Flow rate measurement of liquid and gas fractions in oil-water-gas flow by acoustic sensors

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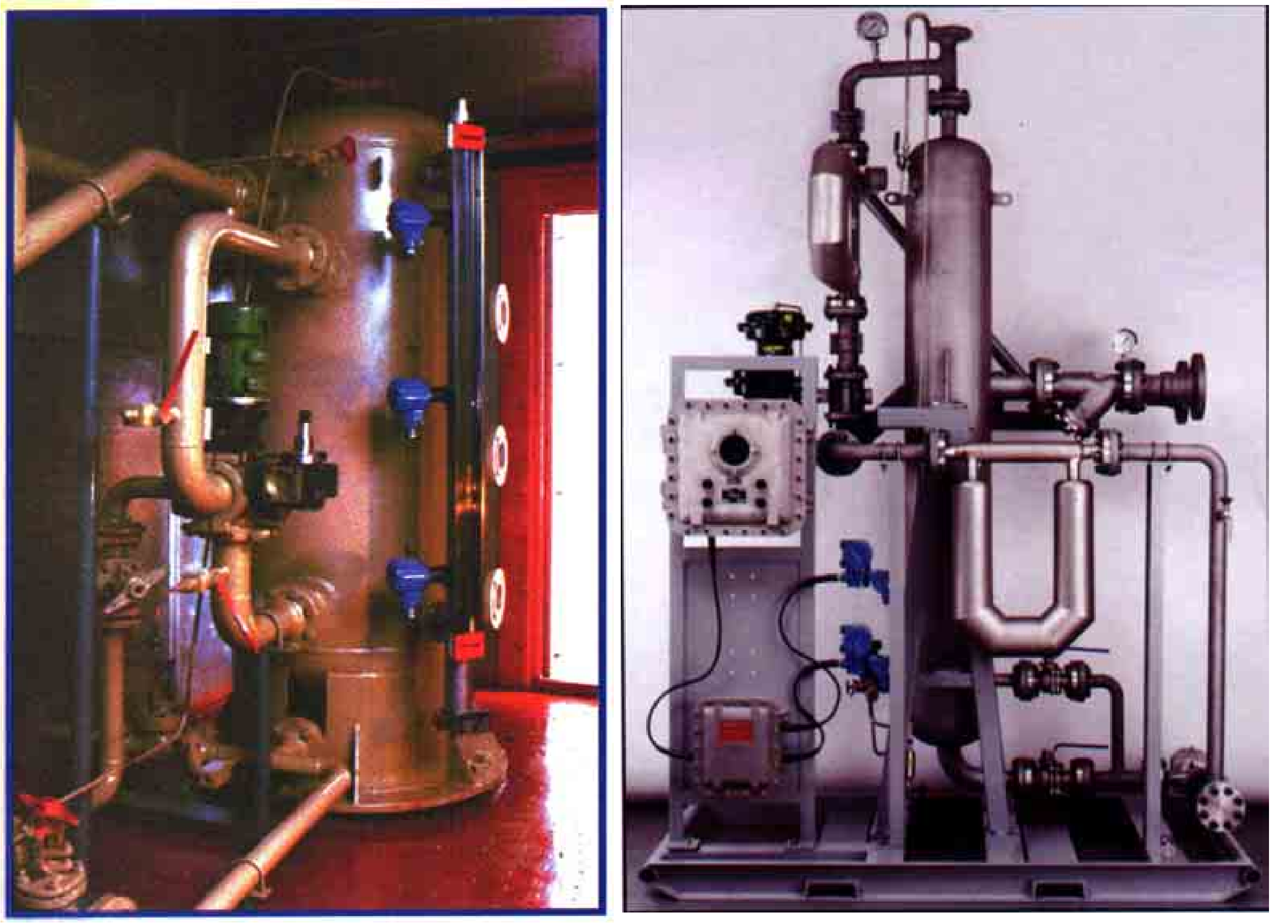
The output of oil wells consists of a multiphase mixture of crude oil, associated gas and water. This mixture contains salts, mechanical impurities; periodically, it may also contain the products occurred as a result of removal of tar-and-wax sediments from the outlet lines.

An accurate and simultaneous measurement of the flow rates of each component in the oil-water-gas mixture and its physical properties, along with the other real-time technological data, is essential to perform a proper oil production regime. Also, it is important to have data base for a long enough period of time. Such approach will allow for constructing the adequate mathematical models of the well operation and the entire pool, making the correct oil production forecast and properly determining the well efficiency. The reliable information on the output products at the well exploration stage is critical to the true evaluation of oil reserves, and consequently, to the correct decision-making on the investments in the given field.

Currently, there are many metering systems to determine the oil well rate. Their principle of operation is typically based on the preliminary separation of the associated free gas and liquid in separators of various types. Among these metering systems are "Sputnik-M" (Russia) and “Agrosy Technology” (USA) (Fig.1). The use of gas separators involves an increase in weight and size of metering units.



"Sputnik-M" (Russia) "Agrosy Technology" (USA)

Fig. 1. Multiphase metering systems with preliminary gas separation.

Over several decades the researches and engineers have been working on the development and deployment of the multiphase metering systems. The complexity of this problem is evident. This involves an optimal ratio of the resources spent on the solution of this task, price of the developed metering system and the obtained results in terms of accuracy of recorded parameters of a multiphase flow, reliability of the system itself as well as ease of its transportation, installation and operation.

The known research centers and companies dealing with this issue are Agar Corporation (USA), Christian Michaelson Research (Norway), Fluenta (Norway), Multiphase Measurement LLP (USA), National

Engineering Laboratory UK (Great Britain), Ohio State University (USA) and Southwest Research Institute (USA). More details on the current status of the problem can be obtained from the materials of the international conference «Multiphase Metering Technology Forum» arranged annually by Ohio State University in Houston (USA).

Various measuring techniques are employed to determine the flow rates of multiphase streams. These techniques are based on the recording of changes in different physical values of a sounded fluid: electric resistance, dielectric constant, acoustic impedance in the ultrasonic range, values of acoustic noises in the audible range, kinetic energy of liquid and gas phases, fluctuations in the mixture density, nuclear magnetic resonance, etc.

The multiphase metering systems utilize both a contact method of measurement with transducers of various types and design and a non-contact method, for example, gamma-ray technique is used to measure fluid.

It should be noted that although there exists great diversity of techniques for measuring the individual physical properties of the mixture, the common concept is used to determine the flow rates of the components present in the multiphase flow. This includes the following: the volumetric flow rate of the multiphase mixture is measured, then, volumetric gas content of the sounded fluid and volume concentration of water in the water-oil emulsion are determined.

