Monitoring of multiphase flows for different applications

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ABSTRACT

The report shows experience in implementing two-phase flow-meters for helium, hydrogen, liquefied natural gas (LNG), and oil-salty/formation water mixtures. Two types of such devices are presented. The first type is flow-meters based on combination of a void fraction RF-sensor and a narrowing device. They can be applied for superconducting accelerators cooled with two-phase helium, refueling hydrogen system for space ships and oil production industry. The second one is based on combination of a gamma-densitometer and a narrowing device. These systems can be used for the diagnostics of LNG and oil-formation water flows. A measuring system based on a modular industrial computer is described as well. The metrological characteristics for different flow-meters are presented and the results obtained are discussed. It is also shown that the experience gained allows separationless flow-meters for three-phase oil-gas-formation water flows to be produced.

INTRODUCTION

Diagnostics of two-phase flows is required in different fields of activity, in particular, in cryogenic systems of superconducting particle accelerators (FAIR, NICA) where cooling of magnet structures is carried out by changing the thermodynamics state of the cryogen – a two-phase single-component helium flow [1]. Another type of two-phase flows appear while filling and empting tankers for LNG and its transportation and for fuelling spacecrafts with liquefied cryogenic fuel (hydrogen) and oxygen, etc. Totally different two-phase flows occur in separation diagnostics systems for oil production – "oil-gas" and "oil-formation/salty water". At present, based on different operating principles separationless flow-meters of type "oil-gas-formation water" are also employed in oil production industry. Let us consider these flow-meters in detail.

NOMENCLATURE

G	[kg/s]	Mass flow rate
ΔP	[Pa]	Pressure drop in the narrowing device depending on the average flow velocity
A	[m^2]	Cross-section area
Q	[m^3/h]	Volumetric flow rate
f	[Hz]	Resonant frequency
P	[Pa]	Pressure
T	[K]	Temperature
x	[-]	Mass quality of the two-phase flow
s	[-]	Slip ratio
k	[-]	Calibration function depending on the two-phase flow pattern
D	[m]	Diameter of pipe
ID	[m]	Inner diameter of pipe
I	[cps]	Intensity of the gamma-beam
w	[-]	Water cut
c	[Pa/(kg^2/s^2)]	Calibration coefficient
d	[Pa/(kg^2/s^2)	Calibration coefficient

Special characters

φ	[-]	Void fraction
ρ	[kg/m^3]	Average density
ξ	[m^2]	Constant defined by geometry parameters of the narrowing device [2]
ε	[-]	Dielectric permittivity
v	[m/s]	Average velocity
μ/ρ	[m^2/kg]	Mass attenuation coefficient of LNG

Subscripts

g	Vapour at equilibrium pressure
l	Liquid at equilibrium pressure
h	Homogeneous flows
1	Large cross section of a cone-typed narrowing device
2	Small cross section of a cone-typed narrowing device
f	Flow temperature
b	Sensors body temperature
s	Saturation conditions
st	Threshold value for a stratified helium flow
0	Intensity of gamma radiation when the pipe is empty

TWO-PHASE FLOW-METERS FOR HELIUM AND HYDROGEN

Real two-phase flow-meters, in particular, for helium with a relatively short period of measuring (about 0.1 s) can be produced using a combination of narrowing devices (ND) and void fraction sensors [2]. However, there have been no two-phase cryogenic flow-meters capable to operate in the whole range of void fraction values from 0 to 100% until recently that is explained by special features of the method to find a mass flow rate of the cryogen. In this case, for arbitrary flow pattern of equilibrium two-phase flow G-value is defined by the following equation:

$$G = k\xi\sqrt{\Delta P \rho}\ , \qquad (1)$$

where $\rho = \rho_g\varphi + \rho_l(1 - \varphi)$ depending on the temperature of saturation T_s, $\varphi = A_g/(A_g + A_l)$, k depending on φ, G, T. Earlier we published a description of the method to define φ by means of dielcometric RF-sensors with the uniform electric field inside the sensitive part. One of the variants of this sensor is presented in Fig. 1.To find the dependence of φ on ε, in Fig. 1.

