The new pVTt facility in NIM

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Abstract

In NIM, the old 2 m³ and 20 m³ pVTt facilities were built in 1986. The temperature stability of the collection tank was easily influenced by the surroundings. So, the new 0.1 m³ and 2 m³ pVTt facilities were built in 2010. The collection tanks were covered with water bath. The uncertainty for the new pVTt facilities were analyzed, and the measurement capability was verified by comparisons among the new pVTt facility, the old pVTt facility and the gas flow facilities in PTB with 14 sonic nozzles.

1. Background

The gas meters are widely used in many fields, such as, energy, environment, medicine, and so on. Among the gas meters, there are many applications for sonic nozzles due to their accuracy, no moving parts and ease of use. When the working fluid is ideal gas and the flow can be assumed to be one dimensional and isentropic, the ideal maximum mass flow rate, q_{mi} can be expressed as[1],

$$q_{mi} = \frac{A_{th} C_* p_0}{\sqrt{R_u T_0 / M}} \qquad (1)$$

Where, A_{th} is the area of throat, m²; C_* is the critical flow function; p_0 is the stagnation pressure, Pa; T_0 is the stagnation temperature, K; R_u is the universal gas constant, J/kmol/K; M is the molecular mass, kg/kmol. In practice, the flow is not isentropic due to the viscous losses of the real gas and the three dimensional flow due to the nozzle geometry. Thus, the real mass flow rate, q_{mr}, is not equal to the ideal mass flow rate. The discharge coefficient, C_d is defined to relate the real mass flow rate to the ideal mass flow rate,

$$C_d = \frac{q_m}{q_{mi}} \qquad (2)$$

Discharge coefficient is an important parameter for sonic nozzle, which can determine by experimental measurement, theoretical calculation and numerical simulation.

Due to the unique characteristics, sonic nozzles frequently used as master meters to calibrate other kinds of gas meters. In China, the sonic nozzles are usually traceable to the pVTt primary standard facility of NIM to guarantee the measurement accuracy.

In NIM, there were three sets of pVTt facilities with nominal volume of 200 L, 2 m³ and 20 m³ respectively built in 1986. The working fluid was atmospheric air, and the flow range was (0.1~1300) m³/h. The collection tank was exposed in the atmospheric condition, which usually resulted in long time to reach the thermal equilibrium.

In NMIJ (National Metrology Institute of Japan)[2], the 13.4 m³ pVTt facility was the primary standard before 2002. The collection tank had a double wall, between which water

was filled and circulated intermittently to make the temperature distribution of the air in the tank highly uniform. In 2002, the smaller new one with nominal volume of 11.1 m³ was built to decrease the distortion of the volume at high pressure. The outer diameter, the outer length and the inner volume were about 1.8 m, 6 m and 11.1 m³, respectively. Four rings, four ferules and two crosswise plates were welded on the inside wall, between the two walls and on the inside wall at both ends, respectively to reinforce the tank and improve the heat exchange between the air in the tank and the inside wall. There were 24 Pt 100 thermometers sensors inside the collection tank to measure the temperature with high accuracy.

In NIST (National Institute of Standards and Technology, USA), there were three sets of pVTt facilities, whose nominal volumes were 34 L, 677 L and 26 m³ respectively. The 26 m³ pVTt facility was built more than 30 years ago, with uncertainty of 0.09% (*k*=2) after the technical improvement for the temperature measurement in the collection tank[3]. The new pVTt facilities with nominal volume of 34 L and 677 L were built in 2000 to improve the measurement capability for small flow rate[4]. The collection tank was immersed in a well-mixed, thermostatted, water bath. To avoid the long equilibration time, the 677 L tank was composed of eight, cylindrical, 2.5 m long, stainless steel shells connected in parallel by a manifold. Each shell had a wall thickness of 0.6 cm and an internal radius of 10 cm. After the collected gas equilibrated with the water bath, the gas temperature was determined by comparatively simple measurements of the temperature of the recirculating water. The water temperature measurements were made with 14 thermometers.

With the reference of pVTt facilities of NMIJ and NIST, in the end of 2010, the new 100 L and 2m³ pVTt facilities were built in NIM. In this paper, the uncertainty analyses and the experimental verification will be presented.

2. Designing scheme

The smallest flow rate for the old 200 L pVTt was 0.1 m³/h. To extend the small flow rate, the new 100 L pVTt facility was designed, whose smallest flow rate was 0.02 m³/h.

