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Low-Pressure Gas Flow Standard in Russian Federation: Principles, Calibration Techniques, Intercomparisons

I.A. Isaev, V.A. Fafurin, A.V. Mingaleev, A.I. Gorchev,
A.B. Yakovlev, O.Yu. Sladovskaya

Federal State Unitary Enterprise «All-Russian Research Institute of Flow Metering» (VNIIR),
St. 2nd Azinskaya, 7a, Kazan, Republic of Tatarstan, Russian Federation, 420088
E-mail (I.A. Isaev): ilya.isaev@mail.ru

Abstract

The article deals with the basics of metrological support of low-pressure gas (air) flow measurements, describes the improved State (National) Primary Standard GET 118-2017 and methods of reproduction and transfer the gas flow rate units implemented in the Russian Federation. The improved GET 118-2017 is a complex of five test rigs that are interconnected by means of the reference sonic nozzles, which received the unit of measure on the initial test rig TR-1 of bell type. For transfer the gas flow rate units to calibratable sonic nozzles from reference sonic nozzles in GET 118-2017 a new comparing method using laminarizers (laminar flow elements) as comparators was developed and patented. The volumetric gas flow rate of the calibratable nozzle is determined by the relative change in the pressure drop on the comparator when the calibratable nozzle and two reference nozzles with nominal flow rates smaller and larger relative to the calibratable value are alternately connected after comparator. The GET 118-2017 on the scientific and technical level corresponds to the modern world achievements and is not inferior in characteristics to the best foreign analogues that is confirmed by the results of international comparisons.

1. Introduction

In 1967, work on the creation of reference facilities for the calibration of measuring instruments for measuring the volume and mass flow rate of low-pressure gas (air) was started in the Russian Federation. VNIIR developed and approved the State Primary Standard GET 62-74 of Gas Volume Rate Units in 1974 and the State Primary Standard GET 118-79 of Gas Mass Flow Rate Units in 1979.

In 2006, according to the results of the scientific and technical measures conducted by “VNIIR”, the State Primary Standard GET 118-2006 of Volume and Mass Gas Flow Rate Units was created, replacing GET 62-74 and GET 118-79. The GET 118-06 included an initial gravimetric-type reference test rig and two reference test rigs with sonic nozzles calibrated on an initial test rig with a general air flow range from $3{\cdot}10^{-3}$ to 10000 m^3/h [1]. The high level of GET 118-2006 and its compliance with the best foreign analogues were confirmed by international comparisons COOMET No.219/Sk-00 (2006-2007) and COOMET No.412/UA/07 (2010). Also, the gravimetric test rig of GET 118-06 confirmed the degree of equivalence at trilateral comparison between NMIs of Russia, Germany and China [2], a side result of which was the confirmation of the independence of the discharge coefficient of sonic nozzles from the calibration method, since the participative reference standards had different principles of gas flow rate reproduction (gravimetric, PVTt and bell). According to the results of these intercomparisons, CMC entries VNIIR-13.01, VNIIR-13.02, VNIIR-13.03 and VNIIR-13.04 were registered in the BIPM database.

Nevertheless, the primary standard of the GET 118-2006 is already outdated by 2012 and did not meet modern requirements for accuracy, performance, reproducible flow ranges and operating pressure. Therefore, in the period from 2012 to 2017, several major steps were taken at the VNIIR to improve the Primary Standard GET-118.

2. Method of sonic nozzle calibration

In the Primary Standard GET 118-06 the sonic nozzles (SN) were used to transfer the gas flow rate units to working standards and measuring instruments. Sonic nozzles are distinguished by high accuracy of gas flow measurement, simplicity of the device and reliability. With a supercritical pressure drop at the SN, the gas volume flow rate *Q* does not depend on the pressure in front of the nozzle, but is determined only by the geometrical parameters of the nozzle and the inlet gas temperature. Therefore SN are used as the basic elements of working standards for calibration and verification of gas flow meters, for accurate reproduction and measurement of gas volume and volume flow, as well as for testing the gas flow meters of various types. In this regard the issues of reliable calibration of the SN are extremely relevant.

The transfer of gas flow rate units to SN is usually carried out from reference standards of bell, gravimetric, piston and other types. But, as a rule, these high-precision reference standards have a high cost and relatively low productivity, that does not allow them to be used for mass calibration of measuring instruments. The use of other reference sonic nozzles (RSN) for calibration of SN at their sequential allocation using the direct comparison method is faced with a number of difficulties related to the discreteness of nozzles readings, relatively large pressure drop, the impossibility of providing identical Reynolds number, and the appearance of flow pulsations in the channel between nozzles.

