APMP.M.P-K9:

APMP Key Comparison of Absolute Pressure from 10 kPa to 110 kPa

Final Report

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Abstract:

This report describes the results of a key comparison of pneumatic pressure standards which was carried out at fourteen National Metrology Institutes (NMIs: NMIA, NSCL, PTB, NIM, VMI, CMS/ITRI, MSL, NMIJ/AIST, NMC A*STAR, NIMT, SCL, NIS, RCM-LIPI and KRISS) during the period of February 2010 to July 2012 within the framework of the Asia-Pacific Metrology Programme (APMP) in order to determine their degrees of equivalence at pressures in the range 10 kPa to 110 kPa in absolute mode. Among them, twelve NMIs' results were compared in the report. The pilot laboratory was Korea Research Institute of Standards and Science (KRISS). The degrees of equivalence in this comparison were transferred to the corresponding CC key comparison, CCM.P-K2. National Measurement Institute, Australia (NMIA) and Physikalisch-Technische Bundesanstalt (PTB) that participated in the CC comparison agreed to be link laboratories.

Most of the participating institutes used pneumatic pressure balances as their pressure standards while two link laboratories used laser interferometer mercury manometers. Precise absolute pressure gauges were used as transfer standards (TSs). The precision pressure gauge has two Quartz-Resonant Pressure Transducers (Q-RPTs) inside. Two identical transfer packages (TS-A and TS-B) were circulated independently to reduce the time required for the measurements. During the comparison, intermediate measurements of two circulated transfer standards were carried out in the pilot laboratory after one or two NMIs measurement and third transfer standard (TS-C) was monitored for the stability characterization, also. The pressures of the comparison were (10, 30, 50, 70, 90, 100, 110) kPa. From the calibration results, the behaviours of the transfer standards during the comparison period were well characterized and it was concluded that the performance of the transfer standards were sufficient in the comparison pressure range except 10 kPa. The TSs used in this comparison were not suitable for the low pressure measurement like 10 kPa because of low display resolution of TS (1 part in 10^5 at 10 kPa). The degrees of equivalence of each national measurement standard were expressed quantitatively by two terms, deviations from the key comparison reference values (KCRVs) and pair-wise differences of their deviations together with the associated uncertainties. The pneumatic pressure standards in the range 30 kPa to 110 kPa for absolute mode of all participating NMIs were found to be equivalent within their claimed uncertainties.

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1. Introduction: At the APMP TCM meeting in Indonesia, November 2008, it was decided to carry out a new key comparison (KC) in the range of 110 kPa in absolute mode. Korea Research Institute of Standards and Science (KRISS) has been approved by the Technical Committee for Mass and Related Quantities (TCM) in the Asia-Pacific Metrology Programme (APMP) to coordinate the comparison program for absolute pressure up to 110 kPa as a pilot laboratory. The comparison was identified as APMP.M.P-K9 by the Consultative Committee for Mass and Related Quantities (CCM) of the International Committee for Weights and Measures (CIPM), the International Bureau of Weights and Measures (BIPM) and APMP.

The objective of this comparison is to determine the degree of equivalence of pressure measurement standards held at National Measurement Institutes (NMIs) in the range and to link the APMP results to the Key Comparison Reference Values (KCRVs). The degrees of equivalence in this comparison were transferred to the corresponding CC key comparison, CCM.P-K2. National Measurement Institute, Australia (NMIA) and Physikalisch-Technische Bundesanstalt (PTB) that participated in the CC comparison made a role as link laboratories.

All of the participating institutes have the opportunity to get results in the comparison at a level of uncertainty appropriate for them. The results of this comparison will be included in the Key Comparison Database (KCDB) of BIPM following the rules of CCM and will be used to establish the degree of equivalence of national measurement standards of NMIs. Those are essential supporting evidence for absolute pneumatic pressure calibration and measurement capabilities (CMCs) of NMIs for the Mutual Recognition Arrangement (MRA).[1]-[2]

2. Participating institutes and their pressure standards

2.1 List of participating institutes: Seventeen National Metrology Institutes (NMIs) participated in this comparison including the pilot institute. Among them, fourteen NMIs submitted the measurement results to the pilot laboratory. The list of participating institutes and contact points are as shown in Table 1. One institute, NML-SIRIM (Malaysia) which was supposed to participate in the comparison, did not evaluate the TS due to their pressure standard issue and withdrew in the period of their measurement term. Two institutes, NMISA (South Africa) and NPLI (India) could not complete the whole measurement process because of the TS's failure caused by over-pressure during the measurement.

NMC A*STAR and NIS submitted their measurement results, but withdrew their submission during the circulation of the draft report since they had found mistakes in the measurement results. NMC A*STAR found the submission for the uncertainty of reference standard did not follow the protocol format, which did not include all measurement uncertainty components. In case of NIS, there was the error of the residual pressure measurement due to the vacuum sensor failure.

Therefore, NML-SIRIM, NMISA, NPLI, NMC A*STAR and NIS were deleted from the list.

The measurement protocol was prepared and circulated among participating institutes. The protocol includes participating institutes, transfer standard information, a way of transportation, a measurement procedure, report format and so on.[9]

Table 1. List of participating institutes and contact points

No.	Participant	Contact Points	Address
1	NMIA National Measurement Institute, Australia	Mr. Neville Owen (Neville.owen@measurement.gov.au)	Bradfield Road, Lindfield 2070, NSW, Australia
2	NSCL National Standards & Calibration Laboratory	Eng. Mohamad Aldammad (nscl@nscl.sy)	P.O.Box: 30116, Damascus, Syria
3	PTB Physikalisch-Technische Bundesanstalt	Dr. Wladimir Sabuga (wladimir.sabuga@ptb.de)	Pressure Working Group Bundesallee 100, 38116 Braunschweig Germany
4	NIM National Institute of Metrology	Mr. Yue Jin (Yuej@nim.ac.cn)	18 Beisanhuan donglu, chaoyang district, Beijing, China
5	VMI Vietnam Metrology Institute	Mr. Nguyen Ngoc Thang (thangnn@vmi.gov.vn)	8 Hoang Quoc Viet Rd., Cau Giay Dist., Hanoi Vietnam
6	CMS/ITRI Center for Measurement Standards/ITRI	Mr. Gwo-Jen Wu (gjwu@itri.org.tw)	Room 109, Bldg. 08, 321 Kuang Fu Rd, Sec. 2, Hsinchu, Taiwan 300, R.O.C.
7	MSL Measurement Standards Laboratory of New Zealand	Dr. Chris Sutton (c.sutton@irl.cri.nz)	69 Gracefield Road, P O Box 31-310, Lower Hutt 5040, New Zealand
8	NMIJ/AIST National Metrology Institute of Japan, AIST	Dr. Momoko Kojima (m.kojima@aist.go.jp)	AIST, Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563 Japan
9	NIMT National Institute of Metrology	Mr. Tawat Changpan (tawat@nimt.or.th)	3/5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120, Thailand
10	SCL Standards and Calibration Laboratory	Mr. Raymond Leung (wmleung@itc.gov.hk)	36/F, Immigration Tower, 7 Gloucester Road, Wanchai, Hong Kong
11	RCM-LIPI Indonesia	Ms. Renanta Hayu (renanta@kim.lipi.go.id)	RCM-LIPI, Kompleks PUSPIPTEK, Cisauk – Tangerang, 15314 INDONESIA
12	KRISS Korea Research Institute Standards and Science	Dr. In-Mook Choi (mookin@kriss.re.kr) Dr. Sam-Yong Woo (sywoo@kriss.re.kr)	267 Gajeong-ro, Yuseong-gu, Daejeon, 34114 Rep. of Korea

2.2 Pressure standards of participating institutes

The pressure standards of most participating laboratories are pneumatic pressure balances of different manufacturer and model. They are equipped with a simple type or a re-entrant type piston-cylinder assembly. Each laboratory has provided the pilot laboratory with its brief information of pressure standard and traceability as listed in Table 2. The details of each participant's pressure standard used for the comparison are shown in Appendix I.

Table 2. Pressure standards of participating institutes.