The 100 L pVTt facility is consisted of two, cylindrical, 1.6 m long, stainless steel shells in parallel. Each shell has a wall thickness of 1 cm and an internal radius of 10 cm. The 2 m³ pVTt facility is consisted of four, cylindrical, 2.5 m long, stainless steel shells in parallel. Each shell has a wall thickness of 1 cm and an internal radius of 25 cm. The wall of all cylinders is doubled, and the spacing between the walls is about 5 cm, which is filled with water. There are 4 PT 100 thermometers in 100 L pVTt facility to measure the temperature of the collection tank, which are 10 Pt 100 thermometers in 2 m³ pVTt facility. The systematic diagram is shown in Figure 1.
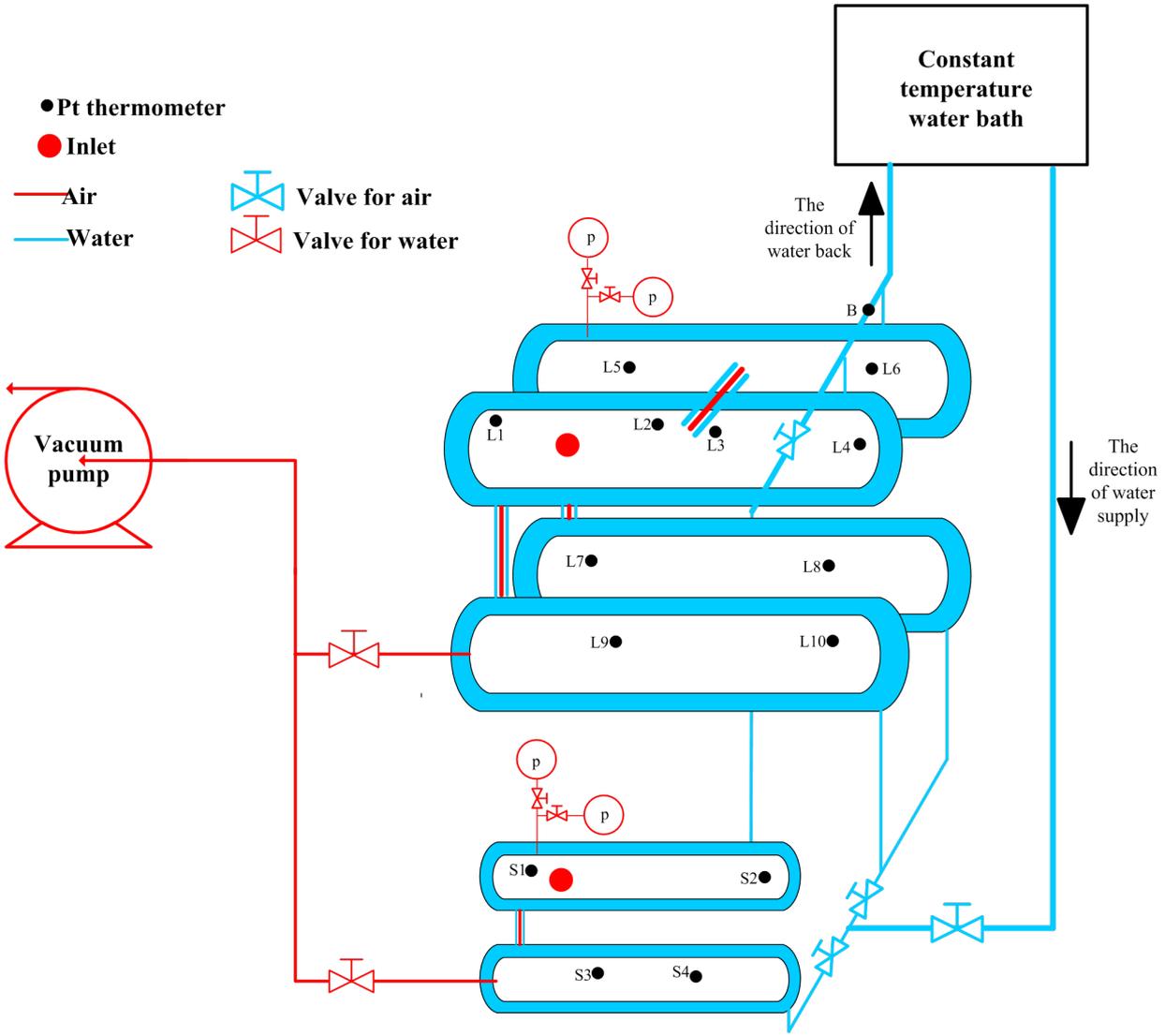
Figure 1   The systematic diagram of new pVTt facilities

The real flow rate through the sonic nozzle can be expresses as Equ. (3), when the critical flow is reached,

$$q_m = \frac{\dfrac{V M_{air}}{R_u}\left(\dfrac{p_f}{T_f z_f} - \dfrac{p_i}{T_i z_i}\right)[1+3\alpha(\theta-20)] - \Delta m}{t - \Delta t} \quad (3)$$

Where, V is the volume of the collection tank at 20℃, m³ ; M_{air} is the molecular mass, kg/kmol ; R_u is the universal gas constant, J/kmol/K ; p_i, p_f is the initial and final pressure in the collection tank, Pa ; T_i, T_f is the initial and final temperature in the collection tank, K ; z_i, z_f is the initial and final compressibility factor in the collection tank ; α is the linear expansive coefficient of the collection tank, ℃$^{-1}$; θ is the surface temperature of the collection tank, ℃ ; Δm is the mass in the inventory volume, kg ; t is the filling time, s ; Δt is the valve time, s.

When the working fluid is the atmospheric air, the humidity compensation is required, then, the discharge coefficient can be expressed,

$$C_d = \frac{k_{q_m} q_m}{k_{q_{mi}} q_{mi}} \quad (4)$$

Where, $k_{q_{mi}}$ is the modification factor for the ideal flow rate ; k_{q_m} is the modification factor for the real flow rate.

2.1 $k_{q_{mi}}$

The empirical equation from ISO 9300[1] is adopted,

$$k_{q_{mi}} = 1 + X_{CO_2}(0.25 + 0.04732\pi) + \varphi AB \quad (5)$$

2.2 k_{q_m}

The following equation is used to calculate, k_{q_m},

$$k_{q_m} = 1 - 0.37805 x_v \quad (6)$$

Where, $x_v = \phi p_s / p_0$, ϕ is the relative humidity; p_s , the saturated pressure calculated on the base of IAPWS-95[5], Pa; p_0 is the stagnation pressure, Pa.

