Indian Journal of Science and Technology, Vol 9(5), DOI: 10.17485/ijst/2016/v9i5/87638, February 2016
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

# Measuring Rate and Quantity of Multiphase Streams

**Alexander Anatolevich Vakulin[1*], Alexander Alexandrovich Vakulin[2] and Yuri Akimovich Gilmanov[1]**

[1]Tyumen State University, Tyumen, The Russian Federation; aavakulin@mail.ru, treff21@gmail.com
[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, The Russian Federation; Glok100@gmail.com

## Abstract

**Background/Objectives**: The problem of correct measuring the multiphase stream component flowrate has been solved since 1830. This problem is particularly acute for oil and gas equipment manufacturers in the Western Siberia – the main Russian 'pantry' of oil and gas. **Methods/Statistical analysis**: The article discusses the main challenges and the existing methods for measurement flowrate and quantity of oil-and-gas condensate multiphase flows typical of Western Siberia. The information about on separating and non-separating multiphase flow meters and data concerning the physical principles underlying their operation are given, their advantages and disadvantages are discussed. **Findings and Improvements**: It is shown that the component consumption and quantity of oil and gas flow is measured, in most cases, using various separators. It is proposed to use non-separating multiphase flow meters-counters to measure the flow rate and quantity of gas-condensate streams with low liquid phase content. To test any type of multiphase flowmeters, in 2015 the largest in Russia the Research and Testing Flow Measuring Unit for Multiphase Streams (RTUMS) was built and put into operation in Tyumen – the basic reference standard of the 1st rank multiphase stream flow rate. The unit was constructed within the joint project "Development and serial production of the metering unit for oil and gas produced in the fields finishing their production" that was implemented together by HMS Neftemash OJSC and FSBEI HPE Tyumen State University (RF Government Order No 218 dd. April 9, 2010). A brief description of the Unit is given. It is noted that RTFMU creation is a necessary prerequisite for MPFM development, creation and application in engineering practice, though insufficient. A conclusion is drawn about the necessity to develop an appropriate infrastructure to create competitive multiphase flowmeters in Russia.

**Keywords:** Gas, Gas Condensate, Measurements, Multiphase Flow Meters, Multiphase Streams, Oil, Testing

## 1. Introduction

The correct measuring of rate and composition quantity of multiphase stream is of high importance. Among the most typical multiphase streams commonly used in the industry we can mark oil and gas mixtures, wet steam, pulps, pulverized coal fuel, water-earth mixtures and low-boiling cryogens. There are a lot of physical and technical reasons which cause difficulties in ensuring the required relative expanded uncertainty of rate measuring in such mediums (2-5% depending on multiphase stream type): for example, differences in phase flow velocities through primary measuring transducers; inhomogeneity of phase distribution in cross section of a stream; considerable fluctuation of velocities, pressures and phase concentrations; temperature influence on quantitative composition of the phases. This is a very complicated scientific-technical task that requires deep knowledge in physics and hydrodynamics of multiphase streams. We should appreciate the substantial contribution of Russian and Soviet scientists in the establishment of hydrodynamics of mixture as a separate sub-discipline within the mechanics of fluids. So the first published paper devoted to this problem (France, 1830) belonged to Russian Engineer M. Timerin, and the terminus 'two-phase' in the title of the published paper was firstly used in the article of Soviet Scientist S. Kosterin "Investigation of the two-phase mixture structure in horizontal pipes".

*Author for correspondence

In hydrodynamics of liquid-gas mixtures the research techniques were finally formed by 1980. There are three branches distinguished among them. The first branch is represented by theoretical investigations, such as derivation of differential equations for two-phase flows based on hydrodynamic equations using ideas and methods of spatial-temporal averaging. Within this branch we can mark the works of Dyunin, Mamaev, Nigmatulin, Semenov, Teletov, Frankl, etc.[1–6] Studies devoted to the wave flow of viscous liquid thin layers started by Kapitza in 1948 belong to the theoretical branch, as well[7].

