The system of metrological provision of the Russian Federation in the field of measurement of gas flows in a vacuum and its future development

A A Chernyshenko

D. I. Mendeleev Institute for Metrology VNIIM, 190005, Russia, St. Petersburg, Moskovsky pr., 19

E-mail: vacuum@vniim.ru

Abstract. The article provides information about the state of the metrological provision in the field of gas flow measurements in a vacuum. The researchers describe the need to build and improve a system of metrological provision in the field of measuring gas flows in a vacuum. There is information about the work on the creation of a piston flow meter as a national standard for gas flow in a vacuum, taking place in the research department of the state standards in the field of pressure measurements of the D. I. Mendeleev Institute for Metrology VNIIM.

Nowadays, nobody has to be convinced that measuring the gas flow in a vacuum is important in all areas of human activity. First of all, it is important to emphasize the great importance of these measurements in science intensive and high-tech industries such as the nuclear industry, aerospace industry, metallurgy, electronics and others. It should be emphasized that this is primarily due to the safety requirements for the operation of technical systems that were created in high-tech branches of science and primarily in the aerospace industry, nuclear energy and others.

Measurements of the gas flow in a vacuum are required when solving application tasks and scientific mission such as: leak tightness control of various objects [6, 8]; investigation of the composition of various materials, eg hydrogen diagnostics [7]; reproduction, storage and transmission of the Pascal pressure unit, since most national standards in high and ultra high vacuum contain reference means for measuring the gas flow in a vacuum [1, 4]. At the same time, such measuring devices and measurement complexes of gas flows in a vacuum are used, such as gas flow measuring devices in a vacuum, leak detectors, leak tightness control complexes and various systems for measuring gas flows in a vacuum.

At the same time, we believe that, despite the demand and the fairly wide range of applications for measuring gas flows in a vacuum, there is currently no harmonious and effective system of metrological support in this field in the Russian Federation. We are concerned that there is no primary (national) standard or state verification scheme for measuring the gas flow in a vacuum. However, it cannot be said that no work is being done to create a metrological provision in this field of measurement. So in the D. I. Mendeleev Institute for Metrology VNIIM the secondary (working) standard of the unit of the gas flow in vacuum, GWET 49-2-2006, and a local measurement chain of the gas flow in a vacuum, which the functions of a national standard and a state measurement chain,
developed and applied, and various industries carry out or initiate work to set up a metrological support system in the field of measuring gas flows in a vacuum. Here are some examples of such works:

- as part of the work of the technical committee for standardization TC 371 "Non-destructive inspection", the state standard GOST R 59286-2020 Non-destructive inspection was developed and approved. Leak testing. Terms and definitions;
- processing of GOST R 53177-2008 Vacuum technology is in operation and planned. Measurement of performance characteristics of mass-spectrometer method of tightness control within the framework of the work of the Technical committee for Standardization TC 249 "Vacuum technology";
- a number of industries, for example, the Aerospace Industry, are developing new industry standards for leak tightness control, instead of outdated ones;
- a number of enterprises are equipped with reference installations designed for verification and calibration of gas flow measures in a vacuum;
- D. I. Mendeleyev Institute for Metrology VNIIM is actively developing a new standard for gas flow in a vacuum as part of the work to improve the reference database.

It is obvious that even a small list of examples of initiatives and developments to create a metrological provision system in the field of measurement of gas flows in a vacuum shows the relevance and importance of the construction of such a system in the Russian Federation.

Let’s delve deeper into the information on the work on building a metrological provision system in the field of measuring gas flows in a vacuum. As mentioned above, the functions of the national standard of the Russian Federation in the field of measuring gas flows in a vacuum are the secondary (working) standard of a gas flow unit in a vacuum GVET 49-2-2006. Standard measurement range: 1.0-10^{-12}…1.00 Pa·m^3/s; net inaccuracy, characterized by the standard deviation, varies from 10 to 1.5 %, depending on the value of the measured flow. This standard implements the following measurement methods:

- Accumulative method. The simplest vacuum schematic diagram of the implementation of this method is shown in Figure 1a. When measuring the flow rate by the accumulation method, a part of the vacuum system with a gas flow source 1, vacuum gauge 2 is separated from the vacuum pump by valve 3 for a fixed time. The pressure builds up in a separated portion of the vacuum system with a known volume. The flow rate is determined based on the equation

\[ Q = V \cdot \frac{\partial p}{\partial \tau} \]  

where \( Q \) is the measured gas flow leaving the vacuum system or flowing into it; \( V \) is the volume of the vacuum system; \( \partial p/\partial \tau \) is the change in gas pressure over time as a result of the outflow.