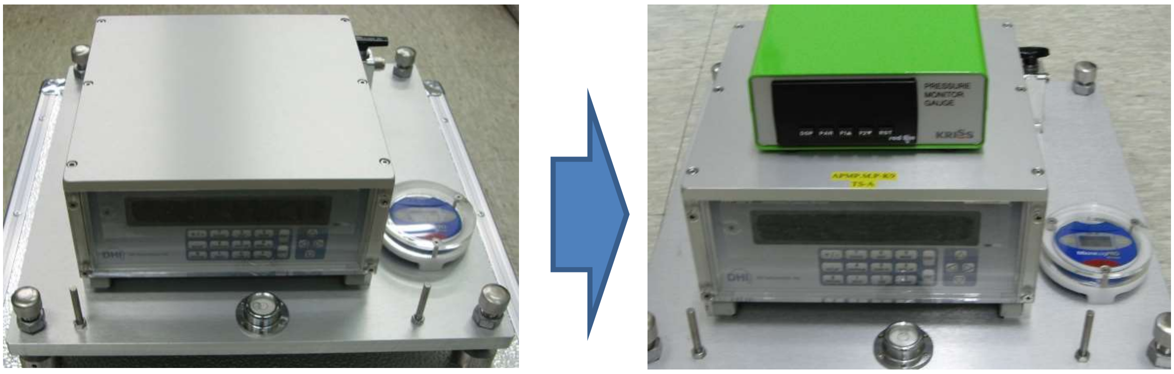
No.	Participant	Type of reference standard	Independent traceability?	Relative Uncertainty of A_0 in 10^{-6} (k = 1)	Reference temperature during measurement
1	NMIA	Liquid Manometer	Yes	3*	(20.0 ± 0.5) °C
2	NSCL	Pressure Balance	PTB	25	(23.0 ± 0.5) °C
3	PTB	Liquid Manometer	Yes	5.7*	(19.93 ± 0.22) °C
4	NIM	Pressure Balance	Yes	4.5	(19.7 ± 0.3) °C
5	VMI	Pressure Balance	NIMT	25.5	(20.0 ± 1.0) °C
6	CMS/ITRI	Pressure Balance	PTB	9.2	(23.0 ± 1.5) °C
7	MSL	Pressure Balance	Yes	4.6	(20.0 ± 0.5) °C
8	NMIJ/AIST	Pressure Balance	Yes	6.5	(22.9 ± 0.3) °C
9	NIMT	Pressure Balance	Yes	8.1	(20.7 ± 0.2) °C
10	SCL	Pressure Balance	NPL	24	(20.0 ± 1.0) °C
11	RCM-LIPI	Pressure Balance	PTB	7.0	(20.0 ± 0.5) °C
12	KRISS	Pressure Balance	Yes	6.0	(23.0 ± 0.5) °C (20.0 ± 0.5) °C

* The national pressure standard is a laser interferometer mercury manometer. The value indicates the relative standard uncertainty of pressure at 100 kPa

3. Transfer Standard

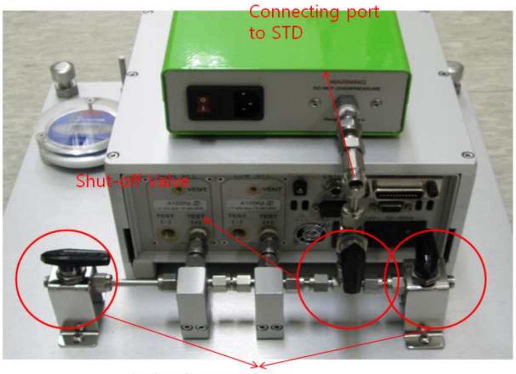
Two precision digital gauges, each with two Q-RPTs (Quartz – Resonant Pressure Transducers) were used for the comparison. The gauges, RPM4^{TM}, were manufactured by DH Instruments, Fluke. The characteristics of these precise digital gauges and the effects caused by environmental conditions were evaluated by the pilot laboratory (KRISS) before, after and during the comparison. The two TSs were circulated during the comparison in order to shorten the KC period. The two Q-RPT sensors in TS-A and TS-B could be distinguished from each other by the notations “HIGH” and “LOW” on the display of the gauge. Regardless of this notation, the two sensors have the same capacity of 110 kPa and the same resolution of 0.0001 kPa. The performance of the sensing elements used in the TS can be dependent on the operating gas because the Q-RPT has a frequency-dependent characteristic. Therefore, the operating gas was decided to be well-filtered clean nitrogen (N2) supplied by each participant. [10]

At first, the TSs had no monitor gauge as shown in Fig.1(a). After sensors in TS were damaged during the TS circulation, two Q-RPTs was replaced with new ones and a monitor gauge was added to the TS as shown in Fig.1(b). TSs were designated as TS-A1 and TS-B1 before the failure, and designated as TS-A2 and TS-B2 after the failure. Additionally, TS-C was monitored in the pilot laboratory in order to evaluate the long-term characteristic. Since TS-B1 could not be characterized after the measurement of NMIJ due to the TS failure, the NMIJ measurement results were compared only with KRISS measurement results before the NMIJ measurement.



(a) Original transfer standard

(b) Modified transfer standard with a monitor gauge



(c) Connection of backside of the modified transfer standard

Fig.1 Picture of Transfer Standard

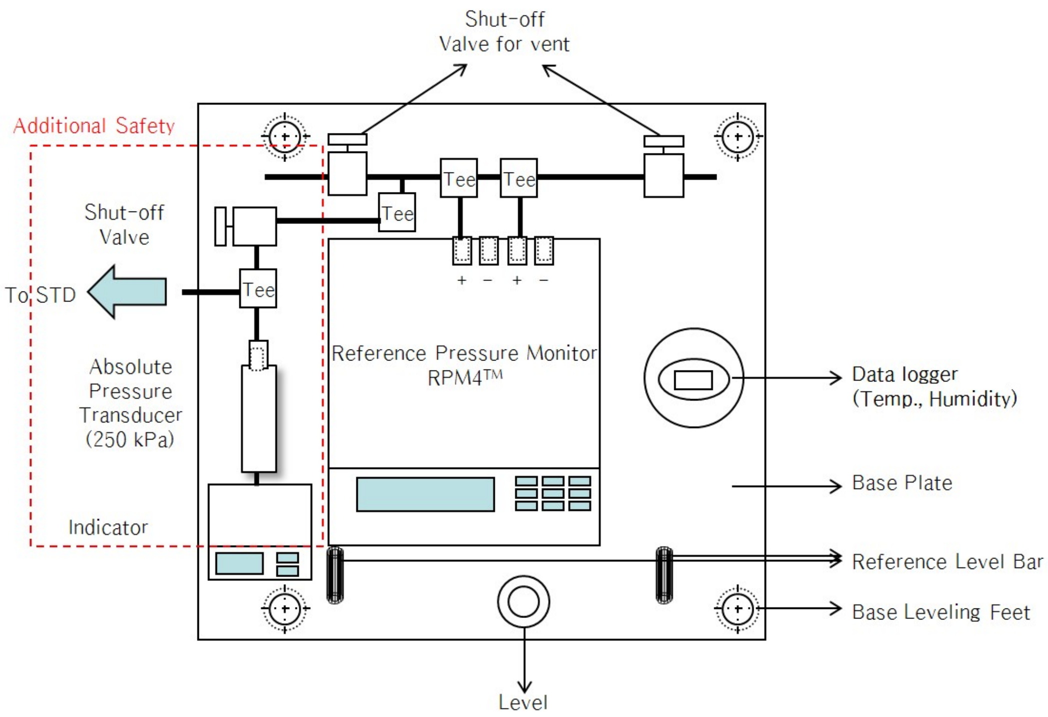


Fig.2 Schematic of Modified Transfer Standard

The schematic of the TS is shown in Fig.2. The monitor gauge has pressure range of 250 kPa in absolute mode. In addition, it has an alarm function which is activated when the pressure is applied over 112 kPa. Before applying the required pressure to the TS, each laboratory could use the monitor gauge to check whether the pressure is appropriate. The TS has connecting ports and two ball valves (SS-42GS4) made by Swagelok. They were used to connect the TS to the pressure standard of each laboratory using a 1/4" tube fitting. A spirit level on the TS base plate was used to check the horizontality of the TS. The reference level bar supplied with the TS was used to measure the reference height difference between the TS and the pressure standard of each participant.

The TS has an electrical power supply from 85 V to 264 V in AC with 50/60 Hz. The TS has an ICE-320-C13 electrical power connector. The use of a power supply regulator was recommended for eliminating possible surge or power variation. General information on the TS was given in the operation and maintenance manuals, which was enclosed with the transfer package.

A list of contents of the TS package is given as follows.

- Carrying box (87 cm × 75 cm × 45 cm), 41 kg (including the TS and the others)
- Transfer standard (42 cm × 42 cm × 28 cm), 18 kg
- Monitor gauge (16 cm × 6 cm × 18 cm), 3 kg
- Power cable: 4 EA
- Spare parts (assembly): 2 Tee/Tube sets, 2 Ball valves

4. Scheduled Time Table

The measurements at each laboratory were performed according to the schedule as shown in Table 3.

The date in the table was the measurement start date of each laboratory. Even though participants were requested to strictly adhere to the schedule, it was delayed due to various reasons.