The second branch concerns the creation of semi-empirical ratio. For example, relations describing velocity distribution and gas concentration in the flow cross section are determined by experiment, after that these relations are used for integration of original differential equations. As the result, we can investigate one of the various possible mixture flow structures. One of the promising research techniques in hydrodynamics is investigation of the two-phase flow rippling components. For this purpose, the method of two-phase flow analysis is used, which is similar to the semi-empirical turbulence theory in single-phase hydrodynamics. Semi-empirical investigations also include studies on phase transformations which can be both the result of the heat exchange and the bubble-point pressure change when a two-phase mixture goes through the pipeline[8,9].

The third branch is represented by experimental fundamental research. To generalize the experimental data, the similarity criteria are used, and to calculate the unknown values the equations of two-phase mixture motion are applied, noted in one-dimensional (hydraulic) approximation. The influence of various radiant on the multiphase stream is being studied and the density (or pressure) fluctuations related to the phase relation and etc. are being analyzed[10].

## 2. Results

The research results mentioned above are necessary for design, construction and operation of the modern multiphase flow meters.

In this article we consider the issue of component rate and quantity measuring for two types of the multiphase stream: oil and gas and gas-condensate streams typical for West Siberia. These streams are different in liquid phase content: the gas-condensate streams have considerably less liquid phase (0.5–5.0 % volume) than the oil and gas streams. Different quantitative composition of the phases within the mentioned multiphase streams allows using the substantially different measuring methods and devices to determine the component flow rate. Herewith, the requirements of the GOST R 8.615-2005 State System for Ensuring Uniform Measurement[11] should be met. In particular, according to the i. 6.1 of the GOST, the limits of the allowable relative measuring error are: a) for the crude oil mass ±2,5 %; b) for the crude oil mass ignoring water for the following percentage of water content in crude oil (volume ratio): under 70 % - ±6 %; from 70 % till 95 % - ±15 %; over 95 % - the limit of the allowable relative error is determined in the measurement procedures (MP), approved and certified as applicable; c) for the oil-associated gas volume: ±5 %.

Traditionally, the Separating Multiphase Flow Meters (SMFM) were and are commonly used for measuring the component rate and quantity of oil and gas stream. The separating method of component rate measuring (or well flow rate acc. to the oil and gas terminology) is the most accepted method in the world, which works according to the scheme, similar to the given in Figure 1.

A well stream flows into the E separator through the individual or personal П switch. Inside the separator gas is extracted (separated) and free water is partly separated. Gas goes into the gas line and then into the collector through the flow meter – РГ gas meter. Free water is accumulated in the lower part as a consequence of density difference, and water level is controlled by the У2 level meter. When the given level is exceeded, water also goes to the collector through the РВ water flow meters-gages.

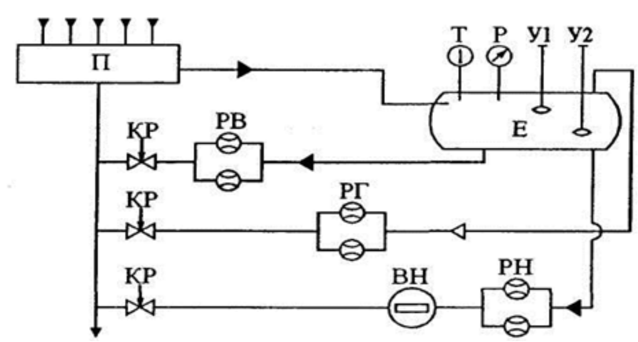


**Figure 1.** Technological layout of separating meters for oil well flow rate[12]. Т – temperature gage; Р – pressure gage; У1, У2 – level gages; РВ, РГ, РН – flow meters – water, gas and oil meters; ВН –hydrometer; КР – control valve.

Partly dehydrated oil flows through the PH flow meter-gage and BH hydrometer into the collector. All the rundown lines of mixture components are equipped with the KP control valves supporting the prescribed operation modes of the unit. The particular implementation of the scheme given in Figure 1 represented by SMFM is produced by many domestic and foreign companies, and some of them are located in Tyumen. So such companies as OJSC IPF SIBNA and OJSC HMS Neftemash, members of the multi-industry holding JSC HMS Group, are currently producing numerous modifications of block automated group metering units SPUTNIK-M and MERA. In Figure 2 you can see a model of the MERA metering unit.