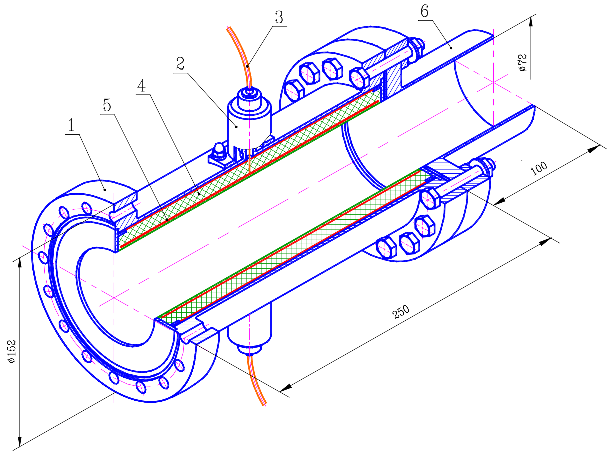


Figure 1 Void fraction RF-sensor of a round cross-section for the TESLA Test Facility: 1 - flange, 2 - RF-input/output node, 3 - RF-cable, 4 - dielectric tube, 5 - dielectric tube with a meander line, 6 - tube for the two-phase superfluid helium flow; temperatures of the two-phase flow and RF-sensor body are measured by TVO temperature sensors.

To find the dependence of φ on ε, the radio frequency (RF) technique is used when the investigated media fill the sensitive volume of a meander resonator connected to an oscillatory circuit. By measuring f of the electric oscillations in the circuit, it is possible to determine the degree of resonator filling with a relatively high accuracy.

Calibration functions for such a sensor are presented in [1, 2]. The main problem of applying Equation (1) for measurement of mass flow rate is to define the function $k(\varphi,G,T)$. It can be done by using a test bench, which is applied to investigate detailed characteristics of a two-phase flow. Such unique data for helium are given in reference [3]. According to the approach described in [2] the calibration function $k(\varphi,G,T) = k(A_1,A_2,s_1,s_2,s_{st},x,T)$ looks quite complicated, where $s = v_g/v_l$, $s_{st} = (\rho_l/\rho_g)^{1/3}$.

A detailed description of an innovative flow-meter with a sensitive element of a circular/round cross-section is presented in [1, 2] and its parts are shown in Fig. 2 borrowed from [1]. This flow-meter should be located with a horizontal cryostat with multi-layer and vacuum insulations. The feature of the RF-sensor is that, for the first time, it has been made on the base of composite metal-ceramic pipe, which provides high long-term stability of readings. In addition, an irregular pitch of the meander line applied on ceramic allows one to create the uniform electric field inside the sensitive part that makes the calibration procedures easier. Moreover, RF-sensor calibration method was developed in the wide range of equilibrium temperatures [1] that significantly extends its application feasibilities.

Temperature sensors on the base of composite carbon-alumina TVO-resistors [4] were used to measure the temperatures of the flow and the RF-sensor's body. They were mounted using a specialized technology to minimize errors due to mounting them on a cold surface in vacuum environment [4]. These temperature sensors were calibrated at our cryometrological facility [4].

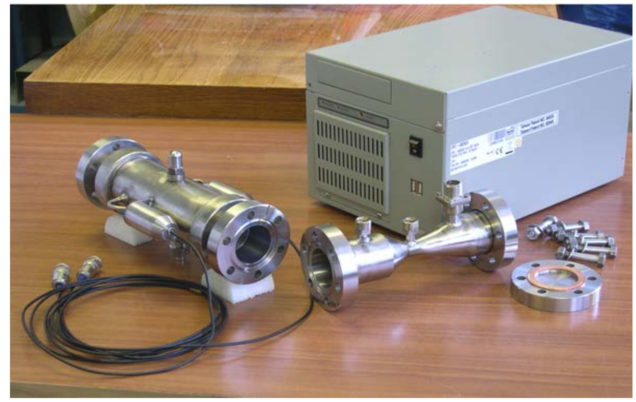


Figure 2 Components of cryogenic two-phase flow-meter for helium and hydrogen: left – RF-sensor of a round cross-section with ID = 38 mm, right – cone ND, background – measuring block based on the 6-slot multichannel industrial computer.

The pressure and pressure drop along the ND have been measured with Sapphire-22MPS transducers.

The data acquisition system is made on the base of a multi-slot industrial computer shown in Fig. 2. The electronic boards fabricated by us to measure temperatures, pressure and pressure drop, resonant frequency and its amplitude are presented in [5]. Server connection can be accomplished if needed through Ethernet cable via TCP/IP protocol.

