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MECHANICAL MEASUREMENTS

THE METROLOGICAL BACKUP FOR MEASUREMENTS OF THE FLOW RATE AND VOLUME OF LIQUIDS AND GASES IN RUSSIA*

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Brief historical information on the development of measurements of the flow rate and volume of liquids and gases in Russia is presented. The metrological characteristics of the State Standards and the main standard documents are given. The future prospects for the development of the standard base of the Mendeleev All-Russia Research Institute of Metrology are considered.

Key words: *flow rate, liquid and gas volume, standards, standard documents, metrological backup.*

Brief historical information. In the last quarter of the 19th century, considerable economic changes occurred in Russia. With the development of new areas of industry, in addition to traditional goods (grain etc.), raw materials, in particular, petroleum, petroleum products and gas became important objects of buying and selling. For operations between enterprises-suppliers (sellers) and consumers (buyers), correct metering (measurement of quantity and quality) began to play an important role, because the cost of goods depends on this.

In reports to the Minister of Finance, D. I. Mendeleev repeatedly emphasized that electrical, water and gas meters by means of which multimillion transactions occur, and the testing and checking of such instruments are of paramount importance for the State.

The gas-meter division of the Main Board of Weights and Measures was equipped by Inspector K. N. Egorov. The idea of an arrangement for checking gas meters was proposed by Mendeleev. The original instrument he developed was of higher accuracy than that previously used to determine volume of gas. Such an instrument was not available in any of the checking establishments of the world. The checking and testing of gas meters began in Russia on March 1, 1905.

The development of city water supplies in Russia at the end of the 19th century, accompanied by the use of water meters, made it necessary to organize the checking of such instruments. The water-metering division was run by F. P. Zavadskii. The initial equipment of the department enabled water meters to be checked for flow rates not exceeding 20 m^3/h. The time rules for checking them were laid down on December 20, 1901. Of the order of 30000 water meters of about ten different systems were used in Russia in 1903.

During the Soviet period up to the middle of the 1970s, work to develop the metrological backup for measurements of flow rate and volume of liquids and gases was carried out at the Mendeleev All-Union Research Institute of Metrology

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(VNIIM), under the direction of Professor P. P. Kremlevskii. By that time, the All-Union Research Institute of Flow Metering (VNIIR) had been set up, which played the role of the leading organization of the State Standard of the USSR in this area of measurement, but the VNIIM has continued operations in the area of flow metering to the present day.

The State Standards and main standard documents. The existing State Standards of Russia in the field of liquid and gas flow-rate and volume measurements, the metrological characteristics of which are given below, have been developed and stored at the VNIIR (here RMSD is the root mean square deviation and USE is the uneliminated systematic error).

State primary standard of the unit of liquid mass flow rate:	
Range of reproduced flow rates	2.5–250.0 tons/h
RMSD	$1 \cdot 10^{-4}$
USE	$1.3 \cdot 10^{-4}$
State primary standard of the unit of liquid volume flow rate:	
Range of reproduced flow rates	0.03–250.0 m^3/h
RMSD	$1 \cdot 10^{-4}$
USE	$3 \cdot 10^{-4}$
State special standard of the unit of water volume flow rate:	
Range of reproduced flow rates	0.01–40.0 m^3/h
RMSD	$1 \cdot 10^{-4}$
USE	$5 \cdot 10^{-4}$
Extended uncertainty	$1 \cdot 10^{-3}$
State special standard of the unit of petroleum product volume flow rate:	
Range of reproduced flow rates	$2.8 \cdot 10^{-4}$–$2.8 \cdot 10^{-3}$ m^3/sec
RMSD	$3 \cdot 10^{-4}$
USE	$5 \cdot 10^{-4}$

An important component when determining the “net” amount of petroleum is its moisture content. Instruments for measuring moisture content are checked using standard liquids, which are produced to a special standard.

State special standard of the unit of volume moisture content of petroleum and petroleum products:	
Range of values of moisture content	0.05–60.0% by volume
RMSD	$2.3 \cdot 10^{-3}$% by volume
USE	$6.5 \cdot 10^{-2}$% by volume

The standard documents on metering petroleum are based on the standards of the Russian Federation and the procedures of the Russian Technical Regulation Institute, which are harmonized with the standards of the ISO and the American ASTM and API, and some of the standards are interstate standards of the Eurasian Council on standardization, metrology and certification.