Table 3. Measurement Schedule

No.	Measurement Time (Starting date)	Participant	
		Comparison loop A	**Comparison loop B**
1	Till 28 Feb. 2010	KRISS	KRISS
2	1 March 2010	NMIA	NMIJ /AIST
3	15 April 2010	NSCL	NMISA (TS Failure)
4	1 June 2010	KRISS	-
5	15 July 2010	NPLi (TS Failure)	-
6	1 December 2010	KRISS	-
7	15 January 2011	PTB	KRISS
8	1 March 2011	KRISS	NMC A*STAR (Withdrawal)
9	15 April 2011		NML-SIRIM (Withdrawal)
10	1 June 2011	NIM	KRISS
11	15 July 2011	KRISS	NIMT
12	1 September 2011	VMI	SCL
13	15 October 2011	CMS-ITRI	KRISS
14	1 December 2012	KRISS	NIS (Withdrawal)
15	15 January 2012	MSL	RCM-LIPI
16	1 March 2012	KRISS	KRISS

5. Characterization of transfer standard

To perform a reliable comparison, environmental effects on the TSs should be evaluated at the pilot laboratory. This includes transmitting medium effect, tilt effect, electrical power effect, temperature effect, long-term time dependency, travelling effect, and unavoidable leak effect.

In order to characterize the TS and compare the results among the participants, the correction values of TS-High (reading, $\mathrm{R}_{\mathrm{H,TS-i}}$) and TS-Low (reading, $\mathrm{R}_{\mathrm{L,TS-i}}$) are given as follows.

$$C_{\mathrm{H,i}} = P_{\mathrm{STD,i}} - R_{\mathrm{H,TS-i}} \qquad (1)$$

$$C_{\mathrm{L,i}} = P_{\mathrm{STD,i}} - R_{\mathrm{L,TS-i}} \qquad (2)$$

$C_{\mathrm{H,i}}$ and $C_{\mathrm{L,i}}$ are the correction values of the TS from each participant's pressure standard, respectively. $P_{\mathrm{STD},i}$ is the pressure of each participant's standard at the reference height of the TS. $\langle C_{\mathrm{H}}\rangle_i$ and $\langle C_{\mathrm{L}}\rangle_i$ are mean values of $C_{\mathrm{H,i}}$ and $C_{\mathrm{L,i}}$, calculated from 5 cycle measurements. The differences were made between participants at each pressure.

5.1 Effect by transmitting medium

The pilot laboratory investigated the medium effect with clean N_2 and dry air even though all of participants had to use clean N_2 as a working medium in this comparison. There was no noticeable difference between N_2 and dry air.

Participants using mercury manometers were recommended to avoid possible contamination of the TS due to mercury vapor by using a precise differential transducer. Intermediate measurement result shows that this effect is not meaningful to the TS. Therefore, this effect was not included in the uncertainty estimation.

5.2 Effect by attitude

To evaluate the influence of TS orientation on the reading value of the TS, we inclined TS with the angle of 0°, 2° and 5°. The correction values according to the applied pressure were obtained. There were no dependency of attitude, and systematic tendency. The maximum deviation among the correction values at 5° are as shown in Table 4. If the TS with a sensitive bubble level of 0.1° resolution was installed carefully, the effect on the reading by the attitude could be reduced to less than the resolution of the TS. Therefore, this effect was not included in the uncertainty estimation.

Table 4 Maximum deviation of TS correction values at 5°

Nominal Pressure (kPa)	Max. Deviation of $\langle C_H \rangle$ (Pa)	Max. Deviation of $\langle C_L \rangle$ (Pa)
10	0.4	0.5
30	0.2	0.4
50	0.3	0.4
70	0.2	0.4
90	0.3	0.4
100	0.2	0.4
110	0.2	0.4

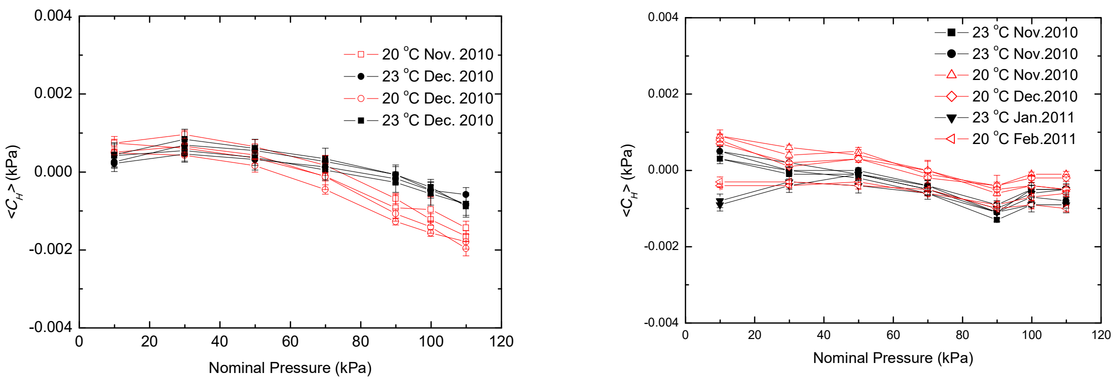
5.3 Effect by electrical power source

To evaluate the effect on the reading value of the TS according to power sources, the voltage was changed from 110 V to 220 V and the frequency was varied from 50 Hz to 60 Hz, respectively, connected to standard Korean power source. The change of reading was monitored at pressures 10 kPa, 50 kPa and 110 kPa respectively, but there was no systematic effect on the voltage and the frequency of power source. Therefore, the TS effect by an electrical power source was considered to be negligible.

5.4 Effect by temperature, u_{temp}

To evaluate the effect on the reading value of the TS according to the reference temperature change, the TSs have been monitored at 20 °C and 23 °C in the pilot laboratory before circulation. The room temperature during measurement in most laboratories was controlled within ±0.5 °C around their reference temperature except CMS/ITRI within ±1.0 °C according to their submitted data sheet.

The temperature effects of TS-A2(HIGH) and TS-B2(HIGH) evaluated at 20 °C and 23 °C are shown in Fig.3.



(a) (b)

Fig.3 Temperature effect of (a) TS-A2(HIGH) and (b)TS-B2(HIGH)

As shown in Fig.3, there are distinguishable behaviours according to the TS. However, when the TSs were evaluated at both temperature conditions within one month, the measurement results according to the temperature condition were repeatable. After one month, the TS might include short-term stability which might be related to time dependency. So the uncertainty due to the only temperature change was considered with two consecutive results within one month at different temperature conditions. Maximum differences due to temperature effect with respect to nominal pressure are shown in Table 5.

Table 5 Maximum deviation according to the temperature change between 20 °C and 23 °C.

Nominal Pressure (kPa)	Max. Deviation of $\langle C_H \rangle$ (Pa)	Max. Deviation of $\langle C_L \rangle$ (Pa)
10	0.30	0.42
30	0.32	0.45
50	0.35	0.44
70	0.37	0.55
90	0.88	0.59
100	0.89	0.60
110	0.95	0.65

In order to obtain the uncertainty due to the temperature effect, the difference can be assumed as a rectangular distribution. In addition, the maximum temperature change could be assumed within ±0.5 °C. From the above deviation, the uncertainty due to temperature effect could be obtain at each pressure by dividing the value by $6\sqrt{3}$. Since the comparisons with the pilot laboratory were carried out at each participant's reference temperature, the only assumed maximum temperature change of ±0.5 °C during measurement should be taken into account. In this case, since temperature effect is not considerable, the uncertainty due to the temperature change can be calculated with the maximum deviation among the TS results at each pressure as in Table 6. If then, the uncertainty could be applied regardless of the TS.

Table 6 Uncertainty due to temperature change of ±0.5 °C (k = 1)

Nominal Pressure (kPa)	Uncertainty due to temperature effect (Pa)
10	0.04
30	0.04
50	0.04
70	0.05
90	0.08
100	0.09
110	0.09

5.5 Effect by long-term time dependency, u_{time}

To evaluate the long-term time dependency on the reading value of the TS, the TS-C has been monitored at same temperature in pilot laboratory during the circulation. As mentioned in temperature effect, the TS showed the temperature dependency within one month, but it was effective within short period. Fig.4 shows the results of TS-C(LOW) according to time for a year as an example. There was no specific time dependency according to time. In this case, absolute difference value between two consecutive correction data as shown in Fig.4 is meaningful. The maximum differences of TS-C(HIGH) and TS-C(LOW) due to time dependency with respect to nominal pressure are shown in Table 7.