Today the best-known multiphase flow meters are “Agar MPFM” Series (Fig.2) manufactured by Agar Corporation. These flow meters employ a selective principle of measuring the multiphase mixture parameters through the individual transducers placed in series along the hydraulic measuring channel. Pietro Fiorentini (Italy) and some other companies make the multiphase flow meters “Flow Sys/Top Flow” (Fig.3).

These flow meters measure the flow rates of liquid and gas phases by the alternating differential pressure method using a Venturi tube.

Fig. 2. Multiphase flow meter "Agar MPFM"

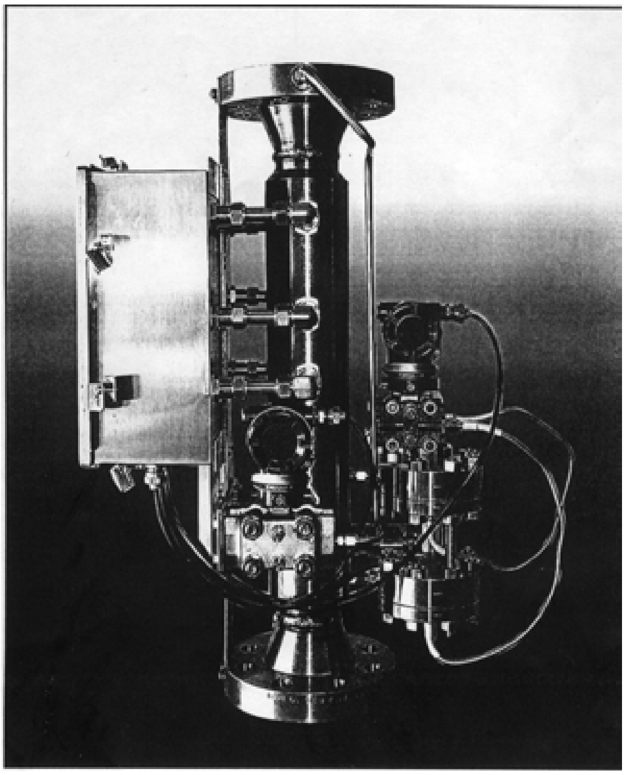


Fig. 3. Multiphase flow meter "Flow Sys/Top Flow"

However, the multiphase metering systems that are available at present have a number of drawbacks objectively incident to the used methods for measuring the fluid parameters and ways of their implementation in a specific design of metering systems. Methodically, among the drawbacks are high errors in measurement of the oil-water-gas mixture volume by using the alternating differential pressure method. In this case, it should be noted that there exists high probability of heavy oil fractions accumulation in the pressure measurement pulse tubes. The said flow meters utilize the electrical sounding technique to measure the volume concentration of water in emulsion. In such case, the readings of transmitters may be uncertain in the mean range of water concentration (40 to 70 %). This involves the inversion of emulsion with the oil- or water-continuous component. Among the disadvantages are the use of a nuclear (radioactive) source to measure the volumetric gas content, high hydraulic resistance of the measuring channel and considerable weight and size of these units.

We managed to eliminate or minimize the above-listed drawbacks through the use of ultrasonic monitoring of the oil-water-gas mixture. Over several years we performed a large scope of research work, both calculation-and-theoretical and experimental work and checked the prototype metering system on the test stands and directly in the CJSC LUKOIL-PERM oil fields.

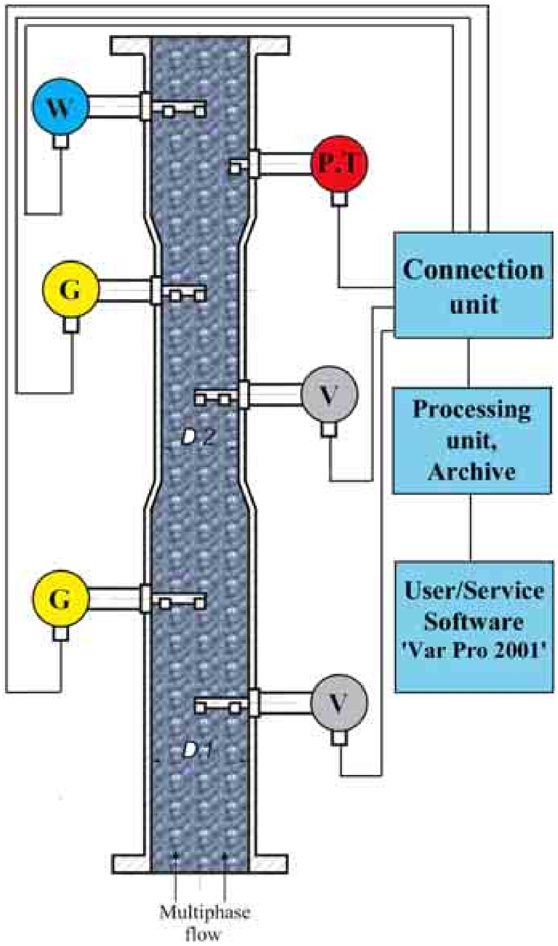


Fig. 4. The hydrodynamic measuring channel.

As a result, the ultrasonic transducers were developed to measure the oil-water-gas flow behavior: velocity, volumetric gas content and volume concentration of water in the mixture. These transducers use the optimal parameters of ultrasonic waves to determine a specific measurable value. A software product for each meter of the oil-water-gas mixture parameters as well as for the control of the meter operation and its diagnostics was created and checked experimentally.

To provide acoustic sounding of the multiphase fluid, the sensing elements of the transmitters, including the miniaturized transmitter and receiver of ultrasonic signals are immersed in a measured fluid that passes through a hydrodynamic measuring channel, 1,300 mm in height (Fig.4).

The hydrodynamic channel consists of two calibrated sections that are placed in series and have different areas of flow sections (the internal diameters of sections are 60 and 42.4 mm). The velocity and volumetric gas content transmitters are located in the wide and narrow sections of the measuring channel, in the hydrodynamic stabilization areas, with the sensing elements of each transmitter at the center and a peripheral part of the flow section of the channel. Such measuring technique eliminated the need to consider the gas phase slip velocity when calculating the volumetric flow rates of liquid and gas phases in the bubbly regime of the multiphase mixture flow. This method for calculating the phase flow rates is discussed in detail in Mr. V. Drobkov's paper «On phases volume flow evaluations in upward gas liquid flow» presented at this conference. The volume water concentration, temperature and pressure transmitters for the sounded fluid are installed at the outlet of the measuring channel.