- Constant pressure method. The simplest vacuum circuit diagram for implementing this procedure is shown in Figure 1b. When measuring the flow rate by the constant pressure method, a part of the vacuum system with a gas flow source 1, a vacuum gauge 2 and a volume regulator 4 is separated from the vacuum pump by valve 3 for a fixed time. Constant pressure is maintained in a separate part of the vacuum system by increasing or decreasing the volume of that part of the vacuum system that is separated from pumping. The flow rate is determined from the equation

\[ Q = p \cdot \frac{\partial V}{\partial \tau} \]  

where \( p \) is the absolute pressure of the gas in the vacuum system; \( \partial V/\partial \tau \) is the change in the volume of the vacuum system over time, necessary to maintain a constant pressure in it.

- Comparative method using a mass spectrometer. This method is used to transfer a unit of gas flow in a vacuum to such working and reference instruments for measuring gas flow in a vacuum as gas flow meters in a vacuum and leak detectors.
Figure 1. Basic vacuum schemes for measuring gas flow in vacuum: (a) – accumulative method, (b) – constant pressure method.

Note that the first two methods are absolute.

State secondary (working) standard of the gas flow unit in a vacuum GVET 49-2-2006 took part in key comparisons CCM.P-K12 [2] in order to determine the equivalence of the measurement results. Note that on the basis of the results of important comparisons, its equivalence has been established, and regarding the standard itself, we can say that its metrological properties are at the average world level. As the comparison results have shown, metrologically developed countries such as the USA, Germany and many other standards have the best metrological properties, and these best standards are based on the implementation of the constant pressure method. Unfortunately, in the state secondary (working) standard of a gas flow unit in a vacuum GVET 49-2-2006, the equipment implementing the constant pressure method has not been improved for more than thirty years, and the accumulation method has been used in comparisons. It made sense to assume that the constant pressure method has better metrological properties compared to other methods [2, 3, 5, 6]. And in D. I. Mendeleev Institute for Metrology VNIIM a number of studies were carried out aimed at developing a standard for gas flow in vacuum that implements the constant pressure method. As a result, the laboratory of state standards and scientific research in the field of measuring low absolute pressure and vacuum of D.I. Mendeleev Institute for Metrology VNIIM, a piston design of the gas flow standard (piston flow meter) was proposed. A schematic representation of this design is shown in figure 2.

Figure 2. Construction of a piston gas flow standard in a vacuum.

Figure 2 shows: 1 – movable piston; 2 – flange for connection to a vacuum system; 3 – Measuring vacuum system from which gas exits or flows into.

The measurement equation for such a flow meter can be written in the form:

\[ Q = p \frac{\partial V}{\partial \tau} = p S \frac{\partial h}{\partial \tau} = p \frac{\pi d^2}{4} \frac{\Delta h}{\Delta \tau} = p \frac{\pi d^2}{4} \frac{|h_1 - h_2|}{|\tau_1 - \tau_2|} \]  \hspace{1cm} (3)

where \( S \) is the cross-sectional area of the piston; \( d \) is the piston diameter; \( \partial h/\partial \tau \) is the piston movement speed required to maintain a constant pressure in the vacuum system; \( \Delta h = |h_1 - h_2| \) is the distance
covered by the piston during the measurement time interval \( \Delta \tau = |\tau_2 - \tau_1| \) covered.

From the measurement equation obtained it follows that the method for measuring the gas flow is reduced to the measurement of the relative displacement of a piston with a known diameter in the time required to maintain a given gas pressure \( p \) in a vacuum system. Let's highlight some of the differences and advantages of a piston flow meter:

- In contrast to the accumulation method, there is no need to measure the volume of the vacuum system, which cannot be measured directly. When carrying out the method of accumulation, the procedure for measuring the volume of the vacuum system from or into which the gas leaks includes several stages: 1) The procedure for weighing a certain calibrated volume, empty and filled with liquid, with the subsequent calculation of the volume by a certain liquid mass and its known density; 2) The method for multiple expansion of a gas with a pressure \( p_1 \), which is measured by means of pressure gauges, from a calibrated volume into a measurement volume of a vacuum system, the pressure after the expansion \( p_2 \) also being measured; 3) Calculation of the measurement volume of the vacuum system from or into which the gas is discharged, based on the Boyle-Mariotte equation.