The flow-meter presented in Fig. 2 can be used not only for helium but also for hydrogen and LNG two-phase flows with the liquid-to-gas density ratio $(\rho_l/\rho_g)\leq 30$-35 in the last case. For homogenized flow patterns the relative errors of flow rate measurements in the φ-range from 0 to 90 % are estimated as (1.7-3.7) % for helium at T = 4.4 K, (2-7.5) % − for hydrogen at T = 23 K and (2-8) % − for LNG (methane) at T = 142 K [1]. The two-phase flow-meter for hydrogen with a sensitive part of annular cross-section operating at the Indian National Space Centre is presented in [2]. It is shown in Fig. 3. Perhaps, it is the first cryogenic two-phase flow-meter.

TWO-PHASE FLOW-METERS FOR LARGE LNG FLOWS

Two-phase LNG flows appear, for example, while filling or unloading a storage tank, when it is necessary to measure the void fraction and the LNG mass flow rate in the cold pipeline during a steady-state regime, at least. One of the variants for a transfer line of ID = 457 mm (18 inches) to solve this problem by means of the RF-sensor of ID = 300 mm and a cone ND of 457 mm/300 mm, was described in [6]. It is shown in Fig. 4. It is noteworthy, that this type of the flow-meter differs with rather low total hydraulic resistance due to recovery of pressure in the output cone.

However, there are some disadvantages in this system. First, it is rather difficult to choose the necessary dielectric material for the RF-sensor of a rather big diameter to provide long-term stability. It could be stipulated with pores where undesirable condensation of vapour or evaporation of the liquid phase could occur that is noted in [1]. For cryogenic void fraction RF-sensors of relatively small diameters these problems are solved

Figure 3 Cryogenic two-phase flow-meter for hydrogen with RF-sensor of annular cross-section (220 mm^2) and hemispherical ND.

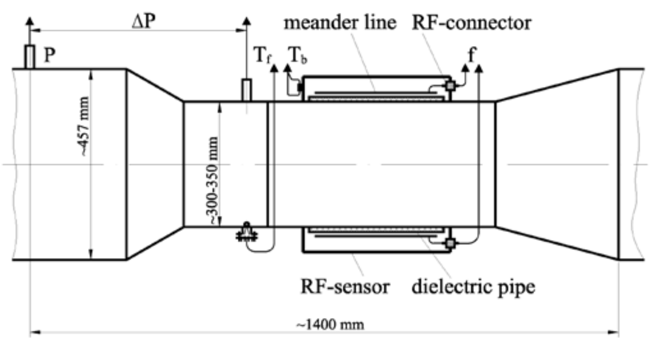


Figure 4 Schematic of the diagnostics system for the two-phase LNG flow based on a void fraction RF-sensor of the meander type and a cone ND.

by using ceramic pipes to mount a meander line on them [1] as it is shown in the previous item. Second, the RF-sensor requires a special calibration system with a cryostat of a relatively big ID – about or more than 500 mm. In addition, a calibration procedure in a wide range of temperatures is not simple [1]. One can avoid these disadvantages if to replace an RF-sensor with a gamma-densitometer (GD). In this case, Equation (1) may also be used. A feature of filling and unloading of an LNG carrier is that it should be as fast as possible due to the expensive rent of dockage. The average velocities under these circumstances must be as high as possible and, consequently, the flow pattern is almost homogeneous in this case. It means that the velocities of the liquid and vapour phases are practically equal and one can regard the two-phase LNG as a single-phase medium with the average density ρ. In this case, k-function in equation (1) can be equal to 1. One can find a necessary density from Equation (2) that responds to the value of the average bulk density of the medium [6]:

$$I = I_0 \exp\left[-(\mu/\rho)\rho D\right], \tag{2}$$

where (μ/ρ) – can be found experimentally or from appropriate tables [7] and ρ is measured along the diameter of the pipe, the so-called “line density”. The values of I_0 and (μ/ρ) depend on the used radioactive source. To find the average bulk density in general, one needs to know not only the line density, but also the flow pattern. However, for the homogenous flow these densities are equal. Knowing the density one can easily find the void fraction and quality, x_h, for the homogenous case:

$$\varphi = \frac{\rho - \rho_l}{\rho_g - \rho_l}, \tag{3}$$

$$x_h = \frac{\varphi}{(\rho_l/\rho_g)(1-\varphi)+\varphi}. \tag{4}$$

One of the advantages of GD over the RF-sensor is as follows: it determines the average bulk density at once, whereas the RF-sensor responds to dielectric permittivity of the medium and one has to determine the density using quite complex dependencies $\rho(\varepsilon, \rho_g, \rho_l)$. This property of GD allows one to simplify its calibration procedure.