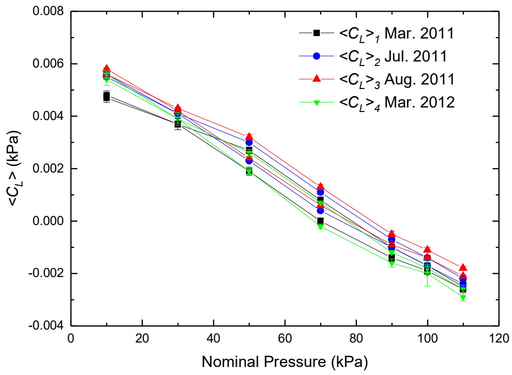


Fig.4 Long-term time dependency of TS-C(LOW)

Table 7 Maximum deviation according to long-term time dependency of TS-C

Nominal Pressure (kPa)	**Max. Deviation of $\langle C_{\mathrm{H}} \rangle$ (Pa)**	**Max. Deviation of $\langle C_{\mathrm{L}} \rangle$ (Pa)**
10	0.80	0.82
30	0.53	0.43
50	0.62	0.64
70	0.79	0.83
90	0.72	0.79
100	0.57	0.76
110	0.84	0.82

In order to obtain the uncertainty due to the long-term time dependency, the difference can be assumed as a rectangular distribution. From the above deviation, the uncertainty due to long-term time dependency could be obtained at each pressure by dividing the value by $2\sqrt{3}$. In this case, since the effect is not considerable, the uncertainty due to the long-term time dependency can be calculated with the maximum deviation among the TS results at each pressure as in Table 8. If then, the uncertainty could be applied regardless of the TS.

Table 8 Uncertainty due to long-term time dependency (k = 1)

Nominal Pressure (kPa)	Uncertainty due to long-term time dependency (Pa)
10	0.24
30	0.15
50	0.18
70	0.24
90	0.23
100	0.22
110	0.24

5.6 Effect by long-term stability including travelling, $u_{\rm ls}$

To evaluate the long-term stability on the reading value of the TS, the TS-A2 and TS-B2 have been monitored in pilot laboratory before and after the measurement at each laboratory. The long-term stability includes the time dependency, and travelling effect due to vibration. Fig.5 shows the results of TS-B2(HIGH) according to time during the circulation as an example. In the same way of section 5.5, the maximum differences due to long term stability with respect to nominal pressure are shown in Table 9.

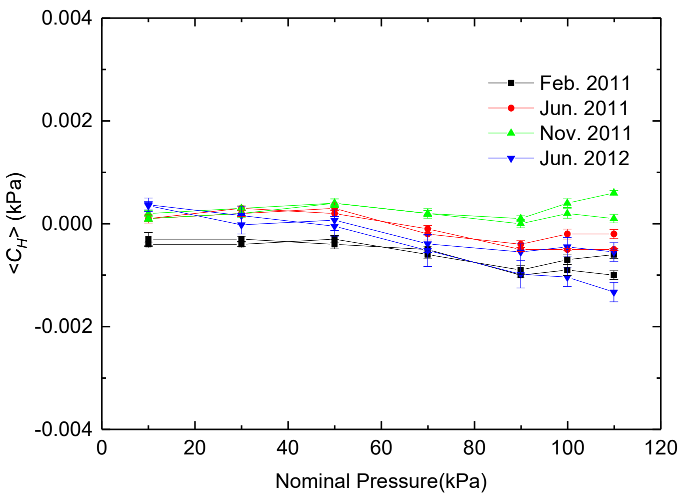


Fig.5 Long-term stability of TS-B2(HIGH)

Table 9 Maximum deviation according to long-term stability of TS-A2 and TS-B2

Nominal Pressure (kPa)	**Max. Deviation of $\langle \mathbf{C_H} \rangle$ (Pa)**	**Max. Deviation of $\langle \mathbf{C_L} \rangle$ (Pa)**
10	0.62	1.42
30	0.59	1.39
50	0.62	1.25
70	0.73	1.43
90	1.18	1.69
100	1.22	1.92
110	1.39	2.07

In order to obtain the uncertainty due to long-term stability, the difference can be assumed to have a rectangular distribution. From the above deviation, the uncertainty due to long-term stability can be calculated at each pressure by dividing the value of $2\sqrt{3}$. In this case, since the effect is not considerable, the uncertainty due to the long-term stability can be calculated with the maximum deviation among the TS results at each pressure as in Table 10. If then, the uncertainty could be applied regardless of the TS.

Table 10 Uncertainty due to long-term stability (k = 1)

Nominal Pressure (kPa)	**Uncertainty due to long-term stability (Pa)**
10	0.41
30	0.40
50	0.36
70	0.41
90	0.49
100	0.55
110	0.60

5.7 Effect by leak, u_{leak}

To evaluate the leak effect on the reading value of the TS, the TS-C has been experimented in pilot laboratory with a leak control valve. Leaks in a pressure calibration system should be as small as possible in order to reduce the pressure difference between the pressure standard and the TS. A pressure difference due to leakage can affect the calibration results. This type of effect was evaluated precisely during the comparison. Experiments were performed according to an applied pressure, leak amount, tube length and pressure media. It is concluded that the uncertainty caused by a possible and leak should be included in the uncertainty evaluation of the calibration results. Fig.6 shows the pressure difference according to the fall rate change of the piston due to leak. It could be concluded that the maximum pressure difference was less than 0.17 Pa over the measurement range in KRISS pressure calibration system. The difference value was reflected into the uncertainty directly in order to consider other possible leak effect which was not considered in the experiment. [11]

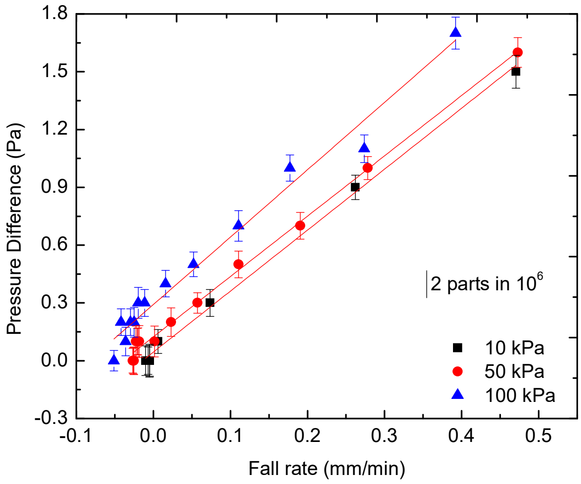


Fig.6 Pressure difference of TS-C according to the fall rate change of the piston due to leak

5.8 Uncertainty of the transfer standard, u_{TS}

During the TS circulation, TS has been modified due to over-pressure as mentioned before. Among the above TS uncertainty factors, temperature effect and long-term stability have been evaluated by TS-A2 and TS-B2 performance. Uncertainties due to long-term time dependency and leak effect have been evaluated with TS-C. However, since the TSs used in the comparison have shown very similar characteristic, it is assumed that the total uncertainty due to TS stability can be applied with the total uncertainty based on the performances from TS-A2, TS-B2 and TS-C. On the other hand, TS-A1 and TS-B1 do not have enough data in order to evaluate the uncertainty due to long-term stability, which might be most critical.

The uncertainty due to the effect by the long-term time dependency, u_{time} could have been included in the uncertainty due to the effect by the long-term stability, u_{ls}. However, the time dependency itself can be expressed as one of the meaningful uncertainty sources in order to show the TS behaviour during the comparison. Since the combined uncertainty of two effects is almost same with the long-term stability (slight increase only), the uncertainty due to the effect by the long-term time dependency was not removed.

Accordingly, the total uncertainty from the TS stability can be calculated by equation (3) and given as in Table 11.

$$u_{\mathrm{TS}} = \sqrt{u_{\mathrm{temp}}^2 + u_{\mathrm{time}}^2 + u_{\mathrm{ls}}^2 + u_{\mathrm{leak}}^2} \qquad (3)$$

Table 11 Uncertainty due to transfer standard stability (k = 1)

Nominal Pressure (kPa)	Uncertainty due to temperature effect (Pa)	Uncertainty due to long-term time dependency (Pa)	Uncertainty due to long-term stability (Pa)	Uncertainty due to leak effect (Pa)	Total uncertainty of TS (Pa)	Total relative uncertainty of TS ($\times 10^{-6}$)
10	0.04	0.24	0.41	0.17	0.51	51
30	0.04	0.15	0.40	0.17	0.46	15
50	0.04	0.18	0.36	0.17	0.44	8.8
70	0.05	0.24	0.41	0.17	0.51	7.2
90	0.08	0.23	0.49	0.17	0.57	6.4
100	0.09	0.22	0.55	0.17	0.62	6.2
110	0.09	0.24	0.60	0.17	0.67	6.1

6. Analysis of Reported Data

Each laboratory reported the correction values of TS reading “HIGH”, $\mathrm{R_{H,TS-i}}$ and TS reading “LOW”, $\mathrm{R_{L,TS-i}}$i as given in equation (1) and (2).