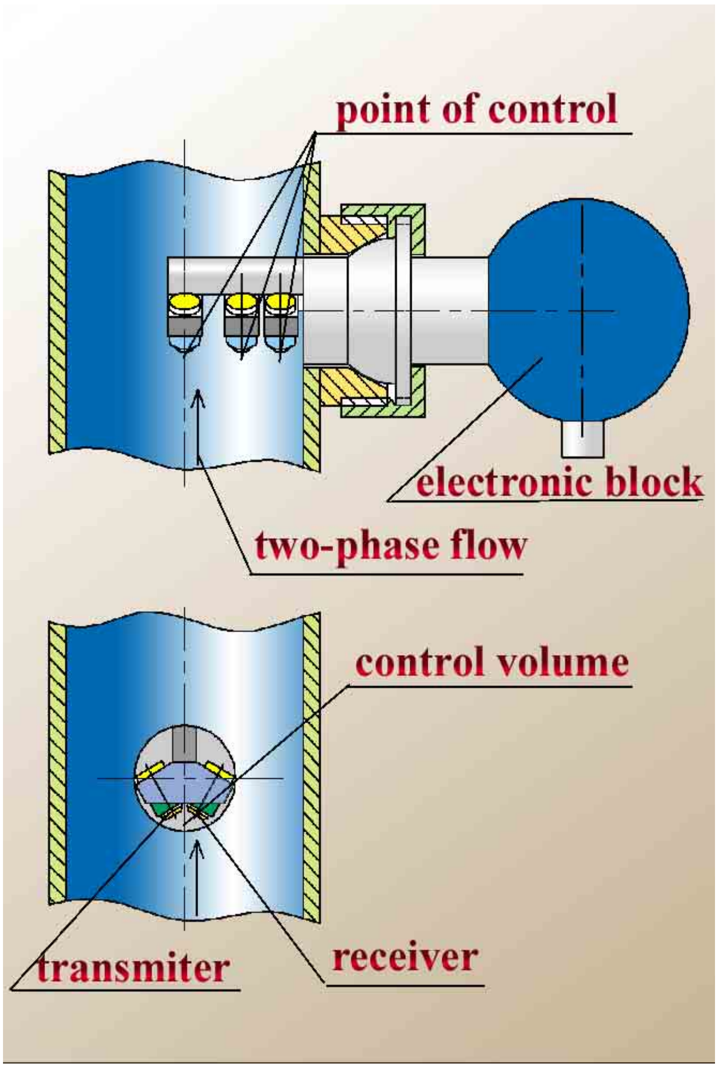


Fig. 5. Doppler

The velocity transmitters (Fig.5) employ the Doppler method for measuring this parameter. In these transmitters, velocity is converted into the Doppler shift in frequency of an ultrasonic signal reflected from the acoustic heterogeneity of the sounded fluid.

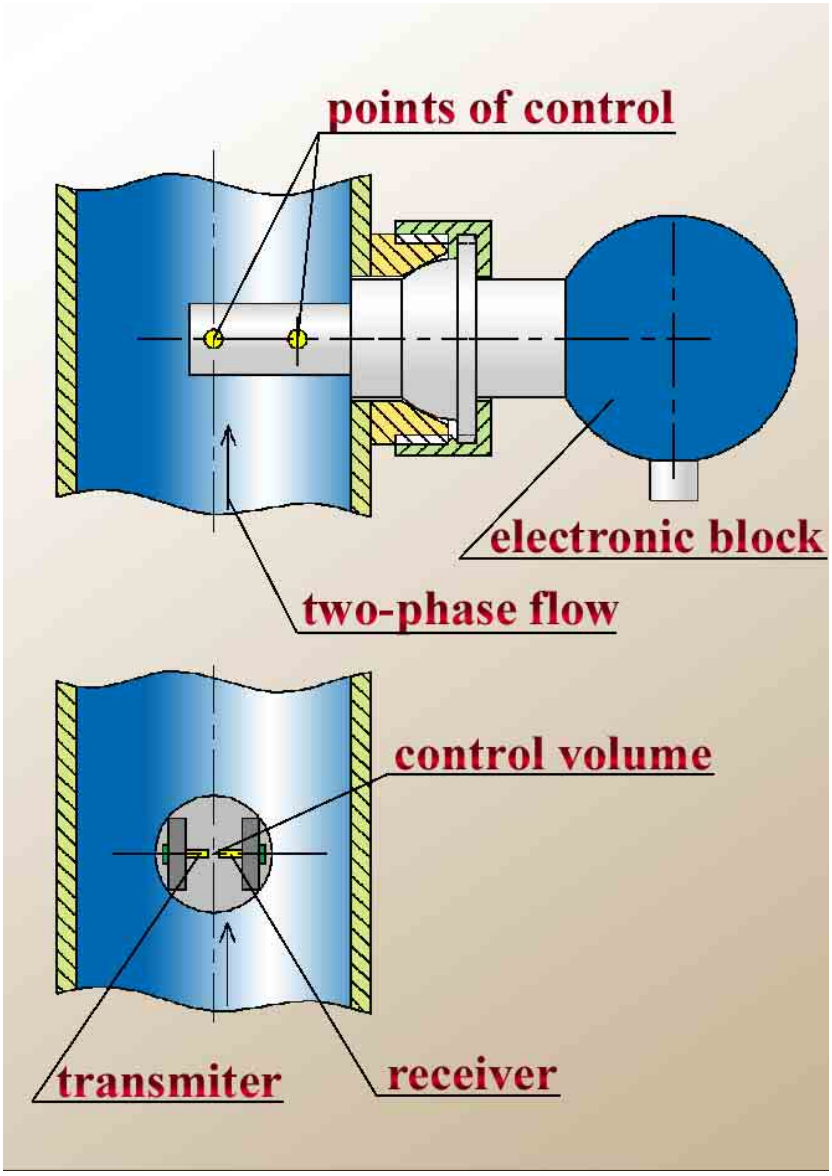


Fig. 6. Volume gas content sensor

The operation of volumetric gas content sensors (Fig.6) is based on determining a phase condition of the fluid in the controlled volume of the multiphase flow through the indication of acoustic conductance of the sounded fluid flowing in the gap between transmitter and receiver of ultrasonic waves.

