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# APMP.M.FF-K6.2018

# Low pressure gas flow

**KEY COMPARISON**



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# APMP Key Comparison for Low-Pressure Gas Flow (APMP.M.FF-K6.2018)

## Final Report

## November, 2024


## Pilot

**Woong Kang – KRISS, Republic of Korea**

## Participants

**Chunhui Li – NIM, China**

**Steven Wang – NMIA, Australia**

**Yan Zeng – NMC, A*STAR, Singapore**

**Sutham Masri – NIMT, Thailand**

**Nguyen Hoang Nam – VMI, Vietnam**

**Shiv Kumar Jaiswal – NPLI, India**

**Win-Ti Lin – CMS, Chinese Taipei**

**Fahmy Munawar Cholil – SNSU-BSN, Indonesia**

# Contents

## 1. Introduction

A comparison is organised for the purpose of determining the degree of equivalence of national primary standards of low-pressure gas flow measurement over range from 10 $m^3/h$ to 100 $m^3/h$ of NMIs of Asia-Pacific region with linkage to key comparison reference value (KCRV) in CIPM key comparison CCM.FF-K6.2011[1] and providing supporting evidence for the calibration and measurement capabilities (CMCs) claimed by the participating laboratories.

KRISS coordinate the comparison and act as a pilot laboratory. The rotary gas meter (Itron Delta S-Flow G65, DN50) provided by the KRISS was used as a transfer standard. The data analysis was conducted by the pilot laboratory following the guidelines and method proposed by Cox [2]. The results of this comparison were linked to the CCM KC by correcting the results of linking laboratories, KRISS – Republic of Korea, NIM - China and NMIA – Australia, which participated in CCM.FF-K6.2011.

## 2. Participants

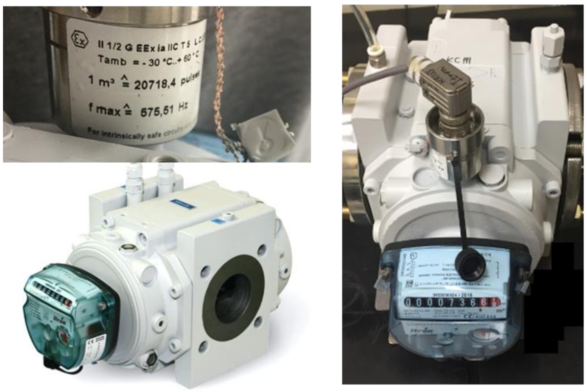
The 9 laboratories participated in the comparison. The 9 participants and the time schedule are shown in Table 1. The comparison measurements started in June 2018 and finished February 2022. Each laboratory had several weeks for providing the measurements for sending the transfer standard to the next laboratory. Due to some problems with custom process and COVID 19, the transfer standard shipment was delayed several times. The transfer standard was calibrated and tested by the pilot laboratory before, during and after the comparison to assess its calibration stability.

*Table 1 Participants and the time schedule*

| No. | Participants | Date | Contact | Remark |
|---|---|---|---|---|
| 1 | KRISS<br>(Republic of Korea) | Jun, 2018 – July, 2018 | Woong Kang | 1st Pilot lab Test |
| 2 | NMIA<br>(Australia) | July, 2018 – Aug, 2018 | Steven Wang | Test finished |
| 3 | NMC, A*STAR<br>(Singapore) | Aug, 2018 – Nov, 2018 | Yan Zeng | Test finished |
| 4 | NIMT<br>(Thailand) | Dec, 2018 – Jan, 2019 | Sutham Masri | Test finished |
| 5 | KRISS<br>(Republic of Korea) | Feb, 2019 – July, 2019 | Woong Kang | Re-scheduling<br>2nd Pilot lab Test |
| 6 | VMI<br>(Vietnam) | Aug, 2019 – Sep, 2019 | Nguyen Hoang Nam | Test finished |
| 7 | NIM<br>(China) | Oct, 2019 – Dec, 2019 | Chunhui Li | Test finished |
| 8 | CSIR-NPLI<br>(India) | Jan, 2020 – Apr, 2020 | Shiv Kumar Jaiswal | Test finished<br>Delay due to COVID 19 |
| 9 | CMS<br>(Chinese Taipei) | Aug, 2020 – Sep, 2020 | Win-Ti Lin | Test finished |
| 10 | SNSU-BSN<br>(Indonesia) | Oct, 2020 – June, 2021 | Fahmy Munawar Cholil | Test finished |
| 11 | KRISS<br>(Republic of Korea) | Sep, 2021- Feb, 2022 | Woong Kang | 3rd Pilot lab Test |

## 3. The transfer standard

The transfer standard was a rotary gas meter, Itron Delta S-Flow G65 as shown in Figure 1. This transfer standard was different with that used in CCM.FF-K6.2011. The transfer standard and a pulse (high) transmitter connector were shipped in one transfer box. K-factor (pulse/m$^3$) of the transfer standard is 20718.4 which is written in pulse transmitter connecter as shown in Figure 1. The stabilities of calibration and temperature for the transfer standard were checked before starting the comparison and during the comparison by pilot laboratory, KRISS.




| |
|---|
| $P_{max}$ = 1600 kPa |
| $Q_{min}$ = 0.65 m$^3$/h |
| $Q_{max}$ = 100 m$^3$/h |
| Operating temp. = -25 ˚C to +55 ˚C |
| Diameter = DN 50 |
| HF pulse generator |
| K-factor (pulses/m$^3$) = 20718.4 |

*Figure 1 The Transfer standard - Rotary gas meter Itron Delta S-Flow G65*

## 4. Measurement procedure

### 4.1 Method of measurement

The participating laboratories used their usual calibration procedure, that was described in their reports, as well as traceability to SI and to the independent realisation of the quantity.

The relative error of the transfer standard *e* in (%) is the quantity used to compare the participants' results. It is defined as the difference between the volume indicated by the transfer standard and the volume measured by the reference standard

$$e = \frac{V_t - V_s}{V_s} \times 100 \text{ (\%)} \tag{1}$$

where $e$ is the relative error of the transfer standard (%)

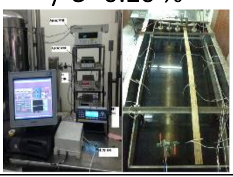
$V_t$ is the volume indicated by the transfer standard (m$^3$)

$V_s$ is the volume indicated by the national standard (m$^3$)

### 4.2 Equipment

Each laboratory described the equipment used in the calibration and sent the information about the range of the flow tested in the comparison in Table 2.