There are many advantages of the separating component meters for oil wells flow rate: firstly, we can almost completely neglect the influence of stream fluctuation on the measurement results by virtue of the fact that separator is a perfect ripple integrator, moreover, the considerable measurement duration additionally smooths these ripples; secondly, taking into account such dividing way of the multiphase stream into single-phase components we can confirm that the measurement accuracy of single-phase components rate is determined by the accuracy of the traditionally used measuring devices and computing algorithms.

Among the disadvantages of the SMFM we should call the following: considerable metal consumption, equipment with large amount of measuring devices, shut off control and switching devices; necessity of regular maintenance servicing by qualified personnel. All that makes such units very expensive. Besides there are problems concerning the phase separation quality. Finally, the separator as the basic element of the SMFM contains many sources of errors, including calibration, mechanical damage, problematic fluid condition, corrosion, solid streams, human error, etc. So we can conclude that the SMFM measurement results need to be corrected periodically.

Using the so-called ‘partial method’ for measuring oil-water-gas stream discharge characteristics based on the principle of selecting an insignificant sample stream part allows reducing metal consumption and overall dimensions of the SMFM. For example, since 2002 TyumenNIIgiprogaz Ltd. has successfully operated their Multiphase Metering Unit (MMU) with the sampling stream ratio 0.010 - 0.001. Measurements of separation gas discharge, unstable condensate and water are made periodically once in 20-40 minutes. Besides that, the samples of unstable condensate and separation gas are taken during the operation. This allows determining the composition of the extracted formation fluid. To conclude, the MMU is equal in its purpose to the wellhead separator, but it allows the well to work not for the flare, but for the gas treatment line, so there is no leakage of the formation gas[12].

The unit exterior is given in Figure 3.

The MMU consists of the sampling apparatus (Figure 3, on the left) and compact separator (Figure 3, in the middle). The sample part of the gas-liquid well stream enters the compact separator, where unstable hydrocarbon liquid and water are released from separation gas, and then the single-phase component rate is measured. The well flow rate of gas, hydrocarbon liquid and water is calculated


**Figure 2.** Model of the MERA metering unit produced by OJSC HMS Neftemash.

**Figure 3.** Photo of the multiphase measuring unit produced by TyumenNIIgiprogaz Ltd.

according to the results of these measurements, as well as the gas (gas-condensate) ratio. We should emphasize that using of the mobile measuring unit allows surveying wells, which are not equipped with fittings for separator hookup, avoiding output of well stream to the flare. Another representative of domestic 'partial' flow meter is the fluid meter produced by the scientific-production association NTES (Bulma, Tatarstan)[13]. This meter is intended for measuring crude oil mass (acc. to GOST R 8.615-2005) contained in oil-gas-water mixture coming from wells. The 'partial' method of discharge characteristics measuring of the oil-gas-water stream is widely used among the foreign manufacturers. For example, in Figure 4 you can see a Haimo MultiPhase Flow Meter (MPFM) produced in China[14].

Measurements of gas/liquid phase flow rate and determination of water content are performed independently of each other. Gas and liquid phase flow rates are determined with the help of two devices, which consist of the Venturi tube and single gamma-detector (59.5 keV). When measuring three-phase flow rate the quantity of water in the multiphase stream is measured with the help of the dual energy gamma water cut meter (22.0 keV and 59.5 keV) and flow conditioner (mini-separator) located upstream. Americium 241 is used as a source of gamma-radiation.

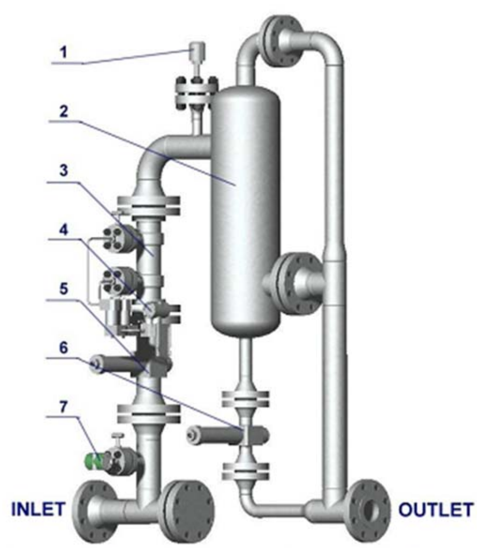


**Figure 4.** Flow diagram of the multiphase flow meter Haimo MPFM. 1 – temperature transmitter; 2 – flow conditioner; 3 – Venturi tube; 4 - differential pressure gage; 5 – single gamma meter; 6 – dual energy gamma water cut meter; 7 – pressure gage.

