Comparison of pVTt Methods Gas Flow Prover

Meng Tao, Wang Chi

Heat Division, National Institute of Metrology of China, No 18 Bei San Huan Dong Lu, Bei Jing, China, 100013

Abstract

We compared 20m^3 and 2m^3 facilities of pVTt methods gas flow primary prover (pVTt prover) in Flow lab of National Institute of Metrology of China (NIM). We used sonic critical venturi nozzle (sonic nozzle) as transfer standard. The flow points of comparison are about 100nm^3/h and 150nm^3/h. We completed four comparison tests whose results are considered acceptable, whereas we found there was a little systematic error between the two facilities.

Keywords: Comparison, pVTt methods, Nozzle

Foreword

The pVTt prover of flow lab of NIM is composed of three experiment facilities, which includes 20m^3 facility, 2m^3 facility and 0.2m^3 facility. They are divided by the volume of standard vessel. For checking the accuracy of pVTt prover, we organized this comparison between the 20m^3 and 2m^3 facilities at their flow joint.

1. Facilities of Comparison

The pVTt prover measures the state parameters of the gas in the standard vessel before and after air enters it. So we can get the mass of the air that enters the standard vessel by gas state equation. And we can calculate the mass flow of air by measuring its entering time. The principle of pVTt prover is shown in Figure 1.

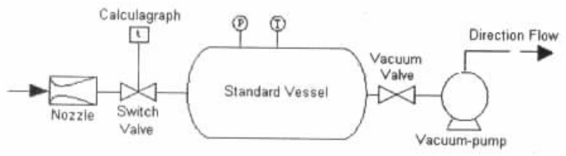

Figure 1. Schematic diagram of pVTt prover of NIM.

The mathematic model of gas mass flow that enters the standard vessel through sonic nozzle is

$$q_s = \frac{\frac{V\times T_n\times z_n\times \rho_n}{p_n}\times\left(\frac{p_b}{T_b\times z_b}-\frac{p_f}{T_f\times z_f}\right)\times[1+3\alpha(\theta-20)]-\Delta m}{t-\Delta t} \qquad (1)$$

Where ***V*** is the volume of standard vessel at 20℃, ***t*** is the time of air entering vessel, p_f, p_b, p_n , T_f, T_b, T_n , z_f, z_b, z_n are the gas's absolute pressure, temperature and compressibility factor in the vessel before and after air entering and air at standard state, ρ_n is the air's density at standard state, Δm is gas additional mass that relate to the structure of facility, Δt is the time of switching valve, α is the linear expansion factor of vessel's material, and θ is the temperature of vessel's surface.

The 20m^3 and 2m^3 facilities have different flow range, and they are shown in Table 1. The flow range of comparison is defined at the overlap part of two facilities.

Table 1. The flow range of pVTt prover.

Facilities	Flow Range（nm^3/h）
20 m^3	80 ~ 1550
2 m^3	8 ~ 155

2. Transfer Standard

Calibrating discharge coefficient of sonic nozzle is the main use of pVTt prover, therefore we chose sonic nozzle as transfer standard. As shown in Figure 2, the sonic nozzle has quite simple structure, small volume and not any movable sub-assemblies.

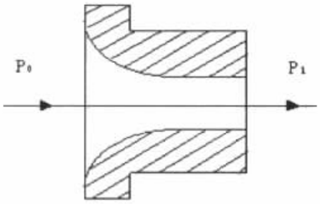

Figure 2. Schematic diagram of sonic nozzle.

If the ratio of upstream gas's pressure (p_0) and downstream gas's pressure (p_1) are less than critical pressure ratio, then the velocity of gas flow at throat of sonic nozzle reaches sonic speed. In ideal conditions, the mass flow of gas that passes through sonic nozzle is

$$q_{m_i} = \frac{A_* C_{*i} p_0}{\sqrt{RT_0}} \quad (2)$$

Where A_* is the area of section at sonic nozzle's throat, C_{*i} is the ideal gas critical flow function, p_0 and T_0 is the gas's stagnant absolute pressture and temperature at nozzle upstream, and R is the universal gas constant. But the mass flow of real gas (q_m) can be get that q_{mi} multiply coefficient C. Then the q_m is

$$q_m = \frac{A_* C C_* \, p_0}{\sqrt{RT_0}} \quad (3)$$

Where C_* is the real gas critical flow function. Therefore, the discharge coefficient, C is

$$C = q_m / q_{m_i} \quad (4)$$

Further more, replacing q_m with q_s in Formula 4, the discharge coefficient, C is

$$C = \frac{q_s}{\frac{A_* C_* P_0}{\sqrt{RT_0}}} = \frac{q_s \sqrt{RT_0}}{A_* C_* P_0} \quad (5)$$

According as definition flow range, we selected two sonic nozzles as transfer standard.