*Table 2 The information of equipment of participating laboratories in the comparison*

| No | Participant | Flow range | NMI Standard / Uncertainty | Contact point |
|---|---|---|---|---|
| 1 | KRISS (Republic of Korea) | 10 to 100 $m^3/h$ | Venturi nozzles / $U$=0.18 %  | Woong Kang |
| 2 | NMIA (Australia) | 10 to 100 $m^3/h$ | Venturi nozzles / $U$=0.15%  | Steven Wang |
| 3 | NMC, A*STAR (Singapore) | 10 to 70 $m^3/h$ | Bell Prover / $U$=0.25 %  | Yan Zeng |
| 4 | NIMT (Thailand) | 10 to 100 $m^3/h$ | Bell Prover / $U$=0.20 %  | Sutham Masri |
| 5 | VMI (Vietnam) | 10 to 100 $m^3/h$ | Bell Prover, PVTt / $U$=0.20 %  | Nguyen Hoang Nam |
| 6 | NIM (China) | 10 to 100 $m^3/h$ | PVTt , Venturi nozzles / $U$=0.18-0.19 %  | Chunhui Li |
| 7 | NPLI (India) | 10 to 72 $m^3/h$ | Venturi nozzles / $U$=0.23 % | Shiv Kumar Jaiswal |

| | | | | |
|---|---|---|---|---|
| | | |  | |
| 8 | CMS (Chinese Taipei) | 10 to 60 $m^3/h$ | Venturi nozzles / $U$=0.15 %  | Win-Ti Lin |
| 9 | SNSU-BSN (Indonesia) | 10 to 70 $m^3/h$ | Bell Prover / $U$=0.30 %  | Fahmy Munawar Cholil |

### 4.3 Measurement and ambient conditions

The measurement range was (10 to 100) $m^3/h$. If participating laboratories were not able to cover all the flow rates, they could make the calibration of the meter in one part of the flow range.

For the reference, Figure 2 shows the experimental set-up the calibration of the transfer standard by the Venturi nozzle at KRISS. According to the participating laboratory's facility, the test set-up for the calibration of the transfer standard was able to determined.

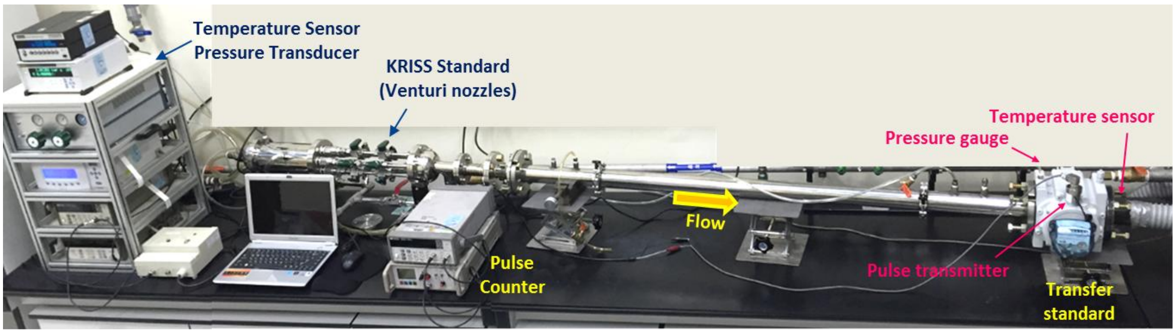



*Figure 2 Experimental set-up the calibration of the transfer standard by the Venturi nozzle at* KRISS

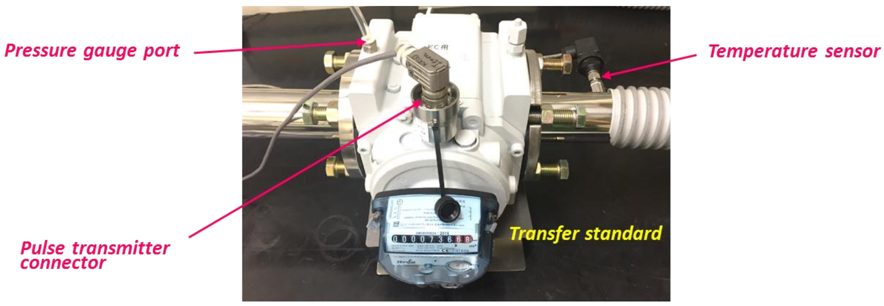



*Figure 3 Installation of the meter and sensors*

Only instructions below mentioned have to be fulfilled.

- The rotary gas meter has to be tested in horizontal position.
- The reference pressure from the rotary gas meter has to be measured from the “pressure gauge port” as shown in Figure 3.
- The reference temperature from the rotary gas meter has to be measured downstream of the rotary gas meter as shown in Figure 3.
- It is necessary to use the pulse transmitter for the test
- There is no lubrication of the meter
- Reference conditions
    - the calibration medium is air
    - air temperature: (20 ± 5) ˚C
    - ambient relative humidity range: 25 % to 75 %
    - ambient atmospheric pressure range: 86 kPa to 106 kPa
- Before the beginning the test of the gas meter has to work for 20 minutes in the flow rate Q=70 $m^3/h$. Laboratories which cannot achieve this warm-up flow rate, use the flow rate equal to 70 % of the maximum flow rate of used standard equipment.
- The rotary gas meter has to be tested in ten points of flow rates: 10 $m^3/h$; 20 $m^3/h$; 30 $m^3/h$; 40 $m^3/h$; 50 $m^3/h$; 60 $m^3/h$; 70 $m^3/h$; 80 $m^3/h$; 90 $m^3/h$; 100 $m^3/h$. Laboratories which cannot achieve all these prescribed testing points perform test in points available to the laboratory from the ten points mentioned above.
- Each participating laboratory has to record the results:
    - absolute pressure in the meter
    - temperature in the meter
    - error of the meter

  for all test flow rates
- The test in one flow rate should be repeated 3 times and then the means of values have to be calculated. The flow rate deviation has to be in the interval of ± 3 % from the required value.
- The interval of each test is required to be minimum of 1 minute. Beforehand the flow rate has to be accurately stabilised.

## 5. Measurement Results

### 5.1 Stability of the transfer standard

The stability of the transfer standard was checked before starting the comparison by pilot laboratory-KRISS in 2018/06, 2019/07, 2022/02, before and during the comparison. The results of the relative errors of the transfer standard measured by the pilot laboratory, KRISS are shown in Table 3 and Figure 4.

