The high pressure sonic nozzle gas flow standard facility in NIM

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Abstract

The high pressure sonic nozzle gas flow facility in China was built in NIM at the end of 2014. There were 16 sonic nozzles used as the reference meters in the facility. The flow range is within (2~400) m³/h, while the pressure range is within the (190~2500) kPa. The sonic nozzles were traceable to the pVTt primary standard facility in NIM. To cover the pressure range, the curve fitting between discharge coefficient and Reynolds number was made for each sonic nozzle. To decrease pressure measurement uncertainty, there is an absolute pressure instrument in the manifold in the upstream of the MUT. The expanded uncertainty of meter factor for meter under test (MUT) is 0.15% (k=2). To verify the uncertainty of the sonic nozzle facility, a comparison between NIM and PTB was made with three Dn 100 turbine meters as transfer meters. The three turbine meters were calibrated by PTB in 2013 with natural gas, which were calibrated in NIM in 2016 and recalibrated in 2017~2018 with dry air. On the base of the good consistency of the comparison results, the uncertainty and the measurement capability of the sonic nozzle facility were verified.

1. Introduction

The coal is the main primary energy source in China, which takes about 70% among all the primary energy consumption. Due to the heavy air pollution resulted from the combustion of coal, the natural gas was more and more widely utilized in China. The annual increase of natural gas consumption had been more than 10%, since 2000. The total consumption was 240.4 billion m³ in 2017, which took about 6.6% among all the primary energy consumption [1].

With the fast development of natural gas, the requirement on the calibration for the high pressure gas flowmeter was increased for the fair of the trade, especially for the natural gas field. The first natural gas station was built in China at Chengdu in 1994. Now, there are 3 natural gas stations with whole transfer chain including primary standard, secondary standard and working standard, respectively located in Chengdu, Nanjing and Wuhan. In the available natural gas station in China, the natural gas supply is coming from the bypass of the main pipeline. Due to the pressure is different for each station, there was no formal domestic comparison for high pressure gas flow. So, the

value of quantity for the high pressure gas was not consistent until now.

As the national institute of metrology of China (NIM), there were only atmospheric pressure air facility before 2010. To meet the requirement of the high accurate calibration for the high pressure gas flowmeter and achieve the value of quantity consistent for the high pressure gas flow in China, the designing of high pressure gas system in NIM was started in 2010. With consideration of the traceability for the value of quantity the economics, the maximum pressure was fixed at 2.5 MPa, and the whole system was consisted with 3 sections.

➢ **Primary standard**
The pVTt facility with nominal volume of collection tank 100 L and 2 m³ was treated as the primary standard. With the limit of the pressure resistance grade of the collection tank, the flowrate for the facility was within (0.019~1367) kg/h, with the best measurement capabilities 0.08% (k=2), which was verified with the comparison among PTB, LNE, NIST and NIM [2].

➢ **Secondary standard**
There were 16 critical flow Venturi nozzles (CFVNs) used as the master in the secondary standard. The CFVNs could be traceable to the pVTt primary standard facility. The maximum flowrate was

expected to 400 m³/h with the uncertainty of 0.15% (*k*=2).

> ➢ **Working standard**

To meet the requirement of the flow meter in application. The close loop facility was built as the working standard. The maximum flowrate could be 1300 m³/h at the pressure of 2.5 MPa with the expected uncertainty of 0.20% (*k*=2).

In this paper, the detailed information the sonic nozzle facility will be presented, including the structure of the facility, the uncertainty analyses, and the verification on the uncertainty.

2. The sonic nozzle facility

2.1 The structure of sonic nozzle facility

There are two compressors with dryer and filter to produce the high pressure dry air. The dry air from the compressors is saved in the buffer tank. There are two stages of buffer tank. The first stage buffer tank is consisted with 2 tanks with the volume of 10 m³ individually, and the second stage buffer tank is consisted with 2 tanks with the volume of 7.5 m³ individually. The maximum pressure in the first stage buffer tank is 10 MPa, while it is 5 MPa in the second stage.