3. Uncertainty analyses

When the working fluid is atmospheric air, the humidity modification is necessary for the real flow rate. On the base of Equ.(3) and (6), the uncertainty of the real flow rate is expressed as,

$$u_r(q_m k_{q_m}) = \left\{ \begin{array}{l} u_r(V)^2 + u_r(M_{air})^2 + u_r(R_u)^2 + u_r(t)^2 \\ + u_r(p_f)^2 + u_r(T_f)^2 + u_r(z_f)^2 + \\ (\frac{p_i}{p_f - p_i})^2 [u_r(p_i)^2 + u_r(T_i)^2 + u_r(z_i)^2] \\ + \dfrac{9\alpha^2}{[1+3\alpha(\theta-20)]^2}[(\theta-20)^2 u_r(\alpha)^2 + \\ \theta^2 u_r(\theta)^2] + [c_r(\Delta m)u_r(\Delta m)]^2 \\ + [c_r(\phi)u_r(\phi)]^2 + (\frac{\Delta t}{t-\Delta t})^2 u_r(\Delta t)^2 \end{array} \right\}^{0.5} \quad (7)$$

Where, $u_r(q_m k_{q_m})$ is the relative uncertainty of the real flow rate with humidity modification for pVTt facility ; $u_r(V)$ is the relative uncertainty of the volume of the collection tank ; $u_r(M_{air})$ is the relative uncertainty of the molecular mass of air ; $u_r(R_u)$ is the relative uncertainty of the universal gas constant ; $u_r(t)$ is the relative uncertainty of the filling time ; $u_r(p_f)$ is the relative uncertainty of the final pressure after filling the collection tank ; $u_r(T_f)$ is the relative uncertainty of the final temperature after filling the collection tank ; $u_r(Z_f)$ is the relative uncertainty of the final compressibility factor after filling the collection tank ; $u_r(p_i)$ is the relative uncertainty of the initial pressure after evacuating the collection tank; $u_r(T_i)$ is the relative uncertainty of the initial temperature after evacuating the collection tank ; $u_r(Z_i)$ is the relative uncertainty of the initial compressibility factor after evacuating the collection tank ; $u_r(\alpha)$ is the relative uncertainty of the linear expansive coefficient of the collection tank ; $u_r(\theta)$ is the relative uncertainty of the surface temperature of the collection tank ; $c_r(\Delta m)$, $u_r(\Delta m)$ are the sensitive coefficient and the relative uncertainty of the mass of the inventory volume respectively; $c_r(\phi)$, $u_r(\phi)$ are the sensitive coefficient and the relative uncertainty of the humidity respectively; $u_r(\Delta t)$ is the relative uncertainty of the valve time.

Because $u_r(V)$, and $u_r(\Delta m)$ are calculated from other measurements, the above two parts are introduced firstly. Then, the uncertainty of pVTt facility will be presented.

3.1 Volume of collection tank, $u_r(V)$

The volume of the collection tank is determined by the weighing of high purity nitrogen, which can be expressed as,

$$V = \frac{mR_u[1+3\alpha(\theta-20)]}{M_{N_2}(\dfrac{p_f}{T_f z_f} - \dfrac{p_i}{T_i z_i})} \quad (8)$$

Where, m is the mass of the nitrogen entering the collection tank, kg ; M_{N_2} the molecular mass of the nitrogen, kg/kmol ; p_i, p_f are the initial pressure after evacuating and the final pressure after filling the collection tank, Pa; T_i, T_f are the initial temperature after evacuating and the final temperature after filling the collection tank, K ;

z_i, z_f are the initial compressibility factor after evacuating and the final compressibility factor after filling the collection tank ; the meanings of the other parameters are the same as those in Equ. (3). So, the uncertainty of the collection tank is expressed as,

$$u_r(V) = \left\{ \begin{array}{l} u_R(V)^2 + u_r(M_{N_2})^2 + u_r(R_u)^2 + u_r(m)^2 \\ + u_r(p_f)^2 + u_r(T_f)^2 + u_r(z_f)^2 + (\dfrac{p_i}{p_f - p_i})^2 \\ [u_r(p_i)^2 + u_r(T_i)^2 + u_r(z_i)^2] + \\ \dfrac{9}{[1+3\alpha(\theta-20)]^2}[(\theta-20)^2 u_r(\alpha)^2 + \\ \alpha^2 u_r(\theta)^2] \end{array} \right\}^{0.5} \quad (9)$$

3.1.1 Repeatability, $u_R(V)$

The high purity nitrogen (99.999%) uses to calibrate the volume of the collection tank. Before the measurement, the collection tank is filled and evacuated by the nitrogen at least 3 times, which is the similar process as the nominal calibration for the discharge coefficient. The experimental results for 100 L pVTt facility are shown in Table.1. The average of the results is treated as the volume of the collection tank, and the standard deviation is treated as the repeatability.,

Table 1 The measurement results

SN	Measurements, V [m³]
1	0.11452818
2	0.11452991
3	0.11454453
4	0.11454825
5	0.11455469
6	0.11454279
Average	0.11454139
Standard deviation	0.01%

3.1.2 Molecular mass[6], $u_r(M_{N_2})$

It is 28.01348kg/kmol, and

$u_r(M_{N_2}) = \dfrac{0.02}{14.0067}\% = 14\,ppm$.

