Improvement of the high-conductivity diaphragm from the composition of the reference 1st category of vacuum gauge reduction VOU-1

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Abstract. The article notes an increase in the number of new vacuum gauges undergoing primary verification at D. I. Mendeleev Institute for Metrology VNIIM. The results are presented in the article in the form of a table reflecting the growth in the number of vacuum gauges of the most common modifications undergoing initial verification for the period from 2018 to the first quarter of 2021. There is also a diagram, which shows the overall growth in the number of new vacuum gauges undergoing initial verification. The article mentions the principles of the measurements made by the reference installation of the 1st category of vacuum gauge reduction (VOU-1). The drawings of the installed diaphragms in the system and as part of the improvement of the system, as well as a general calculation that shows how the properties of the system change after the diaphragm has been replaced.

Nowadays, measurements of low absolute pressures and vacuum are gaining increasing importance in science and industry of the Russian Federation, especially in high-tech industries. This is proven by the data collected and systematized in the research department of the state standards in the field of pressure measurements. In [1] there was an increase in the number of high-precision measuring instruments of low absolute pressures-vacuum gauges verified in D. I. Mendeleev Institute for Metrology VNIIM over the past 10 years. It should be noted that in the total number of calibrated vacuum gauges, the proportion of new vacuum gauges that have undergone an initial test at D.I. Mendeleev Institute for Metrology VNIIM for three years. Table 1 shows data on the number of new vacuum gauges installed at D. I. Mendeleev Institute for Metrology VNIIM in the period from 2018 to the first quarter of 2021. Figure 1 shows the growth dynamics of the number of primary tests of vacuum gauges over the years.

In the diagram in 2021, the number of verifications for the first quarter is shown in black and the forecast number of verifications until the end of the year is shown in gray. In our opinion, the high growth rates in the number of primary calibrations of vacuum gauges indicate primarily the high development speeds of high-tech industries and the high level of government funding for their development. This view enables the national standards research department in the area of pressure measurements of D. I. Mendeleev Institute for Metrology VNIIM to point out the relevance of such scientific and applied problems as:

- Development of modern domestically manufactured vacuum gauges;
- Development and improvement of reference devices for checking and calibrating measuring devices for low absolute pressures and vacuum.
Table 1. The number of first verifications in D. I. Mendeleyev Institute for Metrology VNIIM by year.

| Name of the device | 2018 | 2019 | 2020 | for the first quarter of 2021 |
|--------------------|------|------|------|-----------------------------|
| AIGX               | 3    | 14   | 71   | 55                          |
| PCG550             | –    | –    | –    | 5                           |
| ITR200             | –    | –    | 3    | 2                           |
| WRG                | 31   | 91   | 56   | 25                          |
| Pirani             | 7    | 13   | –    | 2                           |
| MTH10D             | 1    | 1    | –    | 14                          |
| MTP4D              | –    | 1    | 1    | 28                          |
| APG                | 9    | 21   | 28   | 7                           |
| ITR90              | –    | 4    | 10   | 4                           |
| TTR                | –    | –    | 79   | 16                          |
| PKR251             | 2    | 14   | 7    | 1                           |
| TPR280             | –    | 3    | 3    | –                           |
| MPT200             | 1    | –    | 2    | –                           |
| CDG045D            | –    | 1    | 48   | –                           |
| CC-10              | 6    | 5    | 1    | –                           |
| HPT200             | –    | –    | 2    | –                           |
| CVG101             | 3    | 4    | 4    | –                           |
| IGM402             | 3    | –    | 2    | –                           |
| MP4AR              | 4    | –    | –    | –                           |
| CCR361             | 4    | –    | –    | –                           |
| CVM211             | –    | 3    | 1    | –                           |
| **Total**          | **74** | **175** | **318** | **159**                  |

Figure 1. The number of primary tests of vacuum gauges in D. I. Mendeleyev Institute for Metrology VNIIM by year.