There are two stage of the pressure regulators. The pressure in the sonic nozzle facility was controlled by the second stage of the pressure regulator.
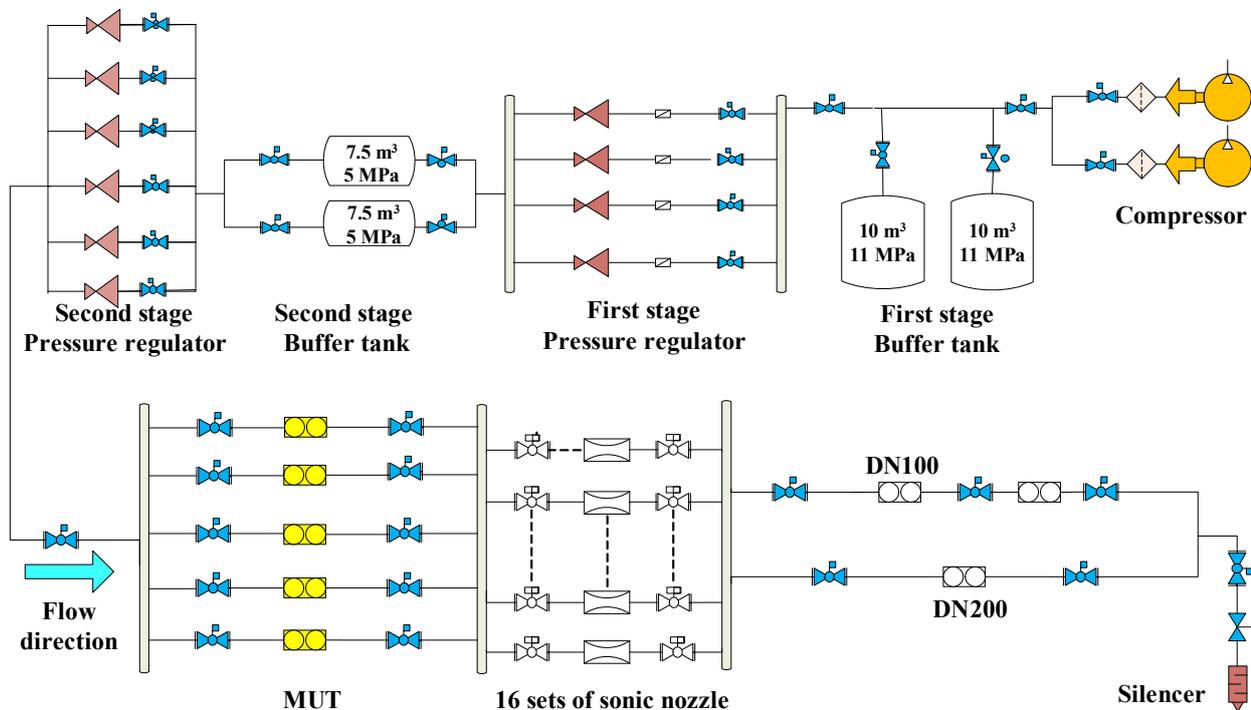

Figure 1 the systematic diagram of the high pressure gas flow system

(a)   The overview of the facility   (b) the sonic nozzle   (c) the MUT

Figure 2 the sonic nozzle facility

The meter under test (MUT) was located in the upstream of the facility, while the sonic nozzles were located in the downstream of the facility.

> ➢ The 16 sets of sonic nozzle were mounted in 4 rows, and there were 4 sets of sonic nozzle in each row.

➢ There were 5 pipelines for the MUT. There were 4 fixed pipelines for the reference meters in the close loop facility. One pipeline for the customer.

The real meter factor of the meter under test (MUT), $K_{MUT,real}$, could be calibrated with the sonic nozzle facility, which could be expressed as,

$$K_{MUT,real} = \frac{N_{MUT}}{t_{MUT} q_{MUT,real}} \quad (1)$$

Where, N_{MUT} is the pulse number; t_{MUT} is the test time; $q_{MUT,real}$ is the real flowrate of the MUT.

According to the mass conservation, $q_{MUT,real}$ could be expressed as,

$$q_{MUT,real} = \frac{q_{SN}}{\rho_{MUT}} = C_d A_* C_* \frac{p_{SN}}{\sqrt{\frac{R_u}{M} T_{SN}}} \Bigg/ \frac{p_{MUT}}{\sqrt{\frac{R_u}{M} T_{MUT} z_{MUT}}}$$

$$= C_d A_* C_* / \left(\frac{p_{MUT}}{p_{SN}} \cdot \frac{\sqrt{T_{SN}}}{T_{MUT}} \cdot \frac{1}{z_{MUT}} \cdot \sqrt{\frac{M}{R_u}} \right) \quad (2)$$