Along with the direct comparison method, one of the most common methods of units transfer from reference standards to working measurement tools is comparing (or calibration using a comparator). The method consists in comparing the comparator's control parameter (related to the measured unit) on the reference sample and on the meter under test and determining from the change of this parameter the measured value on the meter under test.

In the GET 118–06 the comparing method was already used to transfer gas flow rate units from reference standard to calibratable SN. Turbine and rotary flow meters-gas meters with high-frequency output were used as comparators [3]. The volume gas flow rate *Q* of calibratable SN was determined in proportion to the change in the impulse frequency of the comparator output signal when the gas flows at the 1st stage successively through the comparator and the RSN with a known nominal flow rate, and at the 2nd stage through the comparator and calibratable SN. Thus, the gas flow rate indications of the comparator in the comparison procedure were not used, but only its output frequency signals were compared.

The use of the comparing method in the GET 118–06 allowed to increase productivity and, in general, to improve the characteristics of the standard. However, significant disadvantages of this method were noted. First of all, they are connected with the difficulty of taking into account the manifest nonlinearity factor caused by friction in the rotational supports of the used comparators, as a result of which the gas flow rates of the reference and calibratable nozzles should be as close as possible (within 5%). In addition, during operation, the metrological characteristics of such comparators are deteriorated due to their wear.

In this regard, at improvement GET 118 the flow laminarizers (laminar flow elements) were used as comparators for SN calibration. Laminarizers are characterized by high sensitivity, a wide applicable flow range and the absence of moving friction joints. In such devices, there is a sharp decrease in the equivalent hydraulic diameter due to the direction of the main flow into the system of small parallel tubes or flat ducts. As a result, in a large range of operating parameters a laminar flow takes place, which, according to the Puisel law, is characterized by a linear dependence of the volume flow rate Q vs. the pressure drop Δp.

Thus, in the case of SN location directly behind the laminarizer, it is possible to establish a relationship between the Q value of the nozzle and the pressure drop Δp in the stabilized flow section in the comparator. It should be taken into account that in the isothermal gas flow the volume flow rate is not constant along the length of the channel due to changes in pressure, and the value Q corresponds to the gas density at average pressure $p+\Delta p/2$ (where p is the outlet pressure from comparator, approximately equal to the pressure at the entrance to the nozzle) on the section L of the laminarizer.

Based on this, the method was developed for transfer the volume gas flow rate units from reference nozzles to calibratable ones. To improve the accuracy of SN calibration, two RSN are used - with a smaller and larger flow rate relative to the calibratable value (Figure 1), which allows to more accurately determine the character of the dependence $\Delta p(Q)$ within the established range. The output from the comparator and the input sections of the nozzles are located in the common receiver to minimize the pressure drop between them.

For the practical implementation of the presented method in a wide range of gas flow rates, several laminarizers with flat slit channels with a height of 0.8 mm and a length of 230 mm were created.

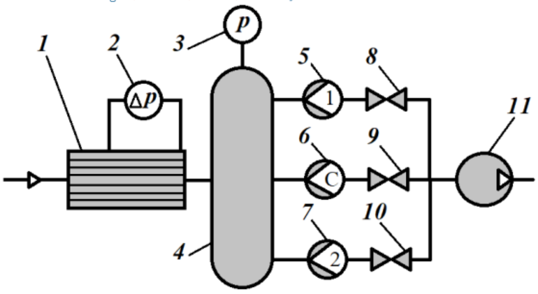

Figure 1: Schematic diagram of the reference installation for sonic nozzles calibrating: *1* – laminarizer (comparator); *2* – pressure differential sensor; *3* – pressure sensor; *4* – receiver, *5* – lower flow RSN; *6* – calibratable nozzle; *7* – higher flow RSN; *8*, *9*, *10* – gas valves; *11* – compressor.

For excluding the initial stabilization section, the first pressure tap is installed at a distance of 90 mm from the laminarizers entrance. Comparators designed for different ranges of measured flow rates differ in width (from 20 to 120 mm) and in the number of slot channels (from 3 to 51).

SN calibration on the developed comparing method is carried out as follows. At first, the volume flow rate (m³/h) of the calibratable nozzle is estimated using the approximate formula $Q_n = 0{,}55 \cdot d_n^2$ (where d_n is the diameter of the nozzle throat, mm). Then a comparator and two RSN with lower and higher flow rate (which differ from the value Q_n within 10%) should be selected.

