EMPLOYMENT OF CONTINUOUS EXPANSION METHOD FOR VACUUM GAUGE CALIBRATION IN MEDIUM VACUUM RANGE

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ABSTRACT

The employment of the continuous expansion method for vacuum gauge calibration in the medium vacuum range is restricted by the condition of free molecular flow through an orifice. In the present work it is proposed to replace the first orifice by a long cylindrical capillary, where the gas flow regime varies from viscous at the entrance to free molecular flow at the exit. An equation describing the real capillary conductance in this transition gas flow regime is derived. Accurate measurements of the internal diameter along the capillary are carried out. The employment of the capillary allows us to expand the range of primary pressure p_1 up to 10^5 Pa, to avoid the exit pressure p_2 measurements $(p_2 << p_1)$ and to use fewer reference vacuum gauges due to the fact that the gas throughput scales with the square of the pressure p_1 . The second orifice was substituted by a thin plate with small circular holes. It was possible to maintain free molecular flow in the holes at a pressure up to 1 Pa. A comparison between the developed vacuum reference apparatus and the reference standard of the "D.I.Mendeleyev Institute for Metrology" (Russia) is made.

2. INTRODUCTION

The continuous expansion method (also called orifice flow method, dynamic expansion method, continuous flow method, method of dynamic reduction of pressure) is widely used for vacuum gauge calibration in the range of high and ultrahigh vacuum [1]. The method consists in the reduction of a relatively high primary pressure by means of gas flowing through two orifices situated one after other when the second orifice conductance is larger that than of the first. The condition of free molecular gas flow in the orifices restricts the application of this method to the medium vacuum range. An increase in the primary pressure causes the appearance of an intermediate viscous-free molecule flow in the first orifice and its conductance, therefore, becomes dependent on the pressure. To avoid this phenomenon, porous plugs are sometimes used instead of the first orifice [2]. The diameters of the plug channels are of a few microns and the free molecular flow regime exists

here up to a pressure of 10 Pa. However, it is difficult to calculate the conductance of the plug because the channel diameter cannot be measured precisely. Therefore, the porous plug conductance is measured experimentally. Moreover, due to their small sizes, channels have a tendency to become obstructed and the plug conductance may be unpredictably decreased. In modern versions of this method [3,4] some kinds of rarefied gas flowmeters are used instead of the first orifice and the need of maintain free molecular flow here is no longer critical. Nevertheless, the second orifice remains as another critical element limiting the measuring range of the method. Because the gas throughput scales linearly with pressure p_2 , it is necessary to apply several flowmeters to cover a wide range of pressure measurements.

3. THEORY

3.1. Continuous expansion method

A schematic diagram of continuous expansion system is shown in Fig.1.



Figure 1 - Continuous expansion calibration apparatus.

The apparatus consists of three vacuum chambers situated in series and connected with the capillary and the orifice. A reference vacuum gauge and a leak valve are fitted to the first of them, which is the reference chamber. Vacuum gauges to be calibrated are fitted to the next one, the calibration chamber. A high vacuum pump is connected to

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the last one, pumping chamber. At the beginning of the calibration process, the pressure of gas p_1 is established in the reference chamber by the leak valve. The gas is introduced into the calibration chamber through the capillary. Then, it passes through the orifice into the pumping chamber where it is pumped by the high vacuum pump at the pressure p_3 . If the pressure p_1 is constant and, under this condition, the gas temperature, outgassing flow and pumping speed of the high vacuum pump are constant too, we can obtain an equilibrium constant pressure p_2 in the calibration chamber. It is calculated according to the well-known equation [1]:

$$p_2 = p_1 \frac{C_c}{C_o} \tag{1}$$

where C_c and C_o are the conductances of the capillary and the orifice, respectively.

