

The high pressure close loop gas flow standard facility in NIM

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Abstract

The first high pressure close loop gas flow facility in China was built in NIM at the end of 2014. The 4 sets of Dn 100 turbine meters were used as the reference meters in the facility. The flow range is within (40~1300) m³/h, while the pressure range is within the (190~2500) kPa. The turbine meter is a kind of velocity type flow meter, which is easily affected by installation. To avoid the installation effect, the reference meters were designed to be calibrated in “original position” without dismounted. To decrease the pressure measurement uncertainty, there is an absolute pressure instrument in the manifold in the upstream of the reference meters, the differential pressure transducers were used for the reference meter and meter under test (MUT). The expanded uncertainty of meter factor for MUT is 0.20% ($k=2$). The uncertainty of the close loop facility was verified with a comparison between the sonic nozzle facility and close loop facility, in which one Dn 100 turbine meter was chosen as the transfer meter. On the base of the good consistency of the comparison results, the uncertainty and the measurement capability of the close loop 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 different pressure 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 was traceable to the primary standard, pVTt facility. The maximum flowrate could be 400 m³/h with the best measurement capabilities 0.15% ($k=2$), which was verified with comparison between PTB and NIM [3].

In reality, the maximum flowrate for the sonic nozzle facility was 7200 Nm³/h, which is the normalized flowrate at pressure 100 kPa and 20°C, due to the

limited of the volume of the storage tank as shown in Figure 1.