Phase determination is based on measuring the relative amount of carbon and oxygen atoms in oil and water, respectively. The total flow rate of the multiphase stream is measured with the Venturi tube; gamma-detector helps to acquire the data on inlet density and fractions number in gas-liquid fluid; flow conditioner (mini-separator) separates the stream; water content is measured by the dual energy gamma-detector; pressure and temperature gages are installed to convert the measured values to the standard condition. The oil flow rate (net) is estimated as a difference of the liquid and water rates.

In the summary we can state that until now the measuring of component rate and quantity of oil and gas stream is performed overwhelmingly using separators of different types.

## 3. Discussion

So now let us discuss the measuring of rate and quantity of multiphase low-liquid streams such as gas-condensate streams. Measuring low-liquid phase, typical for gas-condensate streams, is the more complicated, the less liquid phase content is in the stream. However, the fractional error of liquid phase measuring should not exceed 5 % as regular.

In our opinion it is reasonable to use Non-separating MultiPhase Flow Meters (NMFM) for measuring flow rate and quantity of low-liquid gas-condensate streams. There is no disaggregation of multiphase stream in the NMFM. The flow rate and quantity of every component are estimated according to physical-mathematical and hydrodynamical modeling of multiphase stream using the experimentally measured parameters required for the applied model. The following parameters are measured as regular: volume flow rate of multiphase mixture, gas-liquid phase ratio, and water-condensate phase ratio. The rate of multiphase mixture is determined either by measuring the linear speed of the gas-liquid mixture or with the method of variable pressure drop using the Venturi tubes (or nozzle) as an orifice. By now there are several NMFM types developed and applied by foreign and domestic producers. Among the foreign ones we can consider Haimo[14], Fluenta-Roxar MPFF-1900VI and MPFM2600[15], AGAR MPFM 50[16], Framo-Schlumberger Phase Watcher Vx,[17,18] ALPHA VS/R[19]. Among the Russian ones – RGZH-001-01 (Federal State Unitary Enterprise "FSPC Research Institute of Measuring Systems n.a. Y.E. Sedakov"), DFR-01(Research and production company VYMPEL Ltd.), MFRM DIP (Petroleum Technology Ltd.), etc. Here are some short descriptions of the operating principle of some modern NMFMs.

In Figure 5, you can see the Roxar MPFM 2600multiphase flow meter. The Zector technology is applied for this flow meter that allows analyzing various stream sectors with measurement frequency 12,000 per second.

The Zector technology provides an opportunity to make up fair presentation of the stream regimes and stirring effects, determine speed profile, as well as discover rapid changes of the stream fractional composition in mostly precise and safe way. The technology allows representing gas and oiling flow velocity as a function of their spatial position and timing (4D). This is necessary because the stream velocity near the pipe wall differs from its velocity in the pipe middle and these velocities vary in time by virtue of the changes in fractional composition, turbulence, viscosity and other effects. The standard modification covers the total range of operation conditions and excludes the use of radioactive elements.

The multiphase flow meter ALPHA VS/R produced by WEATHERFORD is shown in Figure 6.

This NMFM is intended for monitoring gas and wet gas streams at wellhead, in particular for measuring gas and condensate flow rate, optimization of the total gas production, condensate production increase and water production control. The Venturi tube and acoustic system of fluid discharge determination are applied in the flow meter design. The volumetric consumption gas content is determined by comparison between the actual value of gas-liquid mixture discharge obtained through the linear speed and the estimated flow rate of single-phase gas obtained with the Venturi tube. Mismatch of actual and estimated flow rates is the measure of liquid phase content. The embedded Red Eye® humidimeter ensures precise and safe determination of water cut level as well as water breakthrough control. The Alphas NMFM is also equipped with pressure and temperature gages and embedded electronic device computing all the necessary data.