Table 3 Relative errors (%) of the transfer standard measured by the pilot laboratory

| Flow rate | Relative error (%) | | |
|---|---|---|---|
| ($m^3$/h) | June 2018 | July 2019 | Feb. 2022 |
| 10 | -0.084 | -0.118 | -0.039 |
| 20 | 0.002 | 0.001 | 0.066 |
| 30 | 0.069 | 0.049 | 0.107 |
| 40 | 0.165 | 0.141 | 0.167 |
| 50 | 0.231 | 0.229 | 0.310 |
| 60 | 0.317 | 0.276 | 0.339 |
| 70 | 0.347 | 0.321 | 0.349 |
| 80 | 0.385 | 0.365 | 0.346 |
| 90 | 0.518 | 0.444 | 0.445 |
| 100 | 0.558 | 0.494 | 0.457 |

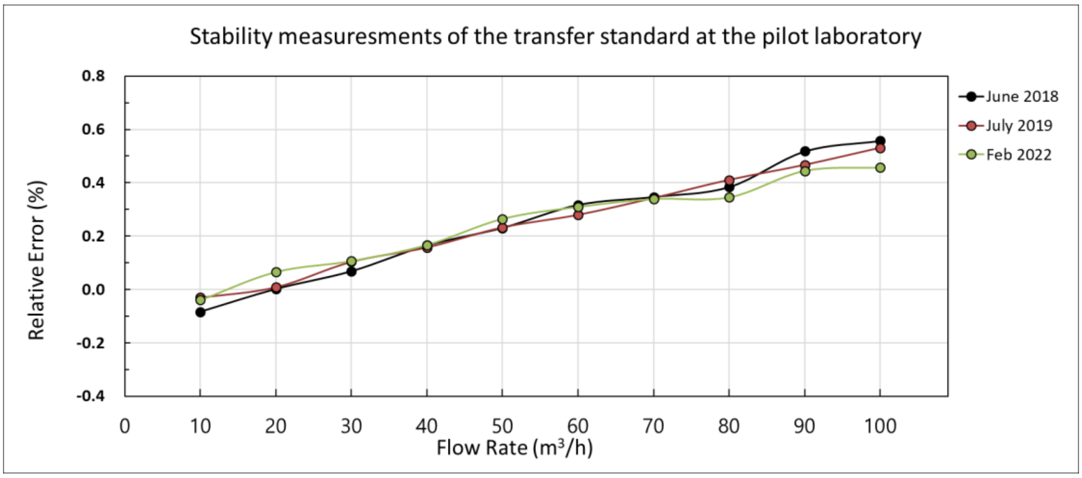



*Figure 4 Stability of the transfer standard*

### 5.2 Laboratory results

All data collected from the participating laboratories are summarized in the following Tables 4 and Figures 5.

*Table 4 Relative errors (%) of the transfer standard obtained by the participants*

| Flow rate | Relative error (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ($m^3/h$) | KRISS | NMIA | NMC, A*STAR | NIMT | VMI | NIM | NPLI | CMS | SNSU |
| 10 | -0.080 | -0.030 | 0.025 | -0.097 | -0.090 | -0.200 | -0.100 | -0.120 | 0.010 |
| 20 | 0.023 | 0.009 | 0.095 | -0.018 | 0.140 | -0.090 | -0.030 | -0.080 | 0.180 |
| 30 | 0.075 | 0.104 | 0.130 | 0.040 | 0.080 | 0.000 | 0.070 | -0.030 | 0.190 |
| 40 | 0.158 | 0.158 | 0.142 | 0.088 | 0.180 | 0.070 | 0.150 | 0.060 | 0.180 |
| 50 | 0.242 | 0.233 | 0.173 | 0.160 | 0.200 | 0.130 | 0.240 | 0.120 | 0.270 |
| 60 | 0.301 | 0.280 | 0.217 | 0.220 | 0.290 | 0.190 | 0.320 | 0.170 | 0.270 |
| 70 | 0.336 | 0.343 | 0.224 | 0.280 | 0.250 | 0.240 | 0.390 | - | 0.260 |
| 80 | 0.365 | 0.411 | - | 0.360 | 0.230 | 0.300 | - | - | - |
| 90 | 0.469 | 0.467 | - | 0.410 | 0.290 | 0.370 | - | - | - |
| 100 | 0.503 | 0.531 | - | 0.460 | 0.370 | 0.450 | - | - | - |

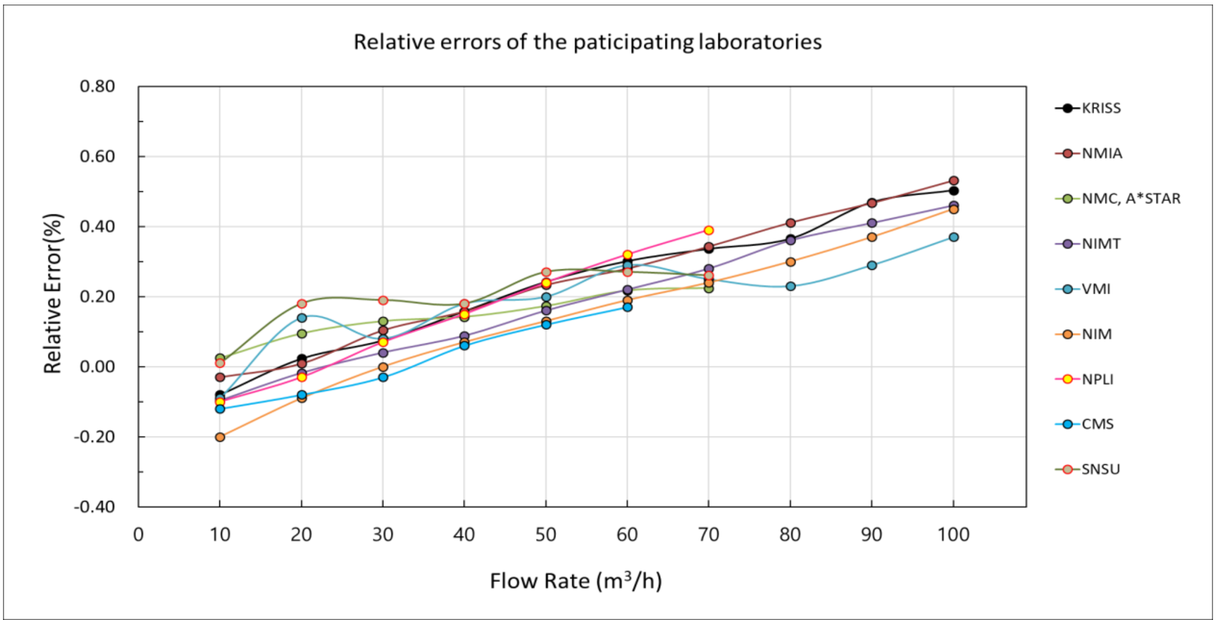



*Figure 5 Relative errors of the participating laboratories*

### 5.3 Laboratory uncertainty

The uncertainties are calculated according to the following formulas (see Guide to Expression of Uncertainty in Measurement [3]).