3.2. Tube flow

The long cylinder capillary (tube) was one of the classic geometrics in rarefied gas dynamics for many years. The equations describing the viscous $(Kn \le 1)$, the free molecular $(Kn \ge 1)$ and the intermediate $(Kn \ge 1)$ gas flows in the capillary are well known [5]. Kn is the dimensionless Knudsen number. It is defined as the ratio of the mean free path of the gas molecules to the characteristic dimension of vacuum system (an internal diameter of the tube). The conductance of long cylindrical tube in viscous gas flow regime is described by the following equation [5]:

$$C_{cv} = \frac{\pi d^4}{128\eta l} \frac{p_1 + p_2}{2}$$
(2)

where *d* and *l* are the internal diameter and the length of the capillary; η is the viscosity of the gas. In free molecular gas flow regime the tube conductance is given by:

$$C_{cm} = \frac{\pi d^3}{3l} \sqrt{\frac{RT}{2\pi M}}$$
(3)

where M and T are the molecular mass and the temperature of the gas. The semi-empirical equation was developed by Knudsen to describe the intermediate gas flow in glass cylindrical capillaries [10]:

$$C_{c} = \frac{\pi d^{4}}{128\eta l} \frac{p_{1} + p_{2}}{2} + k_{k} \frac{\pi d^{3}}{3l} \sqrt{\frac{RT}{2\pi M}} =$$
$$= C_{cv} + C_{cm}$$
(4)

where:

$$k_{k} = \frac{1 + 2.507 \frac{d}{\eta} \frac{p_{1} + p_{2}}{2} \sqrt{\frac{M}{2\pi RT}}}{1 + 3.095 \frac{d}{\eta} \frac{(p_{1} + p_{2})}{2} \sqrt{\frac{M}{2\pi RT}}}$$
(5)

Nevertheless, one kind of gas flow, where the flow regime changes from the viscous at the entrance to the free molecular at the exit of capillary, has been less investigated. This transition gas flow is that, which occurs in the majority of leaks encountered in vacuum systems. Little theoretical and experimental data describing this kind of gas flow are known [5-9]. Some equations [6,8] describing the transition flow regime have been obtained by integration of equation (4) along the capillary, assuming that Eq.4 is valid within a short section of capillary ∂x . Thus, the obtained equation describes the gas flow in a long glass capillary, where the flow regime, i.e. the Knudsen number, changes from viscous at the entrance $(Kn \le 1)$ to free molecular at the exit (Kn >> 1). At the limits, where Kn >> 1 or Kn << 1 along the whole capillary, these equations are transformed to the known classic equations for viscous (Eq.2) or free molecular flow (Eq.3). To obtain more accurate description of this gas flow regime, some phenomena appearing in real capillaries have to be taken into consideration. The real capillary conductance C_l can be written as:

$$C_1 = C_{cv} k_1 k_2 + C_{cm} k_3 k_4.$$
 (6)

Here k_i is the factor accounting for the non-established viscous flow at the entrance of the capillary [11]:

$$k_1 = 1 - \frac{2,28Md^4(p_1^2 - p_2^2)}{4096\eta^2 l^2 RT}$$
(7)

 k_2 is the factor accounting for the appearance of certain element of the turbulent flow in the capillary under higher pressure [12]:

$$k_2 = \sqrt{1 - \frac{Md^4 p_1^2 \ln(p_1 p_2^{-1})}{2048\eta^2 l^2 RT}}$$
(8)

 k_3 is the factor accounting for the finite length of capillary [14]:

$$k_3 = 1 - \frac{3d \ln(2ld^{-1})}{8l} - \frac{91d}{96l} + \frac{d^2 \ln(2ld^{-1})}{l^2} + \dots$$
(9)

 k_4 is the factor derived during the integration of the equation (4):

$$k_{4} = \frac{1}{\beta} + \frac{(\beta - 1)\ln\left(1 + \frac{\beta d}{\eta} \frac{p_{1} + p_{2}}{2} \sqrt{\frac{8M}{\pi RT}}\right)}{\frac{\beta d}{\eta} \frac{p_{1} + p_{2}}{2} \sqrt{\frac{8M}{\pi RT}}}$$
(10)

where β =3.095/2.507 = 1.2345 is the ratio of the empirical Knudsen numbers in Eq.4. Eq.6 was analyzed mathematically and a minimum was found. The minimum is smaller than in Eq.4 (does not exceeds 4% of the molecular flow limit C_{cm}) and occurs at slightly lower pressures.