3.1.3 Universal gas constant[7], $u_r(R_u)$

According to the CODATA released in 2005, R_u is 8314.472 J/kmol/K， $u_r(R_u) = 1.7\,ppm$ 。

3.1.4 Mass, $u_r(m)$

The mass comparator adopts to measure the mass of the cylinder with nitrogen before and after filling the collection tank. The full scale is 64 kg, with 1 mg resolution. For the 2 m³ pVTt facility, the change of the mass for the cylinder is about 1kg, so, $u_r(m) = \dfrac{0.1}{1000 \cdot \sqrt{3}}\% = 0.06\,ppm$, when the distribution is assumed rectangular.

The volume of the cylinder is 40 L. The initial pressure in the cylinder is about 10 MPa, and the final pressure is about 7 MPa. The buoyancy change due to the volume change of the cylinder is not considered. On the base of

Wright et al's[4] research, the influence of buoyancy change is about 0.0035%. Finally, $u_r(m) = 0.0035\%$.

3.1.5 Pressure, $u_r(p_f)$, $u_r(p_i)$

The range of the pressure instrument is (0~0.1) MPa, the uncertainty is 0.01% for full scale. The final pressure is about 50 kPa, so, $u_r(p_f) = \dfrac{100 \cdot 0.01}{50\sqrt{3}} = 115\,ppm$, when the distribution is assumed rectangular.

The initial pressure is lower than 200 Pa, so,

$$u_r(p_i) = \frac{100 \cdot 0.01}{0.2 \cdot \sqrt{3}} = 2.89\% \quad \text{with sensitive coefficient,}$$

$$c_{p_i} = \frac{0.2}{50 - 0.2} = 0.004 \,.$$

3.1.6 Temperature, $u_r(T_f)$, $u_r(T_i)$

The Pt 100 thermometers are used to measure the temperature, which were calibrated at 0 ℃, 18 ℃, 20 ℃, 22 ℃, 24 ℃, 26 ℃, 28 ℃, 30 ℃ with standard Pt thermometer and water bath. According to the resistant characteristics of the Pt thermometer, the following regression uses to calculate the real temperature,

$$T = a_4 \left(\frac{R}{R_0}\right)^4 + a_3 \left(\frac{R}{R_0}\right)^3 + a_2 \left(\frac{R}{R_0}\right)^2 + a_1 \left(\frac{R}{R_0}\right)^1 + a_0 \quad (10)$$

Where, T is the measured temperature, ℃ ; R , R_0 are the measured resistance and the resistance at 0 ℃ ; a_0 , a_1 , a_2 , a_3 and a_4 are the coefficients calculated from the calibration results.

① **Standard facility**

The multi path digital thermometer instrument is used to calibrate the thermometer. The uncertainty of the instrument is 5 mK (k=2).

② **Regression equation**

The maximum deviation between the calculation results from Equ. (10) and the experimental results is 4 mK, which is treated as the uncertainty of the regression equation 4 mK (k=2).

③ **Data acquisition system**

The Keithley 2700 multi function data acquisition system is used to measure the resistance of the Pt 100 thermometer with 4 wires, which has 6.5 resolution. The change of 0.4 Ω resistance will result in 1℃ temperature change. So, the resolution effect on the temperature is about 10 mK (k=2).

On the other hand, the power supply of the data acquisition system itself is used, which has the fluctuation during measurement. The stability effect of power supply on the temperature measurement is estimated as 50 mK (k=2).

④ **Environment effect**

The water bath is used to control the temperature in the collection tank. Because the room mounted the pVTt facility is relative big to the facility itself. Although the air condition is used to control the room temperature, the room temperature is not exactly fixed.

The environment temperature effect is evaluated on the base of the experimental result. When the atmospheric temperature, T_a changes, the temperature in the collection tank which is the average of 10 Pt 100 thermometers for 2 m³ pVTt facility, T will change. The typical relationship is shown in Figure 2.

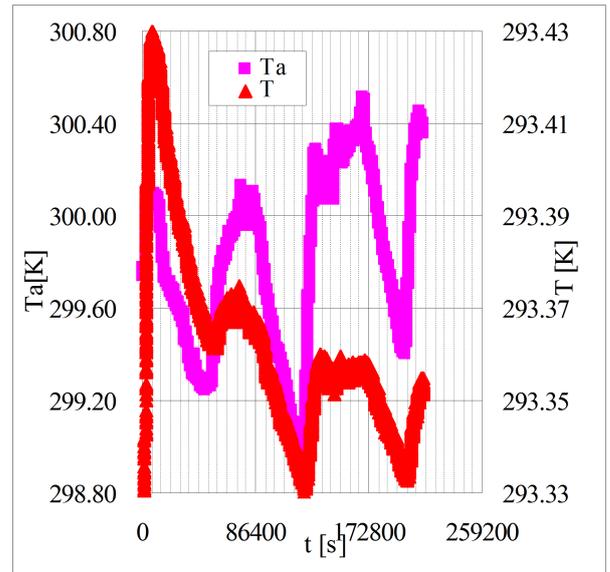
Figure 2　The environment temperature effect

After filling the collection tan, it usually takes about 100 minutes to reach the thermal equilibrium. In about 2.5 days, the change of T_a is within in 2 ℃, while the change of T is within 0.1 ℃ after 100 minutes. it takes about 2.5 hours for one point calibration. During the calibration process, the change of T_a is within in 0.4 ℃. So, the environment temperature change effect on the temperature of collection tank is estimated as 20 mK (k=2).