Type A uncertainty based on statistical methods of measurement results is calculated using following equations:

$$u_A^2 = \frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \overline{x})^2 \qquad (2)$$

Type B uncertainty is determined on the basis of non-statistical methods. It consists the root-sum-of squares of the relevant sources of uncertainty from the mathematical model:

$$u_B = \frac{1}{V_{Em}} \sqrt{\sum_{i=1}^{k} \left(\frac{\partial V_{Em}}{\partial x_i}\right)^2 \cdot u^2(x_i)} \qquad (3)$$

Combined standard uncertainty is calculated according to the following formula:

$$u_c = \sqrt{u_A^2 + u_B^2} \qquad (4)$$

The expanded uncertainty $U$ is obtained by multiplying the combined standard uncertainty $u_c$ by coverage factor according to the formula:

$$U = k \cdot u_c \qquad (5)$$

Where the coverage factor $k$=2 is usually used in the flow community.

Uncertainty values of participating laboratories for each flow rate are stated in Table 5.

*Table 5 Expanded uncertainties (%) of measurements reported by participating laboratories*

| Flow rate | Expanded uncertainty (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ($m^3$/h) | KRISS | NMIA | NMC, A*STAR | NIMT | VMI | NIM | NPLI | CMS | SNSU |
| 10 | 0.18 | 0.15 | 0.25 | 0.20 | 0.382 | 0.18 | 0.23 | 0.15 | 0.43 |
| 20 | 0.18 | 0.15 | 0.28 | 0.20 | 0.385 | 0.18 | 0.23 | 0.15 | 0.32 |
| 30 | 0.18 | 0.15 | 0.26 | 0.20 | 0.379 | 0.18 | 0.23 | 0.15 | 0.34 |
| 40 | 0.18 | 0.15 | 0.38 | 0.20 | 0.352 | 0.18 | 0.23 | 0.15 | 0.33 |
| 50 | 0.18 | 0.15 | 0.25 | 0.20 | 0.345 | 0.18 | 0.23 | 0.15 | 0.34 |
| 60 | 0.18 | 0.15 | 0.32 | 0.20 | 0.338 | 0.18 | 0.23 | 0.15 | 0.31 |
| 70 | 0.18 | 0.15 | 0.28 | 0.20 | 0.335 | 0.18 | 0.23 | - | 0.35 |
| 80 | 0.18 | 0.15 | - | 0.20 | 0.329 | 0.18 | - | - | - |
| 90 | 0.18 | 0.15 | - | 0.20 | 0.325 | 0.18 | - | - | - |
| 100 | 0.18 | 0.15 | - | 0.20 | 0.325 | 0.18 | - | - | - |

### 5.4 Uncertainty corrections and stability of the transfer standard

The standard uncertainties of the error in different laboratories $u_{x1}$, $u_{x2}$ … $u_{xn}$ include the uncertainty contributed by the transfer standard. This uncertainty was calculated according to the following formula

$$u_{xi} = \sqrt{\left(\frac{U(x_i)}{2}\right)^2 + u_{TS}^2} \tag{6}$$

where $U(x_i)$ is the expanded uncertainty($k=2$) determined by participating laboratory $i$ and presented in results of laboratory $i$

$u_{TS}$ is estimated standard uncertainty caused by the stability (reproducibility) of the transfer standard which was measured by the pilot laboratory

$$u_{TS} = \max\left(\frac{\max(x_{TS,i1}, x_{TS,i2}, x_{TS,i3}) - \min(x_{TS,i1}, x_{TS,i2}, x_{TS,i3})}{2\sqrt{3}}\right) \tag{7}$$

where $x_{TS,i}$ is the relative error of the transfer standard;

the subscript 1,2,3 represents the order of the sequence of the measurement of the pilot lab;

the subscript $i$ represents the calibration point corresponding to each flow rate;

The uncertainty due to the stability of the transfer standard in this comparison was 0.058 %. This transfer standard uncertainty component was combined by root-sum-of-squares with standard uncertainty provided by each participating laboratory (equation (6)).

## 6. Evaluation

### 6.1 Linkage to the CCM.FF-K6.2011

APMP.M.FF-K6.2018 is linked to the CCM.FF-K6.2011 by correcting the results of linking laboratories (KRISS – Republic of Korea, NIM – China and NMIA – Australia). The results from APMP.M.FF-K6.2018 are corrected by procedure described by Delahaye and Witt [4]. The calculation was determined for each flow separately.

A correction $D$, which should be applied to the result from KCRV,

$$D = \sum_{i=1}^{3} w_i D_i \tag{8}$$

where $D_i$ is the difference between the results from CCM KC and APMP KC at a linking laboratory (KRISS, NIM, NMIA) and $w_i$ is the weighing coefficient obtained from the uncertainty at each linking laboratory.

$$D_i = x_{i,CCM} - x_{i,APMP} \tag{9}$$

where $x_{i,\,CCM}$ are relative errors of the transfer standard in the linking laboratories in the CCM KC

$x_{i,\,APMP}$ are relative errors of the transfer standard in the linking laboratories in the APMP KC

The weighing coefficient $w_i$ was calculated.

$$w_i = \frac{\frac{1}{u_{xi}^2}}{\frac{1}{u_{x1}^2}+\frac{1}{u_{x2}^2}+\frac{1}{u_{x3}^2}} \tag{10}$$

where $u_{x1}$, $u_{x2}$, $u_{x3}$ are standard uncertainty of the relative error in linking laboratories $i$=1, 2, 3 by the CCM KC including the uncertainty caused by stability of the transfer standard.

The measurement points of flow rates in the CCM.FF-K6.2011 were 2, 4.5, 6.6, 9.1, 13.1, 16, 24, 32, 40, 50, 60, 70, 80, 90, 100 m$^3$/h. In the flow set-points of 10, 20, 30 m$^3$/h, the relative errors were determined by the linear regression and interpolation with near points and values. The KCRV (Key comparison reference value) and uncertainty of CCM.FF-K6.2011 in the flow range from 10 to 100 m$^3$/h shown in Table 6.