3.3. Orifice flow

The conductance C_{om} of an infinitely thin circular orifice situated in an infinitely large vacuum chamber in the free molecular gas flow regime is given by [5]:

$$C_{om} = \frac{\pi D^2}{4} \sqrt{\frac{RT}{2\pi M}} \tag{11}$$

where D is the diameter of the orifice. A real orifice differs from its theoretical model. Taking into account these differences, the orifice conductance C_2 can be expressed as:

$$C_2 = C_{om} K_1 K_2 K_3, (12)$$

where K_1 is the factor accounting for that the orifice plate is not infinitely thin [13]:

$$K_1 = 1 - \frac{L}{D} + \left(\frac{L}{D}\right)^2 - \frac{5}{6} \left(\frac{L}{D}\right)^3 + \dots$$
 (13)

where L is the thickness of the orifice plate. K_2 is the factor accounting for the finite internal diameter of the vacuum chamber where the orifice plate is situated [11]:

$$K_2 = \left(1 - \frac{D^2}{D_c^2}\right)^{-1}$$
(14)

where D_c is the diameter of the vacuum chamber. K_3 is the factor accounting for the appearance of the intermediate flow regime in the orifice at the upper limit of the pressure measuring range [14]:

$$K_3 = 1 + \frac{Dp_2}{8\eta} \sqrt{\frac{2M}{\pi RT}} \tag{15}$$

3.4. Calculation of the calibration pressure

Some gas-dynamic phenomena must be taken into account when using the continuous expansion method in a real calibration apparatus. Let us considerate the gas flow budget in the calibration chamber. The introduced gas flow Q_{in} is:

$$Q_{in} = C_1(p_1 - p_2) + q \tag{16}$$

where q is the outgassing flow in the calibration chamber. The pumped gas flow Q_{out} is:

$$Q_{out} = C_2(p_2 - p_3) + sp_2 \tag{17}$$

where p_3 is the pressure at the entrance of the vacuum pump; *s* is the pumping speed of the vacuum gauges to be calibrated. Obviously $Q_{in} = Q_{out}$ and $C_1 << C_2$ accordingly to the continuous expansion method principles. For our apparatus described below one can obtain C_2 =4,833.10⁻³ m³s⁻¹ and C_1 =(0,0378 - 2,251).10⁻⁷ m³s⁻¹ for nitrogen at p_1 =(10²-10⁵) Pa and *T*=293K. Thus, we can derive

$$p_2 = \frac{p_1 C_1 + p_3 C_2 + q}{C_2 + s} \tag{18}$$

Generally, the outgassing flow q and gauge pumping speed s depend on the pressure p_2 . We shall considerate as a first approximation that the *s* =*const* and $q = C_{2,0}(p_{2,0} - p_{3,0})$, where $p_{2,0}$ and $p_{3,0}$ are the ultimate pressures in the calibration chamber and at the pump entrance, respectively. $C_{2,0}$ is the orifice conductance for the residual gas. During the calibration a sampling gas (nitrogen or some else) is adsorbed on the inner surface of the calibration chamber. Then, a dynamic equilibrium between adsorbed and desorbed sampling gas flows is established under the condition of p_2 =const. Due to this equilibrium the sampling gas sorption process does not add any significant additional error to the calibration uncertainty except for oxygen and water vapor. After calibration, using atmospheric air and pumping down to ultimate pressure, it was higher by (30-50)% than the initial ultimate pressure $p_{2,0}$. After baking out, the outgassing is determined by the gas diffusing into the calibration chamber from the bulk of the chamber walls and from the rubber gasket (see Fig.5). Taking into account Eq.11, we can rewrite Eq.18 as

$$p_2 = \frac{p_1 C_1 / C_2 + p_3 + \sqrt{M / M_{res} (p_{2,0} - p_{3,0})}}{1 + s / C_2}$$
(19)

where M_{res} is the molar mass of the residual gas. It should be noted that Eq.19 is transformed to the classical Eq.1 under the following conditions: p_3 , $p_{2,0}$, $p_{3,0} << p_2$ and $C_2 >> s$.