Interstate standards have been approved [1] and recommendations on metrology can be found in [2].

At the present time, there are a number of documents in the Russian Federation, which regulate measurements of quantity of petroleum, and which define the “net” mass of petroleum – the mass of petroleum after deducting the mass of ballast. The ballast is assumed to be water, sodium chloride and mechanical impurities.

Foreign standard documents specify the measurement of the volume of petroleum, reduced to standard conditions, the “dry” volume of petroleum – the volume of petroleum after deducting water and sediment, and also the measurement of the mass of petroleum and the “dry” mass of petroleum.

In the period from 2002 to 2005, work was carried out at the VNIIR to improve the state standard of the mass flow rate of a gas, and a new *State standard of volume and mass flow rate of a gas* was produced.

The standard is a set of three standard arrangements, namely, initial, with a set of standard critical nozzles, and a set of standard critical micronozzles. The overall range of flow rates of the standard are $3\cdot10^{-3}$–$1\cdot10^{4}$ m^3/h, ($3.6\cdot10^{-3}$–$1.2\cdot10^{4}$ kg/h), and the root mean square deviation is $3.5\cdot10^{-4}$ and the uneliminated systematic error is $4\cdot10^{-4}$.

Work at the VNIIM on the Metrological Backup of Measurements of Flow Rate and Volume of Liquids and Gases

Standard equipment and checking instruments for measuring the flow rate and volumes of liquids and gases have been developed at the institute.

Below we give a brief description of the measuring instruments in this equipment, their main metrological characteristics and their area of application.

Measurements of the flow rate and volume of a liquid. The working standard of the unit of volume and mass flow rate of water (RE VT 6-98) contains the GDS 80/20R, ER-50 and ER-150 hydrodynamic measuring equipment.

The GDS 80/20R equipment includes a closed hydrodynamic tube with flowmeter sections, a system for setting the flow rate of water, and a panel for controlling, recording and processing the results of measurements.

The ER-50 equipment is designed to test, check, and calibrate water meters with conventional diameters D_c = 10–50 mm and a range of water flow rates of 0.012–40 m^3/h. It contains standard electromagnetic flowmeters made by Krohne of Germany. The limits of the permissible relative error in measuring flow rate using this equipment is ±0.3%. For periodic checking of standard flowmeters, we have standard measures of capacity (V_1 = 0.1 m^3 and V_2 = 0.5 m^3) with limits of the permissible relative error of ±0.1%.

Limits of the permissible relative error of the equipment for measuring volume using standard flowmeters:	
in the flow-rate range 0.1–40 m^3/h	±0.3%
in the flow-rate range 0.012–0.1 m^3/h	±0.5%
when measuring volume using standard measures of capacity	±0.1%
Water temperature when checking meters	15–90°C
Number of simultaneously installed meters:	
for D_c = 10, 15, 20 mm	10
for D_c = 25, 32, 40, 50 mm	6

The ER-150 equipment is designed for testing, checking, and calibrating water meters with conventional diameters of D_c of 50–200 mm in the water flow-rate range 2–320 m^3/h. It contains standard electromagnetic flowmeters made by Krohne. The limits of the permissible relative error in measuring flow rate are ±0.3%.

For the periodic checking of standard flowmeters, the standard measure of capacity (V_1 = 2 m^3) contained in it, the limits of the permissible relative error of which is ±0.1%, and a standard instrument for measuring mass with an absolute error of 0.1 kg in the range 2–2000 kg are used.

Limits of the permissible relative error of the equipment for measuring volume in the flow-rate range 2.0–320 m^3/h:	
standard flow meters	±0.3%
standard measure of capacity	±0.1%
standard instrument for measuring mass	±0.05%
Temperature of the water when checking meters	15–90°C
Number of simultaneously installed meters:	
for D_c = 50–100 mm	4
for D_c = 150, 200 mm	2

Equipment for checking apartment water meters is designed to check water meters with conventional channel diameters of 15 and 20 mm, and with a nominal flow rate of up to 3 m^3/h. The measurement procedure involves determining the mass of the liquid flowing through the meter and then calculating the volume, taking the water temperature into account.