The type and activity of the radioactive source can be found from the condition that the pipe with ID = 457 mm made of stainless steel SS304 must withstand the pressure of about 20 bar. The thickness of the pipe wall in this case is estimated as 5-6 mm. The optimal choice of a radioactive source in this case is Cs^{137} with radiation energy of about 662 keV and half lifetime of about 30 years. The attenuation of the beam on the pipe walls is about 51 %. Our experience has shown that the source with radioactivity of 17 mCi or some less fully meets the requirements of the task mentioned above, i.e. the unabsorbed part of the beam is sufficient to respond adequately to the density changes of LNG. This source and gamma-detector can be easily bought at the market. Metrological characteristics of the considered flow-meter are presented in Fig. 5.

The data acquisition system is similar to the one which was used for the two-phase helium flow-meter. It also allows one to measure I by means of the gamma-detector-electronics which is connected with the CPU-board via USB-port.

Since it was impossible for us to rent any certified two-phase LNG diagnostics system, the State Primary Special Standard of the Unit of Mass Flow Rate of Gas-Liquid Mixtures (GET195-2011), VNIIR, Kazan, Russia, was used for this aim as a flow simulator. It is shown in Fig. 6. Its media are Exxsol-D100 of 815.54 kg/m^3 and viscosity 3.45 sSt at T = 293 K, water and compressed air at pressure of 5 bar. The maximum parameters for tests were the volumetric flow rate of Exxsol Q_l = 60 m^3/h (G_l = 13.6 kg/s), the volumetric flow rate of air reduced to standard conditions Q_g = 250 m^3/h. It could provide the maximum gas void fraction, GVF = $Q_g/(Q_g+Q_l)$, of the two-phase flow of about 45 % at P = 5 bar.

A multiphase flow-meter of ID = 100 mm with the cone ND of 98/70 mm was used during the tests at GET 195-2011. Its components are shown in Fig. 7, and a Cs^{137}-gamma-densitomenter was used during tests. It is necessary to note that GD could be calibrated in-situ while operating with pure liquid and gas. It is shown in [6] that for homogeneous flows the

$\Delta P/G^2$-ratio depends linearly on x_h, which, in its turn, depends on void fraction φ according to (4):

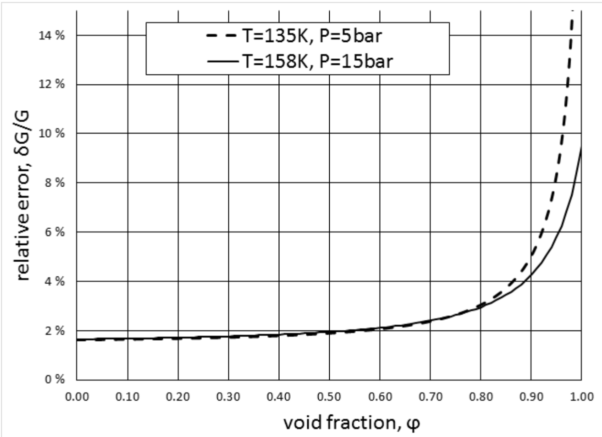


Figure 5 Relative error, $\delta G/G$, versus φ, for the (GD + ND)-flow-meter while operating with homogeneous two-phase methane flows at saturated pressures of P_s = 5 bar and 15 bar.

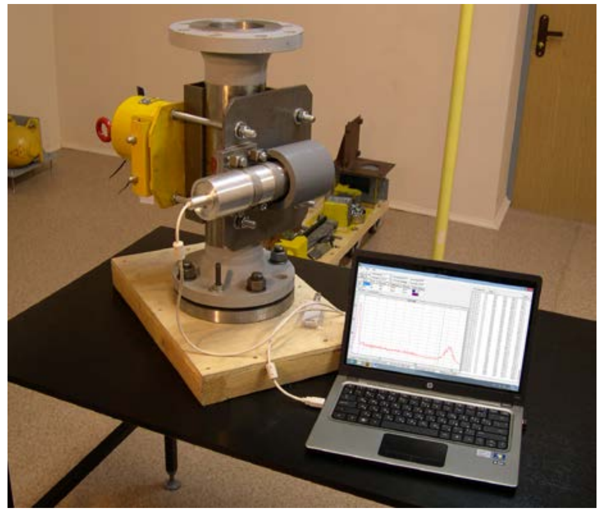
Figure 6 Three-phase test bench (GET195-2011) at VNIIR, Kazan, Russia.