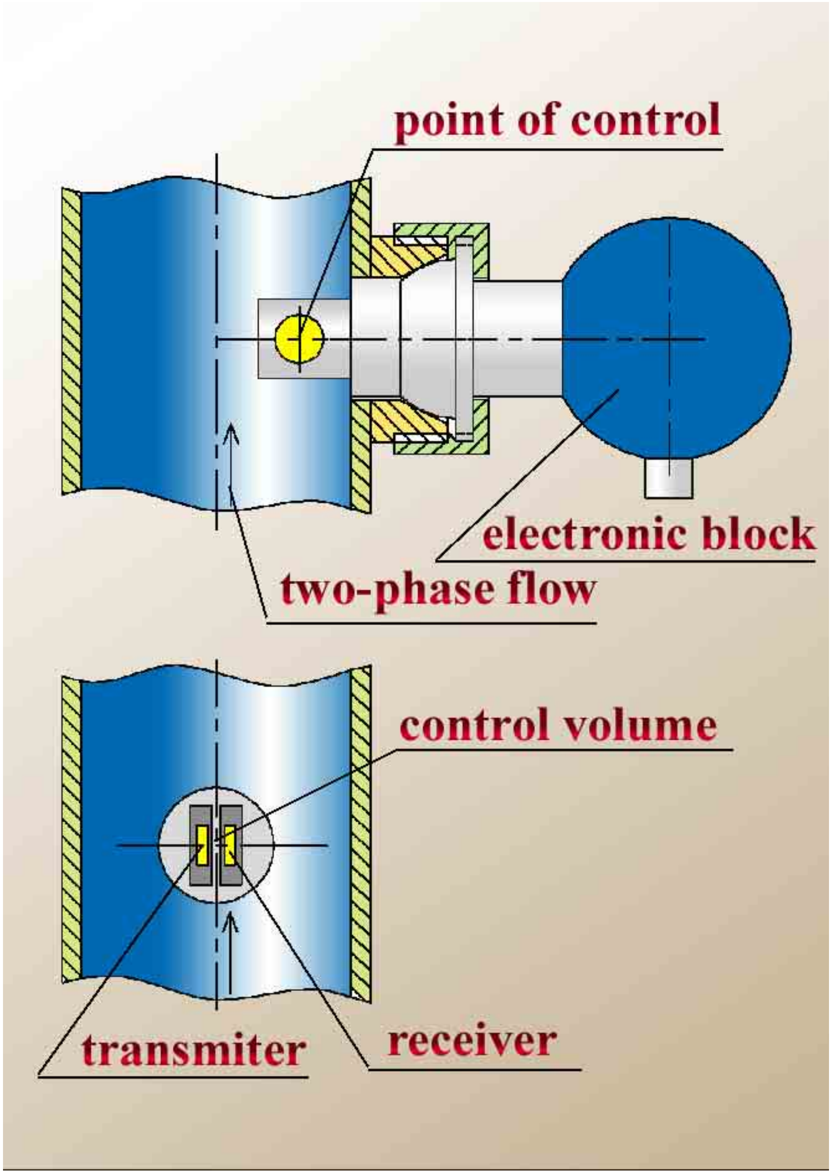


Fig. 7. Volume water concentration sensor

The operation of volume water concentration sensors (Fig.7) is based on measuring transit time of ultrasonic pulses via the gap between transmitter and receiver of acoustic signals, where the sounded oil-water emulsion is present. We obtained functional relationship between the volume concentration of water and ultrasonic pulse transit time in the oil-water emulsion. The sounding of the direct emulsion, which is a heterogeneous fluid with the oil inclusions of various shape and size, has to do with random occurrence of the emulsion components in the controlled volume of fluid. In view of this fact, a change in the acoustic impedance in the given volume also occurs at random. This is taken into consideration in the input signal processing algorithm. The value of volume concentration of water in the invert emulsion is determined by the amount of water globules in the volume element of the measured fluid. There is a relationship between water-cut of emulsion of this type and rate of ultrasonic pulse propagation through the controlled volume of the fluid. Program for computing the volume concentration of water automatically takes into account the type of emulsion and determines a signal processing algorithm with consideration for the temperature calibration characteristic of the measured fluid and concentration of mineral salts in water.

The flow parameter meters have the microprocessors fitted with an adequate program for processing the transmitter signals. The signals converted into digital codes are sent, via the RS-485 industrial interface and installation distributor, to the controller designed for the electric connection of primary transducers with the external computer, data accumulation and recording into a nonvolatile history file for further transfer of historical data on the external computer demand via the RS-232 channel. The accumulated data can be stored within one month. The computation operations and representation of the results in a graphical and tabular format are carried out in situ with a portable computer of «Notebook» type. It may be also possible to connect the external computer via radio-modem or line communication as well as to use a special reading device.

The external computer has a program for calculating the component flow rates of the oil-water-gas mixture («Var Pro 2000»). The program automatically considers a change in the multiphase flow regime: from bubbly to slug and annular. The program also includes correction of parameters on the fluid temperature, pressure and viscosity. This program provides high reliability of calculated data on the flow rates of oil-water-gas mixture, because it analyses and compares the initial data acquired from the transducers installed in various calibrated sections of the hydrodynamic channel. The program compares the values of component volumes passed through various sections of the measuring channel, which should be equal under normal operation of the «Ultraflow» system. In case the values are not equal, the program identifies a cause of deviation. To enhance reliable operation of the metering system, the «Var Pro 2000» program also provides control over the accuracy of measured parameter values by comparison with the obtained calculated data of these values.

The developed «Ultraflow» metering system was tested on a specially made flow loop (Fig.8). The test loop allows the implementation of various flow regimes of the multiphase mixture in the range of consumption gas content from 0 to 98 %. The liquid flow rate can be set in the range between 0 (bubbly regime) to 140 m^3 per day.

A multiphase mixture consisting of industrial oil, water with different salinity and gas (air) was used as the working fluid. This working fluid was selected based on the fact that the physical parameters of industrial oil, including ultrasound velocity, are close to the mean values of crude oil parameters.

The water-oil emulsion with a strictly specified ratio of volume concentration of water and oil was prepared in the bottom dump tank. The emulsion composition was controlled by the optical methods. The prepared emulsion was fed via a circulating pump to the gas/liquid mixer at the test stand. The flow rate of the fed liquid was determined by the reference mass flow meters with the measuring range of 0.1 – 1.0 t/hr and 0.3-5.6 t/hr and relative measurement accuracy of ± 0.1%.

The gas (air) flow rate was measured by the reference flow meters with the measuring range of 1-10 and 10-100 m^3/hr and measurement accuracy of 1.0 %, and in case of small gas flow rates – by using the roller

- turbo type flow meters with the relative measurement accuracy of ± 0.4%.

Data on measuring the volumetric flow rates of liquid and gas obtained from the reference flow meters were fed to the test stand computer.