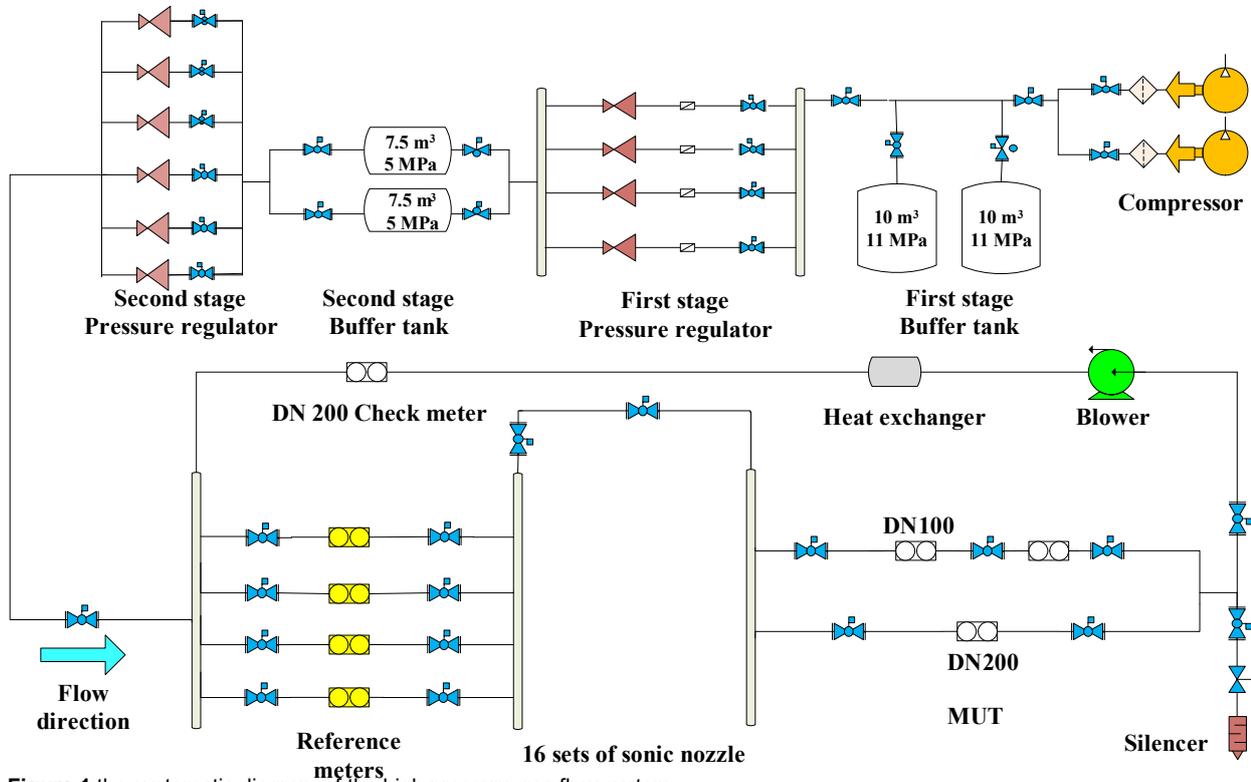


Figure 1 the systematic diagram of the high pressure gas flow system

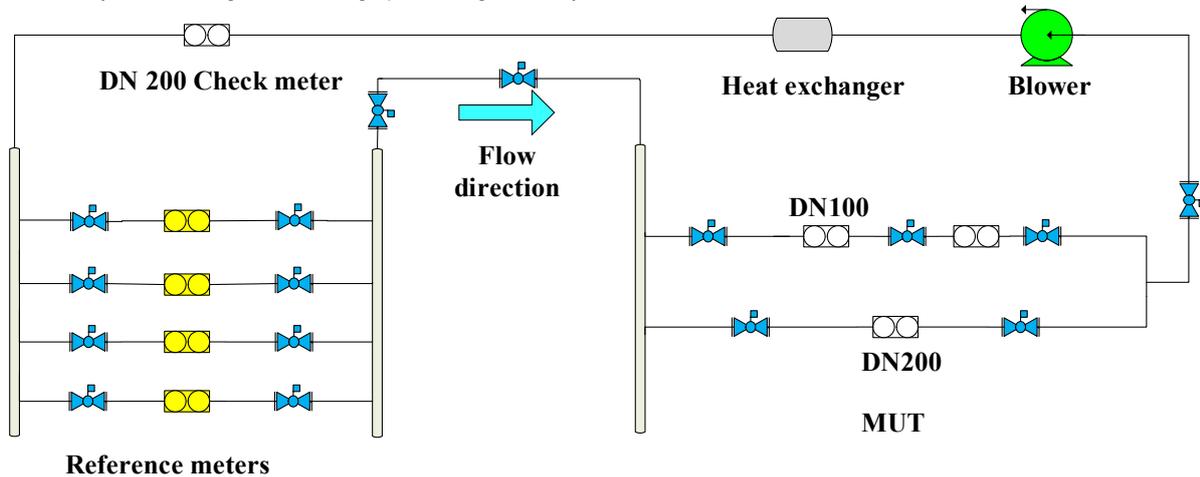


Figure 2 the detailed diagram of the close loop facility

➤ **Working standard**

The working standard are used for the daily calibration for the customer. The typical technologies in use are turbine meter or rotary meter [4 错误!未找到引用源。] because of their well-proven reproducibility and high flexibility regarding operating of different flow rates and reasonable pressure loss (energy efficiency of the test rigs).

To meet the requirement of the flow meter in application. The close loop facility was built. The

maximum flowrate could be 1300 m³/h at the pressure of 2.5 MPa, with the expected best measurement capabilities 0.20% ($k=2$).

In this paper, the close loop facility will be introduced in detail, including the structure of the facility, the uncertainty analyses, and the comparison between the close loop facility and the sonic nozzle facility to verify the uncertainty.

2. The close loop facility

2.1 The structure of close loop facility

As shown in Figure 1, 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.

As shown in Figure 2, the references meters were located in the upstream, while the MUT was located in the downstream. The blower was used to circulate the air in the loop. The heat exchanger was used to keep the temperature stable.

The real meter factor, $K_{MUT,real}$, could be calibrated with the close loop 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 of the meter under test (MUT); t_{MUT} is the test time of the MUT; $q_{MUT,real}$ is the real volumetric flowrate of the MUT.

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

$$q_{MUT,real} = q_{ref} \cdot \frac{\rho_{ref}}{\rho_{MUT}} \quad (2)$$

$$= \frac{N_{ref}}{K_{ref} \cdot t_{ref}} \cdot \left(\frac{p_{ref}}{p_{MUT}} \cdot \frac{T_{MUT}}{T_{ref}} \cdot \frac{z_{MUT}}{z_{ref}} \right)$$

Where, q_{ref} is the real volumetric flowrate of the reference meter; K_{ref} is the real meter factor of the reference meter; p is the pressure; T is the temperature; z is the compressibility factor. The subscript of "ref" referring the reference meter, while "MUT" referring the meter under test.