4. EXPERIMENTS

First, exact measurements of the internal capillary diameter by an optical microscope for metallographic research with the magnification till 1600^x have been made. This microscope was equipped by special optical micrometer with minimum scale division of 0,001 mm. Distance between two divisions was sufficiently large to divide it visually into five parts. The microscope was calibrated *in situ* by the standard glass marked scale whose uncertainty was of ± 0.0002 mm. The diameter was measured at both ends of the capillary in 8 directions. To minimize a random error 10 readings in each direction have been made. Deviations of readings from it average value did not exceed of 0.0002 mm. The ends of the capillary orifice had very sharp borders (see Fig. 2). Therefore, it was easy to coincide the orifice border with the microscope zero mark. Ellipticity of the capillary orifice was of 0,004 mm.



Figure 2 - The capillary orifice (magnified 300^x).

Difference between average internal diameters of the both capillary ends was of 0,002 mm. The exact measurements of the internal diameter of the capillary were very important because the diameter value is included as a fourth in Eq.3 and the corresponding error brings a large contribution to the uncertainty budget. An estimation of the non-uniformity of the capillary internal diameter has been carried out. One droplet of mercury was injected into the capillary. Here, it took up a columnar shape, as shown in Fig.3. Moving this column, we measured its length by an optical measuring microscope whose uncertainty was of ± 0.001 mm. Due to the convex form of the mercury meniscus and the transparency of the capillary glass it was easy to coincide exactly the optical microscope zero mark with the column ends.



Figure 3 - Measurement of the capillary internal diameter uniformity.

Column length fluctuations should correspond to internal diameter changes because the droplet volume is constant and liquid mercury is not compressible. No fluctuations were observed. Thin glass capillaries were fabricated by stretching of hot soft glass tubes with bigger diameter. Therefore, there were no reasons for any sharp deviations of geometric form and any optic distortions in the glass over the short section of the capillary. Thus, it was assumed that, in spite of the relatively long column of mercury (2-3 mm), the results of measurements were correct.

5. CALIBRATION APPARATUS

Two tension resistance diaphragm vacuum gauges (TDG) model SAPFIR 22DA (MANOMETR), full scale of 100 kPa and 1 kPa with errors of $\pm 0.25\%$ and $\pm 0.5\%$, respectively, have been used for measurement of the primary pressure p_1 in the range of $(10-10^5)$ Pa. This range was chosen to avoid any significant influence of the thermal transpiration [15] which is one of the most serious sources of errors inherent to reference diaphragm vacuum gauges with active thermal stabilization at pressures lower 10 Pa (BARATRON, BAROCELL, etc.). Using of a glass capillary in the transition flow regime in place of the first orifice allows the measuring range of the apparatus to be extended because the pressures p_2 scales with the power 2 of the pressure p_1 in accordance with Eq.1 and Eq.6. In other words, having a reference vacuum gauge with primary pressure range of $(10^2 - 10^5)$ Pa we can calibrate vacuum gauges in the range of $(10^{-5}-1)$ Pa. An absolute pressure piston manometer has been used for calibrations in situ of the diaphragm vacuum gauges. Thus, a primary pressure measurement uncertainty of about $\pm 0.1\%$ was achieved. The general view of the calibration chamber is presented in Fig. 4.