*Table 6 The KCRV (Relative errors (%)) and uncertainty in the CCM.FF-K6.2011*

| Flow Rate (m$^3$/h) | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| *KCRV* (%) | 0.114 | 0.177 | 0.214 | 0.233 | 0.250 | 0.261 | 0.282 | 0.301 | 0.314 | 0.332 |
| $u_{KCRV}$ (%) | 0.023 | 0.022 | 0.022 | 0.022 | 0.022 | 0.022 | 0.023 | 0.023 | 0.025 | 0.025 |

These KCRV are used as the reference values after the results from APMP KC are corrected by Delahaye and Witt.

Table 7 shows the results of CCM.FF-K6.2011 for three linking laboratories (KRISS – Republic of Korea, NIM – China and NMIA – Australia). In the low flow set-points from 10 to 30 m$^3$/h, the relative errors were also determined by the linear regression with near points and values.

*Table 7 Relative errors (%) of three linking laboratories of APMP in CCM.FF-K6.2011*

| Flow rate (m$^3$/h) | KRISS | | NIM | | NMIA | |
|---|---|---|---|---|---|---|
| | Relative error (%) | Expanded Uncertainty (%) | Relative error (%) | Expanded Uncertainty (%) | Relative error (%) | Expanded Uncertainty (%) |
| 10 | 0.03 | 0.18 | 0.16 | 0.18 | 0.27 | 0.16 |
| 20 | 0.17 | 0.18 | 0.20 | 0.18 | 0.30 | 0.16 |
| 30 | 0.26 | 0.18 | 0.25 | 0.18 | 0.33 | 0.16 |
| 40 | 0.25 | 0.18 | 0.29 | 0.18 | 0.36 | 0.16 |
| 50 | 0.27 | 0.18 | 0.32 | 0.18 | 0.38 | 0.16 |
| 60 | 0.28 | 0.18 | 0.35 | 0.18 | 0.38 | 0.16 |
| 70 | 0.30 | 0.18 | 0.38 | 0.18 | 0.40 | 0.16 |
| 80 | 0.30 | 0.18 | 0.40 | 0.18 | 0.40 | 0.16 |
| 90 | 0.32 | 0.18 | 0.41 | 0.18 | 0.40 | 0.16 |
| 100 | 0.30 | 0.18 | 0.42 | 0.18 | 0.41 | 0.16 |

For the correction between APMP.M.FF-K6.2018 and CCM.FF-K6.2011, the correction $D$ were calculated by equation(8), (9) and (10). The corrected value $x_i'$ for each flow and each participant of APMP was calculated as

$$x_i' = x_{i,APMP} + D \tag{11}$$

where $x_1$, $x_2$, … $x_n$ are relative errors of the transfer standard in one flow in different laboratories *i=1, 2, … n*

This correction *D* provide an estimate of what would have been the results from the APMP.M.FF-K6.2018 participants, if they had actually participated in CCM.FF-K6.2011.

The corrected relative error (%) of participating laboratory and KCRV of CCM.FF-K6.2011 was shown in Figure 6.

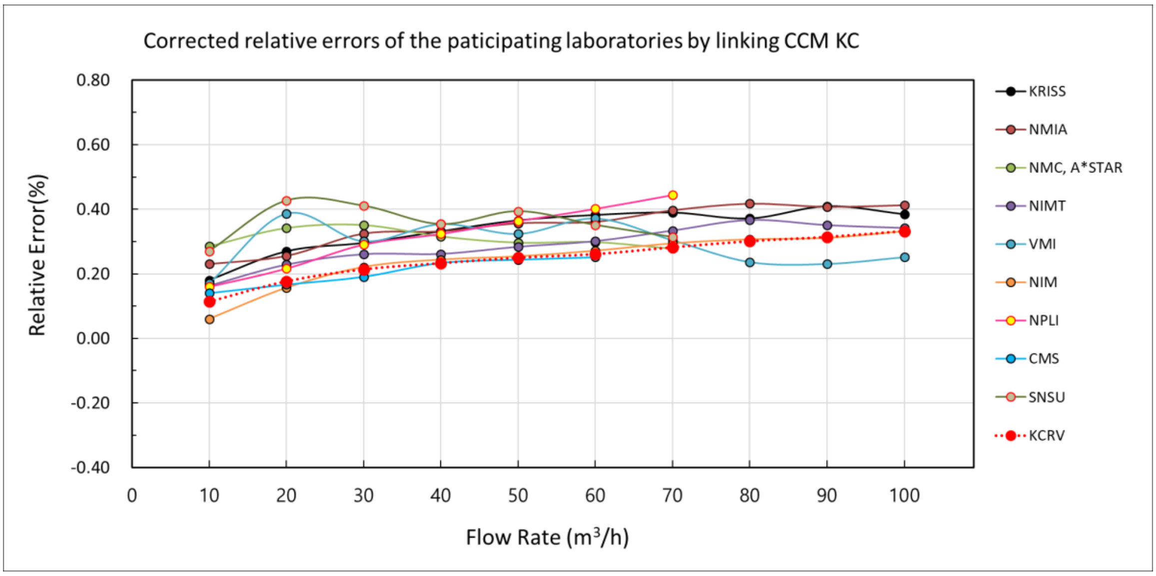



*Figure 6 Corrected relative errors of the participating laboratories by linking with CCM.FF-K6.2011*

### 6.2 Degree of Equivalence to KCRV

For each participating laboratory, the degree of equivalence (DoE) to KCRV, $d_i$ was calculated using a following equation.

$$d_i = x_i' - x_{KCRV} = x_{i,APMP} + D - x_{KCRV} \tag{12}$$

where $x_{KCRV}$ is the relative error from KCRV of the CCM.FF-K6.2011

The expanded uncertainty was obtained using following equations

$$U(d_i) = 2u(d_i) \tag{13}$$

$$u^2(d_i) = u^2(x_i) + u^2(D) + u^2(x_{KCRV}) \tag{14}$$

where $u(x_1)$, $u(x_2)$, … $u(x_n)$ are the standard uncertainties of the relative error in different laboratories *i=1, 2, … n* including the uncertainty caused by the stability of the transfer standard.

*u(D)* is the standard uncertainty of the correction D including the uncertainty caused by linking laboratories *i=1, 2, 3.*

$$u^2(D_l) = u^2_{xl(CCM)} + u^2_{xl(APMP)} \tag{15}$$

$$\frac{1}{u_D^2} = \frac{1}{u_{D1}^2} + \frac{1}{u_{D2}^2} + \frac{1}{u_{D3}^2} \tag{16}$$

$u(x_{KCRV})$ is the standard uncertainty of the KCRV.

Table 8 shows the correction *D* and its uncertainty applied to the results.