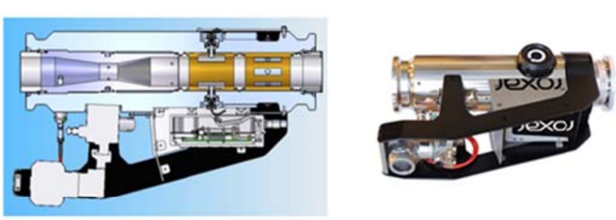

**Figure 5.** Roxar MPFM 2600 Multiphase flow meter[15].

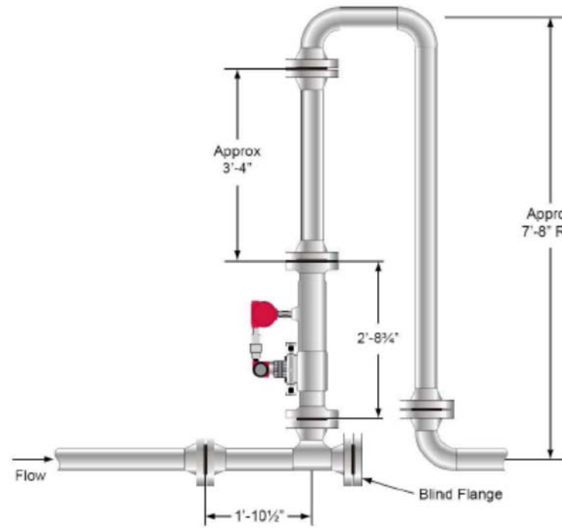


**Figure 6.** Flow diagram of the ALPHA VS/R multiphase flow meter[19].

In 2004 a group of companies from different countries (Statoil, Hydro, ConocoPhillips, ENI, Shell and Total) founded the Multi Phase Meters AS Company (MPM). The main target of the company is creation of high performance multiphase flow meter without stream separation, which could be effective both for the multiphase stream and combination gas stream[20]. The exterior of NMFM manufactured by MPM is shown in Figure 7.

To reduce the measurement error, the 3D wide band tomography technology is applied in this flow meter. MPM is able to make up to 100 measurements per second. By every measurement it is possible to calculate the flow rate for each of three phases in the multiphase stream. The NMFM is equipped with very fast electronics that enables to analyze up to 30 various measuring planes in the pipe in a hundred of various frequencies during a few thousandths of a second. Measurement errors caused by circular gas concentration (for vertical stream) are reduced in this case. Making fast measurements we can take into account fluctuation in the multiphase stream (shell, etc.) correctly. The measurements of high value water cut, dielectric permittivity, electrical conductivity, water salinity and density are made more precise.

The NMFMs produced by Schlumberger are widely used in Russia. See the details in [17,18]. Among the Russian developments we should pay special attention to the

**Figure 7.** MPM Multiphase flow meter[20].

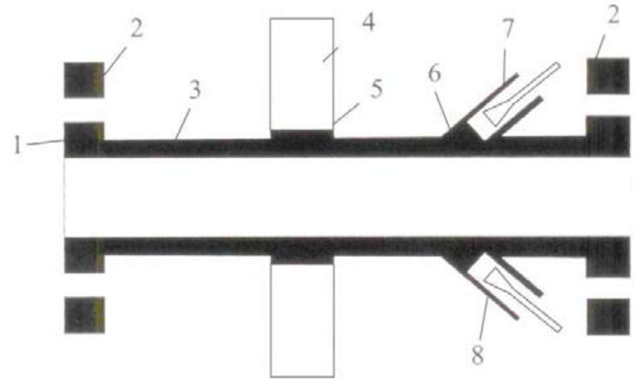


**Figure 8.** Measuring section of the flow meter. 1–pressure vessel; 2 – attachment flange; 3 – open cylindrical ultra-radio-frequency resonator (URF-resonator); 4 – closed cylindrical super-radio-frequency resonator (SRF-resonator); 5 – radio transparent insertion, withstanding the operation pressure; 6 – radio transparent window; 7,8 – exploring and receiving antennas of metering channel for gas-condensate stream velocity.