Table 2. Parameters of transfer standards.

Code of Transfer Standards	Diameter of Throat (mm)	Nominal Flow (nm^3/h)
8608#	12.444	104
8610#	15.071	153

3. Procedure

The comparison has two groups. Each group includes four tests that two transfer standards are tested on two facilities, i.e. two comparison tests are done in one group. The experimental method of the two groups is similar, but there is an interval between them. The second group not only is one part of result but also tests the stability of transfer standards.

In Jan 2004, we finished four tests of the first group, and the second was completed in March. The result of test is listed in Table3.

Table 3. The result of test.

Serial No.	Date	Facilties	Code of Transfer Standards	C	repeatability%	Group
6	2004-1-1	$20m^3$	8610	0.99096	0.006	Group 1
7	2004-1-2	$2m^3$	8610	0.98978	0.003	Group 1
8	2004-1-5	$2m^3$	8608	0.98299	0.009	Group 1
10	2004-1-7	$20m^3$	8608	0.98383	0.009	Group 1
12	2004-3-27	$2m^3$	8608	0.98304	0.022	Group 2
13	2004-3-27	$2m^3$	8610	0.99019	0.013	Group 2
14	2004-3-29	$20m^3$	8610	0.99089	0.017	Group 2
15	2004-3-30	$20m^3$	8608	0.98365	0.024	Group 2

4. Analysis

4.1 Effectiveness of Comparison Data

To guarantee the effectiveness of the comparison data, we compared the stability of transfer standards in the two groups. The same transfer standard was tested on the same facility for two times. If their results of test are similar, then we found satisfaction in the stability of them, and the result of comparison is believable.

Table 4. The relative difference between two groups.

Code of Transfer Standard	Facility	C		Relative Difference
		Group 1	Group 2	
8608#	2 m^3	0.98299	0.98304	0.005%
	20 m^3	0.98383	0.98365	-0.018%
8610#	2 m^3	0.98978	0.99019	0.041%
	20 m^3	0.99096	0.99089	-0.007%

As shown in Table 4, there are three relative differences are less than 0.02%, which are close to the average of single test repeatability. Only one is approximate 0.04%, but we think it is acceptable. On the whole, the transfer standards are steady, and the comparison data is believable.

4.2 Uncertainty of Calibration of Sonic Nozzle

We can analyze the uncertainty of calibration of sonic nozzle, i.e. uncertainty of calibration capability of pVTt prover from Formula 5. It is composed of six items that further details are available in [2]. The uncertainty of No.8 test is shown in Table 5 as an instance.

Table 5. The uncertainty of No.8 test.

Source of Uncertainty		Input Uncertainty (%)	Probability Distribution	Coverage factor	Standard Uncertainty of *y* $u_r(x_i)$ (%)	Sensitivity Coefficient $c_r(x_i)$	$c_r(x_i)u_r(x_i)$ (%)
q_s	pVTt Prover	0.05	Normal	2	0.025	1	0.025
R	Gas Universal Constant	0.03	Rectangular	$\sqrt{3}$	0.017	0.5	0.009
T_0	Gas's Temperature at Nozzle Upstream	0.034	Rectangular	$\sqrt{3}$	0.020	0.5	0.010
C_*	Critical Flow Function	0.002	Rectangular	$\sqrt{3}$	0.0012	1	0.0012
P_0	Gas's Absolute Pressure at Nozzle Upstream	0.02	Rectangular	$\sqrt{3}$	0.012	1	0.012
C	Repeatability of C	—	—	—	0.009	1	0.009

Combined Standard Uncertainty: u = 0.032%;

Expended Combined Uncertainty: U = 0.064%, k = 2

Because the value of *R* and C_* is same in data processing of comparison. We took out these two items when we calculated the combined standard uncertainty of test. The uncertainty of No.8 test is 0.031% by recalculated. Table 6 shows the uncertainty of all tests.

Table 6. The uncertainty of all tests.

		Serial No.	Facilities	C	Repeatability %	Standard Uncertainty (%)
Group 1	Comparison 1	Transfer Standard 8608#				
		8	2 m^3	0.98299	0.009	0.031
		10	20 m^3	0.98383	0.009	0.031
	Comparison 2	Transfer Standard 8610#				
		6	20 m^3	0.99096	0.006	0.030
		7	2 m^3	0.98978	0.003	0.030
Group 2	Comparison 3	Transfer Standard 8608#				
		12	2 m^3	0.98304	0.022	0.037
		15	20 m^3	0.98365	0.024	0.038
	Comparison 4	Transfer Standard 8610#				
		13	2 m^3	0.99019	0.013	0.032
		14	20 m^3	0.99089	0.017	0.034

The uncertainty of 20m^3 and 2m^3 facilities is same that they are both 0.025% (See [2] for more details about uncertainty analysis of pVTt prover). The difference of uncertainty mainly comes from the repeatability of calibration test.