In a summary, the total uncertainty of the temperature measurement is 89 mK (k=2). The temperature of the collection tank is fixed at 20 ℃, so, the relative uncertainty of temperature measurement,

$$u_r(T_f) = u_r(T_i) = \frac{0.89}{293.15 \cdot 2}\% = 152\,ppm \,.$$

3.1.7 Compressibility factor[6], $u_r(z_f)$, $u_r(z_i)$

According to reference, $u_r(z_f) = u_r(z_i) = 10\,ppm$.

3.1.8 Surface temperature, $u_r(\theta)$

The similar thermometer as that in the collection tank is used to measure the surface temperature of the tank, so, $u_r(\theta) = \dfrac{0.89}{293.15 \cdot 2}\% = 152\,ppm$, the sensitive coefficient,

$$c_\theta \approx \frac{3\alpha\theta}{1 + 3\alpha(\theta - 20)} = 0.01 \,.$$

3.1.9 Linear expansive coefficient, $u_r(\alpha)$

According to the thermal physical property of the material of the collection tank, the coefficient is 17.3×10^{-6} ℃⁻¹[8]. The uncertainty is estimated as, $u_r(\alpha) = 5\%$ [9]. The temperature of the water bath is fixed 20 ℃. The surface temperature of the collection tank is the same as the temperature of the air in the tank. The difference between the expected 20 ℃ and the real temperature is within 0.1℃. The sensitive coefficient,

$$c_\alpha \approx \frac{3\alpha(\theta - 20)}{1 + 3\alpha(\theta - 20)} = 5.2 \times 10^{-6} \,.$$

In a summary, the components of the relative uncertainty of the collection tank are listed in Table 2.

Table 2　The uncertainty of the collection tank

SN	Symbols	Source	$u_r(x_i)$ [%]	$c_r(x_i)$ [/]	$c_r(x_i) \cdot u_r(x_i)$ [%]
1	$u_R(V)$	Repeatability	0.01	1	0.0100
2	$u_r(M_{N_2})$	Molecular mass of nitrogen	0.00143	1	0.0014
3	$u_r(R_u)$	Universal gas constant	0.00017	1	0.0002
4	$u_r(m)$	Mass of nitrogen	0.00408	1	0.0041
5	$u_r(p_f)$	Final pressure after filling	0.01155	1	0.0115
6	$u_r(T_f)$	Final temperature after filling	0.01518	1	0.0152
7	$u_r(z_f)$	Final compressibility factor after filling	0.001	1	0.0010
8	$u_r(p_i)$	Initial pressure after evacuating	2.88675	0.00402	0.0116
9	$u_r(T_i)$	Initial temperature after evacuating	0.01518	0.00402	0.0001
10	$u_r(z_i)$	Initial compressibility factor after evacuating	0.001	0.00402	0.0000
11	$u_r(\theta)$	Surface temperature	0.01518	0.01	0.0002
12	$u_r(\alpha)$	Linear expansive factor	5	0.000005	0.0000
Combined standard uncertainty, $u_r(V)$=0.0249%					

3.2 Mass of the inventory volume, $u_r(\Delta m)$

The mass of the inventory volume, Δm can be expressed as,

$$\Delta m = \frac{M_{air}\Delta V}{R_u}(\frac{p_{inv,i}}{T_{inv,i}z_{inv,i}} - \frac{p_{inv,f}}{T_{inv,f}z_{inv,f}}) \qquad (11)$$

Where, ΔV is the volume of the inventory volume between sonic nozzle and valve, m^3 ; M_{air} is the molecular mass of air, kg/kmol ; $p_{inv,i}$, $p_{inv,f}$ are the initial and final pressure in the inventory volume, Pa ; $T_{inv,i}$, $T_{inv,f}$ are the initial and final temperature in the inventory volume, K ; $z_{inv,i}$, $z_{inv,f}$ are the initial and final compressibility factor in the inventory volume. The meanings of other parameters are the same as former. So, the relative uncertainty, $u_r(\Delta m)$ can be expressed as,

$$u_r(\Delta m) = \left\{ \begin{array}{l} u_r(\Delta V)^2 + u_r(M)^2 + u_r(R_u)^2 + \\ (\frac{p_{inv,i}}{p_{inv,i} - p_{inv,f}})^2[u_r(p_{inv,i})^2 + u_r(T_{inv,i})^2 \\ + u_r(z_{inv,i})^2] + (\frac{p_{inv,f}}{p_{inv,i} - p_{inv,f}})^2[u_r(p_{inv,f})^2 \\ + u_r(T_{inv,f})^2 + u_r(z_{inv,f})^2] \end{array} \right\}^{0.5} \qquad (12)$$

3.2.1　Volume of the inventory volume, $u_r(\Delta V)$

The vernier calliper with uncertainty of 0.02 mm (k=2) is used to measured the geometry of the inventory volume. For 2 m^3 pVTt facility, the inventory volume is almost cylinder. The length of the cylinder is about 108 mm, while the diameter is about 50 mm. So,

$\Delta V = \frac{\pi d^2 L}{4} = 0.00021206 m^3$. Although the uncertainty for the vernier calliper is 0.02 mm (k=2), the uncertainty for the geometric measurement is estimated 0.1 mm (k=2) with consideration of the irregular shape. So,

$u_r(d) = \frac{5}{50}\% = 0.1\%$; $u_r(L) = \frac{5}{108}\% = 0.05\%$, then,

$u_r(\Delta V) = \sqrt{[2u_r(d)]^2 + [u_r(L)]^2} = 0.20529\%$.