*Table 8 Correction D and its uncertainty*

| Flow Rate (m³/h) | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| *D* (%) | 0.26 | 0.25 | 0.22 | 0.17 | 0.12 | 0.08 | 0.05 | 0.01 | -0.06 | -0.12 |
| $u_D$ (%) | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |

Based on these differences the Degree of Equivalence (DoE) to KCRV was calculated according to

$$E_{n,i} = \left|\frac{d_i}{U(d_i)}\right| \tag{17}$$

The Degree of equivalence (DoE) to KCRV is a measure for the equivalence of the results of any laboratory with the KCRV, respectively:

- the results of a laboratory were equivalent (passed) if $E_{n,i} \le 1.0$
- the laboratory was determined as not equivalent (failed) if $E_{n,i} > 1.2$
- for the value of DoE in the range $1< E_{n,i} \le 1.2$ the "warning level" was defined. In this case some actions to check are recommended to the laboratory

The calculation of the DoE requires information about the uncertainty of the difference $d_{iD}$. To make statements about this, it is necessary to consider first the general problem of the difference of two vales $x_1$ and $x_2$. If we look to the pure propagation of standard uncertainty we find [5]:

$$u^2_{x_1-x_2} = \begin{pmatrix} \frac{\partial(x_1-x_2)}{\partial x_1} & \frac{\partial(x_1-x_2)}{\partial x_2} \end{pmatrix} \begin{pmatrix} u_1^2 & cov \\ cov & u_2^2 \end{pmatrix} \begin{pmatrix} \frac{\partial(x_1-x_2)}{\partial x_1} \\ \frac{\partial(x_1-x_2)}{\partial x_2} \end{pmatrix} = u_1^2 + u_2^2 - 2\cdot \mathrm{cov} \tag{17}$$

The standard uncertainty of the difference is the quadratic sum of the uncertainties of the input ($u_1$ and $u_2$) subtracting twice the covariance(cov) between the two input values.

Therefore, it is possible to handle the difference cases in this comparison.

a) Independent laboratories with contribution to the KCRV

The covariance between the results of a laboratory (with contribution to the KCRV) and the KCRV is the variance of the KCRV itself. Therefore, the uncertainty of that laboratory's degree of equivalence with the KCRV is

$$u(d_i) = \sqrt{u_{xi}^2 + u_D^2 + u_{KCRV}^2 - 2 \cdot u_{KCRV}^2} \tag{18}$$

b) Independent laboratories without contribution to the KCRV

There is no covariance between the results of a laboratory without contribution and the KCRV and the uncertainty of its degree of equivalence is

$$u(d_i) = \sqrt{u_{xi}^2 + u_D^2 + u_{KCRV}^2} \tag{19}$$

The expanded uncertainty *U(d<sub>i</sub>)* is determined by equation (13). Degree of Equivalence (DoE) to KCRV of each participating laboratory was calculated according to equation (17) as shown in Table 9 and Figure 7.

*Table 9 Degree of equivalence (DoE) of participating laboratories to KCRV*

| Flow rate | Degree of Equivalence | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ($m^3/h$) | KRISS | NMIA | NMC, A*STAR | NIMT | VMI | NIM | NPLI | CMS | SNSU |
| 10 | 0.29 | 0.56 | 0.58 | 0.19 | 0.14 | 0.23 | 0.17 | 0.12 | 0.34 |
| 20 | 0.40 | 0.38 | 0.51 | 0.20 | 0.50 | 0.09 | 0.14 | 0.05 | 0.70 |
| 30 | 0.36 | 0.53 | 0.45 | 0.18 | 0.21 | 0.03 | 0.28 | 0.11 | 0.53 |
| 40 | 0.43 | 0.48 | 0.20 | 0.11 | 0.31 | 0.05 | 0.33 | 0.00 | 0.33 |
| 50 | 0.50 | 0.51 | 0.16 | 0.13 | 0.19 | 0.02 | 0.41 | 0.03 | 0.38 |
| 60 | 0.53 | 0.48 | 0.10 | 0.16 | 0.30 | 0.04 | 0.50 | 0.04 | 0.26 |
| 70 | 0.47 | 0.56 | 0.01 | 0.20 | 0.06 | 0.05 | 0.58 | | 0.08 |
| 80 | 0.31 | 0.56 | - | 0.26 | 0.18 | 0.02 | - | | |
| 90 | 0.42 | 0.45 | - | 0.14 | 0.23 | 0.01 | - | | |
| 100 | 0.23 | 0.39 | - | 0.04 | 0.22 | 0.00 | - | | |

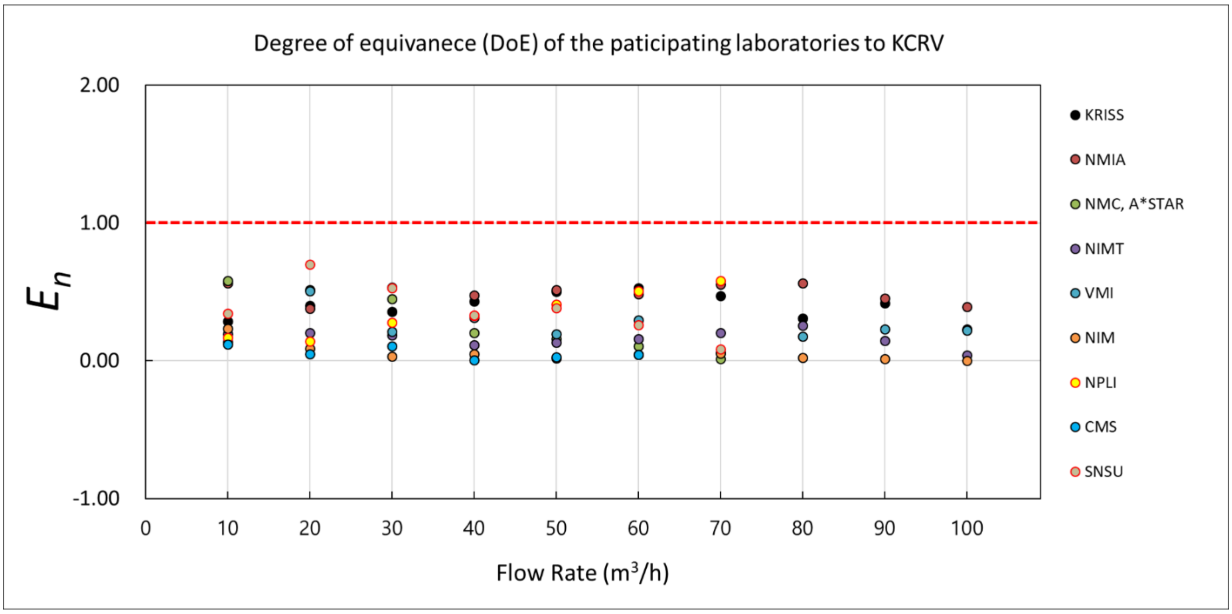



*Figure 7 Degree of equivalence (DoE) of participating laboratories to KCRV*

## 7 Conclusion

The nine NMIs participated in APMP.M.FF-K6.2018 for the linkage to key comparison reference value (KCRV) in CIPM key comparison CCM.FF-K6.2011. KRISS coordinated the comparison and acted as a pilot laboratory. The rotary gas meter had been circulated as a transfer standard.