4.3 Uncertainty of Comparison

We referred to the methods in [3] when we analyzed the uncertainty of comparison. The combined standard uncertainty of comparison is:

$$u_i = \sqrt{u^2_{i,2} + u^2_{i,20}} \qquad (6)$$

where u_i is the combined standard uncertainty of No.i comparison, and $u_{i,20}$ and $u_{i,2}$ are the standard uncertainty of transfer standard tests on 20m^3 and 2m^3 facilities of No.i comparison.

Table 7. The combined standard uncertainty of comparisons.

		Serial No.	Facilities	Standard Uncertainty of Test (%)	Combined Standard Uncertainty of Comparison (%)	Expanded Combined Uncertainty k=2 (%)
Group 1	Comparison 1	8	2 m^3	0.031	0.044	0.088
		10	20 m^3	0.031		
	Comparison 2	6	20 m^3	0.03	0.042	0.085
		7	2 m^3	0.03		
Group 2	Comparison 3	12	2 m^3	0.037	0.053	0.106
		15	20 m^3	0.038		
	Comparison 4	13	2 m^3	0.032	0.047	0.093
		14	20 m^3	0.034		

5. Result

The relative difference of discharge coefficient of transfer standards which has been tested on the different facilities is

$$\Delta_i = \frac{2(C_{i,20} - C_{i,2})}{C_{i,2} + C_{i,20}} \times 100\% \qquad (7)$$

where Δ_i is the relative differences of discharge coefficient of No.i comparison, and $C_{i,20}$ and $C_{i,2}$ are the discharge coefficient tested on $20m^3$ and $2m^3$ facilities of No.*i* comparison.

Table 8. The relative differences of discharge coefficient of four comparisons.

Comparison	Code of Transfer Standard	C: 2 m^3	C: 20 m^3	Relative Difference
1	8608#	0.98299	0.98383	0.085%
2	8610#	0.98978	0.99096	0.119%
3	8608#	0.98304	0.98365	0.062%
4	8610#	0.99019	0.99089	0.071%

The value of *En* is the criterion of this comparison project. The *En* is ratio of relative difference of discharge coefficient of comparison and expended combined uncertainty of comparison test (shown in Table 7).

$$En = \Delta_i / U_i \qquad (8)$$

$|En| < 1$—Acceptable, $|En| \geq 1$—Unacceptable.

Table 9. The value of *En*

Comparisons	1	2	3	4
En	0.974	1.404	0.585	0.757

The *En* of three comparisons is ideal. Only En of comparison 2 is more than 1. But we paid attention to the comparison 1; its En is very close to 1. We further analyzed the result with Figure 3.

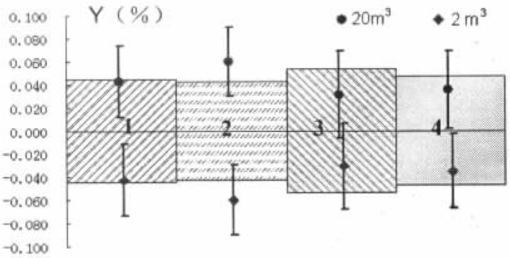

Figure 3. In the figure 3, the four comparisons are indicated by four rectangles. The length of rectangle on Y denotes expended combined uncertainty of comparison test. The symbol of roundness is the test on the $20m^3$ facility, and the symbol of diamond is the test on the $20m^3$ facility. The extended line of the symbol is the expended combined uncertainty of that test. One roundness and one rectangle indicate one comparison test. Their distance on Y is the relative difference of discharge coefficient. If they are both in their rectangle area, we can think this result of comparison is acceptable otherwise it is unacceptable.

We considered the most result of comparisons is acceptable. But we paid attention to the point that the all the values of *En* are more then zero in the Table 5-2 and all symbols of roundness are upon X axis in the Figure 3. So we thought that there was a little systematic error between $20m^3$ and $2m^3$ facilities. We need further research what caused the systematic error in future. More details and tables of numerical data are available from the authors.

References

[1] JJG620-94, Verification Regulation of Critical flow meter, CHINA METROLOGY PUBLISHING, 1995

[2] Chi Wang, Uncertainty Analysis of Flow Metrology, CHINA METROLOGY PUBLISHING, 2002

[3] Robert F Berg and Giorgio Cignolo, NIST-IMGC comparison of gas flows, METROLOGIA, INSTITUTE OF PHYSICS PUBLISHING, 2003

[4] NIM 8104 Project Team, Development Report of pVTt methods gas flow prover, 1985