The chamber was made of stainless steel and has an internal diameter of 125 mm and length of 400 mm. The glass capillary has an average internal diameter of 0.1102 mm and length of 42.10 mm. The sealing of the capillary in the reference chamber was by a quick-connect coupling and is not shown in the figure. The only rubber element in the chamber is the gasket for the capillary seal. It was made of thermoresistant rubber IRP-2043 (Viton) with a working temperature up to 150°C. The rubber surface facing the calibration chamber is about 4 mm². The other gaskets were made of annealed cooper sheet. A small planar metal disk with the diameter of 30 mm was installed at a distance of 20 mm from the capillary exit end to dissipate the outflowing molecular beam. The orifice was fabricated of copper sheet with a thickness of 0.049 mm. It was a disk with 24 small orifices uniformly distributed on the disk plane. The diameter of the orifice was 1.500 mm. This design allows us to achieve a negligible deviation from the free molecular flow regime in the orifices up to a pressure of 1 Pa and to obtain a more homogeneous gas distribution in the cylinder calibration chamber. The disk was soldered to the cooper gasket situated between the calibration chamber and the pumping chamber.



Figure 4 - Calibration chamber.

The pump has a pumping speed of 500 $1.s^{-1}$ for N₂ and the ultimate pressure was 7.10^{-8} Pa. The calibration chamber was baked out at a temperature of 250°C. The installation was equipped with a monopole mass-spectrometer MX-7304A (SELMI) to measure the residual gas composition for calculation of the corresponding correction factor. The typical residual gas composition is shown in MX-7304A output diagram (Fig.5).

Total pressure was measured by a hot cathode vacuum gauge and it was of 3.10^{-6} Pa in nitrogen equivalent. The presence of water in the residual gas could be explained, probably, by outgassing of the rubber gasket. The massspectrometer analyzer casing was baked out using its own incorporated heater at a temperature of 150°C. This limit is established due to a secondary electron amplifier incorporated in the mass-spectrometer analyzer, whose bakeout temperature should not exceed of 105°C. The final pressure in the calibration chamber was lower than 10⁻⁶ Pa after baking out for 48 hours (without the MS analyzer). Using the developed apparatus [16] we could calibrate simultaneously up to 24 vacuum gauges in the range of $(10^{-5}-1)$ Pa by the continuous expansion method. This included 8 open-type vacuum gauges (or 7 gauges when the mass-spectrometer analyzer was connected to one port) and 16 closed-type vacuum gauges. Usually, they were hot-cathode vacuum gauge sensors with glass casings. The sensors were connected to the calibration chamber by quick-connect glass-to-metal adapters with an elbow. The sensors and the connecting glass tubes were baked out utilizing the heat energy from the sensor grid heaters by means of special thermal screens. The apparatus is connected to a computer for processing the gauge output signals and for calculation of the pressure p_2 values as well as the errors of the vacuum gauges being calibrated. The data acquisition system had a special controller to transform the analog outputs of old types vacuum gauges to the digital ones. The apparatus was employed by the Pump & Power Engineering Works "NEM" (Ukraine) to calibrate the vacuum gauges for vacuum pump testing. The installation of similar design also is used at Kharkov State Scientific Research Institute of Metrology (KSSRIM, Ukraine).



Figure 5 - Residual gas composition.

6. COMPARISON

A comparison between the present apparatus and the vacuum reference standard of State Research Center of the Russian Federation "D.I.Mendeleyev Institute for Metrology" (VNIIM, Russia) was carried out. The McLeod manometer (LEYBOLD, 0.5-100 Pa, $\pm 1.5\%$) and the hot cathode vacuum gauge VIO-1 (TOKAMAK, 7.10^{-9} - 10^{-1} Pa, $\pm 10\%$) served as transfer standards. Firstly, transfer standards had been calibrated on our apparatus. Then they were relocated to Russia and were calibrated on standards of VNIIM (McLeod manometer and continuius flow apparatus) at the same values of absolute pressure. Finally, transfer standards were returned to us and third calibration was fulfilled. The comparison results are presented in Fig. 6.

Relative errors δ were calculated by:

$$\delta = \frac{p_v - p_{oa}}{p_v} 100\% \tag{20}$$

where p_v is the pressure values obtained in VNIIM; p_{oa} – pressure values, obtained on our apparatus and averaged through first and third calibration. It is shown that there was some increase of the errors caused, probably, by the appearance of the intermediate flow regime in the orifice as well as the turbulent flow regime in the capillary at the upper limit of measurement range and by the increasing contribution of the residual pressure measurement uncertainty at the lower limit.