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

$$K_{MUT,real} = K_{ref} \cdot \frac{p_{MUT}}{p_{ref}} \cdot \frac{T_{ref}}{T_{MUT}} \cdot \frac{z_{ref}}{z_{MUT}} \cdot \frac{N_{MUT}}{N_{ref}} \cdot \frac{t_{ref}}{t_{MUT}} \quad (3)$$

The compressibility factor for MUT and master meter was calculated by the REFPROP 9.1, the uncertainty was neglected.

So, the uncertainty of the $K_{MUT,real}$ can be expressed as [5],

$$u(K_{MUT,real}) = \sqrt{\begin{matrix} u(K_{ref})^2 + u(p_{ref})^2 + u(p_{MUT})^2 \\ + u(T_{ref})^2 + u(T_{MUT})^2 \\ + u(N_{ref})^2 + u(N_{MUT})^2 \\ + u(t_{ref})^2 + u(t_{MUT})^2 \\ + u_R(K_{MUT,real})^2 \end{matrix}} \quad (4)$$

2.2 The "original position" calibration for reference meters

The turbine meter is a kind of velocity type flow meter, which is easily affected by installation. To avoid the installation effect, the reference meters could be directly in "original position" traceable to the sonic nozzle facility in NIM without dismounted.

The calibration procedure is following,

- Each reference meter was calibrated at 5 pressures, ie, 190 kPa, 360 kPa, 690 kPa, 1300 kPa, and 2500 kPa.
- For each pressure, the meter was calibrated with 8 flow rate, ie, 40 m³/h, 54 m³/h, 76 m³/h, 106 m³/h, 147 m³/h, 206 m³/h, 288 m³/h and 400 m³/h.
- For each flow rate, the calibration was repeated at least 5 times.

Note: due to the limited of the capability of the sonic nozzle facility, the maximum flowrate is about 288 m³/h at 2500 kPa, referring to the 7200 Nm³/h at pressure 100 kPa and 20°C.

To cover the flow range, the curve fitting between error, instead of meter factor, and Reynolds number was made for each pressure.

The curve fitting was used to cover the flow range of the [6]

- For the pressure range within (190~400) kPa, the curve fitting was expressed as, Equ. (5-a),

$$E_{ref,CF} = a_0 + a_1 \ln(\text{Re}) + a_2 \ln(\text{Re})^2 + a_3 \ln(\text{Re})^3 \quad (5-a)$$

- For the pressure range within (400~2500) kPa, the curve fitting was expressed as, Equ. (5-b),

$$E_{ref,CF} = a_0 + a_1 \ln(\text{Re}) + a_2 \ln(\text{Re})^2 \quad (5-b)$$

The additional residual from the curve fitting was considered in the uncertainty analyses, which could be evaluated as,

$$u(E_{ref,CF}) = \sqrt{\frac{(E_{ref,CF} - E_{ref})^2}{N - m}} = u(K_{ref,CF}) \quad (6)$$

Where, $m=4$ when the pressure is within (190~400) kPa; $m=3$ when the pressure is within (400~2500) kPa. The maximum of $u(E_{ref,CF})$ was smaller than 0.05%.

So, the maximum uncertainty of K_{ref} could be expressed as,

$$u(K_{ref}) = \sqrt{u(K_{ref,SN})^2 + u(K_{ref,CF})^2} \quad (7)$$

$$= \sqrt{0.075^2 + 0.05^2} \% = 0.0885\%$$

The test results for SN.U1 were shown in Figure 3.

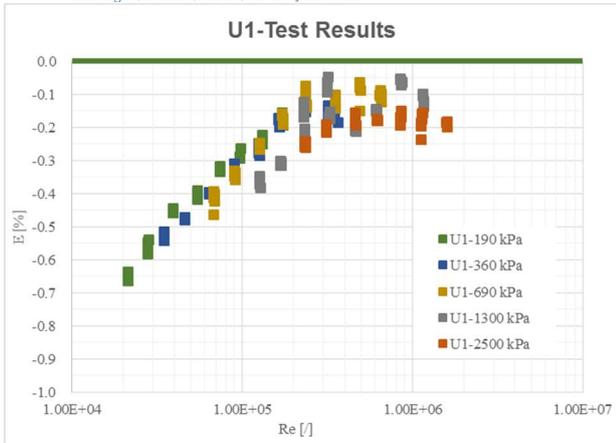


Figure 3 the test results for U1 at different pressures

With the prediction from Equ. (5-a), the comparison between the test and curve fitting (CF) at pressure 360 kPa as shown in Figure 4.