Hereafter, the gas is pumped sequentially through the comparator and the calibratable nozzle, and the differential pressure Δp on the comparator is recorded in the first calibration stage. On the second and third stages, respectively, the pressure drops Δp_1 and Δp_2 are fixed at the comparator when the gas passes alternately through the first and second RSN with known nominal flow rates Q_1 and Q_2, reduced to standard conditions. The volume gas flow rate of calibratable nozzle under standard conditions is determined by the formula:

$$Q = \Delta p \left[\frac{Q_1}{\Delta p_1} + \frac{\Delta p - \Delta p_1}{\Delta p_2 - \Delta p_1} \left(\frac{Q_2}{\Delta p_2} - \frac{Q_1}{\Delta p_1} \right) \right]. \quad (1)$$

According to the results of the experiments, it was found that a simpler equation could be used instead of equation (1):

$$Q = Q_1 + (Q_2 - Q_1) \frac{\Delta p - \Delta p_1}{\Delta p_2 - \Delta p_1}. \quad (2)$$

The patent was received on the presented method and device in the form of a laminariser for SN calibration [4].

At implementing the developed method for SN calibration in the improved State Primary Standard GET 118-2017, the Yokogawa differential pressure sensors with a reduced error of ±0.04% were used to measure the pressure drop at the comparator. This allows to calibrate the SN with an expanded uncertainty *U* (at coverage factor k=2) not exceeding 0.1%.

3. The content of improved State Primary Standard GET 118-2017 of Volume and Mass Gas Flow Rate Units

To improve the GET 118 several important activities were carried out at the VNIIR.

First, as an initial test rig TR-1 for reproducing and transfer volume gas (air) flow rate units from 0.4 to 100 m³/h at atmospheric pressure the high-precision bell prover was used instead of morally and physically outdated gravimetric test rig.

Secondly, to expand the range of reproducible gas flow rate in the region of large values (up to 16000 m³/h) at atmospheric pressure the test rig TR-2 with a SN-set was introduced into the GET 118.

Thirdly, highly-productive test rig TR-3 including a SN-set was created with reproducible gas flow rate from 1 to 64 m³/h at atmospheric pressure.

Fourthly, the test rig TR-4 with a SN-set and a reference gas meter was introduced into the GET 118 to transfer the gas flow rate units from 10 to 2300 m³/h at gage pressure up to 1 MPa.

Fifth, for reproduction gas flow rate units in ultra-low range (from $3 \cdot 10^{-4}$ to 3 m³/h) at atmospheric pressure a piston prover (test rig TR-5) was used.

Thus, the improved GET 118-2017 is a complex of five test rigs that are interconnected by means of the reference sonic nozzles, which received the unit of measure on the initial test rig TR-1 (Figure 2). In addition, due to the limited gas flow rate range of the TR-1, the ECS of a larger flow rate (up to 410 m³/h) is also being calibrated at the TR-2 in several stages with an increase the flow rate using as reference standards not individual RSN, but sets of parallel-mounted reference nozzles (by the "bootstrapping" procedure). The nozzles calibrated in this way are subsequently used in the composition of both the TR-2 itself and the TR-4.

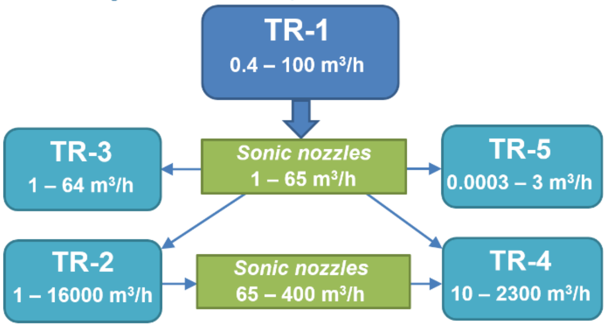

Figure 2: Diagram of the transfer of gas flow rate units in the GET 118-2017.

The RSN-sets are part of the test rigs TR-2, TR-3, TR-4, and also are used to calibrate the reference flow meter of test rig TR-4 and measurement cells of piston prover TR-5.

4. Description of the test rigs included in the GET 118-2017

4.1 Initial test rig TR-1

The initial test rig TR-1 based on a bell prover is designed to reproduce and transfer units of volume and mass flow rates, as well as to calibrate RSN and reference gas flow meters used in other test rigs of GET 118-2017 (Figure 3). It was developed and produced in collaboration with the German National Metrology Institute PTB. The created test rig is analogous to the Primary Standard of Germany [5].