Each reported data (mean correction values of TS reported by each participant) have been compared with the mean correction values of TS which were calibrated at the pilot laboratory before and after each participant’s measurement. As mentioned in the TS characterization, the correction values were not compensated in this comparison because most influence factors of the TSs are not correlated.

The difference of the averaged correction values from up and down measurement results between each participant and the pilot laboratory was calculated as in following equation. The KRISS correction value to be compared was averaged with data obtained before and after each participant’s measurement according to the time schedule of the measurement. However, in case there was not available pilot data after due to the TS failure, only KRISS data before the participant’s measurement was used. In addition, in case there was a remarkable change in the pilot data before and after the participant’s measurement, one data before or after the participant’s measurement could have been chosen for the better comparison. However, even if the correction values of TS-A1(High) has been changed during the measurement between NMIA and NSCL, mean correction values of KRISS data before and after their measurements were used for the comparison.

$$d_{\mathrm{j,l,i}} = \langle C_l \rangle_{\mathrm{j,i}} - \langle C_l \rangle_{\mathrm{KRISS,i}} \qquad (4)$$

where j is NMIs’ index, l is the mean correction data of “HIGH” and “LOW”, and i is nominal pressure. $\langle C_l \rangle$ is an averaged value with up and down mean data of 5 repeated cycles.

The participant's correction values and corresponding uncertainties as reported is shown in Appendix II. In case of the pilot laboratory, the only representative uncertainties of the correction values are given since the correction values to be compared with each participant's results are changed. The KRISS corresponding correction value ($\langle C_l \rangle_{\mathrm{KRISS,i}}$) for each participant can be calculated according to eq.(4) with the difference ($d_{\mathrm{j,l,i}}$) and Appendix II ($\langle C_l \rangle_{\mathrm{j,i}}$).

6.1. Analysis of link laboratory results

According to the MRA, the linking should be established by means of the link laboratories taking part in both the International Committee for Weights and Measures (CIPM) and the Regional Metrology Organization (RMO) key comparisons. This APMP key comparison, APMP.M.P-K9 is linked to the corresponding CC key comparison, CCM.P-K2. In order to link the participants result to KCRV, two link laboratories such as NMIA and PTB were considered as mentioned in the introduction. The values for the link could be calculated by a weighted mean method using the results of the corresponding differences of the link laboratories in both comparisons.

The weighted mean and the corresponding uncertainties in CC results can be calculated using equation (5) and (6). Table 12 shows the deviation of the weighted mean from KCRV and corresponding uncertainties in CC results. In fact, the TS used in CCM.P-K2 was a gas pressure balance. The effective area of the piston/cylinder assembly in the pressure balance was compared. However, it can be transferred to the expected mean pressure with the same unit of the TS used in this comparison. In this case, the sign of the deviation from KCRV should be changed.[5]

$$\Delta_{cc,i} = \frac{\frac{d_{cc,NMIA,i}}{u^2(d_{cc,NMIA,i})} + \frac{d_{cc,PTB,i}}{u^2(d_{cc,PTB,i})}}{\frac{1}{u^2(d_{cc,NMIA,i})} + \frac{1}{u^2(d_{cc,PTB,i})}} \tag{5}$$

$$\frac{1}{u^2(\Delta_{cc,i})} = \frac{1}{u^2(d_{cc,NMIA,i})} + \frac{1}{u^2(d_{cc,PTB,i})} \tag{6}$$

In the above equations, $\Delta_{\mathrm{cc,i}}$ and $u(\Delta_{\mathrm{cc,i}})$ are the weighted mean of two link laboratories in CC results and the corresponding uncertainty, respectively. All the deviation values agree to within their uncertainties.

Table 12 CC weighted mean deviations and corresponding uncertainties (k = 1) of link laboratories

Nominal Pressure (kPa)	**NMIA**		**PTB**		**CC Weighted Mean**	
	Deviation from KCRV (Pa)	Standard Uncertainty (Pa)	Deviation from KCRV (Pa)	Standard Uncertainty (Pa)	Deviation from KCRV (Pa)	Standard Uncertainty (Pa)
10	0.04	0.17	-0.02	0.10	-0.01	0.08
30	-0.05	0.25	0.00	0.17	-0.01	0.14
50	-0.18	0.34	-0.27	0.25	-0.24	0.20
70	-0.33	0.49	-0.19	0.44	-0.24	0.33
90	-0.38	0.63	-0.35	0.63	-0.36	0.45
100	-0.30	0.83	-0.24	0.79	-0.26	0.57
110	-0.56	0.97	-0.46	0.97	-0.51	0.68

In the same way, the weighted mean of two link laboratories in APMP can be calculated. Using the comparison among NMIA, PTB and KRISS, APMP weighted mean values can be obtained.

Equation (8) and (9) were used to obtain the weighted mean of two link laboratories in APMP and the corresponding uncertainty, respectively. Table 13 shows the deviations of the weighted mean from the pilot laboratory and corresponding uncertainties in APMP results.

$$\Delta_{APMP,i} = \frac{\frac{d_{APMP,NMIA,i}}{u^2(d_{APMP,NMIA,i})} + \frac{d_{APMP,PTB,i}}{u^2(d_{APMP,PTB,i})}}{\frac{1}{u^2(d_{APMP,NMIA,i})} + \frac{1}{u^2(d_{APMP,PTB,i})}} \qquad (8)$$

$$\frac{1}{u^2(\Delta_{APMP,i})} = \frac{1}{u^2(d_{APMP,NMIA,i})} + \frac{1}{u^2(d_{APMP,PTB,i})} \qquad (9)$$

where $\Delta_{\mathrm{APMP,i}}$ and $u(\Delta_{\mathrm{APMP,i}})$ are the weighted mean of two link laboratories' results in APMP comparison and the corresponding uncertainty. All the deviation values agree to within their uncertainties.

Table 13 APMP weighted mean deviations and corresponding uncertainties (k = 1) of link laboratories

Nominal Pressure (kPa)	**NMIA**		**PTB**		**APMP Weighted Mean**	
	Deviation from KRISS (Pa)	Standard Uncertainty (Pa)	Deviation from KRISS (Pa)	Standard Uncertainty (Pa)	Deviation from KRISS (Pa)	Standard Uncertainty (Pa)
10	-0.10	0.54	0.52	0.52	0.22	0.37
30	-0.33	0.50	0.14	0.50	-0.10	0.35
50	-0.23	0.51	0.17	0.53	-0.03	0.37
70	-0.17	0.61	0.17	0.65	-0.01	0.44
90	-0.34	0.69	0.23	0.76	-0.08	0.51
100	-0.45	0.76	0.23	0.84	-0.15	0.56
110	-0.69	0.82	0.23	0.92	-0.28	0.61

By considering the relationship of both deviations, the degrees of equivalence of each participating laboratory in APMP.M.P-K9 comparison can be linked to KCRV as follows with a correction value, $\Delta = \Delta_{\mathrm{cc}} - \Delta_{\mathrm{APMP}}$ as in Table 14.

$$D_{\mathrm{j,i}} = (\Delta_{\mathrm{cc,i}} - \Delta_{\mathrm{APMP,i}}) + d_{\mathrm{j,i}} \qquad (10)$$

where $D_{j,i}$ is the deviation of j-th participant from KCRV and $d_{j,i}$ is the deviation of j-th participant from the pilot laboratory at i-th nominal pressure.

Table 14 Correction values and corresponding uncertainties (k = 1) of link laboratories

Nominal Pressure (kPa)	$\boldsymbol{\Delta_{cc,i} - \Delta_{APMP,i}}$		
	Correction values (Pa)	**Standard uncertainty (Pa)**	**Relative standard uncertainty ($\times 10^{-6}$)**
10	-0.23	0.38	38
30	0.08	0.38	13
50	-0.20	0.42	8.4
70	-0.24	0.55	7.9
90	-0.28	0.68	7.5
100	-0.12	0.80	8.0
110	-0.23	0.92	8.3

The reliability of the correction values given in Table 14 is dependent on the consistency between two link laboratories in CC and APMP KC results. Each difference between two link laboratories at 110 kPa is 0.10 Pa and 0.92 Pa in CC and APMP KC results respectively. The correction value at 110 kPa is -0.23 Pa, which is consistent because it is smaller than its uncertainty 0.92 Pa (8.3×10^{-6}). On the other hand, each difference between two link laboratories at 10 kPa is 0.06 Pa and 0.62 Pa in CC and APMP KC results respectively. The difference between two link laboratories in APMP KC is relatively bigger than in CC KC. This results from relatively low performance of the TS used in APMP KC at low pressure However, the correction value at 10 kPa is -0.23 Pa, which is consistent because it is smaller than its uncertainty 0.38 Pa (3.8×10^{-5}).

