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Measurement Standards of Ukraine for Gas Volume Flow Rate at Pressures of 1 MPa to 5 MPa

Rozhnov Mykhailo[1], Melnyk Dmytro[2], Levbarg Ovsii[3]

[1,2,3] SE «Ukrmetrteststandart»

E-mail: molar@ukrcsm.kiev.ua

Abstract

The characteristics of the primary measurement standards of the volume gas flow rate at high pressure developed in various countries are considered. A hierarchical scheme for gas flow measuring instruments and a corresponding metrological traceability chain are presented. Described is a PVTt method, on which the primary standards of gas flow rate used in the USA, France, Japan, and Taiwan are based. The need to create in Ukraine primary measurement standards of gas flow rate at high pressure covering different parts of the total flow rate interval from 0,3 m^3/h to 1800 m^3/h at a pressure of 1 MPa to 5 MPa is substantiated. Metrological traceability of gas flow measurements is realized through a sequence of critical flow Venturi nozzles, which play a role of the reference flow rate material measures. The standards might be used to calibrate the primary reference Venturi nozzles of the most common 0,1 mm to 8 mm diameters. The characteristics and parameters of the standards are determined. By their metrological and technical characteristics, the standards will correspond to the state-of-the-art level. According to the programme of developing the measurement-standard facilities in Ukraine, in 2019 the primary standard PVTt-65 was created and work had started on the development of the primary standard PVTt-1800 and the working standard PE-5400. A detailed study of the metrological characteristics of the measurement standards will be the topic of further work.

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1. Main body

The unity of gas flow rate measurements at high pressure is based on the metrological traceability of measurements that is realized through the sequence of critical flow Venturi nozzles, which play a role of reference flow rate measures[1].

Primary reference nozzles are calibrated using primary gas flow rate standards, which may be based on three principles: PVTt, volumetric and gravimetric. The characteristics of some primary standards of gas volume flow rate at high pressure based on these methods are given in Table 1. The generally accepted hierarchical scheme for the gas flow rate measuring instruments and the corresponding metrological traceability chain for the gas volume flow rate measurements at pressures up to 5 MPa are shown in Table 2.

Generally, the system of metrological traceability includes measurement standards, a set of measuring systems, and a set of measurement methods[2]. The measurement standards are the main components of the system. In 2016 a work has started in Ukraine to create a system of metrological traceability of measurements of the gas volume flow rate at high pressure from 1 MPa to 5 MPa based on critical flow Venturi nozzles that are used as flow rate material measures.

For primary measurement standards of gas volume and volume flow rate over the pressure range of 1 MPa to 5 MPa, the PVTt method is used. The method is insensitive to pressure fluctuations downstream of the nozzle in critical flow conditions and enables precisely determining the boundaries of the volume to be taken into account. In the course of calibration, gas passing through the nozzle over a measured time interval fills the evacuated collection vessel located downstream of the nozzle. The mass flow rate is calculated by multiplying the volume of the collection vessel by the change in gas density and dividing by

Table 1. *Primary measurement standards of gas volume flow rate at high pressure*