3.2.2　Molecular mass of air[10]，$u_r(M_{air})$

The molecular mass is 28.9653 kg/kmol, the uncertainty is $u_r(M_{air}) = 32 ppm$.

3.2.3　Pressure, $u_r(p_{inv,i})$ ， $u_r(p_{inv,f})$

There is a pressure instrument in the inventory volume to measure the pressure. The range of the pressure instrument is (0～0.31) MPa, and the uncertainty is 0.01% for full scale. The initial pressure and final pressure are about 100 kPa and 50 kPa respectively, so,

$u_r(p_{inv,i}) = \frac{310 \cdot 0.01}{100\sqrt{3}} = 179 ppm$,

$u_r(p_{inv,f}) = \frac{310 \cdot 0.01}{50 \cdot \sqrt{3}} = 358 ppm$, when the distribution is assumed rectangular.

3.2.4　Compressibility factor[6]，$u_r(z_{inv,i})$ ， $u_r(z_{inv,f})$

According to the reference,

$u_r(z_{inv,i}) = u_r(z_{inv,f}) = 10 ppm$.

The relative uncertainty for the mass of the inventory volume are shown in Table 3,

Table 3　The uncertainty of the mass of the inventory volume

SN	Symbols	Source	$u_r(x_i)$	$c_r(x_i)$	$c_r(x_i) \cdot u_r(x_i)$
			[%]	[/]	[%]
1	$u_r(\Delta V)$	Volume	0.20529	1	0.2053
2	$u_r(M_{air})$	Molecular mass of air	0.0032	1	0.0032
3	$u_r(R_u)$	Universal gas constant	0.00017	1	0.0002
4	$u_r(p_{inv,i})$	Initial pressure	0.01790	2	0.0358
5	$u_r(T_{inv,i})$	Initial temperature	0.01518	2	0.0304
6	$u_r(z_{inv,i})$	Initial compressibility factor	0.001	2	0.0020
7	$u_r(p_{inv,f})$	Final pressure	0.00358	1	0.0036
8	$u_r(T_{inv,f})$	Final temperature	0.01518	1	0.0152
9	$u_r(z_{inv,f})$	Final compressibility factor	0.001	1	0.0010
	Combined standard uncertainty, $u_r(\Delta m)$=0.2112%				

3.3 pVTt facility, $u_r(q_m k_{q_m})$

The uncertainty for pVTt facility is expressed in Equ. (7). Besides the volume of collection tank and the mass of inventory volume, the other components are discussed in the following part.

3.3.1 Filling time, $u_r(t)$

The uncertainty of the timer is 0.1 ms with rectangular distribution, and the shortest time for filling is 30 s. So,

$$u_r(t) = \frac{0.01}{30\sqrt{3}}\% = 1.9\,ppm .$$

3.3.2 Valve time, $u_r(\Delta t)$

The geometrical middle of the valve is chosen as the trigger to start or stop the timer. The process for the opening and closing is not absolutely asymmetry. So, the time of the opening and closing is measured, and the difference between them treated as the valve time. According to the measurement result, this value is estimated as 5 ms with consideration of the long stability of the timer. The shortest time for the filling time is 30 s, so, the sensitive coefficient,

$$c_{\Delta t} = \frac{5}{30000 - 5} = 0.00017 .$$

3.3.3 Mass of the inventory volume, $u_r(\Delta m)$

For 2 m³ pVTt facility, $\Delta V = \frac{\pi d^2 L}{4} = 0.00021206 m^3$,

so, the sensitive coefficient, $c_{\Delta V} = 0.00011$.

3.3.4 Humidity, $u_r(x_v)$

The uncertainty for the humidity measurement is 5%,

$u_r(\phi) = \frac{5}{\sqrt{3}}\% = 2.887\%$, when the distribution is assumed rectangular. The Equ.(6) is adopted to make the humidity modification. When the $x_v = \phi p_s / p_0$ is adopted into Equ. (6), then,

$$k_{q_m} = 1 - 0.37805 x_v = 1 - 0.37805 \phi \frac{p_s}{p_0} \qquad (13)$$

When $p_0 = 101325\,pa$, $T_0 = 293.15K$, $\phi = 50\%$, the sensitive coefficient $c_r(\phi) = 0.00044$.

3.3.5 Leak, $u_r(leak)$

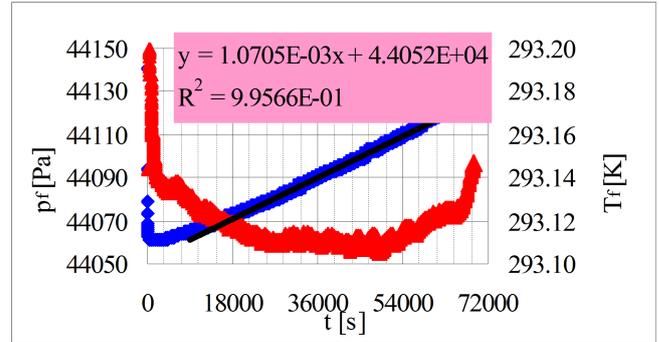There is leak for the pVTt facility, which can be observed in Figure 3.

Figure 3 The leak measurement for 100 L pVTt facility

From Figure 3, it is clear that the temperature change is within 40 mK after 40 minutes, but the pressure almost continuously linear increases after thermal equilibrium.