NMFM RGZH-001-01 produced by Federal State Unitary Enterprise "FSPC Research Institute of Measuring Systems n.a. Y.E. Sedakov". This flow meter is intended for automated measurements of gas and liquid phase rates within the multiphase stream of condensate wells[10,13]. The flow meter operation is based on measurement of the linear speed of gas-liquid stream in terms of the Doppler Effect as well as its density using the microwave radiation with 8 mm wave length. From the stream density we can estimate liquid-gas phase ratio. The sketch of the measuring section of the flow meter is given in Figure 8.

The velocity of gas-liquid stream is measured with the Doppler radar by shifting the frequency of liquid drops echo. The density of gas-liquid stream is measured with the panoramic meter with amplitude frequency characteristics. The permanent signal within the frequency band from 32 to 35 GHz arrives from generator to the resonator 4 which transmits gas-liquid mixture. The resonance frequency of the resonator varies proportionally with the stream density. To measure the gas-liquid mixture flow rate and phase ratio the NMFM should be regularly calibrated in the operating range of formation mixture rates with an external standard instrument.

The market research of the modern NMFMs enables to state that the majority of NMFMs intended for measuring flow rate and quantity of low-liquid gas-condensate stream are equipped with an orifice device represented by the Venturi tube and density meter based on the translucent radiation principle (or radioactive, or super-high-frequency radiation).

We would like to mention that the list of the MPFM given in this paper is by no means exhaustive; the manufacturers of MPFMs are steadily representing their new developments.

The manufacturers of MPFMs of all types should have access to the flow measuring unit for multiphase streams which should be used for investigations, MPFM prototype tests, as well as for metrological works (for example, MPFM calibration and testing) [21]. Our foreign colleagues frequently use the unit in Bergen (Norway) for this purpose. Until recently there were several flow measuring units that could be called 'multiphase' only in Tatarstan and Bashkiria inside Russia. In 2015 HMS Neftemash OJSC constructed the Research and Testing Flow Measuring Unit for Multiphase Streams (RTUMS) in Tyumen – the standard of the 1$^{st}$ rank multiphase stream flow rate. The unit was constructed within the joint project "Development and serial production of the metering unit for oil and gas produced in the fields finishing their production" that was implemented together by HMS Neftemash OJSC and FSBEI HPE Tyumen State University (RF Government Order No 218 dd. April 9$^{th}$, 2010). The photo of the unit section is given in Figure 9.

The unit is intended for presentation and storage of a unit of gas-liquid mixture mass rate within the limits from 0.2 to 100 t/h, as well as for transmission of its size to the 2$^{nd}$ rate working standards and working measurement instruments for gas-liquid mixtures mass rate. Exxsol D100 (oil imitation), pressed air (hydrocarbon gas imitation), and water are used as the components of the multiphase stream. See the unit details in[22,23]. The

**Figure 9.** Section of the RTUMS with storage tanks for operating mediums.

RTUMS automation system was developed on the basis of the NI PXIe – 8135 high-productive module platform (by National Instruments Company) specifically intended for construction of automated measuring and testing complexes. PXI unites the speed and productivity of the PCI bus bar and the advanced clocking and synchronization opportunities in the safe case of the CompactPCI module platform.

The RTUMS software was developed in the LabVIEW graphic programming environment, where the code is performed not with symbol commands line by line, but using graphic symbols and objects implementing functions similar to the functions of the procedures, constructed from the symbol commands in the others programming languages.

The client/server architecture is implemented. The lower level contains about 90 units of measuring transducers and actuating mechanisms. The sensor scanning period is 200 ms. Exchange is made according to the industry protocols Modbus and RS-232/422/485. The middle level contains multifunctional platform with input/output modules. Collection and preprocessing of technological data as well as management of controlling and locking mechanisms is performed at this level. The regulating PID-algorithm and Ethernet TCP/IP are applied. The top level is represented by Automated Work Station of an operator (AWS) where the information about all the technological objects is collected, stored, displayed in tables, graphs, mnemocircuits, and also archived. The SCADA-system is implemented using the LabVIEW DSC Module. In Figure 10 you can see the screenshot of the primary window mnemocircuit on the RTUMS operator's monitor.