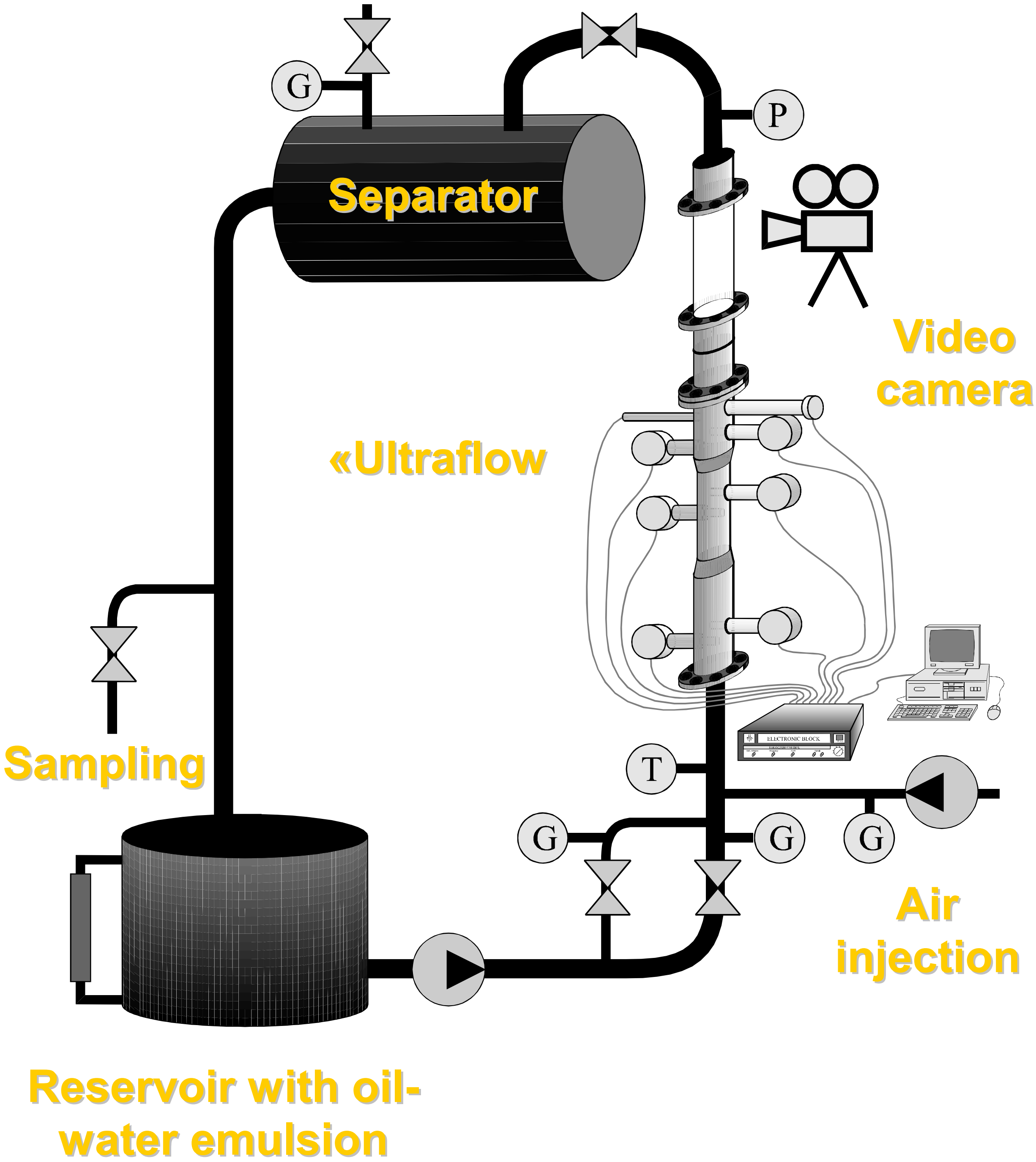
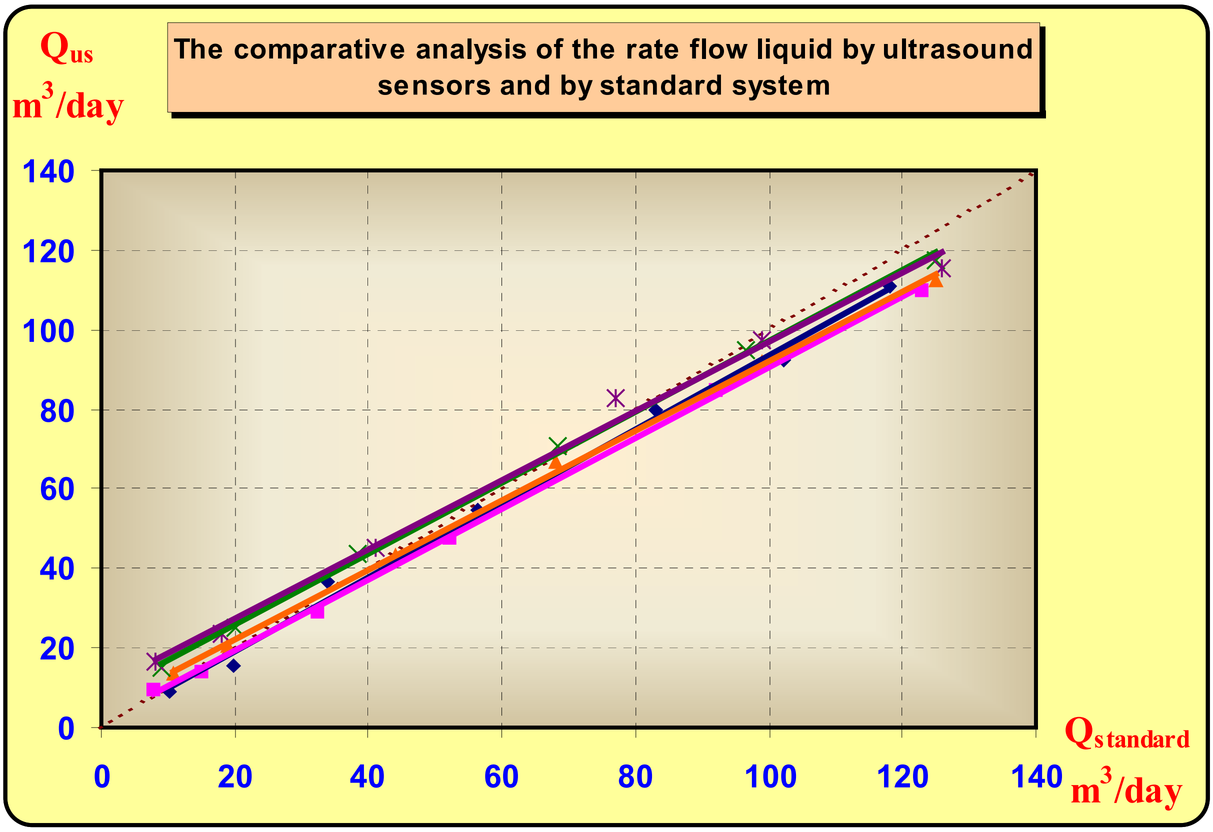