Figure 6 - Comparison results. Squares – hot cathode vacuum gauge as a transfer standard; rhombs – McLeod vacuum gauge as a transfer standard.

7. ANALYSIS OF UNCERTAINTY SOURCES

The pressures $p_{2,0}$ and $p_{3,0}$ are usually measured by the hot cathode reference vacuum gauge taking into account the residual gas composition and relative sensitivities of the vacuum gauge. The error of the gauge does not exceed of $\pm 10\%$ in the range of $(10^{-3}-10^{-7})$ Pa. This vacuum gauge and the mass spectrometer were calibrated using the apparatus mentioned above in the range of $(10^{-1}-10^{-5})$ Pa for nitrogen, hydrogen and carbon dioxide. The sensitivity values, obtained during the calibration, were extrapolated linearly up to a pressure of 10^{-7} Pa. The sensitivity values for water vapor were taken from the manual. Partial pressures of the residual gas components were determined from the mass-spectrometer data (see Fig. 4). It should be noted, that the term $(M/M_{res})^{1/2}$ in Eq.19 is equal to 1,68 and the contribution of the residual pressures values in the calibration result is larger due to the prevailing content of hydrogen in the residual gas composition. The pressures $p_{2,0}$ and $p_{3,0}$ are determined in accordance with the following equation:

$$p_{2,0} = \frac{p_{2,0\nu}}{p_{2,0ms}} \sum_{i=1}^{n} p_i \tag{21}$$

where $p_{2,0v}$ is the reading of the vacuum gauge in the nitrogen equivalent; p_i is the partial pressure of the residual gas components determined from the mass spectrometer data and $p_{2,0ms}$ is the vacuum gauge reading in the nitrogen equivalent obtained simultaneously with the mass spectrometer data. The molar mass of the residual gas is calculated according to the following equation:

$$M_{res} = \left(\sum_{i=1}^{n} p_i\right)^{-1} \sum_{i=1}^{n} p_i M_i$$
 (22)

where M_i is the molar mass of the residual gas components. The value of the vacuum gauge pumping speed was estimated using the special feature that, on the apparatus, one can calibrate a number of vacuum gauges simultaneously. For example, we calibrated 16 hot cathode vacuum gauges at a pressure of 4,0.10⁻³ Pa. Then, we switched off all the gauges. The reading of the vacuum gauge VIO-1 increased from p_{g1} =4,0.10⁻³ Pa to p_{g2} = 4,1.10⁻³ Pa. Considering the gas flows into the calibration chamber, we can derive, supposing that $p_2 >> p_3$:

$$s = C_2 (p_{g2} - p_{g1}) / 16 p_{g1}$$
(22)

Hence, $s \approx 8.10^{-6} \text{ m}^3 \text{s}^{-1}$. Notice, that this value is the average for the 16 gauges. However, it can be used as an estimation of the vacuum gauge pumping speed. The uncertainty budget of the proposed calibration apparatus, calculated in accordance with Eq.19 (2σ , quadratic addition), is presented in Table 1.

Table 1 - Uncertainty budget calculation.		
Source of uncertainty	Measuring value	Uncer-
		tainty ,%
TDG 100 kPa full scale	(1 – 100) kPa	0,5-0,1
TDG 1 kPa full scale	(0,01 – 1) kPa	1,0-0,2
Conductance C_I	$(0,0378-2,251).10^{-7} \text{ m}^3 \text{s}^{-1}$	0,66-0,96
Capillary diameter, d	(0,1102±0,0002) mm	0,23
Capillary length, l	(42,10±0,05) mm	0,06
Viscosity of gas, $\eta(N_2)$	(1,75±0,01).10 ⁻⁵ Pa.s	0,33
Molar mass of gas, M	$(28,0\pm0,1)$ g.mol ⁻¹	0,21
Temperature, T	(293±5) K	0,1
Conductance C_2)	$4,833.10^{-3} \text{ m}^3 \text{s}^{-1}$	0,21
Orifice diameter, D	(1,500 ±.0,005) mm	0,02
Orifice thickness, L	(0,049±0,001) mm	1,0
Coefficient K_3	1-1,029	<0,12
Pump inlet pressure p_3	(0,0002-8).10 ⁻³ Pa	5
Residual pressures $p_{2,0}$, $p_{3,0}$	(0,1-5).10 ⁻⁶ Pa	8
Gauge pumping speed s	$8.10^{-6} \text{ m}^3 \text{s}^{-1}$	10
Molar mass M_{res}	9,7 g.mol ⁻¹	5
Universal gas constant, R	8,31441 J.mol ⁻¹	0,002
Pressure p_2 (2 σ)	(5-250000).10 ⁻⁵ Pa	1,7-2,2