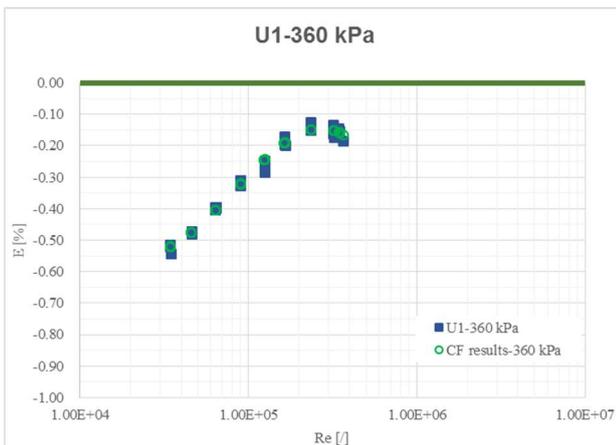


Figure 4 the comparison between test and CF

With the prediction from Equ. (5-b), the comparison between the test and curve fitting (CF) at pressure 2500 kPa as shown in Figure 5.

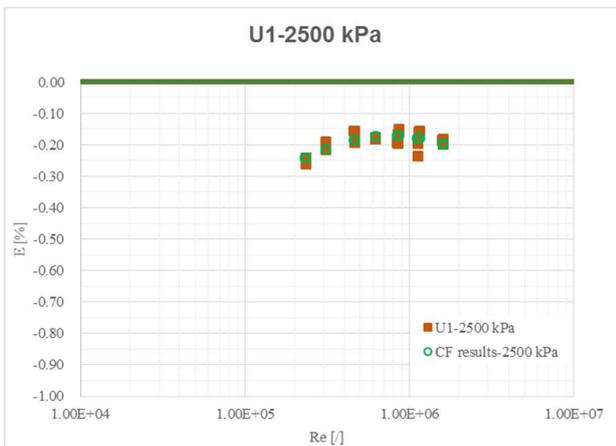


Figure 5 the comparison between test and CF

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 reference meter and MUT, Δp_{ref} , Δp_{MUT} . Due to $\Delta p_{ref}, \Delta p_{MUT} \ll p_{abs}$ so, the pressure measurement in Equ. (1) could be expressed as

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

So,

$$u(p_{ref}) = \frac{\Delta p_{ref}}{p_{abs}} \sqrt{u(\Delta p_{ref})^2 + u(p_{abs})^2} \quad (9-a)$$

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

In the close loop facility,

- $U(p_{abs}) = 0.01\%$, $U(\Delta p_{ref}) = U(\Delta p_{MUT}) = 0.05\%$, 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 sensitivity factor could be evaluated as $\frac{\Delta p_{ref}}{p_{abs}} = \frac{\Delta p_{MUT}}{p_{abs}} = \frac{50}{2500} = 0.02$.
- $U(T_{ref}) = U(T_{MUT}) = 0.1^\circ\text{C}$ ($k=2$), 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 pulses 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 close loop facility was shown in Table 1. The total uncertainty of $K_{MUT,real}$ was 0.20% ($k=2$).

3. The verification on the measurement capabilities for the close loop facility

To verify the capability of the close loop facility, one Dn 100 turbine meter was used as the transfer meter to make the comparison between the sonic nozzle facility and the close loop facility.