Fig. 8. The testing loop



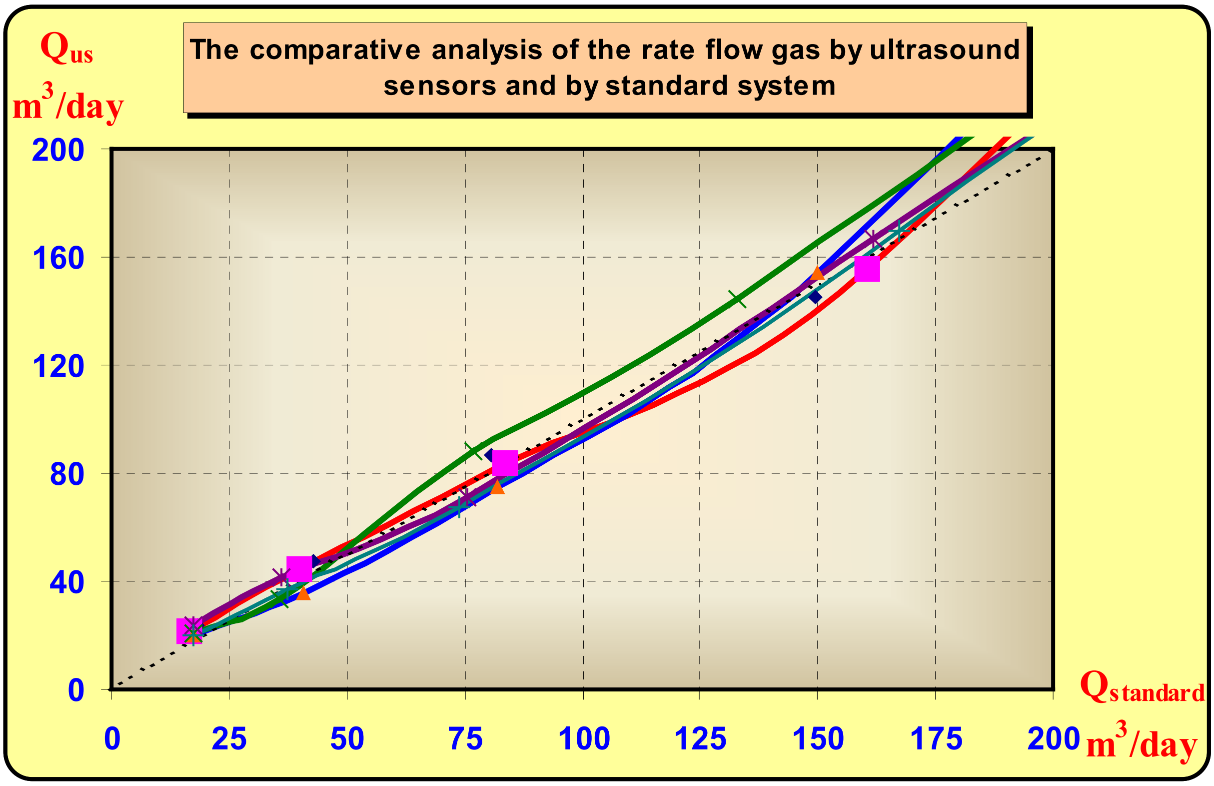


Fig. 9. The graphical views of the testing information.

After the gas/liquid mixer, the multiphase mixture was routed to the inlet of the hydrodynamic measuring channel of the «Ultraflow» system. The measurements were made at various values of volumetric flow rates of liquid and gas. The liquid flow range was between 0 and 140 m^3 per day. The gas flow range varied from 0 to 400 m^3 per day at the operating parameters of the measured fluid. Data on the volumetric flow rates of the components generated by the reference flow meters and «Ultraflow» system were transmitted to the test stand computer where the measurement results were compared. The obtained data were represented in tabular and graphical format. Example of the graphical data representation is illustrated in Fig. 9.

Fig. 10. Multiphase flow meter "Ultraflow" connected in series with measuring system "Sputnik".

To conduct the commercial tests, at the end of September, 2001 a prototype «Ultraflow» metering system was installed in the pipeline at the inlet of the «Sputnik» field metering system determining the oil well rates in the CJSC LUKOIL-PERM oil field (Fig.10). To date no faults were found with the operation of the metering complex. The accumulated information is periodically read out by the oil field specialists from storage of the controller of the metering system. The examples of measuring the oil well rates by using the «Ultraflow» system are presented in Fig. 11.

Fig.12 shows the random comparison of volumetric flow rates of liquid and volume concentration of water based on the readings of the «Ultraflow» system and readings of a regular liquid volume meter of the «Sputnik» system. The analysis of the given data shows that the ratio between the readings of the «Ultraflow» and «Sputnik» systems with respect to the volumetric flow rates of liquid is not stable. We can look at two cases here. In Case I, the readings of the field liquid meter are little higher that those of the «Ultraflow» system. This is typical for the majority of wells (well nos. 292, 574 and 595). In Case II, the readings of the «Ultraflow» system exceed the readings of this meter (well nos. 573 and 596). The higher readings of the «Sputnik» liquid meter are related to an incomplete separation of free gas in the separator of the «Sputnik» metering system. This occurs where the output of the oil well liquid product is high. The reason is that if the output is high, time required to accumulate liquid in a separation tank and accordingly, time required to remove the gas inclusions from the emulsion is reduced. Some amount of free gas (~10-15%) had no time to separate. It is common knowledge that the gas inclusion rise velocity is determined by its size and emulsion viscosity. The given conditions: separation time, size of gas inclusions and emulsion viscosity determine the amount of free gas reaching the measurement chamber of the «Sputnik» liquid meter. This results in an increase of its readings.