One of the works to improve the reference equipment of D. I. Mendeleyev Institute for Metrology VNIIM, intended for the verification and calibration of measuring devices for low absolute pressures and vacuum, is the research work "Improvement of the high-conductivity diaphragm from the composition of the reference 1st category of vacuum gauge reduction VOU-1". This device is used to measure most of the vacuum gauges from table 1. The system has the following metrological
properties: Pressure measuring range $1.0 \cdot 10^{-7} - 1.00 \cdot 10^3$ Pa, the limits of the permissible relative error $\pm (7 \ldots 3)$ %.

The large measuring range of the system is guaranteed by the implementation of several measuring principles, such as:

- static expansion method;
- dynamic expansion method;
- method of direct comparison.

Currently, the main task of improving the installation of the reference category of the 1st category of vacuum gauge reduction VOU-1 is to improve the metrological properties of the dynamic expansion method. The method is based on a decrease in gas pressure flowing through holes of known conductivity under a steady molecular regime of gas flow. A simplified representation of the implementation of the dynamic expansion process is shown in figure 2. The pressure $P_0$ is set in the pre-pressure chamber CV3, which is constantly evacuated by a vacuum pump and the A2 diaphragm. The CV2 measuring chamber is also evacuated by an ultra-high vacuum pump through the A1 diaphragm. In the case of molecular gas flow, the pressure in the CV2 chamber to which the calibrated vacuum gauge is connected is determined by formula (1).

$$P = K_{exp} \cdot P_0$$  \hspace{1cm} (1)

where $K_{exp}$ is determined by formula (2).

$$K_{exp} = \frac{U_0}{U}$$  \hspace{1cm} (2)

where $U_0$, $U$ are the conductivities of diaphragms A2 and A1.

Figure 2. Connection diagram of the vacuum chambers of the VGR-1 facility.

A diaphragm with a hole of about 10 mm in diameter is currently used as the hole of known conductivity A1. Its sketch is shown in figure 3a. This diaphragm is relatively easy to manufacture, but it restricts the options for extending the measuring range of the reduction process, since:

- the upper limit of the pressure that can be reproduced with this method is limited by the criterion of compliance with the molecular flow regime through the membrane A1 and for a diameter of 10 mm is about $1 \cdot 10^{-3} - 1 \cdot 10^{-2}$ Pa. To expand the low vacuum range, it is necessary to downsize the conductivity membrane A1, that is, reduce the hole diameter $D_1$;
- on the other hand, in order to expand the range of pressure measurements in the range of the high and ultra high vacuum according to expressions 1 and 2, it is necessary to increase the conductivity of the diaphragm A1, the diameter of the hole $D_1$.

In order to circumvent these mutually exclusive factors, the research department of the state standards in the area of pressure measurements suggests manufacturing a new diaphragm, the overall view of which is shown in figure 3b.

In contrast to the existing one, the new diaphragm does not have one hole, but $N$ holes in the diameter. In this case the diameter of these holes is smaller than the diameter of the hole of the existing diaphragm, i.e. $D_2 < D_1$. Let's show how much the upper measurement limit of the dynamic
method of reducing the installation increases if the diameter of the holes of the new diaphragm is \( n \) times smaller than the diameter of the hole of the existing one, i.e. \( D_2 = D_1/n \).

\[ \text{Figure 3. Overall view of the high conductivity diaphragm of the reduction unit: (a) currently in existing; (b) being developed as part of the work to improve the reduction unit.} \]

It is known that the gas flow regime in a vacuum system is determined by the ratio of the frequency of collision between molecules to the frequency of collision of molecules with walls: the Knudsen criterion - \( K_n \), which is determined according to [2] by expression (3).

\[ K_n = \frac{L}{d_{eff}}. \]  

where \( L \) is the average length of the free path of gas molecules; \( d_{eff} \) is the effective size of the vacuum system of the installation, which is taken to be equal to the diaphragm holes.