The stability of transfer standard was checked during the comparison by pilot laboratory. The results of each participating laboratory were linked to KCRV of CCM.FF-K6.2011 by correcting the results of linking laboratories, KRISS, NIM and NMIA, which participated in CCM KC.

Degree of Equivalence (DoE) to KCRV of all participating laboratory shows $|E_n| \leq 1$ which means equivalent and consistent with KCRV. The results of this comparison will be used for supporting evidence for the calibration and measurement capabilities (CMCs) claimed by the participating laboratories.

## 8 Reference

[1] Final report on CIPM Key comparison CCM.FF-K6.2011, *Comparison of the Primary(National) Standards of Low-Pressure Gas Flow*, 2014.

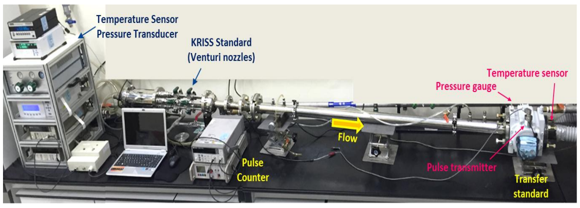
[2] Cox M.G., *Evaluation of key comparison data*. Metrologia, 2002, 39

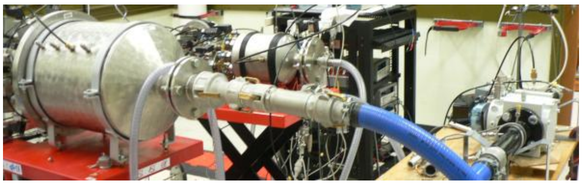
[3] JCGM 100:2008 (GUM 1995 with minor corrections) Evaluation of measurement data – Guide to the expression of uncertainty in measurement

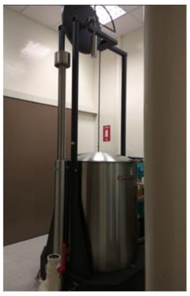
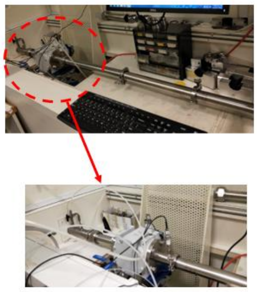
[4] Delahaye F. and Witt T. J., Linking the results of key comparison CCEM-K4 with 10 pF, Metrologia, 2002, 39

[5] EURAMET Regional Key Comparison EURAMET.M.FF-K6, *Comparison of the Primary(National) Standards of Low-Pressure Gas Flow(Project No.1180)*

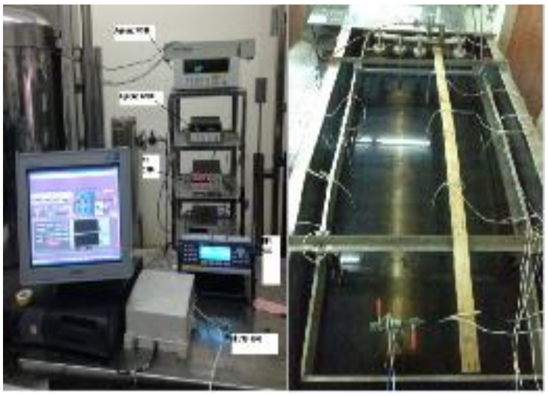
## 9 Annex: Test facilities of each participants

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">KRISS<br>Korea Research Institute of Standards and Science<br>267 Gajeong-Ro, Yuseong-Gu, Daejeon 34113<br>Republic of Korea<br>
</td><td rowspan="5">The sonic nozzle bank was used to calibrate the transfer standard. Transfer standard was installed at the downstream of sonic nozzle bank. Straight pipe of 60D and 35D was installed at the upstream and downstream of transfer standard. The sonic nozzles were manufactured according to the ISO 9300 specification. These sonic nozzles were calibrated with a mercury sealed piston prover and bell provers which are primary gas flow standards of KRISS.</td></tr>
<tr><td>Range of flow rate</td><td>(10 to 100) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(20 ± 2)℃</td></tr>
<tr><td>Working pressure</td><td>Ambient</td></tr>
<tr><td>Expanded uncertainty(k=2)</td><td>0.18%</td></tr>
</table>

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">NMIA<br>National Measurement Institute Australia<br>36 Bradfield Road, Lindfield 2070<br>Australia<br></td><td rowspan="5">The sonic nozzle array was used to calibrate the transfer standard. Transfer standard was installed at the upstream of sonic nozzle array. Straight pipes were installed at the upstream and downstream of transfer standard. A suction pump was used at downstream of nozzles to ensure sonic conditions were occurring at nozzle throats. During testing, air was drawn from the laboratory through the meter under test then to the nozzles. These sonic nozzles were calibrated with a mercury sealed piston prover and bell prover which are primary gas flow standards of NMIA.</td></tr>
<tr><td>Range of flow rate</td><td>(10 to 100) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(20 ± 0.5)℃</td></tr>
<tr><td>Working pressure</td><td>Ambient</td></tr>
<tr><td>Expanded uncertainty(k=2)</td><td>0.15%</td></tr>
</table>

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">NMC, A*STAR<br>National Metrology Centre, A*STAR<br>8 Cleantech Loop #01-20, Singapore, 637145<br><br>Bell Prover<br><br>Transfer standard</td><td rowspan="5">The Bell Prover was used to calibrate the transfer standard. The transfer standard was installed at the upstream of the Bell Prover. The straight pipes of approximately 80 diameters (80D) and 40 diameters (40D) in length were installed at the upstream and downstream of the transfer standard. The Bell Prover is the primary gas flow standard maintained in National Metrology Centre, A*STAR.</td></tr>
<tr><td>Range of flow rate</td><td>(10 to 70) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(20 ± 1.5) ℃</td></tr>
<tr><td>Working pressure</td><td>Ambient</td></tr>
<tr><td>Expanded uncertainty($k$=2)</td><td>0.25% – 0.38%</td></tr>
</table>