Principal characteristics of the equipment:

Range of water flow rates	0.004–3 m^3/h
Limits of permissible relative error when measuring volume	±0.3%
Number of simultaneously installed meters with D_c = 15 mm	10
Power consumption	1.5 kW

SVP-150-5 platform scales (150 kg, error 50–60 g) are used to measure mass. On the platform of the scales there is a tank in which water which has passed through the meter is collected (the meters are placed in succession in the two measuring parts).

Two MP-400 electromagnetic flowmeters (D_c = 20 mm and 10 mm) made by EESA of the Czech Republic are used as flowmeters.

The portable UPP-3000 checking equipment is used to check liquid meters (light petroleum products) at the point of use and consists of a cylindrical graduated measuring tank equipped with systems for filling and decanting petroleum products and thermometers set up on a biaxial trailer. The nominal capacity is 3000 dm^3. The limits of the permissible relative error when measuring volume using the numbered scale divisions is ±0.05%. The mass of the measuring tank is 850 kg, the scale has 30 divisions, and the value of each scale division is 1 dm^3 (20 divisions down from the nominal capacity and 10 upwards).

The trailer with the tank can be transported by a Gazel truck.

The GDS-400/05 equipment is used to check ultrasonic sewage meters and is a closed hydrodynamic tube with an open channel (a gutter) of circular cross section with a diameter of 400 mm and a length of 6 m. The average speed of the water flow in the range of 0.05–0.5 m/sec is reproduced in the channel. The primary ultrasonic transducer of the measuring instrument being checked is placed at the bottom of the channel. A flow of liquid is produced using a centrifugal pump with a variable speed and an output of 320 m^3/h. The flow rate of the water is measured by an electromagnetic flow meter with an error of ±0.3%.

The equipment is supplied with three water-measuring glasses with measuring lines for measuring the water level in the channel. The error in measuring level is ±1 mm.

The GDS-400/05 equipment is used to check ultrasonic sewage flowmeters together with the URG-6000 equipment.

The URG-6000 level-measuring equipment is designed to reproduce the level of a liquid and to test floating and hydrostatic level meters. Its operating principle is based on a measurement of the liquid level in a vertically placed section of a pipeline. The liquid level can be reproduced by two methods: a change in the level in the pipeline itself and a change in the depth of immersion of the primary level transducer (with the container) in the pipeline completely filled with liquid.

The equipment consists of the following main systems: filling (emptying) with the liquid, immersion of the primary level transducer in the equipment, measurement of the level of immersion of this transducer and measurement of the liquid level in the equipment.

Basic characteristics of the equipment:

Range of reproduced level	0–6000 mm
Limits of the permissible absolute error when measuring liquid level	±1 mm
Limits of the permissible absolute error when measuring the displacement (level) of the container	±1 mm
Discreteness of the reading of the container displacement	±1 mm
Internal diameter of the pipeline	370 mm
Power consumption	500 W

The URG-6000 level-measuring equipment was introduced into the State Register of Measuring Instruments of the Russian Federation (No. 29565-05) and is included in the existing State Checking System [3].

Measurements of thermal power and quantity of heat in hot-water supply systems. Measurements of thermal power and quantity of thermal heat in hot-water supply systems touches directly on the region of liquid-flow measurements, since the water flow rate is the most important parameter required to determine the thermal power and quantity of heat.

Using the ER-50 and ER-150 equipment, a *working standard of the units of thermal power and the quantity of heat (RE VT 9-98)* was constructed at the Mendeleev Institute, designed to test and check heat meters and to transmit the dimensions of the unit of measurement by checked measuring instruments of lower accuracy, and consists of the ER-50T and ER-150T hydrodynamic measuring instruments and the TVP-6 liquid thermostat.