When the computer mouse pointer is over the required object we can open the proper window.

The interface of the operator's work with the actuating mechanisms is given in Figure 11.

The automated control system for Research and Testing Unit for Multiphase Streams provides:

- operation of Research and Testing Unit in the manual and automated mode;
- forming of hydraulic circuit by opening and closing shut-off and control valves;
- reception, processing, storage and indication of measuring, signal and control information;
- reception, processing, indication and storage of information released to the verifiable Measuring Device (MD);

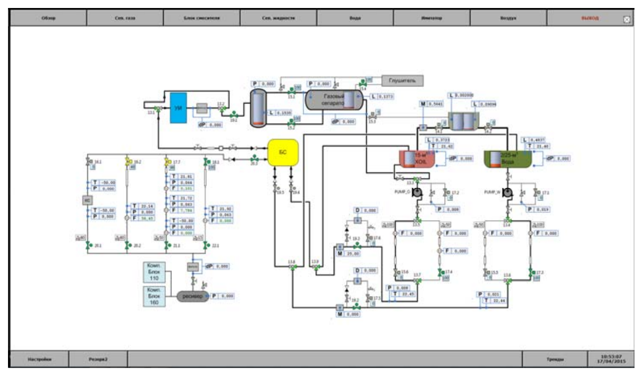

**Figure 10.** Screenshot of the RTUMS primary window mnemocircuit.

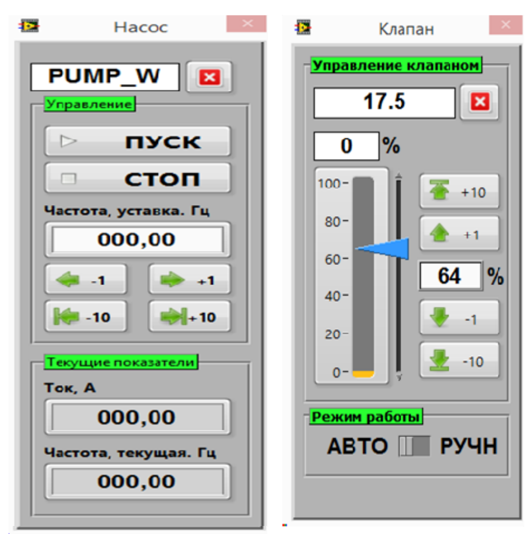


**Figure 11.** Valve and pump operation interface.

- forming and printing of set form protocols;
- synchronization of measurement information signals arriving from the verifiable MD and MD within the RTUMS;
- manual input of the conditional-constant parameter values from the control panel;
- manual and remote control of electric and pneumatic valve drives;
- forming of generalized alarm signal in case of deviance of the equipment operation; interpretation of the signal on-site, depending on the emergency specific features; activation of the alarm system if needed and alarm signal transmission to the telemechanics system.

## 4. Conclusion

Construction of the RTUMS as a source of standardized multiphase streams is a necessary but insufficient condition for development, creation and application of MFM in the engineering practice. Artificially created multiphase mixtures differ greatly from the natural multiphase systems such as formation gas and oil, and air solubility in water is much less than hydrocarbon gas solubility in liquid hydrocarbons[10]. Further, in[13] it is experimentally proved that MFM application is related with the range of problems that occur when the environmental temperature changes. Air temperature fluctuations can cause fluctuations of the MPFM measuring line and proper fluctuations of gas and liquid phase quantity.

To ensure the MPFM correct operation certain mobile units are to be used for periodic MPFM calibration in the field operation conditions. The mobile unit should be equipped with a high-performance separator as well as with high-precise flow meters – flow rate gages for gas and liquid phase with relative measuring error no more than 1%. The unit should be also equipped with a heat exchanger with stringent control of input stream heating to keep the separation temperature at the required level. The unit should be closely connected to the MPFM. In this case the same thermobaric parameters will be set in the separator and testing flow meter and the stream rates of gas and liquid phases flowing through the flow meter sequentially will be equal. Finally, the unit in the discharge gas line should be equipped with a measuring device for drop condensate entrainment with separation gas. That will ensure the safe control over the efficiency of the separator operation. The sequential operation of the multiphase flow meter and separation unit will allow determining the metrological characteristics of the multiphase flow meter within the limits of the mixture rate and volumetric gas content for the concrete well and making periodical calibration of the MPFM.