6.2. Deviation of each participant from the pilot laboratory

Each participant deviation value from the pilot laboratory can be given by a mean correction value of the TS even though there are two measurement results to be compared. For example, two TS sensors designated as "HIGH" and "LOW" have been used for the comparison in the KC. In all the cases, one of them showed better performances than the other, which should be selected or discarded.

In order to obtain each participant's deviation from pilot, equation (4) was used. Participants' deviations from the pilot laboratory are shown in Table 15-1 and 15-2. The values were calculated by comparing each participant's correction values given in Appendix II with pilot laboratory's correction values.

Its corresponding uncertainty could be expressed as follows.

$$u(d_{j,i}) = \sqrt{u^2(\langle C\rangle_{j,i}) + u^2(\langle C\rangle_{KRISS,i}) + u_{TS,i}^2} \qquad (11)$$

where $u(d_{j,i})$ is the standard uncertainty of j-th participant's deviation, and $u(\langle C\rangle_{j,i})$ and $u(\langle C\rangle_{KRISS,i})$ are standard uncertainties of corresponding correction values at i-th nominal pressure, respectively. $u_{TS,i}$ is the standard uncertainty of TS values at i-th nominal pressure. Each participant's combined standard uncertainty for the deviation value $d_{j,i}$ is shown in Table 16-1 and 16-2.

Table 15-1 Each participant's deviation ($d_{j,i}$) from the pilot laboratory in Pa

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	-0.10	-0.26	0.52	-0.30	-0.90	0.50	-0.15	-0.15	0.42	-0.37	-0.93	0.00
30	-0.33	-0.38	0.14	-0.28	-0.55	0.35	-0.22	0.05	0.11	1.52	-1.07	0.00
50	-0.23	-0.21	0.17	-0.04	-0.46	0.39	0.19	0.30	0.23	1.94	-0.95	0.00
70	-0.17	-0.26	0.17	0.23	-0.46	0.48	0.25	0.50	0.30	1.84	-1.05	0.00
90	-0.34	0.23	0.23	0.48	-0.48	0.67	0.33	0.73	0.40	1.89	-0.69	0.00
100	-0.45	0.19	0.23	0.56	-0.47	0.72	0.32	0.80	0.48	1.99	-1.13	0.00
110	-0.69	-0.40	0.23	0.69	-0.43	0.78	0.37	0.93	0.46	2.18	-0.64	0.00

Table 15-2 Each participant's relative deviation ($d_{j,i}$) from the pilot laboratory in 10^{-6}

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	-10.4	-25.8	52.3	-30.1	-89.5	50.5	-15.1	-14.7	41.7	-37.3	-93.2	0.0
30	-11.0	-12.5	4.6	-9.3	-18.3	11.7	-7.5	1.7	3.8	50.8	-35.8	0.0
50	-4.6	-4.1	3.5	-0.7	-9.2	7.8	3.9	6.0	4.5	38.7	-18.9	0.0
70	-2.5	-3.8	2.4	3.3	-6.6	6.9	3.6	7.1	4.3	26.3	-15.1	0.0
90	-3.7	2.6	2.6	5.3	-5.3	7.4	3.6	8.1	4.4	20.9	-7.7	0.0
100	-4.5	1.9	2.3	5.6	-4.7	7.2	3.2	8.0	4.8	19.9	-11.3	0.0
110	-6.3	-3.6	2.1	6.2	-3.9	7.1	3.4	8.5	4.2	19.8	-5.8	0.0

Table 16-1 Combined standard uncertainty of each participant's deviation value ($u(d_{j,i})$) in Pa (k = 1)

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	0.54	0.66	0.52	0.52	0.56	0.53	0.52	0.53	0.53	0.89	0.52	0.52
30	0.50	0.79	0.50	0.49	0.59	0.52	0.48	0.52	0.53	0.89	0.51	0.51
50	0.51	1.1	0.53	0.52	0.75	0.56	0.49	0.58	0.59	0.89	0.57	0.55
70	0.61	1.5	0.65	0.64	0.97	0.69	0.59	0.72	0.74	0.89	0.71	0.68
90	0.69	1.9	0.76	0.74	1.1	0.82	0.69	0.86	0.88	0.89	0.86	0.81
100	0.76	2.0	0.84	0.81	1.2	0.89	0.75	0.95	0.97	0.89	0.90	0.89
110	0.82	2.2	0.92	0.88	1.4	0.97	0.80	1.0	1.1	0.89	0.98	0.97

Table 16-2 Relative combined standard uncertainty of each participant's deviation value ($u(d_{j,i})$) in 10^{-6} (k = 1)

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	54	66	52	52	56	53	52	53	53	89	52	52
30	17	26	17	16	20	17	16	17	18	30	17	17
50	10	21	11	10	15	11	9.9	12	12	18	11	11
70	8.7	21	9.3	9.1	14	9.9	8.4	10	11	13	10	9.8
90	7.7	21	8.5	8.2	13	9.1	7.6	9.6	9.8	9.8	9.5	8.9
100	7.6	20	8.4	8.1	12	8.9	7.5	9.5	9.7	8.9	9.0	8.9
110	7.4	20	8.3	8.0	13	8.8	7.3	9.4	9.6	8.0	8.9	8.8

6.3 Link to KCRV

By linking the results of participants listed in Table 15-1 to KCRV with correction values using Table 14 and equation (10), the deviations of APMP participants from KCRV ($D_{j,i}$) can be calculated as shown in Table 17-1 and Table 17-2.

The uncertainty of the deviations from KCRV, $u_{D_{j,i}}$ can be combined with (i) u_{TS}, uncertainty due to TS stability as in Table 11, (ii) $u_{d_{j,i}}$, uncertainty of each participant's deviation from the pilot laboratory as in Table 16, (iii) u_{Δ}, uncertainty of the correction value from two link laboratories' weighted means as in Table 14. However, since the uncertainty of the correction value already includes the uncertainty due to TS stability, the combined standard uncertainty can be calculated only with $u_{d_{j,i}}$ and u_{Δ} as given in following equation. The deviations of each participant from KCRV and their uncertainties are shown in Table 18-1, Table 18-2, and Table 18-3.

$$u_{D_{j,i}} = \sqrt{u_{\Delta}^2 + u_{d_{j,i}}^2} \qquad (12)$$

Table 17-1 Each participant's deviation ($D_{j,i}$) from KCRV in Pa

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	-0.33	-0.49	0.30	-0.53	-1.12	0.28	-0.38	-0.37	0.19	-0.60	-1.16	-0.23
30	-0.25	-0.30	0.22	-0.20	-0.47	0.43	-0.15	0.13	0.19	1.60	-1.00	0.08
50	-0.43	-0.41	-0.03	-0.24	-0.66	0.19	-0.01	0.10	0.02	1.73	-1.15	-0.20
70	-0.41	-0.50	-0.07	-0.01	-0.70	0.24	0.01	0.26	0.06	1.60	-1.29	-0.24
90	-0.62	-0.05	-0.05	0.20	-0.76	0.39	0.05	0.45	0.11	1.60	-0.97	-0.28
100	-0.57	0.07	0.11	0.44	-0.59	0.60	0.20	0.68	0.36	1.87	-1.25	-0.12
110	-0.92	-0.63	0.01	0.46	-0.66	0.55	0.15	0.71	0.24	1.96	-0.87	-0.23

Table 17-2 Each participant's relative deviation ($D_{j,i}$) from KCRV in 10^{-6}

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	-33.2	-48.6	29.5	-52.9	-112.3	27.7	-37.9	-37.5	18.9	-60.1	-116.0	-22.8
30	-8.4	-9.9	7.2	-6.7	-15.7	14.3	-4.9	4.3	6.4	53.4	-33.2	2.6
50	-8.6	-8.2	-0.6	-4.8	-13.3	3.7	-0.2	2.0	0.5	34.7	-23.0	-4.1
70	-5.9	-7.2	-1.0	-0.1	-10.0	3.4	0.2	3.7	0.9	22.9	-18.5	-3.4
90	-6.9	-0.5	-0.5	2.2	-8.5	4.3	0.5	5.0	1.3	17.8	-10.8	-3.1
100	-5.7	0.7	1.1	4.4	-5.9	6.0	2.0	6.8	3.6	18.7	-12.5	-1.2
110	-8.3	-5.7	0.1	4.2	-6.0	5.0	1.3	6.4	2.2	17.8	-7.9	-2.1