№	Name and location of the standard	Ref.	Year of commissioning and reconstruction	Pressure range, MPa	Flow rate range, m^3/h	Expanded uncertainty, %	Principle of operation	Working gases
1	PVTt 34 L, NIST, Gaithersburg, Maryland, USA	[3]	2002	0,1–7	0,06–6	0,03–0,045	PVTt, 34 L collection vessel	Safe gases
2	PVTt 677 L, NIST, Gaithersburg, Maryland, USA	[3]	2002	0,1–1,7	0,6–120	0,02–0,05	PVTt, 677 L collection vessel	Safe gases, natural gas
3	PVTt-PISCINE LNE-LADG, Alfortville, France	[4]	1970	0,6–5,5	9–9000	0,15–0,18	PVTt, 2070 L collection vessel	Natural gas
4	PVTt-M6, LNE, Poitiers, France	[5]	2008	0,3–6	6–10800	0,15	PVTt, 100 L, 2500 L collection vessels	Natural Gas, Air, Nitrogen
5	CMS, Hsinchu, Taiwan	[6]	2013	0,2–1	0,006–18	0,1	PVTt, 2 L, 30 L, 500 L collection vessels	Safe Gases
6	NMIJ, Tsukuba, Japan	[7]	2013	0,2–1	0,1–18	0,17	PVTt, 11000 L collection vessel	Air
7	Pigsar ™ Dorsten, Germany	[8]	1993	1,4–5	8-6500	0,16	250 mm diameter variable volume piston	Natural gas
8	CESAME LNE Ouest, Poitiers, France	[9]	2000	0,1–4	0,01-4	0,2	A piston in a closed loop	Natural gas, air
9	GET 118 -2013, VNIIR, Kazan, Russia (EU-4 installation)	[10]	2013	Up to 1	10–2300	0,11	Scales with pontoon, 1 m^3 gas tank	Natural gas, air

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the time of gas collection. The change in density is determined through the equations of state and the measured initial and final values of pressure and temperature.

Most of the available primary standards based on the PVTt method provide realisation of the gas volume flow rate unit at high pressure over the flow rate interval from 0,5 m^3/h to 10000 m^3/h and enable calibrating the primary reference critical flow nozzles with a throat diameter of 0,1 mm to 20 mm (see Tables 1 and 3).

In Ukraine, there is a pressing need to create primary standards that will realize the unit of gas volume flow rate over the range of 0,3 m^3/h to 1800 m^3/h at a pressure of 1 MPa up to 5 MPa to enable calibration of the primary reference critical nozzles with the most common 0,1 mm to 8 mm diameters (see Table 3). For these standards, we have to determine the

Table 2. *System of unity of the flow rate measurements for gas pressure up to 5 MPa*

Metrological level of the gas flow rate measuring instruments	Types of the gas flow rate measuring instruments	Relative expanded uncertainty U (coverage factor $k=2$)
Primary standards of the National Metrology Institutes	Primary standards for high-pressure gas: — gravimetric systems; — PVTt systems; — volumetric systems (e.g. HPPP in PTB); — indirect gravimetric systems.	(0,06…0,25) %
Working standards of the calibration service	Working standards for high-pressure gas: — turbine meters (e.g. in Pigsar); — ultrasonic meters; — critical nozzles.	(0,13…0,35) %
Working measuring instruments for gas metering	Working measuring instruments (except for domestic gas meters): — diaphragm meters; — turbine, ultrasonic, and rotary meters; — vortex meters.	(0,3…1) %

Table 3. *Air volume flow rate realised by the primary nozzles at an inlet pressure of 5 MPa and a temperature of 20 °C depending on the throat diameter*

d, mm	Q (20 °C, 0,1 MPa), m^3/h	d, mm	Q (20 °C, 0,1 MPa), m^3/h	d, mm	Q (20 °C, 0,1 MPa), m^3/h	d, mm	Q (20 °C, 0,1 MPa), m^3/h
0,01	0,002735	1	28,49	7	1400	14	5602
0,1	0,2822	1,5	64,15	8	1828	15	6431
0,15	0,6366	2	114,1	9	2314	16	7317
0,2	1,133	3	256,9	10	2857	17	8261
0,3	2,555	4	456,8	11	3458	18	9261
0,4	4,547	5	714,0	12	4115	19	10319
0,5	7,110	6	1028	13	4830	20	11434

d — nozzle throat diameter, Q (20 °C, 0,1 МПа) — volume flow rate reduced to a temperature of 20 °C and a pressure of 0,1 MPa.

The flow rate in Table 3 is calculated according to ISO 9300: 2005 [1].

pipe diameters that would provide sufficient capacity to transmit the required amount of gas. Data on the capacity of gas pipes of a 6 mm to 200 mm diameter at the inlet of the standard at a pressure of 0,1 MPa, 1 MPa, and 5 MPa for air flow velocity of 15 m/s are given in Table 4.