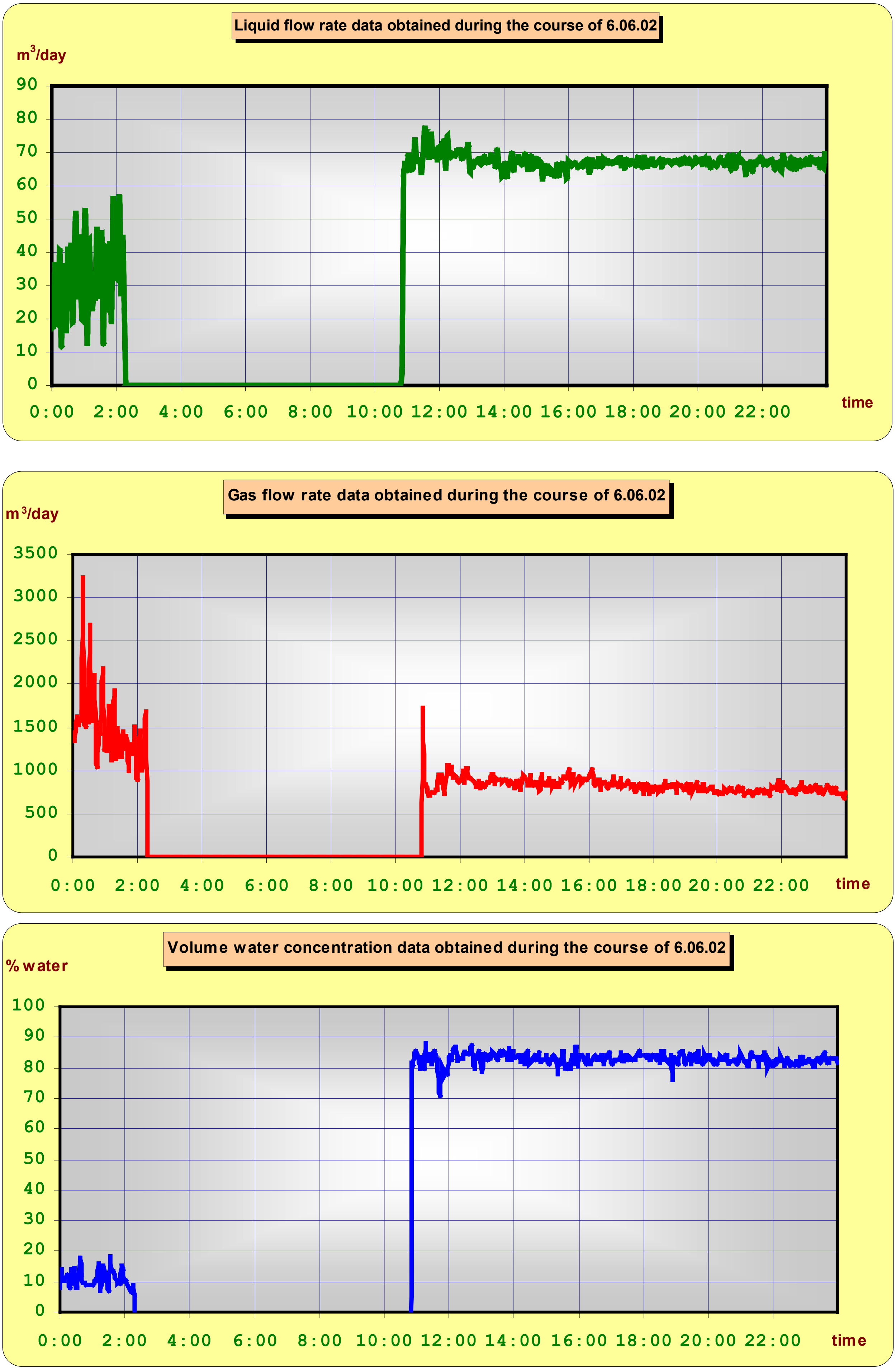
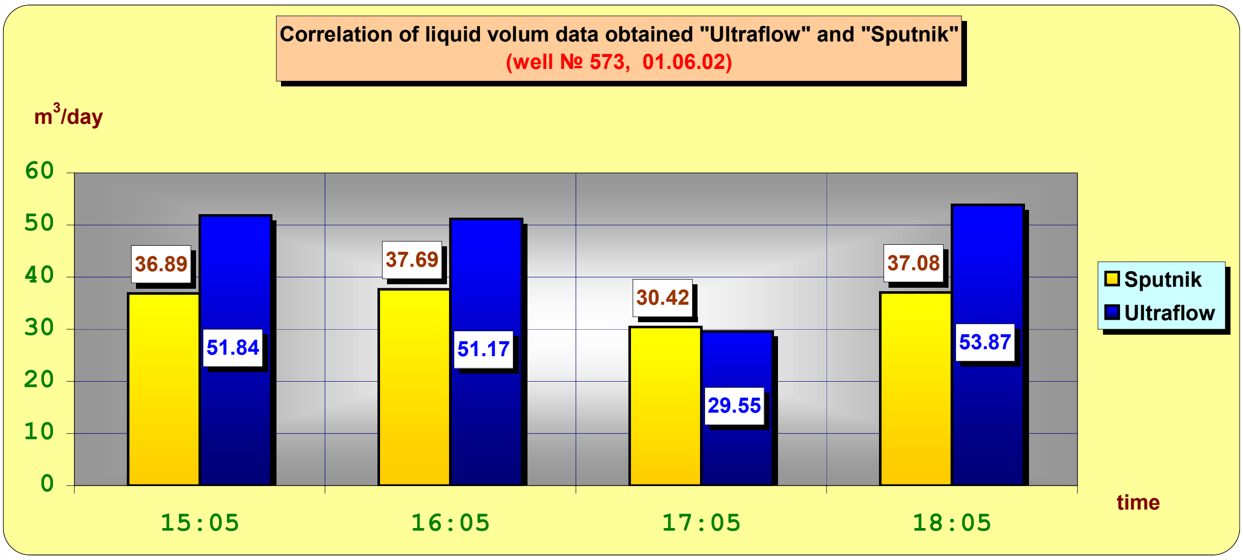
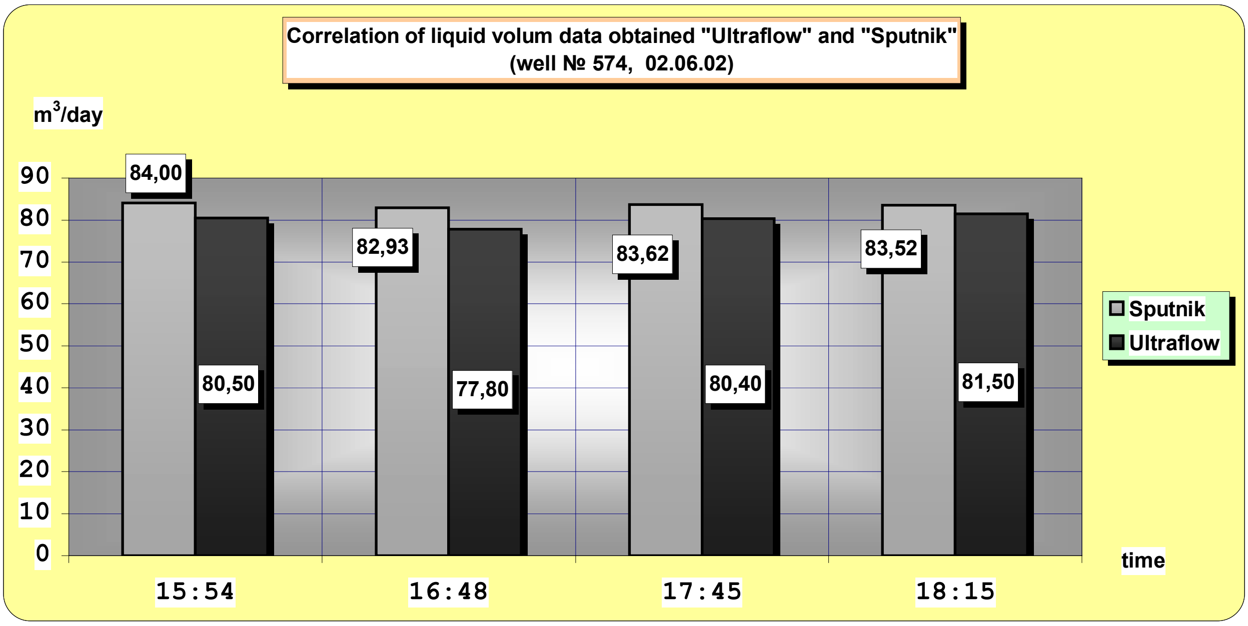