Table 18-1 Combined standard uncertainty of each participant's deviation value ($u(D_{j,i})$) from KCRV in Pa (k = 1)

Nominal Pressure (kPa)	NMIA	NSCL	PTB	NIM	VMI	CMS-ITRI	MSL	NMIJ	NIMT	SCL	RCM-LIPI	KRISS
10	0.66	0.76	0.65	0.65	0.68	0.65	0.64	0.65	0.66	0.97	0.65	0.65
30	0.63	0.88	0.62	0.62	0.70	0.64	0.61	0.64	0.65	0.96	0.64	0.63
50	0.66	1.1	0.67	0.67	0.86	0.70	0.65	0.71	0.72	0.98	0.71	0.69
70	0.82	1.6	0.85	0.84	1.1	0.89	0.81	0.91	0.92	1.0	0.90	0.88
90	0.97	2.0	1.0	1.0	1.3	1.1	0.96	1.1	1.1	1.1	1.1	1.1
100	1.1	2.2	1.2	1.1	1.5	1.2	1.1	1.2	1.3	1.2	1.2	1.2
110	1.2	2.4	1.3	1.3	1.7	1.3	1.2	1.4	1.4	1.3	1.3	1.3

Table 18-2 Relative combined standard uncertainty of each participant's deviation value ($u(D_{j,i})$) from KCRV in 10^{-6} (k = 1)

Nominal Pressure (kPa)	NMIA	NSCL	PTB	NIM	VMI	CMS-ITRI	MSL	NMIJ	NIMT	SCL	RCM-LIPI	KRISS
10	66	76	65	65	68	65	64	65	66	97	65	65
30	21	29	21	21	23	21	20	21	22	32	21	21
50	13	23	13	13	17	14	13	14	14	20	14	14
70	12	22	12	12	16	13	12	13	13	15	13	13
90	11	22	11	11	15	12	11	12	12	12	12	12
100	11	22	12	11	15	12	11	12	13	12	12	12
110	11	22	12	12	15	12	11	13	13	12	12	12

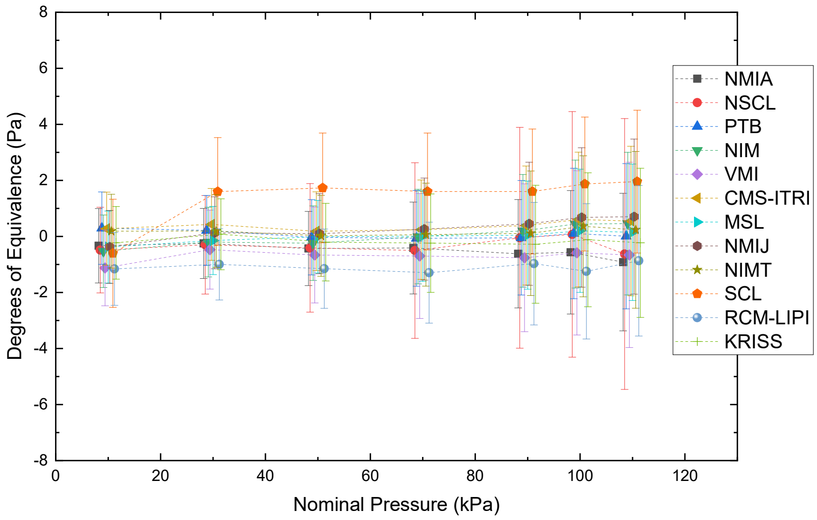
Table 18-3 Relative expanded uncertainty of each participant's deviation value ($U\left(D_{j,i}\right)$) from KCRV in 10^{-6} (k = 2)

Nominal Pressure (kPa)	**NMIA**	**NSCL**	**PTB**	**NIM**	**VMI**	**CMS-ITRI**	**MSL**	**NMIJ**	**NIMT**	**SCL**	**RCM-LIPI**	**KRISS**
10	130	150	130	130	140	130	130	130	130	200	130	130
30	42	59	42	41	47	43	41	43	43	64	42	42
50	26	46	27	27	34	28	26	29	29	39	28	28
70	23	45	24	24	32	25	23	26	26	30	26	25
90	21	44	23	22	29	24	21	24	25	25	24	23
100	22	44	23	23	29	24	22	25	25	24	24	24
110	22	44	24	23	30	24	22	25	25	23	24	24

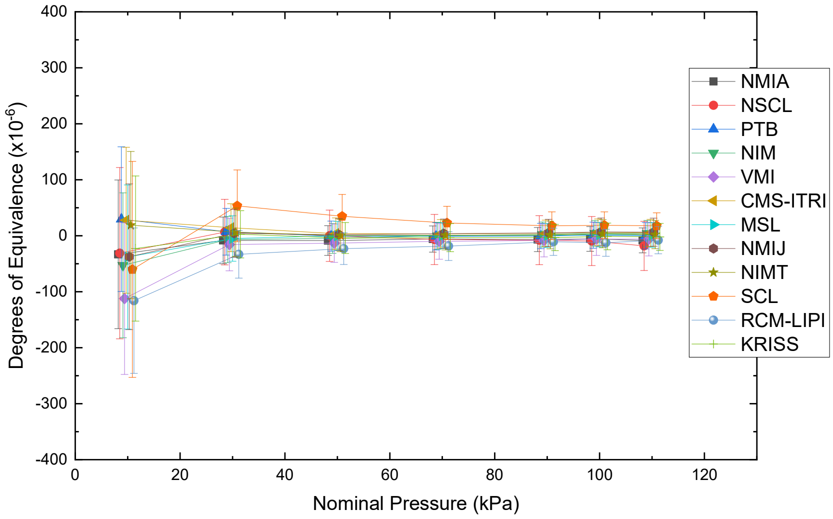
10. Degrees of Equivalence

The degree of equivalence is expressed quantitatively by two terms: the deviation from the key comparison reference value and the corresponding expanded uncertainty at a 95 % level of confidence (in practice, this is often approximated by using a coverage factor of k = 2). The "graph of equivalence" shows the degrees of equivalence relative to the key comparison reference value.[3]

From the results in section 6, Fig.7 shows the degrees of equivalence of each participant, that is, the deviation from KCRV in the range of 10 kPa to 110 kPa of absolute pressure in Pa and in 10^{-6}.



(a)



(b)

Fig.7 Degrees of equivalence (DoE) of each participant (a) in Pa and (b) in 10^{-6} (k = 2)

The degrees of equivalence, that is, the deviations of each participant's results from KCRV at 10 kPa, 50 kPa and 100 kPa are shown in Fig.8, Fig.9 and Fig.10, respectively. The error bar represents expanded uncertainty taken from Table 18 with a coverage factor of 2. Pairwise degrees of equivalence were not reported here.

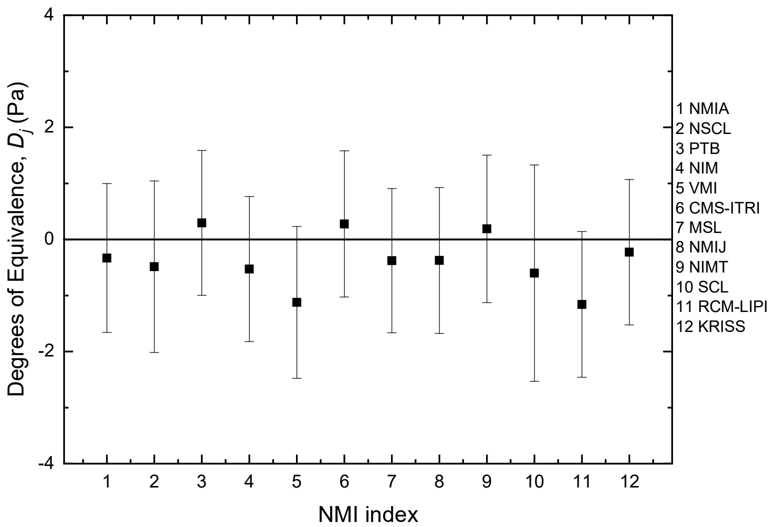


Fig.8 Degrees of equivalence (DoE) of each participant at 10 kPa (k = 2)