Metrological characteristics of the standard:

Range of reproduced values:	
thermal power	0.001–10 MW
quantity of heat per hour	0.004–40 GJ
Range of variation of the water temperature	20–90°C
Confidence limits of the error for a confidence coefficient of 0.99	0.2–0.5%

A standard has been developed: GSI. The State Checking System for Instruments for Measuring Quantity of Heat in Apartment Hot-Water Systems. A special standard is included in the system, which consists of two interconnected standard instruments developed at the VNIIM and at SNIIM–Rostest-Moscow.

The State special standard includes the following:

channel standard equipment (VNIIM), which included automated systems:

• for specifying and measuring the flow rate of the heat carrier,

• for specifying and measuring the temperature of the heat carrier and keeping it at a constant temperature,

• a system for weighing the heat carrier,

• instruments for collecting and processing the measured data;

standard calorimeter equipment (SNIIM–Rostest-Moscow), containing the following:

• a heat exchanger,

• an automated system for specifying and measuring the heat flux, the flow rate and the temperature of the heat carrier,

• a system for collecting and processing the measurement data;

• a comparator, i.e., a set of standard heat meters.

The standard channel equipment reproduces the unit of heat flux as the result of indirect measurements over a wide range of values of the physical quantity ($2 \cdot 10^{-4}$–25 MW). The standard calorimeter equipment gives a direct reproduction of the unit of quantity of heat by introducing into the system a normalized electric power in a narrow range of values of the physical quantity ($2 \cdot 10^{-4}$–0.1 MW).

The combined use of both systems as the highest section of the checking scheme enables high reliability in reproducing the unit of measurement to be achieved. These instruments mutually supplement one another, since comparisons can be carried out periodically to check the stability of one part using another, employing different methods of reproducing the unit.

The dimensions of the unit of quantity of heat is transferred along the checking scheme in the heat-flux range $2 \cdot 10^{-4}$–$2.5 \cdot 10^{2}$ MW.

The State checking scheme is both a complex method of checking heat meters, and a component-by-component method; it covers the transfer of the dimensions of the unit of quantity of heat by single and composite single-channel and multichannel heat meters of classes C, B, and A (the terminology corresponds to the EN 1434 European standard "Heat Meters") [4].

The State special standard provides for the reproduction and storage of the unit in the range of heat fluxes of $2 \cdot 10^{-4}$–25 MW with a relative root mean square error of the result of measurement of $S_{\bar{x},\mathrm{r}} = 9 \cdot 10^{-4}$ and relative values of the uneliminated systematic error $\Theta_\mathrm{r} = 7.5 \cdot 10^{-4}$ and in the range of heat fluxes of $2 \cdot 10^{-4}$–0.1 MW with a relative root mean square error of the results of measurements $S_{\bar{x},\mathrm{r}} = 1 \cdot 10^{-3}$ and with a relative value of the uneliminated systematic error $\Theta_\mathrm{r} = 1 \cdot 10^{-3}$.

Measurements of the flow rate and volume of a gas. Measuring instruments based on different principles are used for these purposes at the present time. The most widely used instruments are the following:

• constricting devices (the variable pressure drop method);

• turbine, rotor, and compartment flowmeters (the tachometer method);
• single-radial and multiradial notch flowmeters (the ultrasonic method);
• vortex flowmeters (the "Karman street" method);
• mass flowmeters (the thermoanemometer method); and
• flowmeters based on time recording of thermal markers, etc.

Methods of measurement are continually being developed which improve the measuring instruments and extend their inventory.

Work in this area has been intensively carried out at the VNIIM since the beginning of the 1990s. As a result of such efforts, a range of standard equipment and checking instruments for measuring flow rate and gas volume has been developed, based on different measurement principles, covering the whole range of measurements required by industry, power engineering and science.

Below we give a brief description of the measuring instruments which form part of this system, and we describe their main metrological characteristics and area of application.

The REVT 7-98 working standard of the unit of the volume flow rate of air (gas) has a range of variation of the flow rate of 2–130,000 m^3/h and limits of the permissible relative measurement error of ±0.3%. It includes the ADS 100/100M and ADS 700/100 equipment.