It should be noted that the conductances C_1 and C_2 were calculated at the temperature of 293K for nitrogen. The conductance C_2 value is presented without the contribution of the coefficient K_3 , which depends on the pressure p_2 (Eq.13). The value of K_3 is significant only at the upper limit of the measuring range and is taken into account in the uncertainty value calculation.

8. CONCLUSIONS

A long cylinder capillary has been proposed for use as the first orifice in the continuous expansion method. A gas flow regime varies in it from viscous at the entrance to free molecular at the exit. The capillary sizes and shape deviations have been measured.

An improved design of the second orifice made as a thin disk with a number of small circular holes uniformly distributed on the disk plane has been used.

A reference standard apparatus for vacuum gauge calibration has been constructed and a comparison between this apparatus and the reference standard apparatus of Russia has been made.

An analysis of uncertainty sources and a calculation of uncertainty budget have been carried out.

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10. REFERENCES

- 1. REDHEAD, P.A.; HOBSON, J.P.; KORNELSEN, E.V., *The physical basic of ultrahigh vacuum*. New York, AIP, 1993.
- JENKO, V.; POVH, B.; ŠETINA, J., *Vacuum* 46 (1995) 817.
 JOUSTEN, K.; MENZER, H.; WANDREY, D.;
- JOUSTEN, K.; MENZER, H.; WANDREY, D NIEPRASCHK, R., *Metrologia* 36 (1999) 493.
- BERGOGLIO, M.; CALCATELLI, A.; MARZOLA, L.; RUMIANO, G., *Vacuum* 38 (1988) 887.
- 5. GUTHRIE, A.; WALKERLING, R.K., *Vacuum equipment and techniques*. New York, McGraw Hill, 1949.
- 6. OCHERT, N.; STECKELMACHER, W., *Braz. J. Appl. Phys.* 2 (1951) 332.
- 7. ROTH, A., Vacuum 22 (1972) 219.
- 8. ZHITOMIRSKY, I.S.; POYMANOV, A.I., *Cryogenics and vacuum techniques* 3 (1973) 25 [in Russian].
- KUZ'MIN, V.V.; ODNORALOV, V.N., General and nuclear physics 1 (1980) 78 [in Russian].
- 10. KNUDSEN. M., Ann. Phys. 28 (1909) 75.
- 11. DUSHMAN, S., The scientific foundation of vacuum technology: New York: Wiley, 1962.
- 12. ZALMANZON, L.M., *Throughput elements of pneumatic devices for control and monitoring*, Moscow, Acad. Sci. USSR, 1961 [in Russian].
- 13. BERMAN, A.S., J. Appl. Phys. 36 (1965) 3356.
- 14. LIEPMANN, H.W., J. Fluid Mec. 10 (1961) 65.
- 15. POULTER, K.F.; RODGERS, M-J.; NASH, P.J.; THOMPSON, T.J.; PERKIN, M.P.; *Vacuum* 33 (1983) 311.
- ODNORALOV, V.N., Annals of Kiev Polytechnic Institute. Ser. Instrumentation 19 (1989) 10 [in Russian].
- 17. TISON, S.A., Vacuum 44 (1993) 1171.