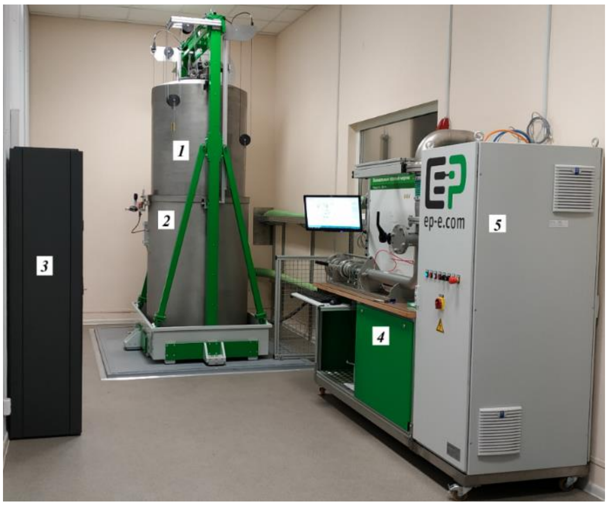

Figure 3: Photograph of initial test rig TR-1: 1 – bell (in the highest position), 2 - oil tank, 3 - cabinet of the climate precision system, 4 - test bench, 5 - cabinet of the automated control system.

The operating principle of bell prover is based on the displacement of a certain gas volume from under the bell at its lowering into the sealing liquid.

The expanded uncertainty *U* of gas flow rate reproduction at the TR-1 is not more than 0.06% in the flow range from 1 to 65 m³/h and not more than 0.1% in the flow ranges from 0.4 to 1 m³/h and from 65 to 100 m³/h

To maintain the specified constant values of temperature and humidity a climate-controlled climate system based on the Clima Processor CA S01 conditioner was used.

4.2 Test rig TR-2

The automated test rig TR-2 with a SN-sets includes two modules:

- module 1 designed to transfer the gas flow rate units to working standards and working measuring instruments based on positive displacement gas flowmeters in the range of volumetric flow rate from 10 to 16000 m³/h;
- module 2 designed to transfer the gas flow rate units to working standards and working measuring instruments based on sonic nozzles and positive displacement gas flowmeter in the range of volumetric flow rates from 1 to 1600 m³/h.

Gas is pumped on the suction line by means of three air blowers.

The transfer of the gas flow rate units in module 1 is carried out by comparing the mass air flow through sequentially placed calibratable gas flow meter and measuring system, which includes 45 parallelly installed RSN of various typical sizes.

The operating principle of module 2 is based on a comparison of gas flow rate through a reference nozzle (or RSN set) and a calibratable nozzle by means of the developed comparing method using laminarizers. The module contains 13 various RSN.

With the inclusion of various combinations of RSN in modules 1 and 2, the change in air flow rate is ensured. Each RSN is connected and disconnected by means of pneumatic actuated valves.

According to the research results, the test rig TR-2 ensures the reproduction of volume and mass gas flow rate units with an expanded uncertainty of no more than 0.1%.

4.3 Test rig TR-3

The automated test rig TR-3 with a RSN-set is designed to transfer the volume and mass flow rate units to working standards and measuring instruments by means of direct comparison method, as well as to calibrate sonic nozzles by means of comparing method using laminarizers. A photograph of the EU-3 reference module is shown in Figure 4.

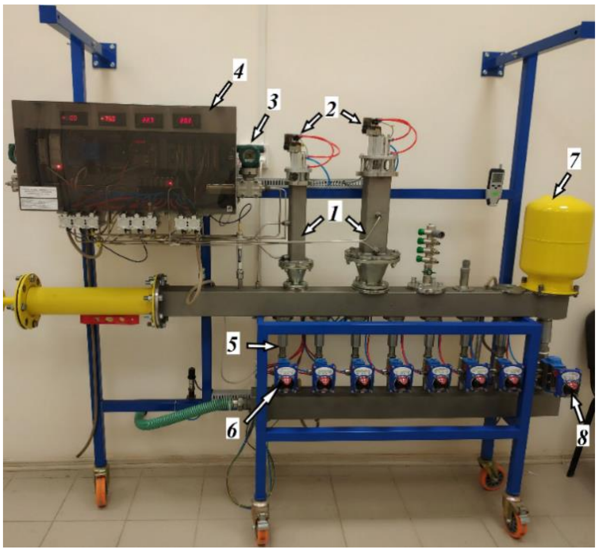

Figure 4: Photograph of test rig TR-3: 1 – laminarizer (comparator); 2 – inlet pneumatic valve; 3 – pressure differential sensor; 4 – control unit; 5 – set of parallel mounted RSN; 6 – pneumatic cranes of RSN; 7 – receiver with calibratable nozzle inside; 8 – pneumatic crane of calibratable nozzle.

The air flow in TR-3 is provided by gas rarefaction created by the vacuum pump in the receiver. Through various combinations of open RSN, the air flow rate is varied in the range from 1 to 64 m^3/h.