So, Equ. (1) could be expressed as,

$$K_{MUT,real} = \frac{N_{MUT}}{t_{MUT}} \cdot \frac{1}{C_d} \cdot \frac{p_{MUT}}{p_{SN}} \cdot \frac{\sqrt{T_{SN}}}{T_{MUT}}$$
$$\cdot \left(\frac{1}{A_* C_*} \cdot \frac{1}{z_{MUT}} \cdot \sqrt{\frac{M}{R_u}} \right) \quad (3)$$

Here,
➢ A_* is the area of the throat of sonic nozzle, it was the same value when the sonic nozzle was calibrated by the pVTt facility and used as the reference meter in the sonic nozzle facility. So, the uncertainty was neglected.
➢ R_u is the universal gas constant, which is fixed at 8314.4598 J/kmol/K. So, the uncertainty was neglected.
➢ M is the molecular mass of dry air, which is fixed at 28.965294 kg/kmol. So, the uncertainty was neglected.
➢ C_* is the critical flow function of the sonic nozzle, Z_{MUT} is the compressibility factor of MUT, which were calculated by the REFPROP 9.1. The uncertainty was neglected.

So, the uncertainty could be expressed as, [4]

$$u(K_{MUT,real}) = \sqrt{\begin{array}{l} u(C_d)^2 + u(p_{SN})^2 + u(p_{MUT})^2 \\ +0.25u(T_{SN})^2 + u(T_{MUT})^2 \\ +u(N_{MUT})^2 + u(t_{MUT})^2 + u_R(K_{MUT,real})^2 \end{array}} \quad (4)$$

2.2 The calibration for sonic nozzles
The sonic nozzles were traceable to the pVTt primary standard facility in NIM.

Table 1 the parameters of the sonic nozzles

SN	Nominal throat [mm]	Nominal flowrate [m³/h]	Amount
01	1.92	2	1
02	2.71	4	1
03	3.78	8	1
04	5.36	16	1
05~16	7.35	32	12

The calibration procedure is following,
➢ Each sonic was calibrated at least 9 pressures, ie, 100 kPa, 150 kPa, 220 kPa, 330 kPa, 500 kPa, 750 kPa, 1150 kPa, 1670 kPa and 2500 kPa.
➢ For each pressure, the calibration was repeated 2~3 times.

To cover the pressure range, the curve fitting between discharge coefficient and Reynolds number was made for each nozzle.
➢ For SN.01, the curve fitting was shown in Equ. (5-a), due to the slight boundary transition .

$$C_{d,CF} = a + \frac{b}{\sqrt{Re}} + \frac{c}{Re} \quad (5\text{-}a)$$

The comparison between the test results and the curve fitting (CF) results based on Equ. (5-a) for SN.01 was shown in Figure 2.
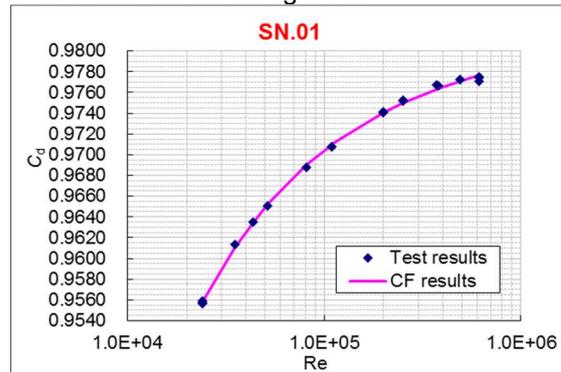

Figure 2 the comparison between the test results and the CF results for SN.01

➢ For SN.02~16, the curve fitting was shown in Equ. (5-b) due to the obviously boundary layer transition, with the reference of Ishibashi's research [5].

$$C_{d,CF} = \left(a + \frac{b}{\sqrt{Re}} \right) + \frac{c + \dfrac{d}{\sqrt{Re}}}{1 + \exp\left(e - \dfrac{Re}{7000}\right)} \quad (5\text{-}b)$$

The comparison between the test results and the CF results based on Equ. (5-b) for SN.07 was shown in Figure 3.
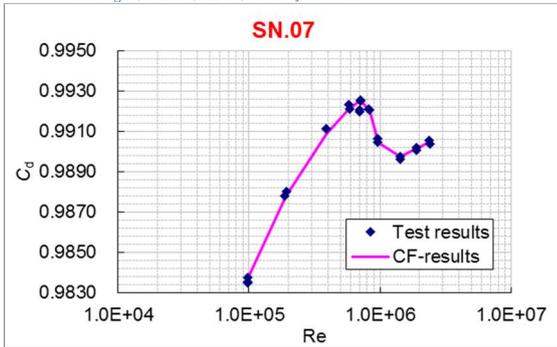
Figure 3 the comparison between the test results and the CF results for SN.07

The additional residual from the curve fitting was considered in the uncertainty analyses, which was smaller than 0.035%.

$$u(C_{d,CF}) = \sqrt{\frac{(C_{d,CF} - C_d)^2}{N - m}} \qquad (6)$$

Where, m=3 for SN.01; m=5 for SN.02~16.