To calibrate nozzles with throat diameters of 0,1 mm to 8 mm, it is necessary to produce a gas flow rate of 0,3 m^3/h to 1800 m^3/h at a pressure of 1 MPa to 5 MPa and to ensure that the resulting expanded measurement uncertainty is not greater than 0,15 %.

It is almost impossible to produce the required gas flow for the full flow rate range of 0,3 m^3/h to 1800 m^3/h by the same technical means. Therefore, it is reasonable to divide the nozzles of the diameter ranging from 0,1 mm to 8 mm into two groups: the first one for the nozzles of a throat diameter of 0,1 mm to 1,5 mm (flow rate from 0,3 m^3/h to 65 m^3/h) and the second one for the nozzles of a throat diameter of 2 mm to 8 mm (flow rate from 114 m^3/h) to 1828 m^3/h). According to the nozzle grouping, two primary standards should be developed, and the pipes of 6 mm and 28 mm inner diameter may be used for the first standard and the second one, respectively.

Most of the metrological characteristics of the primary measurement standards of volume gas flow rate (standard deviation, uncorrected systematic error, standard and expanded uncertainty) are determined by experimental studies. When designing the standards, first the volume flow rate is specified, based on which the installation piping diameter for the standard (Table 4) and the diameter of the nozzles to be calibrated (Table 3) are determined.

At the same time, such important characteristics of the standards design as capacities of the collection vessel, gas source tanks, and gasholders, which depend on the maximum gas flow rate and are interrelated, can be determined only by considering the standards as an integral system and based on the experience of developing similar standards in other countries. The PVTt-principle standards of the USA and France that regularly participate in the international comparisons (and the latter has also taken part in realising harmonized European gas cubic meter for natural gas) were considered.

It is worth paying attention to the following characteristic ratios:

- the ratio of the maximum gas flow rate that can be reproduced by the standard, Q_{max}, to the capacity of the gas source V_s, from which the gas is supplied, Q_{max} / V_s;
- the ratio of Q_{max} to the capacity of the collection vessel V_{coll}, Q_{max} / V_{coll};

Table 4. *Pipe capacity for air at a flow velocity $v = 15 m/s$ depending on the diameter*

Pipe diameter *D*, m	Pipe cross-section area, S, 10^{-3}, m^2	Capacity $Q = S \cdot v$, m^3/h		
		p = 0,1 MPa	p = 1 MPa	p = 5 MPa
0,006	0,0282	1,5	15	75
0,01	0,0786	4,24	42,4	212
0,02	0,314	16,9	169	845
0,03	0,707	37,8	378	1890
0,04	1,26	67,8	678	3390
0,05	1,96	108	1080	5400
0,06	2,83	153	1526	7630
0,07	3,85	208	2077	10384
0,08	5,03	271	2713	13565
0,09	6,36	343	3434	17170
0,1	7,86	424	4239	21195
0,15	17,7	954	9536	47680
0,20	31,4	1696	16960	84780

- the ratio of the capacities of the gas source and the collection vessel, V_s / V_{coll}.

The ratio Q_{max} / V_s predetermines the ability to ensure that the required duration of the experiment is sufficient not only for the measurement itself but also for purging the entire gas circuit and establishing a steady gas flow in it. The ratio Q_{max} / V_{coll} determines the time of the actual measurement during the calibration of the nozzle, and this time should be sufficient so that the total measurement uncertainty does not exceed the target value. The ratio V_s / V_{coll} combines both criteria.