For the molecular regime of gas flow, the Knudsen criterion should be \( K_n \leq 1.5 \). For the calculation, we take the extreme point \( K_n = 1.5 \).

Then, in accordance with expression (3), the free path length of gas molecules at \( K_n = 1.5 \) for the existing diaphragm is determined by formula (4).

\[ L_1 = 1.5 \cdot D_1 \]  

For the developed diaphragm, the free path length of gas molecules at \( K_n = 1.5 \) is determined by formula (5).

\[ L_2 = 1.5 \cdot D_2 = 1.5 \cdot \frac{D_1}{n} = \frac{L_1}{n} \]  

Using to calculate the length of the free path of gas molecules, we can apply the formula (6) ([2], formula 1.46).

\[ L = \frac{6.7 \cdot 10^{-3}}{p} \]  

where \( p \) is the pressure in the measuring chamber.

It is possible to determine the ratio of the values of the limit gas pressures at which the molecular regimes of the gas flow are still observed if the existing and new diaphragms are used according to the formulas (7), (8).
where \( p_1 \) is the boundary pressure of the gas, when using the existing diaphragm; 
\( p_2 \) is the boundary pressure of the gas, when using the new diaphragm.

It can thus be seen that the use of the developed membrane with hole diameters which are \( n \) times smaller than the hole diameter of the existing membrane increases the upper limit of the pressure \( p_2 \) reproduced in the measuring chamber by \( n \) times.

Assume that the number of holes in the developed diaphragm is \( N \). Let us use the equation to calculate the conductivity of a round hole (9) ([2], table № 3.7).

\[
U = 91 \cdot D^2 ,
\]

where \( D \) is the diameter of the aperture hole;
\( U \) is the calculated conductivity of the diaphragm.

Then the conductivity of the existing diaphragm will be determined by the formula (10).

\[
U_{D_1} = 91 \cdot D_1^2
\]

The conductivity of the diaphragm with the hole diameter \( D_2 = \frac{D_1}{n} \) will be determined by the formula (11).

\[
U_{D_2} = 91 \cdot D_2^2 = \frac{91 \cdot D_1^2}{n^2}
\]

Therefore, the conductivity of the \( N \)-hole diaphragm can be calculated according to formula (12).

\[
U_{D_{2sum}} = N \cdot \frac{91 \cdot D_1^2}{n^2}
\]

Let us determine the ratio of the conductivities of these two diaphragms by the formula (13).

\[
\frac{U_{D_{2sum}}}{U_{D_1}} = \frac{N \cdot 91 \cdot D_1^2}{n^2 \cdot 91 \cdot D_1^2} = \frac{N}{n^2}
\]

It follows from the obtained ratio that such a number of holes \( N \) can be made in the developed diaphragm so that the conductivity of the developed diaphragm is equal to or greater than the existing one. In other words, the inequality (14) must be satisfied.

\[
\frac{U_{D_{2sum}}}{U_{D_1}} \geq 1
\]

If this condition is met, it follows from the equations for measuring the dynamic reduction method (1) and (2) that at the same pressure in the initial pressure chamber, the value of the pressure reproduced in the measuring chamber is much less than the conductivity compared to the developed diaphragm the existing.

In summary, it should be noted that with D. I. Mendeleyev Institute for Metrology VNIIM is constantly being carried out aimed at improving the reference base of the Russian Federation in the field of measurements of low absolute pressures. One of these works is research to improve the standard installation of the 1st category of vacuum gauge reduction (VOU-1), in the context of which a new diaphragm with high conductivity is being developed. The development, manufacture and implementation of a new diaphragm will improve the metrological properties of the reference device in the 1st category vacuum measurement reduction, in particular expand the measurement range, both in the high vacuum and in the low vacuum range.
References

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[2] Rozanov L N 1990 Vacuum technology (Moscow, Higher School)