The ADS 100/100M equipment with a range of reproduction of the unit of gas flow rate of 2–1000 m^3/h enables one to transfer the dimensions of the unit of flow rate of a measuring instrument with a channel diameter of up to 200 mm.

The measurement procedure involves calculating the volume flow rate of air (gas) under a pressure drop at the input and output of a Vitashinskii nozzle (VNIIM). The pressure drop is measured by a standard micromanometer of accuracy grade 0.02. The volume flow rate of a gas through the nozzle is proportional to the square root of the values of the pressure drop at the nozzle. There are two changeable nozzles with exit diameters of 22 mm and 80 mm in the equipment.

A flow of air is produced by a compressor operating on suction (the measuring part is at the compressor input). The error in measuring the volume and flow rate of air is ±0.3% (all the calculations are carried out on a computer). The equipment contains a digital barometer and a thermal hygrometer to take the effect of the external conditions into account.

The ADS 700/100 equipment enables gas flow rate to be reproduced in the range 1000–130,000 m^3/h. The diameter of the equal-velocity zone is 700 mm. The measurement procedure is the same as for the ADS 100/100M. In addition to a standard micromanometer with an accuracy grade of 0.02, the equipment also contains a standard Pitot tube, which can be used to transfer the dimensions of the unit of measurement of both gas flow rate and its rate of flow.

However, because of the structural features in the measuring part of this equipment, it is impossible to insert a total-flow meter or a flow-rate meter in the equipment. Using the ADS 100/100M and the ADS 700/100, one can check various instruments for measuring the flow rate and volume of a gas, but the tests occur in air at atmospheric pressure, which is permitted by the existing standard documentation. Due to the fact that the calibration characteristic depends on the composition of the gas, thermoanemometer flowmeters can only be tested in air when it is possible to recalculate the result to the actual experimental conditions.

The UERG-100 equipment is designed to test and check instruments for measuring the flow rate and volume of a gas in the 0.012–6 m^3/h range, and the limits of its permissible relative error are ±0.1%. Its operating principle is based on the displacement of air from a gas measuring tank by oil and a measurement of the time it takes to fill up to a certain level. Knowing the time taken for the tank to fill up and the level of the oil one can determine the flow rate and volume of gas at its exit.

The prospects for the development of a standard base. The most recent promising development of a standard base at the Mendeleev Institute is the construction of equipment for calibrating and checking gas meters and water meters of large diameter and high capacity.

The equipment for calibrating and checking gas meters is intended for pipelines 200–500 mm in diameter and with a gas flow rate of greater than 10000 m^3/h, with an error of less than 0.3%. The velocity-area method is employed in the equipment. A laser Doppler anemometer is used to measure velocity fields.

The equipment for calibrating and checking water meters is designed for use with pipelines having a diameter of 200–600 mm and a water flow rate of greater than 300–4000 m^3/h, with an error of less than 0.01%. This equipment is based on the gravimetric principle of specifying the liquid flow rate. The liquid from the storage reservoir is directed along pipelines into a distributor, which is situated in an underground room at a depth of 45 m. The measuring lines and weights for measuring the mass and volume of the liquid are placed further away. The liquid from the measuring lines is fed into a collecting tank and is then pumped back into the storage reservoir. The height difference of 45 m between the storage reservoir and the distributor enables the flow rate in the measuring lines to be sustained with an error of 0.01%, which is better than the root mean square deviation of the standard [5]. The measurement of the values of the flow rate and volume or mass themselves reduces solely to measuring the time and mass of the liquid (the time taken for the gravimetric tank to fill). Hence, by measuring the mass and time, one can determine the average flow rate, which will be equal to the instantaneous flow rate with an error of 0.01%, which cannot be achieved using instruments at present available in the Russian Federation.

This equipment is similar to that used in the Slovak National Institute of Standards, which has international accreditation from the International Bureau of Weights and Measures. The unique possibility of stabilizing the flow rate enables the dynamic characteristics of working measuring instruments to be investigated. It is intended to change the height of the column of liquid in the storage reservoir in order to produce normalized pulsations of the flow rate (fixed frequency, amplitude and form of variation). These investigations are necessary to determine the additional errors of instruments for measuring flow rate and volume, operating under practical conditions.

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