The test rig TR-3 consists of an inlet and outlet manifolds, between which a receiver with a calibratable nozzle and seven reference nozzles with electric motorized ball valves are installed. Two comparators (with flow ranges of 1–10 m^3/h and 8–64 m^3/h, respectively) are located on the inlet manifold. Comparators are included in the operation by means of full-way electric ball valves.

According to the research results, the test rig TR-3 ensures the reproduction of volume and mass gas flow rate units with an expanded uncertainty not exceeding 0.09%.

4.4 Test rig TR-4 at gage pressure up to 1.0 MPa

Reproduction of gas volume and mass flow units in TR-4 is based on a direct comparison of the air flow rate through sequentially installed meter under test and reference flow transducers (RSN-set or reference flow meter).

The flow generator is a compressor that provides a volumetric flow rate of up to 2300 m^3/h (under standard conditions) and gage pressure up to 1.0 MPa. Using a system of ball valves and valves, the air flow from the compressor to the point of release into the atmosphere can be carried out either sequentially through a reference meter and meter under test or sequentially through a meter under test and RSN-set.

A rotary gas meter IRM-A-DUO with a measured flow rate of up to 400 m^3/h is used as a reference flow meter (reference standard).

The RSN-set consists of inlet and outlet collectors, between which there are five various reference nozzles (with a gas flow rate from 10 to 400 m^3/h), calibrated in test rigs TR-1 and TR-2.

According to the research results, the test rig TR-4 ensures the reproduction of volume and mass gas flow rate units with an expanded uncertainty not exceeding 0.11%.

4.5 Test rig TR-5

The automated piston type test rig TR-5 consists of two measuring cells (Figure 5): SL-800-10 (Q=0.0003…0.03 m^3/h) and SL-800-44 (Q=0.03…3 m^3/h).

Figure 5: Photograph of test rig TR-5.

The method of reproducing the flow rate is based on the displacement of a certain volume of gas when the piston moves inside a tube during the measured time interval. The distance traveled by the piston is determined by means of photodiodes mounted on the initial and final marks. The piston is made of graphite composite having a low coefficient of friction and resistant to wear. The tube inside which the piston moves is made of borosilicate glass having a low coefficient of thermal expansion.

According to the research results, the test rig TR-5 ensures the reproduction of volume and mass gas flow rate units with an expanded uncertainty of no more than 0.1%.

5. Conclusion

As a result of the improvement of the GET 118, the following was achieved:

- the expanded uncertainty of reproduction of volume and mass flow rate units of gas (air) at the initial test rig in the flow range from 1 to 65 m³/h was reduced from 0.08% to 0.06%, and in general an expanded uncertainty of reproduction of volume and mass gas flow rate units in GET 118-2017 is from 0.06 to 0.11%;

- the range of reproducible gas flow rate was significantly expanded, and now it is from 0.0003 to 16000 m³/h);

- the upper value of the gage pressure of gas (air) was increased to 1 MPa in the range of gas flow rate from 10 to 2300 m³/h;

- the application of the developed comparing method using laminarizers allowed: 1) to calibrate SN with gas flow values much higher than the maximum value of the reproduction range of the initial test rig TR-1 of bell type, 2) to reduce the load and wear of the expensive initial test rig TR-1, 3) to significantly increase the productivity of calibration works.

The general metrological characteristics of State Primary Standard GET 118-2017 of Volume and Mass Gas Flow Rate Units are shown in Table 1.

Table 1: Metrological characteristics of GET 118-2017.

Test rig	Parameter		
	Q, m³/h	*p*, kPa	*U*, %
TR-1	1 – 65 0,4 – 1 65 – 100	96 – 104	0,06 0,10 0,10
TR-2	1 – 16000	96 – 104	0,10
TR-3	1 – 64	96 – 104	0,09
TR-4	10 – 2300	to 1100	0,11
TR-5	0,0003 – 3	96 – 104	0,10

In 2018, according to Euramet project No. 1396 the international comparison of the GET 118-2017 with similar national standards of Germany (PTB) and the Czech Republic (CMI) in the range from 1 to 250 m³/h was made using reference standards based on sonic nozzles [6]. Positive results were obtained: the stated metrological characteristics of the bell prover TR-1 were confirmed over the entire flow range. Thus, the GET 118-2017 on the scientific and technical level corresponds to the modern world achievements and is not inferior in characteristics to the best foreign analogues.

Currently, GET 118-2017 participates in international comparisons of COOMET project No. 680/RU/16 in the range of gas flow rate from 20 to 6500 m³/h using reference standards based on turbine and rotary gas meters.

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