Fig. 11. Sample "Ultraflow" reading.





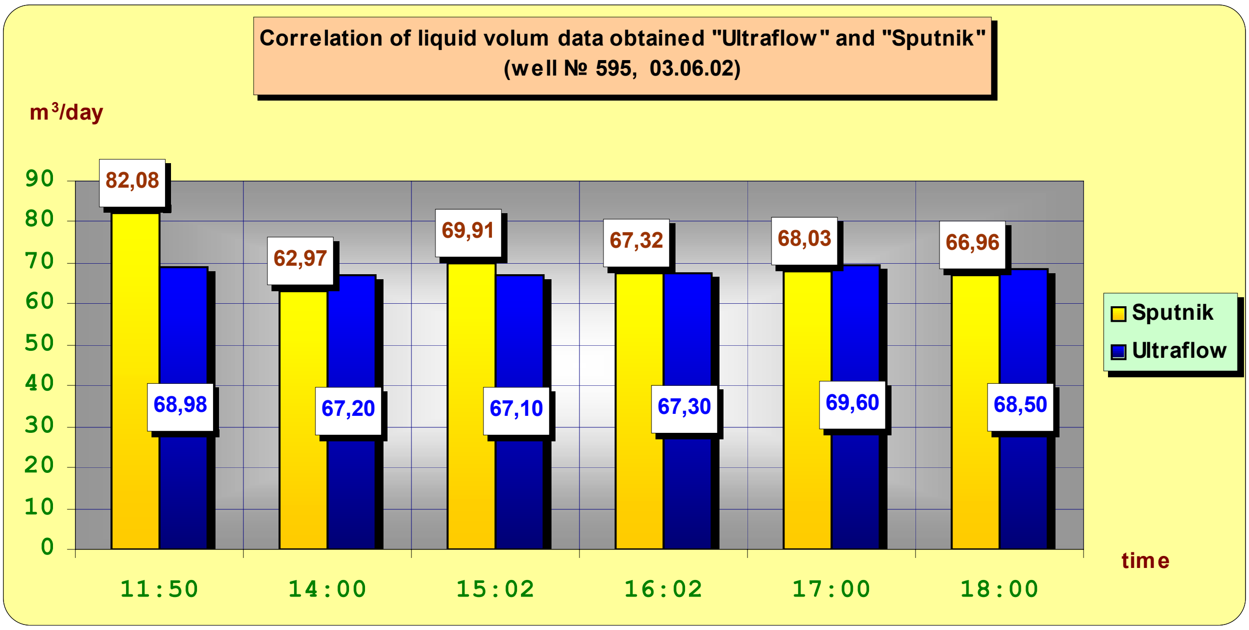


Fig. 12. Comparison of "Ultraflow" and "Sputnik" reading.

In Case II, the situation is opposite: a decrease in the liquid meter readings in relation to the readings of the «Ultraflow» system. This is caused by two cases. The first case involves the ingress of products, occurred as a result of removing the tar and wax sediments from the well pipes, into the measurement chamber of the liquid meter. This is supported by the fact that when taking measurement in well no. 573, a scraper was in operation. The second case requires a detailed explanation. When considering the gas separation process in the «Sputnik» separator, attention should be given to the value of a true volumetric gas content in the mixture entering the separator. When taking measurements in wells no. 573 and 596, this value was in the range from 73.1 to 82.3% according to the readings of the «Ultraflow» system. This corresponds to the transfer from the slug to annular flow regime in the feed pipeline. In this case, large volumes of gas separated from liquid enter the separator. This leads to an efficient separation of gas phase from liquid in the gravity separation section. Accordingly, gas is adequately separated in the accumulating zone of the separator, and a well-separated liquid is fed to the inlet of the measuring chamber of liquid meter. The difference between the viscosity values of water on which the meter-flow meters are calibrated and those of liquid products of oil wells results in a decrease of the readings of the «Sputnik» liquid meter.

As mentioned in the second part of the paper, there was no opportunity to compare the results of measuring free gas by using the «Sputnik» regular flow meter and «Ultraflow» metering system. However, if we compare the dynamics of changes in gas and liquid flow rates, it might be pointed out that the ratio of these flow rates is fairly stable. This is good indirect evidence that the readings of the «Ultraflow» metering system are reliable.

CONCLUSION

1. The correctness of technical solutions implemented in the «Ultraflow» metering system to determine the flow rates of the multiphase stream by local acoustic sounding of the fluid has been confirmed.
2. The operability of the «Ultraflow» metering system has been confirmed under trial operation within the entire specified ranges for measuring the oil-water-gas mixture parameters:
   - Gas content (the range of measured volumetric gas content was from 0 to 98 %);
   - Water-cut (the range was between 0 and 100 %),
   - The range of measured liquid flow rates varied from 35 to 90 m^3 per day,
   - The range of measured gas flow rates varied from 320 to 3,600 nm^3 per day.
   - The obtained data testify that the «Ultraflow» system provides a stable measurement of the well rates within the entire spectrum of flow regimes of the oil-water-gas mixture without having first to separate out free gas.
3. The developed signal processing algorithms adequately reflect the composition of the oil-water-gas mixture and the actual fluid flow processes in the outlet pipelines of the oil production wells.
4. The design features of the «Ultraflow» metering system allow its use to measure the output of oil well products with high viscosity.