$$\frac{\Delta P}{G^2} = \frac{\xi^{-2}}{\rho_h} = \xi^{-2}\left(\frac{1}{\rho_g} - \frac{1}{\rho_l}\right)x_h + \frac{\xi^{-2}}{\rho_l} = cx_h + d\,. \quad (5)$$

The values of c and d in relation (5) are: c = 14563.00 Pa/(kg^2/s^2) and d = 132.92 Pa/(kg^2/s^2). The mass flow rates of air and Exxsoil can be found as follows:

$$G_g = Gx_h\,,\; G_l = G(1 - x_h)\,. \quad (6)$$

The experimental results have confirmed the applicability of the offered system for quasi-homogeneous flows: at φ < 50 % and G_l > 11 kg/s ($Re_l \geq 5\times10^4$) the relative errors to determine the mass flow rate of Exxsol for all the experimental points do not exceed 2 %. This is in a good agreement with the theoretical estimation (see Fig. 5). The absolute errors to find the gas void fraction values do not exceed 5 % for all the noted ranges [6]. These values can be improved by tuning of the gamma-detector characteristics. Metrological characteristics seem to be better for the two-phase LNG flows because, as it is expected, the slip ratio and viscosities of the components for such flows will be smaller than for the simulated Exxsol-air flows.



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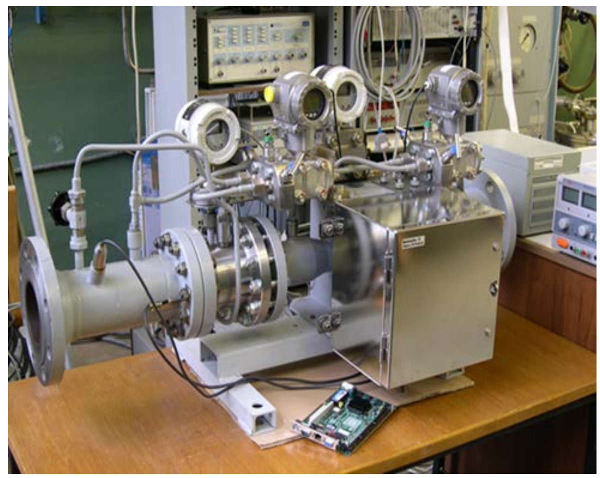


b)

Figure 7 Components of a separationless three-phase flow-meter: a) − spectrometric two-channel GD during tests with pure components, b) − cone ND with measuring system.

TWO-PHASE FLOW-METERS FOR OIL PRODUCTION

Two types of measuring systems are used in oil production industry: separation systems when a three-phase flow of oil, formation water and gas is separated into an oil-formation water mixture and gas and separationless systems. In principle, the "oil-formation water" two-phase flow-meters for this aim can be analogous to the one described for cryogenic flow-meters. However, while the efficiency of systems for mixtures consisting of two dielectrics (oil and sweet water) gives no room for doubt, the capabilities of the "oil-formation water" flow-meters may be limited in the water cut range w due to significant impact of salts as sources of conductivity on performance of dielcometric sensors. It has been confirmed by the tests [8] with the so-called direct “oil-in-formation-water” emulsions (w>70 %). The results acceptable for practical operation of the “RF-sensor + ND” two-phase flow-meter of ID = 100 mm with real inverted emulsions (formation water-in-oil) in the range 0<w<60÷70 % are presented in [8]. These results were obtained at the test bench at Tatneft, Nurlat, Russia. An uncommon algorithm for defining G, w and water salinity ratio using such a flow-meter is given in [8] for laminar and turbulent flows taking into account features of hydrodynamics and electrodynamics in the flow-meter. The new algorithm to process the obtained measuring data is presented in [9]. It takes into account the temperature dependence of physical properties of the flow as well as own temperature dependence of RF-sensor characteristics. The results are presented in Fig. 8. One can see that this new algorithm is surely more accurate than the previous one that leads to significantly better results of measurements. In addition, δw-distribution becomes classical instead of the previous unusual shape.