The comparison results were shown in Figure 6 with different pressures, 690 kPa, 1300 kPa and 2500 kPa. The curve fitting, the similar as Equ. (5-b) was made to analyse the consistent of the result.

$$E_{MUT,CF} = a_0 + a_1 \ln(\text{Re}) + a_2 \ln(\text{Re})^2 \quad (10)$$

Within the overlap region of Reynolds number, the E_n value [7~8] was used to evaluate the result,

Table 1 the uncertainty component of close loop facility

SN	Symbols	Meaning	u	c	$u \cdot c$
			[%]	[/]	[%]
1	$u(K_{ref})$	The meter factor of reference meter	0.0899	1	0.0899
2	$u(p_{abs})$	The absolute pressure	0.0058	0.028	0.0002
3	$u(\Delta p_{ref})$	The differential pressure of reference meter	0.0289	0.02	0.0006
4	$u(\Delta p_{MUT})$	The differential pressure of MUT	0.0289	0.02	0.0006
5	$u(T_{ref})$	The temperature of reference meter	0.0085	1	0.0085
6	$u(T_{MUT})$	The temperature of MUT	0.0085	1	0.0085
7	$u(N_{ref})$	The pulse number of reference meter	0.0029	1	0.0029
8	$u(N_{MUT})$	The pulse number of MUT	0.0029	1	0.0029
9	$u(t_{ref})$	The time of the reference meter	0.0002	1	0.0002
10	$u(t_{MUT})$	The time of MUT	0.0002	1	0.0002
12	$u_R(K_{MUT,real})$	The repeatability	0.040	1	0.040

$u(K_{MUT,real})=0.098\%$, $U(K_{MUT,real})=0.20\%$ ($k=2$)

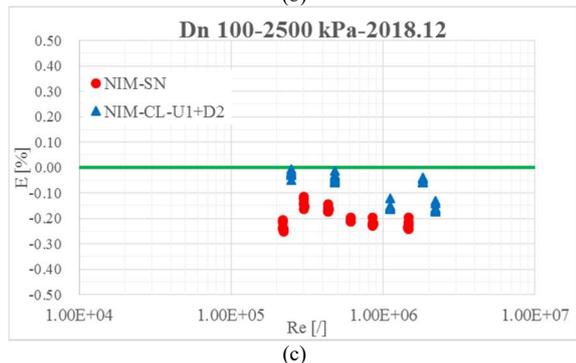
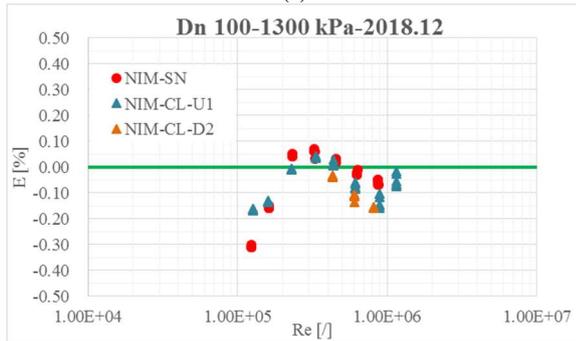
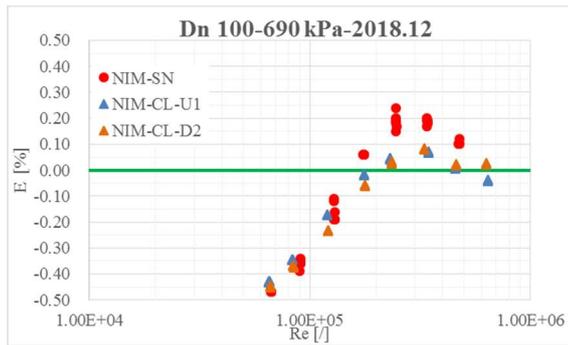


Figure 6 the comparison results between sonic nozzle facility and close loop facility

$$E_n = \frac{|E_{MUT,CL,CF} - E_{MUT,SN}|}{\sqrt{U_{MUT,CL}^2 + U_{MUT,SN}^2 + U_{CF}^2}} \quad (11)$$

- For sonic nozzle facility, the expanded uncertainty of meter factor for meter under test (MUT) is 0.15% ($k=2$).
- For close loop facility, the expanded uncertainty of meter factor for meter under test (MUT) is 0.20% ($k=2$).

Due to the curve fitting, the additional curve fitting uncertainty, the same as Equ. (6), U_{CF} , which was evaluated by Equ. (12),

$$U_{CF} = 2 \sqrt{\frac{(E_{MUT,CF} - E_{MUT})^2}{N - 3}} \quad (12)$$

The comparison results were shown Figure 7 in detail, which were summarized in Table 2.