In the summary, we should mention that we need to create the infrastructure for development, manufacturing, and further application of the multiphase flow meters competitive to the foreign ones. Looking forward we should perform systematic fundamental and applied research in physics and hydrodynamics of gas-liquid streams. These studies are targeted to develop measuring procedures and metrological assurance of rate and quantity of oil-and-gas products.

## 5. Acknowledgement

The work was supported by the Ministry of Education and Science of the Russian Federation within the project by Government Order No 218 dd April 9th, 2010, by contract No 02. G 25.31.0020 JSC “HMS Neftemash” in collaboration with FSBEI HPE Tyumen State University.

## 6. References

1. Dyunin AK, Borschevsky YT, Yakovlev NA. Fundamentals of mechanics of multicomponent streams. Nivosibirsk. AS USSR, Siberia Department; 1965.
2. Mamaev VA, Odishariya GE. Experimental studies of true gas content and hydraulic resistance of gas-liquid flows in horizontal and inclined pipes. Proceedings of VNIIGAZ; 1967.
3. Nigmatulin RI. Dynamics of multiphase medium. Moscow; 1987.
4. Semenov NI, Tochigin AA. An analytical analysis of the laminar separated two-phase flow in inclined pipes. Journal of Engineering Physics and Thermophysics. 1961; 4(11):29–36.
5. Teletov SG. Problems on hydrodynamics of two-phase mixtures. MGU Bull. Series Mathematics-mechanics. 1958; 2.
6. Frankl FI. Energy equations for the motion of liquids with suspended solids. SAR USSR; 1955.
7. *Kapitza PL. Wave flow* of thin layers of a viscous fluid. Journal of Experimental and Theoretical Physics. *1948;* 1(19):3–35.
8. *Odisharia GE.* Some mechanisms of gas-liquid flows in pipes: Candidate Thesis in Engineering. Moscow; 1966.
9. Martinelly RC, Nelson DB. Trans ASME. 1948 ; 70 :695.

10. Vakulin AA, Shabarov AB. Diagnosis of the thermal physical parameters in the oil-gas technologies. Novosibirsk; 1998.
11. Gost R. 8.615-2005 state system for ensuring uniform measurements. Measurements of recovered oil and petroleum gas. General metrological and technical requirements.
12. Operational analysis of different types of multiphase flow meters at wells and well pad units and evaluation of their application in OJSC Gazprom. Scientific and research report of TyumenNIIgiprogaz Ltd. Tyumen; 2010.
13. Abramov GS, Barychev AV. Practical flow measurement in the oil industry. Moscow. OJSC VNIIOENG; 2002.
14. Haimo. [Cited 2015 Nov 8]. Available from: http://www.haimotech.com.
15. Roxar. [Cited 2015 Nov 8]. Available from: http://www.roxar.ru.
16. Agarcorp. [Cited 2015 Nov 8]. Available from: http://www.agarcorp.com.
17. Toski E, Hanssen BV, Smith D, Teuveni B. Evolution of multiphase streams measurement and their influence on the operational control. Oil-and-gas Review. 2003: 69–77.
18. Rymarenko KV. Multiphase flow metering: operational principles and experience through the example of Vx technology. Technics and Technologies. 2011: 28–35.
19. Weatherford. [Cited 2015 Nov 8]. Available from: http://www.weatherford.com.
20. MPM. [Cited 2015 Nov 8]. Available from: http://www.mpm-no.com.
21. Vakulin AA, Khamov EA. Experimental unit for multiphase streams research at different temperatures. TSU bull. 2010; 6:75–9.
22. Vakulin AA, Golubev EV, Kotlov VV, Lischuk AN, Nikulin SG, Filippova NB. A scientific-experimental unit for testing multiphase flows. Chemical and Petroleum Engineering. 2014; 12: 13–16.
23. Vakulin AA, Golubev EV, Kotlov VV, Lischuk AN, Nikulin SG, Filippova NB. Automation of scientific test unit for multiphase flows. Science and Business: Development Ways. 2014; 12(42):87–92.