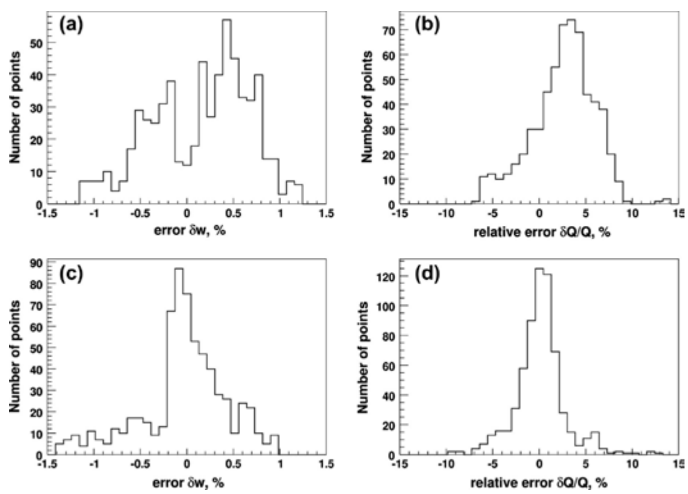


Figure 8 Comparison of the data processing results for the previous [8] and new [9] algorithms: (a) δw-distribution, the temperature is not taken into account; (b) δQ/Q-distribution, the temperature is not taken into account; (c) δw-distribution, the temperature is taken into account and (d) δQ/Q-distribution, the temperature is taken into account.

We have made efforts to use additional measurements of admittance of the mixture in the range of 60 %<w<100 % in order to extend the range of the system operation. But it has not led to significant success. In this regard, one of the nuclear physics methods has been used to solve the problem as it was done for large LNG flows. In particular, we have employed gamma densitometer (GD) based on a Cs^{137} source. A two-phase “GD + ND” flow-meter has been tested at an “oil-gas-salt water” test facility of the firm TUV SUD NEL (Glasgow, Scotland). The test results have shown [10] that such a flow-meter meets the requirements of Russian National Standard (GOST R8.615-2005) in respect to volumetric flow rate measurements for crude oil in the range of 0<w<95 % for ≈95 % of the measurement points. It is illustrated in Fig. 9.

In its turn, GD can be used for water cut measurements in the whole range of w from 0 to 100% with the accuracy not worse than 1÷2 % that is enough for practice. Such competitive measurement instruments are not produced in Russia, at least.

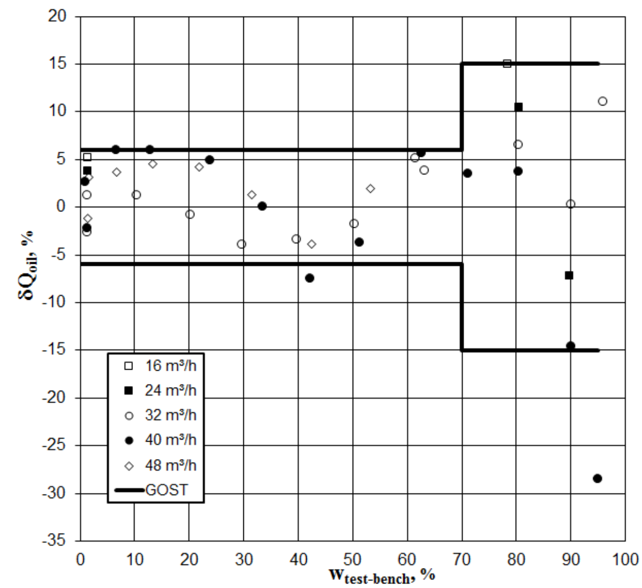


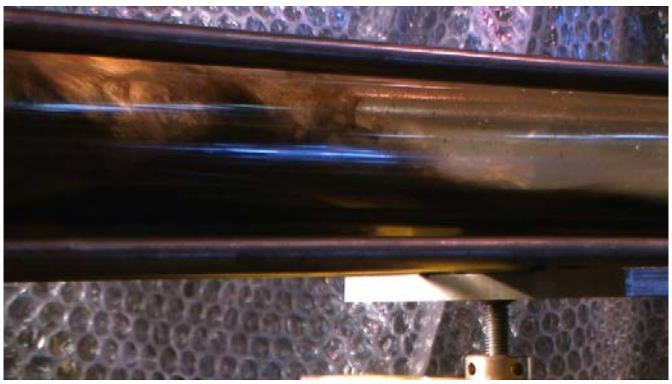
Figure 9 Relative errors to find volumetric flow rate of crude oil, δQ_{oil}, versus the water cut of the test bench, $w_{\text{test-bench}}$: lines are limits of errors according to Russian State Standard (GOST P 8.615-2005).