Obviously, such a complicated procedure for measuring the volume of a vacuum system results in a significant loss of accuracy in the accumulation process. This disadvantage is avoided by using a piston flow meter.

- In addition, unlike other constructions of standards that implement the method of constant pressure, for example, in the existing state, secondary (working) standard of the unit of gas flow in a vacuum GVET 49-2-2006 bellows flow meter (where the change in volume the vacuum system required to maintain a constant pressure, performed by compressing or expanding the bellows filled with a liquid), the piston flow meter has the following advantages: 1) no liquid is required; 2) The change in volume is directly proportional to the displacement of the piston, which cannot be said about the bellows flow meter, because when the bellows is expanded and compressed, the change in volume is from the degree of compression and the homogeneity of the physical properties of the material that makes up the bellows; 3) In addition, the volume of the liquid displaced from the bellows must be determined indirectly by weighing the displaced liquid when it is compressed by pulling, which complicates the measurement process and increases the measurement error.

In order to determine the measuring range of the piston flow meter as well as the initial data for the development of a system of linear movement of the piston, the Laboratory for State Standards and Scientific Research in the Field of Measurement of Low Absolute Pressure and Vacuum D. I. Mendeleyev Institute for Metrology VNIIM was established proposed and manufactured a model of a piston flow meter, a photo of the flow meter model is shown in figure 3.

![Figure 3. A model of the piston flow meter.](image-url)
As you can see, the design of the piston flow meter has advantages such as compactness (the maximum overall size is no more than 20 cm), versatility (the layout has a uniform standard vacuum flange for connection to a measuring vacuum system), which makes it into almost any existing Vacuum system can be implemented. Let's emphasize some of the more obvious advantages of the piston flow meter. On the one hand, its use enables an elaborate length measuring system to be dispensed with; commercially available mechanical positioning systems (e.g. stepper motor) are sufficient. Second, a significant advantage is the already established method for measuring the piston diameter, since this method is similar to the method for measuring the piston diameter of pressure compensators.

Further investigations of the model of the piston flow meter included the following work:

- Measurements of the self-leakage of the developed structure were carried out, which had a value in the order of magnitude of $1 \cdot 10^{-7} \text{ Pa} \cdot \text{m}^3/\text{s}$, which suggests that the lower measurement limit at around $1 \cdot 10^{-7} - 1 \cdot 10^{-8} \text{ Pa} \cdot \text{m}^3/\text{s}$;
- The forces required to set the volumetric piston in motion were determined, which amounted to a force of approximately 100 N, which is necessary for the development of a linear positioning system for the piston.

As part of the research work, a project of a metrological provision system in the area of measuring gas flows in a vacuum was set up in the form of a structure-hierarchical diagram, which is shown in figure 4.

Let me reiterate that such a hierarchical scheme can be accurately constructed due to such advantages of a piston flow meter as compactness, unification, and sufficient simplicity of design. All this enables the use of a piston flow meter not only as a standard, but also as a working device for measuring gas flow in a vacuum, such as gas flow meters in test complexes for leakage control.

**Figure 4.** Structural and hierarchical diagram of the metrological provision system in the field of measurement of gas flows in a vacuum based on a piston flow meter.

In conclusion, I would like to say that today in D. I. Mendeleev Institute for Metrology VNIIM, we are concentrating our efforts on the development of a piston flow meter as a national standard for gas flows in a vacuum. For this purpose, proactive work such as the development of a vacuum schematic diagram of a piston flow meter to select the standard components of a vacuum flow meter system as well as the development and selection of a piston positioning system are carried out in order to carry out a design calculation of the metrological properties of a piston flow meter. In my opinion, this is
one of the most promising directions for setting up an effective system for metrological provision in the field of measuring gas flows in a vacuum. And we invite everyone who has constructive ideas and suggestions for the implementation of such tasks to discussion and cooperation.

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