When the sonic nozzle was calibrated at the atmospheric pressure, about 100 kPa with the pVTt facility, the uncertainty of discharge coefficient was 0.10% (*k*=2) [6]; when the sonic nozzle was calibrated at other higher pressures with the pVTt facility, the uncertainty was 0.08% (*k*=2) [2]. So, the maximum uncertainty of C_d could be expressed as,

$$u(C_d) = \sqrt{u(C_{d,pVTt})^2 + u(C_{d,CF})^2}$$
$$= \sqrt{0.05^2 + 0.035^2}\,\% = 0.0602\% \qquad (7)$$

2.3 The "absolute + differential" pressure measurement

To decrease the pressure measurement uncertainty, there is an absolute pressure instrument in the manifold in the upstream of the reference meters, p_{abs}, the differential pressure

transducers were used for the sonic nozzle and MUT, Δp_{SN}, Δp_{MUT}. Due to $\Delta p_{SN}, \Delta p_{MUT} \ll p_{abs}$ so, the pressure measurement in Equ. (1) could be expressed as

$$\frac{p_{MUT}}{p_{SN}} = \frac{p_{abs} + \Delta p_{MUT}}{p_{abs} + \Delta p_{SN}} = 1 + \frac{\Delta p_{MUT}}{p_{abs}} - \frac{\Delta p_{SN}}{p_{abs}} \qquad (8)$$

So,

$$u(p_{SN}) = \frac{\Delta p_{SN}}{p_{abs}} \sqrt{u(\Delta p_{SN})^2 + u(p_{abs})^2} \qquad (9\text{-}a)$$

$$u(p_{MUT}) = \frac{\Delta p_{MUT}}{p_{abs}} \sqrt{u(\Delta p_{MUT})^2 + u(p_{abs})^2} \qquad (9\text{-}b)$$

In the sonic nozzle facility,

➢ $U(p_{abs}) = 0.01\%$, $U(\Delta p_{SN}) = U(\Delta p_{MUT}) = 0.05\%$, the distribution could be assumed as rectangle. At the maximum pressure, 2500 kPa, the maximum differential pressure for the reference meter and MUT was about 50 kPa. So, the sensitively factor could be evaluated as $\frac{\Delta p_{SN}}{p_{abs}} = \frac{\Delta p_{MUT}}{p_{abs}} = \frac{50}{2500} = 0.02$.

➢ $U(T_{SN}) = U(T_{MUT}) = 0.1°C$ (*k*=2), the temperature could be assumed 20 °C.

➢ With the application of the pulse interpolation technique, $U(N) = 0.1$, the distribution could be assumed as rectangle. The minimum pules collection was 2000.

➢ The resolution of the timer is 0.1 ms, the distribution could be assumed as rectangle. The minimum time was 30 s.

With the combination of Equ. (4) and (9-a), (9-b), the detailed uncertainty component of sonic nozzle facility was shown in Table 1. The total uncertainty of $K_{MUT,real}$ was 0.15% (*k*=2).

Table 1 the uncertainty component of sonic nozzle facility

| SN	Symbols	Meaning	u [%]	c [/]	$u \cdot c$ [%]
1	$u(C_d)$	The discharge coefficient	0.0602	1	0.0602
2	$u(p_{abs})$	The absolute pressure	0.0058	0.028	0.0002
3	$u(\Delta p_{SN})$	The differential pressure of sonic nozzle	0.0289	0.02	0.0006
4	$u(\Delta p_{MUT})$	The differential pressure of MUT	0.0289	0.02	0.0006
5	$u(T_{SN})$	The temperature of sonic nozzle	0.0085	0.5	0.0085
6	$u(T_{MUT})$	The temperature of MUT	0.0085	1	0.0085
7	$u(N_{MUT})$	The pulse number of MUT	0.0029	1	0.0029
8	$u(t_{MUT})$	The time of MUT	0.0002	1	0.0002
9	$u_R(K_{MUT,real})$	The repeatability	0.040	1	0.040
$u(K_{MUT,real})$ =0.073%, $U(K_{MUT,real})$ =0.15% (*k*=2)					

3. The verification on the measurement capabilities for the sonic nozzle facility

The expanded uncertainty of meter factor for meter under test (MUT) is 0.15% (k=2).