When the leakage rate is measured at different final pressure, the relationship between the leakage and the pressure can be gotten, which can be used to compensate the leakage at the different initial pressure and final pressure.

For two facilities, the leakage measurement are shown in Figure 4,

(a) 100 L pVTt facility

$$y = -1.9801\text{E-}09x + 9.6060\text{E-}05$$
$$R^2 = 7.3572\text{E-}01$$
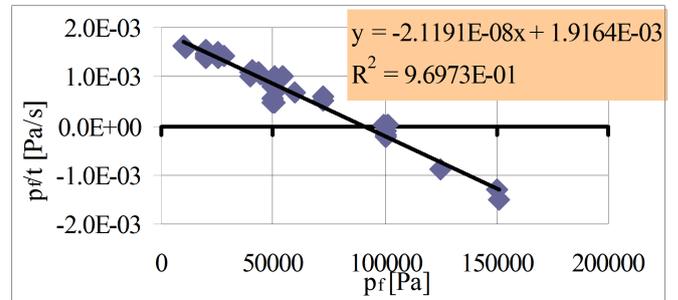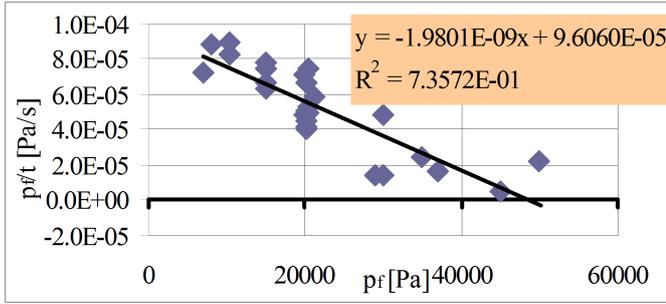
(b) 2 m³ pVTt facility

Figure 4   The leakage measurement results

According to the leakage measurement, the maximum leakage rate is about 0.1 sccm for the pVTt facility when the final pressure is 0 Pa.
1) For the 2 m³ pVTt facility, the flow range is (2~100) m³/h, the leakage effect can be neglected ;
2) For 100 L pVTt facility, the flow range is (0.02~5) m³/h, the ratio of leakage to the smallest flow rate is 50 ppm. So, the leakage effect is estimated 0.01% for 100 L pVTt facility.

In a summary, the uncertainty for the pVTt facility is shown in Table 4.

Table 4   The uncertainty of pVTt facility

SN	Symbols	Source	$u_r(x_i)$	$c_r(x_i)$	$c_r(x_i) \cdot u_r(x_i)$
			[%]	[/]	[%]
1	$u_r(V)$	Volume	0.02486	1	0.0249
2	$u_r(M_{air})$	Molecular mass of air	0.0032	1	0.0032
3	$u_r(R_u)$	Universal gas constant	0.00017	1	0.0002
4	$u_r(t)$	Filling time	0.00019	1	0.0002
5	$u_r(\Delta t)$	Valve time	1	0.00017	0.0002
6	$u_r(p_f)$	Final pressure in the collection tank	0.01155	1	0.0115
7	$u_r(T_f)$	Final temperature in the collection tank	0.01518	1	0.0152
8	$u_r(z_f)$	Final compressibility factor in the collection tank	0.001	1	0.0010
9	$u_r(p_i)$	Initial pressure in the collection tank	2.886751	0.00402	0.0115
10	$u_r(T_i)$	Initial temperature in the collection tank	0.015180	0.00402	0.0001
11	$u_r(z_i)$	Initial compressibility factor in the collection tank	0.001	0.01215	0.0000
12	$u_r(\theta)$	Surface temperature	0.01518	0.01	0.0002
13	$u_r(\alpha)$	Linear thermal expansive coefficient	5	0.000005	0.0000
14	$u_r(\Delta m)$	Mass of the inventory volume	0.211	0.01060	0.0022
15	$u_r(x_v)$	Humidity	2.887	0.00044	0.0013
16	$u_r(leak)$	Leak	/	/	0.0000

Combined standard uncertainty, $u_r(q_m)$ =0.036% ;

Combined expanded uncertainty, $U_r(q_m)$ =0.07%(k=2)

For 100 L pVTt facility, the working fluid can be atmospherically air or compressed air. The maximum pressure can be 0.6 MPa for the compressed air. The maximum pressure in the collection tank is 150 kPa, then, the full scale of pressure instrument is 160 kPa. For the pressure instruments of stagnation pressure and the pressure for inventory volume, the full scale of the pressure instrument is 690 kPa. Finally, the uncertainty for 100 L pVTt facility is 0.09% (k=2).

4   **Experimental verification**

Since 2010, the experimental verification for the new pVTt facilities were conducted. The information on the sonic nozzles are shown in Table 5.
1) For 2 m³ pVTt facility within (2~105) m³/h, 10 sonic nozzles with throat diameter of (1.920~13.674) mm were chosen to make the experiments between the new pVTt and old pVTt, and the new pVTt and bell prover in PTB ;
2) For 100 L pVTt facility within (0.02~5) m³/h, 5 sonic nozzles with throat diameter of (0.1961~3.030) mm were chosen to make the experiments between the new pVTt facility and the gas flow facilities in PTB.