Table 5. *Characteristics of the primary PVTt flow rate standards of France, USA, and Ukraine*

№	Name of the standard	Name of the characteristic				Characteristic ratios		
		Pressure range, p, MPa	Flow rate range, Q, m^3/h	Collection vessel capacity, V_{coll}, m^3	Gas source capacity, V_S, m^3	V_S/V_{coll}	Q_{max} / V_S, h^{-1}	Q_{max} / V_{coll}, h^{-1}
1	PVTt-M6, LNE, France	0,3–6	6–10800	2,5	100	40	108	4320
2	PVTt-Piscine, LNE-LADG, France	0,6–5,5	9–9000	2,07	83	40	108,4	4348
3	PVTt 34 L NIST, USA	0,1–7	0,06–6	0,034	0,055	1,62	109	176,5
4	PVTt 677 L NIST, USA	0,1–1,7	0,6–120	0,677	1,1	1,62	109	177,2
5	PVTt-65, Ukraine	0,3–6	0,3–65	0,015	0,6	40	108,3	4333
6	PVTt-1800, Ukraine	1–6	100–1800	0,417	16,66	40	108	4320
7	PE-5400, Ukraine	1–6	6–5400	–	50	–	108	–

Table 6. *Characteristics of the Ukrainian standards of the gas volume flow rate at a pressure of 1 MPa to 5 MPa*

№	Metrological and technical characteristics	Measurement standard		
		PVTt-65	PVTt-1800	PE-5400
1	Flow rate range, m^3/h	0,3–65	100–1800	6–5400
2	Pressure range, MPa	0,3–6	1–6	1–6
3	Expanded uncertainty, %	0,1–0,2	0,1–0,2	0,3–0,5
4	Collection vessel capacity, V_{coll}, m^3	0,015	0,417	–
5	Gas source capacity, V_S, m^3	0,6	16,66	50

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Table 6. *Characteristics of the Ukrainian standards of the gas volume flow rate at a pressure of 1 MPa to 5 MPa (Continuation)*

№	Metrological and technical characteristics	Measurement standard		
		PVTt-65	PVTt-1800	PE-5400
6	Gasholder capacity, V_{gh}, m^3	0,2	5,5	16,6
7	Throat diameter of the nozzles to be calibrated at the standard, d, mm	0,1–1,5	2–8	0,1–14
8	Maximum gas pressure in the collection vessel, P_{coll}, MPa	6	6	6
9	Maximum gas pressure in the gasholder, P_{gh}, MPa	4	4	4
10	Maximum gas pressure in the gas source, P_s, MPa	15	15	15
11	Piping inner diameter, mm	6	30	50
12	Total power consumption of the electrical equipment, kW	30	600	600

It has been found that the ratio Q_{max} / V_s for all considered standards is (108 - 109) h^{-1}. The ratio Q_{max} / V_{coll} for the French standards is 4320 h^{-1}, and for the US standards it equals 177 h^{-1}. The ratio of capacities V_s / V_{coll} is equal to 40 for the French standards and 1,6 for the US standards.

According to the programme of developing the measurement-standard facilities in Ukraine, in 2019 the primary standard PVTt-65 was created and work had started on the development of the primary standard PVTt-1800 and the working standard PE-5400. The capacity of collection vessels and gas sources of the primary standards of Ukraine was determined through the above ratios, the values of which are close to the corresponding characteristics of the primary PVTt standards of France.

Characteristics of the US and French standards, as well as their established values for the Ukrainian standards, are given in Table 5.

Detailed characteristics of the Ukrainian standards are given in Table 6. Detailed technical description of the primary measurement standard may be found in [11].

2. Conclusions

1. In 2016 work has started in Ukraine to create a system of metrological traceability of the gas volume flow rate measurements at high pressure of 1 MPa to 5 MPa based on critical flow Venturi nozzles, which play a role of the reference flow rate material measures.

2. To cover the range of gas volume flow rate from 0,3 m^3/h to 5400 m^3/h at a pressure of 1 MPa to 5 MPa, it is necessary to create two primary measurement standards based on the PVTt method, one of which will be used to calibrate the critical flow nozzles of 0,1 mm to 1,5 mm diameter, and another one — to calibrate the nozzles of 1,5 mm to 8 mm diameter, as well as a working standard to calibrate working reference nozzles of 0,1 mm to 14 mm diameter.

3. By their metrological and technical characteristics the standards will correspond to the state-of-the-art level.

4. A detailed study of the metrological characteristics of the measurement standards will be the topic of further work.

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