To verify the uncertainty of the sonic nozzle facility, a comparison between NIM and PTB with turbine meter facility was made with 3 Dn 100 turbine meters. The 3 turbine meters were calibrated in PTB in 2013 with natural gas, which were calibrated in NIM within 2016~2018 with air. The comparison results was shown in in Figure. 1. For turbine meter facility in PTB, the expanded uncertainty of meter factor for meter under test (MUT) is 0.13% (k=2).
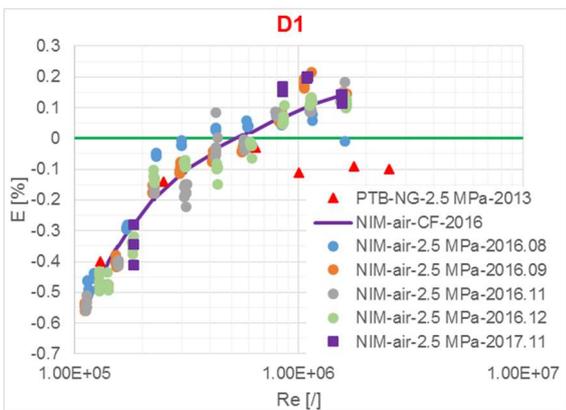
(a)
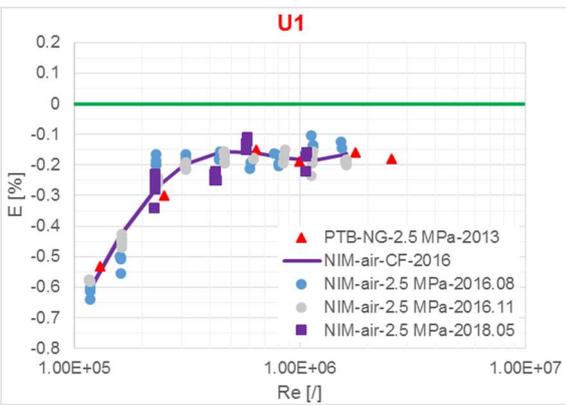
(b)
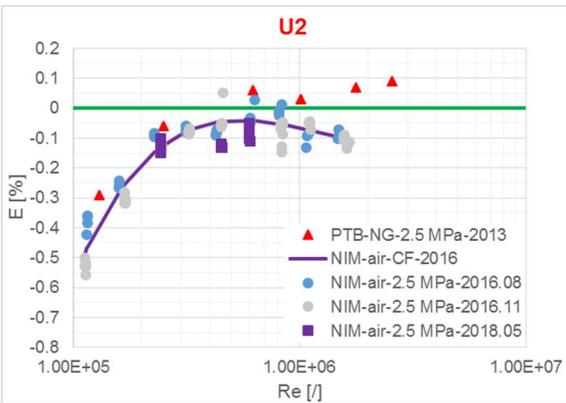
(c)

Figure 4 the comparison results

The consistence of the comparisons was evaluated with the value of E_n. Instead of meter factor, the error was used in the analyses, whose uncertainty was the same as the meter factor.

$$E_n = \frac{\left|E_{NIM,CF} - E_{PTB}\right|}{\sqrt{U_{NIM}^{\ 2} + U_{PTB}^{\ 2} + U_{NIM,CF}^{\ 2} + U^2}} \qquad (10)$$

The turbine meter is a kind of velocity type meter, so, the error of the turbine meter is strongly related with the Reynolds number. In this comparison, the Reynolds number cannot be exactly matched, due to the different working fluid. Therefore, the curve fitting between the error and the Reynolds number as shown in Equ. (6), was made for each meter [7].

$$E_{NIM,CF} = a_0 + a_1 \ln(\mathrm{Re}) + a_2 \ln(\mathrm{Re})^2$$
$$+ a_3 \ln(\mathrm{Re})^{-1} + a_4 \ln(\mathrm{Re})^{-2} \qquad (11)$$

With the Equ. (6), the $E_{NIM,CF}$ was calculated at the same Reynolds number as the PTB's result.