Table 5   The sonic nozzles

SN	Throat diameter	SN	Throat diameter
[/]	[mm]	[/]	[mm]
620	0.1961	8603	7.002
623	0.4944	8604	7.982
625	0.9970	8605	9.0855
9903	1.920	8606	9.936

9902	3.030	8607	11.032
8601	4.025	8608	12.444
8602	5.909	8609	13.674

The uncertainties of throat diameter, d, universal gas constant, R_u, molecular mass, M and critical flow function, C_* calculated by the empirical equation from ISO 9300 [1] are not considered. So, the uncertainty of the discharge coefficient can be expressed as,

$$u_r(C_d) = \left\{ \begin{array}{l} u_r(q_m)^2 + u_r(p_0)^2 + 0.25u_r(T_0)^2 \\ +[c_r(k_{m_i})u_r(k_{m_i})]^2 + u_r(R)^2 \end{array} \right\}^{0.5} \quad (14)$$

Where, $u(k_{m_i})$ is the uncertainty of the humidity modification for ideal flow rate which is calculated by the empirical equation from ISO 9300 ; $u(R)$ is the repeatability. The uncertainty analyses of discharge coefficient for 2 m³ pVTt facility is shown in Table 6.

Table 6　The uncertainty of discharge coefficient

SN	Symbols	Source	$u_r(x_i)$	$c_r(x_i)$	$c_r(x_i) \cdot u_r(x_i)$
			[%]	[/]	[%]
1	$u_r(q_m)$	pVTt facility	0.0336	1	0.0337
2	$u_r(p_0)$	Stagnation pressure	0.00635	1	0.0064
3	$u_r(T_0)$	Stagnation temperature	0.01518	0.5	0.0076
4	$u_r(k_{m_i})$	Humidity effect	-	-	0.0200 *
5	$u_r(R)$	Repeatability	0.03	1	0.0300

Combined standard uncertainty, $u_r(C_d)$ =0.050%

Combined expanded uncertainty, $U_r(C_d)$ =0.10%(k=2)

* Note : besides the humidity instrument effect, the absorption of water in the surface of the collection tank and the condensation of water in the inventory volume are considered as the humidity effect, which can be found in Ref. [11] in detail.

For 100 L pVTt facility, the uncertainty of the discharge coefficient, $U_r(C_d)$ =0.15% (k=2).

The value of En is used to evaluate the consistence of the comparison,

$$En = \frac{C_{d,1} - C_{d,2}}{\sqrt{u_{C_{d,1}}^2 + u_{C_{d,2}}^2}} \quad (15)$$

Where, the foot mark 1, 2 express the different facilities. When $|En| \leq 1$, the facilities are consistent. The comparison results are shown in Figure 5 and 6.
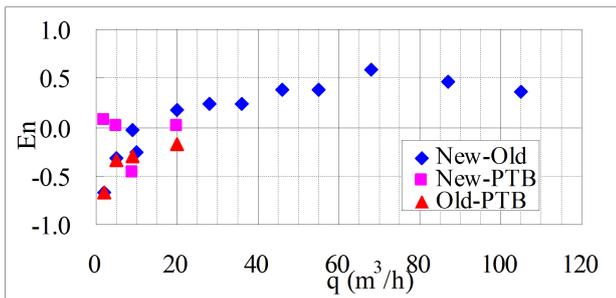

Figure 5　For 2 m³ pVTt facility

From figure 5, it is clear that all the values of En are all smaller than 1, which means the results are consistent.

For 100 L pVTt facility, the compressed air with the maximum pressure 600 kPa is used to make the comparison, besides the atmospheric air. In Figure 6, the green line is $En = 1.0$, which means the results are consistent. The red line is $En = 1.2$, which is treated as the critical line.

There are two points for the maximum volumetric flow rate 5 m³/h $En > 1.5$. The filling time is smaller than 30 s for the maximum flow rate, when the stagnation pressure high than 100 kPa, which results in the failing of the

comparison. The detail results and analyses can be found in Ref. [12].
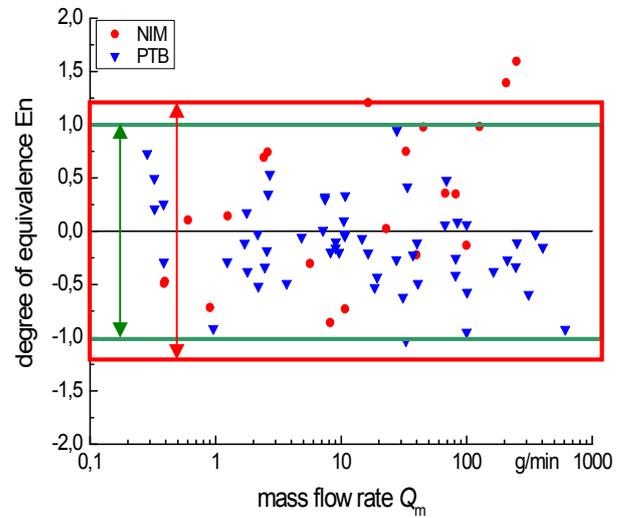

Figure 6　For 100 L pVTt facility

5　Conclusions

The uncertainty analyses for new pVTt facility were presented in this paper, mainly taking 2 m³ pVTt facility as example. According to the uncertainty analyses, the uncertainty for 2 m³ pVTt facility is 0.07% (k=2), while it is 0.09% (k=2) for 100 L pVTt facility.

There were 14 sonic nozzles chosen to make the comparisons among the new pVTt facility, old pVTt facility and gas flow facilities in PTB. The measurement capabilities for the new pVTt facilities were proved by the good consistence of the comparison results.

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