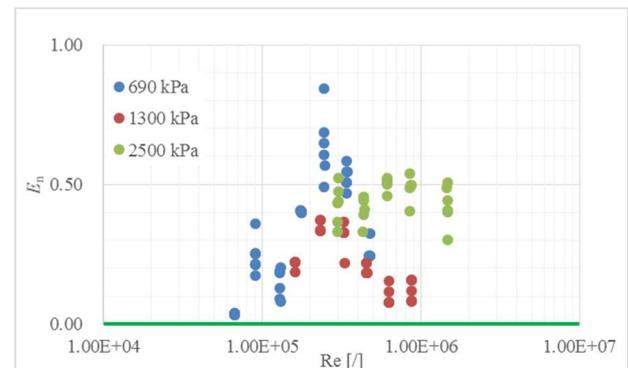


Figure 7 the detailed comparison results

It was clear that all the value of E_n was smaller than 1, which meant that the 0.20% ($k=2$) uncertainty of the close loop facility was verified.

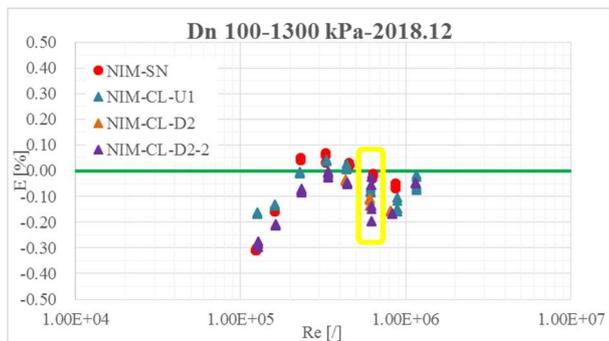
Table 2 The comparison results

Pressure [kPa]	Re range for CF	U_{cr} [%]	E_n
690	$6.5 \times 10^4 \sim 6.4 \times 10^5$	0.06	0.03~0.84
1300	$1.3 \times 10^5 \sim 1.2 \times 10^6$	0.11	0.08~0.37
2500	$2.5 \times 10^5 \sim 2.2 \times 10^6$	0.09	0.30~0.54

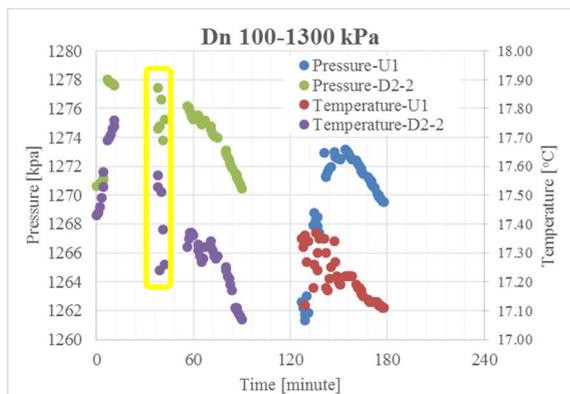
For the close loop facility, the pressure and temperature stability was the important parameter, which influence the repeatability very much. In general, the repeatability was smaller than 0.04%, $u_R(K_{MUT,real})$ which was used in the uncertainty analyses in Table 1.

As shown in Figure 8 (a) with yellow square, the poor repeatability, 0.07%, occurred, when the flowrate was about 210 m³/h. The pressure and temperature change during the test was shown in Figure 8 (b).

From the Figure 8 (b), it was clear that the temperature changed about 0.3 °C within 4 minutes. Due to the slow response of the temperature sensor, the real temperature change might not be caught. So, the temperature change was kept within 0.3 °C in one hour for the close loop facility.



(a) The poor repeatability for error



(b) The pressure and temperature change

Figure 8 the pressure and temperature effect

4. Conclusion

The close loop facility with 4 sets of Dn 100 turbine meters as the reference meters was built in NIM. The flow range is within (40~1300) m³/h, while the pressure range is within the (190~2500) kPa. To avoid the installation effect, the reference meters were designed directly in “original position” traceable to the sonic nozzle facility (SN). To decrease the pressure measurement uncertainty, there is an absolute pressure instrument in the manifold in the upstream of the reference meters, the differential pressure transducers were used for the reference meter and MUT. So, the expanded uncertainty of meter factor for meter under test (MUT) was 0.20% ($k=2$), which was verified with the comparison between sonic nozzle facility and close loop facility.

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