For the better freedom of the curve fitting, the individual test point was used. The residual of the curve fitting was evaluated with the following Equ. (7) with the consideration of the freedom.

$$U_{NIM,CF} = 2\left[\frac{\sum_{i=1}^{N}(E_{NIM,i} - E_{NIM,i,CF})^2}{N-5}\right]^{\frac{1}{2}} \times 100\% \qquad (12)$$

On the other hand, the additional uncertainty U was considered in Equ. (5), with the long term stability and the working fluid effect for the turbine meter.

The each uncertainty component for Equ. (5) for each turbine meter was shown in Table 2.

Table 2 The uncertainty component

SN	U_{NIM} [%]	U_{PTB} [%]	$U_{NIM,CF}$ [%]	U [%]
D1	0.15	0.13	0.10	0.05
U1	0.15	0.13	0.08	0.05
U2	0.15	0.13	0.08	0.05

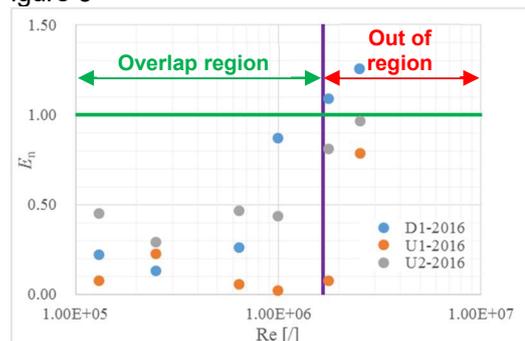So, the value of E_n for each turbine meter is shown in Figure 5

Figure 5 the comparison results analyses

It was clear from Figure 5, all the E_n value was smaller than 1 within the overlap region of Reynolds number, which meant the uncertainty of the sonic nozzle facility was verified.

The recalibration of the 3 transfer meters was conducted from 2017 to 2018 as shown in Figure 4. Due to the pressure and temperature change, the test condition could not be matched very well. The reproducibility of the facility was evaluated with the following equation

$$\Delta E = E_{NIM,new} - E_{NIM,CF,2016} \qquad (13)$$

Where $E_{NIM,new}$ is the newest test result, $E_{NIM,CF,2016}$ is the calculation result from the curve fitting based on the test result in 2016.
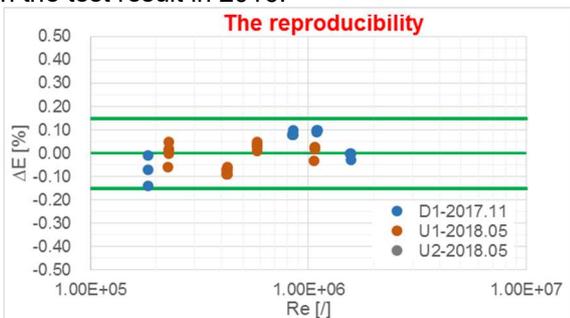

Figure 6 the reproducibility of the sonic nozzle facility

It was clear that the reproducibility was smaller than the uncertainty of the close loop facility.

4. Conclusion

With 16 sonic nozzles used as the reference meters, the sonic nozzle facility was built in NIM. The flow range is within (2~400) m³/h, while the pressure range is within the (190~2500) kPa. The sonic nozzles were traceable to the pVTt primary standard facility in NIM. To cover the pressure range, the curve fitting between discharge coefficient and Reynolds number was made for each sonic nozzle. To decrease pressure measurement uncertainty, there is an absolute pressure instrument in the manifold in the upstream of the MUT. The expanded uncertainty of meter factor for meter under test (MUT) is 0.15% (k=2). To verify the uncertainty of the sonic nozzle facility, a comparison between NIM and PTB was made with three Dn 100 turbine meters as transfer meters. The three turbine meters were calibrated by PTB in 2013 with natural gas, which were calibrated in NIM in 2016. On the base

of the good consistency of the comparison results, the uncertainty and the measurement capability of the sonic nozzle facility were verified.

Due to the limited of the volume of the storage tank as shown in Figure 1, the temperature stability for the maximum flowrate of 400 m³/h at 2.5 MPa was relative poor. So, the maximum E_n value occurred for D1 at the maximum flowrate 400 m³/h as shown in Figure 5. Therefore, the maximum flowrate for the sonic nozzle facility was generally claimed as 7200 Nm³/h, which was the normalized flowrate at pressure 100 kPa and 20°C, referring to the flowrate 288 m³/h at 2.5 MPa.

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