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">NIMT<br>National Institute of Metrology (Thailand)<br>3/4-5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand<br></td><td rowspan="5">The bell prover, a primary standard of NIMT which is traceable to SI units, is a volume standard for gas in low-pressure range. The transfer standard is connected to the downstream of the bell prover. The air is filled into the bell and then expelled out through the transfer standard. With the available data regarding pressure and temperature over the calibration procedure, the reference flow rate and the error of the transfer standard are determined.</td></tr>
<tr><td>Range of flow rate</td><td>(1 to 100) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(23 ± 2)℃</td></tr>
<tr><td>Working pressure</td><td>Ambient</td></tr>
<tr><td>Expanded uncertainty($k$=2)</td><td>0.20%</td></tr>
</table>

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">VMI<br>Vietnam Metrology Institute<br>Building D; No. 8, Hoang Quoc Viet street., Cau Giay district., Ha Noi, Viet Nam<br></td><td rowspan="5">The artifact was calibrated employing both the 1000 L Bell Prover and 1000 L PVTt systems. Both of these systems are serving as primary standard gas calibration systems of VMI. The 1000 L Bell Prover and PVTt system at VMI are capable of achieving a flow rate of up to 120 $m^3/h$, with uncertainty as low as 0.2%. The flow rate of the systems is generated through a 45 kW piston-type air compressors, storage tanks, and pressure regulation valve systems.<br>The calibration process can be summarized as follows: The artifact is installed at upstream of the standard systems; Through a pressure control valve system, desired flow rates are generated; The artifact in conjunction with the standard systems, is operated and controlled through software developed in the Labview programming language; During the calibration process, in addition to measuring parameters on the standard systems (such as temperature, pressure, collecting time, displacement), pulses, temperature, and pressure at the artifact are also measured.</td></tr>
<tr><td>Range of flow rate</td><td>(10 to 100) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(20 ± 2) ℃</td></tr>
<tr><td>Working pressure</td><td>Ambient</td></tr>
<tr><td>Expanded uncertainty(k=2)</td><td>0.20%</td></tr>
</table>

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">NIM<br>National Institute of Metrology, China<br>NIM Hepingli campus: 18, Beisanhuandonglu, Chaoyang District, 100029, Beijing<br>NIM Changping campus: 18, Changchilu, Changping District, 102200, Beijing<br></td><td rowspan="5">The sonic nozzle gas flow facility was utilized to calibrate the transfer meter, which is in NIM Changping campus. The transfer meter was mounted in the upstream of the sonic nozzle as shown in the picture. The sonic nozzles were manufactured within the requirement of ISO 9300, which were traceable to the pVTt gas flow primary facility in NIM.</td></tr>
<tr><td>Range of flow rate</td><td>(10 to 510) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(20 ± 2)°C</td></tr>
<tr><td>Working pressure</td><td>(100 ± 2) kPa</td></tr>
<tr><td>Expanded uncertainty(k=2)</td><td>(0.18~0.19)%</td></tr>
</table>

| Characteristic information of the standard used by measurements in comparison | Working Procedure |
|---|---|
| **NPLI**<br>**CSIR-National Physical Laboratory**<br>Dr. K.S. Krishnan Marg, New Delhi-110012, India<br> | The sonic nozzles were used to calibrate the artefact (i.e. transfer standard). The sonic nozzles are operated between 50 kPaa to 600 kPaa fed through Air Compressor System. The artefact was installed at the downstream of sonic nozzle. In the set-up, 36D upstream and 14D downstream straight pipe lengths were provided to artifact for improved flow profile. The digital thermometer and digital reference pressure monitor were installed downstream of artefact for measurement of air temperature and pressure for converting the volume to standard conditions. These sonic nozzles were calibrated through primary Gravimetric Gas Flow Calibration System of Fluke Corporation, USA. |

| | |
|---|---|
| Range of flow rate | (10 to 72) $m^3/h$ |
| Working temperate | (25 ± 2)℃ |
| Working pressure | 50 kPaa to 600 kPaa |
| Expanded uncertainty($k$=2) | 0.23% |

| Characteristic information of the standard used by measurements in comparison | Working Procedure |
|---|---|
| **CMS**<br>**Centre for Measurement Standards**<br>30 TA Hsueh Rd., Hsinchu,<br>Chinese Taipei 30080, R.O.C.<br> | The reference standard used in this low pressure gas flow key comparison is a set of four critical flow Venturis (CFVs) with throat diameters ranging from 0.6150 mm (0.024 inch) to 5.1847 mm (0.204 inch), having a flow range from 10 L/min to 1000 L/min. The reference standard is calibrated by the primary flow standard (Bell Prover) maintained by CMS once every 2 years. A photograph of the calibration setup is shown in the figure.<br>Compressed air is dried first to reach a dew point of -40 ℃ by flowing through a refrigeration dryer and an adsorption dryer successively. The dry air is then stored in three tanks with a total volume of 5 $m^3$ and maximum gauge pressure of 8 bars. The CFVs are installed upstream of the meter under test (MUT). Pressure and temperature sensors are installed upstream of the CFVs for the measurement of flow. Instrumentation for measuring pressure, differential pressure, pulse, time or temperature may be selected to acquire outputs from the MUT.<br>During calibration, the dry air discharged from the pressurized storage tanks passes through two stages of manual pressure regulation to adjust the pressure at the CFV and hence flow. To set up the reference standard, a CFV is selected to achieve the desired range of flows. |

| | |
|---|---|
| Range of flow rate | (10 to 60) $m^3/h$ |
| Working temperate | (23 ± 1.5) ℃ |
| Working pressure | Ambient |
| Expanded uncertainty($k$=2) | 0.15% |

<table>
<tr><th colspan="2">Characteristic information of the standard used by measurements in comparison</th><th>Working Procedure</th></tr>
<tr><td colspan="2">SNSU-BSN<br>KST BJ. Habibie, Gedung 420, Setu, Tangerang Selatan 15314 – Banten<br>Indonesia<br></td><td rowspan="5">Bell prover was used to calibrate the transfer standard. The bell prover uses dry air as medium. The volume of bell is determined dimensionally and traceable to SI through SNSU-BSN. The transfer standard was installed at the upstream of bell prover. Camera is used to record measurement data simultaneously. All pressure and temperature sensors are attached properly on bell prover and transfer standard to measure air parameters.</td></tr>
<tr><td>Range of flow rate</td><td>(10 to 70) $m^3/h$</td></tr>
<tr><td>Working temperate</td><td>(20 ± 2)℃</td></tr>
<tr><td>Working pressure</td><td>Ambient</td></tr>
<tr><td>Expended uncertainty($k$=2)</td><td>0.30%</td></tr>
</table>