wise composition of the total flow. The random nature of intensity change function \( N(t) \) during the interaction with the total flow of the useful medium in the pipeline results from the fact that changing the total flow density function would be represented via the sum of individual components of total flow \( \rho_i(t) \), that is subject to change randomly.

It comes out of the abovementioned that using the proposed method inevitably gives errors during measurements.
The random component of the measurement error may generally result from the random nature of such processes as radiation, interaction with the controlled medium and gamma quanta registration. To reduce the error, one has to rely only upon the informative (useful) component of the detection block signals, rather than the sum of the useful and background signals. Random errors may also emerge resulting from multiple transformations of the measurement information signal. The systemic component of the measurement error in direct and scattered gamma radiation channels may result from the nonlinear nature of the output signals of detection blocks, caused by inaccuracies during primary calibration of controlled media physical features. To reduce systemic errors, employing the moving-average method with density values averaged every 0.005s of measurements sounds reasonable. The moving average belongs to the most common method of smoothening the time series. The method is useful in a field of processing signal digital to eliminate high frequency components and noises, i.e. it is applicable as a low-frequency filter. Figure 4 shows the functional diagram of finding the average density of the mixture in a pipeline.

![Functional diagram](image)

**Figure 4.** A functional diagram of finding the average density of the mixture in a pipeline.

To implement the said methodology, an algorithm was developed to automatically correct the calibration characteristics; the algorithm averages the measured and the calculated indications from the secondary convertor during the minimal time interval of about 5ms.

Therefore, there is the ongoing correction of the volume density value during the current moment of time, eliminating both systemic and random measurement errors.

4. Conclusion

The proposed automated system has the following advantages:

1) There is no contact between measuring equipment equivalents and the controlled medium flow. No additional hydraulic resistance to the flow is created; neither its shape, nor its rate or its direction would be modified;
2) There is no need for preliminary preparation of the flow (separation and homogenization);
3) There is no restriction on physical and chemical properties of the controlled medium (temperature, pressure, viscosity, aggressiveness);
4) The system is insensitive to resin and paraffin sediments;
5) It operates within the wide range of flow rates (from 1 cm/s to 10 m/s) and flow composition changes (free water content is 0-95%, free gas content is 10-90%);
6) The system is equivalent regardless the flow structure hydrodynamic changes.

The proposed method allows measuring densities and concentrations of oil, free gas and water in heterogeneous oil-gas-water flow. The expected absolute measurement error during density measurement in this case shall not exceed 0.001 g/cm$^3$, while the relative error in connection with water concentration is ± 5%, which for gas would be ± 5%.
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