Apart from these results, there have been compiled flow pattern maps for the three-phase “oil-gas-salty water” flows based on the TUV SUD NEL test data. The visual part of this test bench is shown in Fig. 10. It lays a solid foundation for the development of an algorithm of processing signals from three-phase flow-meters. Some flow patterns are shown in Fig. 11.

POSSIBILITY TO PRODUCE A SEPARATIONLESS THREE-PHASE “OIL-GAS-WATER” FLOW-METER

The obtained experience allows one to develop the most complicated type of the flow-meter – separationless three-phase flow-meters for “oil-gas-formation water” mixtures. It can be done if to add one more independent signal to the two-phase flow-meter of “GD + ND” type. Thus, to use Equation (2) at another radiation energy, it seems reasonable to apply the second GD, for example, with Am^{241}-source operating at energy of about 60 keV. Its half lifetime is more than 400 years. This gamma-source can be located within the device shown in Fig. 7a, and each source (Am^{241} or Cs^{137}) or both simultaneously can be used depending on technical requirements. In the second case a specific gamma-detector and program have to be used to provide a spectrometric two-channel GD. To do this, the experience of the Institute of Physics and Technical Problems (Dubna, Russia) has been used in development of gamma control systems for oil processing and coal mining. Using a suitable calculation model (homogeneous and/or with variable slip ratio), one can take into account different flow patterns of three-phase flows (Fig. 11).

Figure 10 TUV SUD NEL test bench: visual section of ID=102 mm (left), video-camera (right) and investigated flow-meter based on Cs^{137} GD (yellow color) and cone ND.



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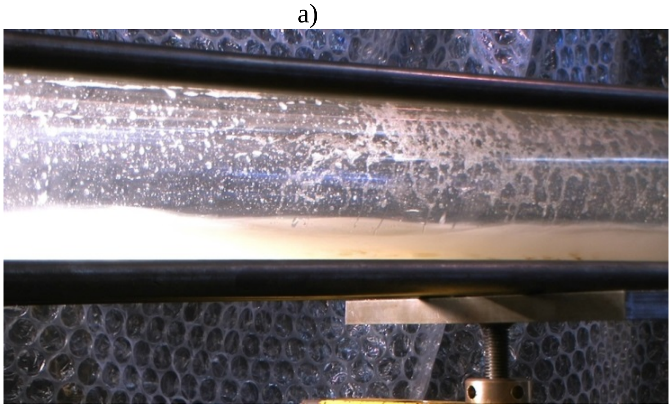

b)

Figure 11 Flow patterns of multiphase flows: a) – "oil-salty water-gas" at w = 60%, φ = 90%, Q = 24 m^3/hour; b) – "salty water-gas" at φ = 80%, Q = 24 m^3/hour.

The characteristics of this three-phase flow-meter were studied on test bench GET 195-2011 (VNIIR, Kazan, Russia) mentioned above. The preliminary analysis has confirmed the operability of the flow-meter, definiteness of its characteristics and repeatability in all the ranges of the pre-set parameters of gas-liquid mixtures – "gas-oil emulator", "gas-water" and "oil emulator-water". The results obtained are under processing now.

CONCLUSIONS

The offered design of the void fraction RF-sensors (RF), gamma-densitometers (GD) and narrowing devices (ND) can be used as a reliable base to develop the pressure-drop two-phase flow-meters which are able to provide full information about two-phase flows allowing to measure and find values of temperature, T, pressure, P, void fraction, φ, quality, x, or water cut, w, and mass flow rate, G. The choice of the combination (RF + ND) or (GD +ND) depends on technical requirements: the first combination is suitable for helium and hydrogen flows whereas the second one can be used for large LNG flows and oil-formation water mixtures. These devices can operate in the whole range of x- or w-values from 0 to 100 %. The upgraded system with two gamma-sources and spectrometric two-channel gamma-detector can be applied for the "oil-gas-formation water" separationless three-phase flow-meter.

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