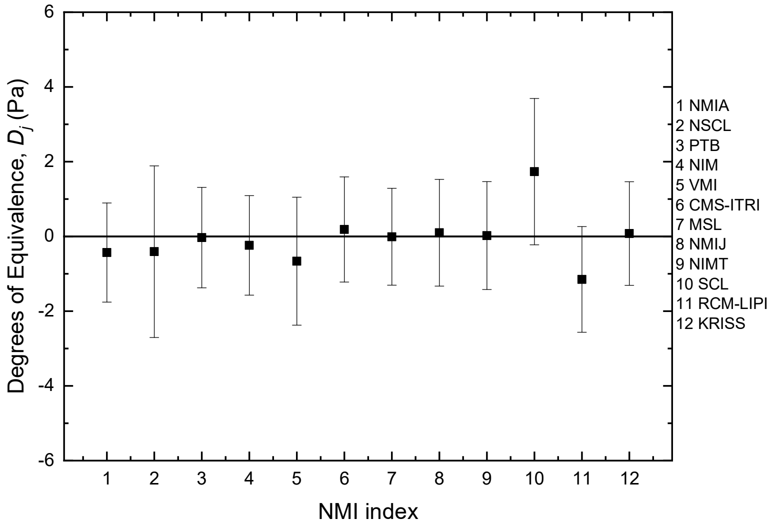


Fig.9 Degrees of equivalence (DoE) of each participant at 50 kPa (k = 2)

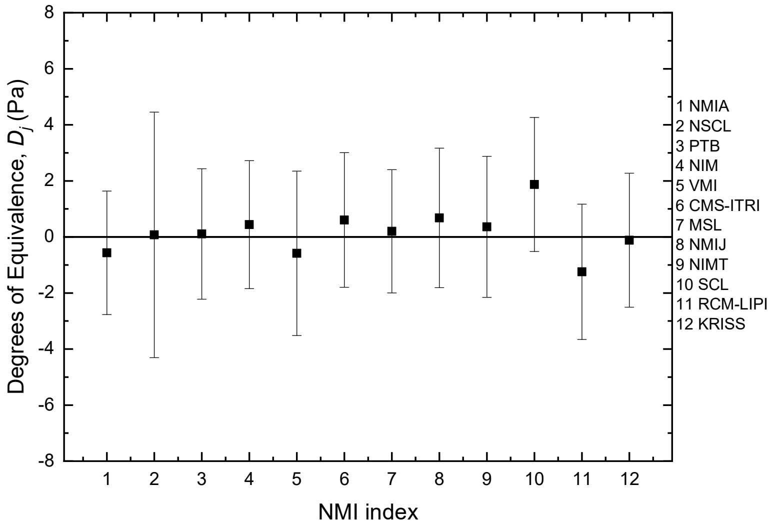


Fig.10 Degrees of equivalence (DoE) of each participant at 100 kPa (k = 2)

11. Conclusions

Seventeen National Metrology Institutes (NMIs) including a pilot laboratory participated in this APMP key comparison of pneumatic pressure standards from 10 kPa to 110 kPa in absolute mode. Among them, fourteen NMIs submitted the measurement results to the pilot laboratory, but NIS and NMC A*STAR withdrew their results during the circulation of the draft report. Precise absolute pressure gauges were used as transfer standards. The pressures of the comparison were carried out at (10, 30, 50, 70, 90, 100, 110) kPa. NMIA and PTB participated in this comparison as a role of link laboratory.

All of the participants' measurements are in good agreement with KCRV within the associated uncertainties. In overall, the low resolution of the transfer standard (1 part in 10^5) at 10 kPa was not good enough to compare NMIs' measurement capabilities to each other because it caused the big uncertainty of the TS compared to one of the NMI's standards.

12. References

[1] Mutual recognition of national measurements standards and of calibration and measurement certificates issued by national metrology institutes (MRA), Technical Report, International Committee for Weights and Measures, 1999

[2] Guidelines for CIPM key comparisons, Appendix F to Mutual recognition of national measurements standards and of calibration and measurement certificates issued by national metrology institutes, Technical Report, International Committee for Weights and Measures, 1999

[3] Measurement comparisons in the CIPM MRA, CIPM MRA-D-05

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Appendix I. Details of each participant's pressure standard used for the comparison

Institute: NMIA

Pressure Standard: Mercury manometer

Manufacturer & Model	NMIA
Measurement range in kPa	1 to 120
Medium (i.e. Mercury, oil, water)	Mercury
Operating gas (N_2/Dry air)	Dry nitrogen
Height measurement method (Ultrasonic/Laser)	Laser
Local acceleration due to gravity (g) in m/s^2	9.796 377 79
Relative uncertainty of g in 10^{-6}	0.42
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	-113
Uncertainty of h in mm	1.5
Pressure in the reference column of liquid manometer, kPa	0.0007 to 0.0015
Room Temperature during measurement in °C	(20.0±0.5) °C
Traceability	Laser to the SI metre via the NMIA He/Ne laser standard; Density: Comparison with a sample of mercury measured by Cook at NPL, UK. Gravity: Absolute measurement conducted by Geoscience Australia.
Use of a precision differential transducer	No

Institute: NSCL-Syria

Pressure Standard: Pressure balance

Manufacturer & Model	Futaba AV-02
Measurement range in kPa	5 to 200
Material of piston	Steel
Material of cylinder	Steel
Reference temperature (t_0) in °C	23°C
Zero-pressure effective area (A_0) at reference temperature in mm^2	199.9738
Relative uncertainty of A_0 in 10^{-6}	25×10^{-6}
Pressure distortion coefficient (λ) in MPa^{-1}	0
Uncertainty of λ in MPa^{-1}	0
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	11.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	11.5×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.794 027
Relative uncertainty of g in 10^{-6}	$8.8\cdot10^{-6}$
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	-4.7
Uncertainty of h in mm	6
Operating gas (N_2/Dry air)	N_2
Gauge for residual pressure measurement	CDG, MKS, 13.3 Pa
Piston rotation speed during measurement in rpm	30~40
Room Temperature during measurement in °C	23.0±0.5
Traceability	PTB - Germany

Institute: PTB

Pressure Standard: Mercury manometer

Manufacturer & Model	*Schwien Engineering*, Pomona, California, USA
Measurement range in kPa	0 to 180
Medium (i.e. Mercury, oil, water)	Mercury
Operating gas (N_2)	N_2, other gases possible
Height measurement method (Ultrasonic/Laser)	Laser interferometry & capacitance bridge to detect Hg menisci
Local acceleration due to gravity (g) in m/s^2	9.812 533
Relative uncertainty of g in 10^{-6}	0.53
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	-34
Uncertainty of h in mm	2
Pressure in the reference column of liquid manometer, kPa	$1.2 \cdot 10^{-4}$
Room Temperature during measurement in °C	19.71 – 20.15
Traceability	PTB
Use of a precision differential transducer	No

Institute: National Institute of Metrology (NIM)

Pressure Standard: Pressure balance

Manufacturer & Model	DHI PG7607
Measurement range in kPa	5 to 175
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Reference temperature (t_0) in °C	20
Zero-pressure effective area (A_0) at reference temperature in mm^2	1961.0622
Relative uncertainty of A_0 in 10^{-6}	4.5
Pressure distortion coefficient (λ) in MPa^{-1}	7.15×10^{-6}
Uncertainty of λ in MPa^{-1}	1.5×10^{-6} ($k = 2$)
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	4.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.801 245
Relative uncertainty of g in 10^{-6}	0.4 ($k = 2$)
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	168.3
Uncertainty of h in mm	2.0 ($k = \sqrt{3}$)
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	MKS-690A, 133 Pa×0.01
Piston rotation speed during measurement in rpm	30~40
Room Temperature during measurement in °C	19.7±0.3
Traceability	NIM

Institute: Vietnam Metrology Institute (VMI)

Pressure Standard: Pressure balance

Manufacturer & Model	PG 7607-DHInstrument
Measurement range in kPa	5 to 175
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Reference temperature (t_0) in °C	20
Zero-pressure effective area (A_0) at reference temperature in mm^2	1961,053
Relative uncertainty of A_0 in 10^{-6}	25,5 (k = 2)
Pressure distortion coefficient (λ) in MPa^{-1}	0
Uncertainty of λ in MPa^{-1}	
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	$4,5\times10^{-6}$
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	$4,5\times10^{-6}$
Local acceleration due to gravity (g) in m/s^2	9,786 689 27
Relative uncertainty of g in 10^{-6}	$5,0\times10^{-6}$
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0
Uncertainty of h in mm	±1
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	Convectron, (0-20) Pa
Piston rotation speed during measurement in rpm	(30- 40)
Room Temperature during measurement in °C	(20 ± 1)
Traceability	NIMT

Institute: CMS/ITRI

Pressure Standard: Pressure balance

Manufacturer & Model	DHI PG7607
Measurement range in kPa	5 to 175
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Reference temperature (t_0) in °C	23
Zero-pressure effective area (A_0) at reference temperature in mm^2	1961.078
Relative uncertainty of A_0 in 10^{-6}	9.2
Pressure distortion coefficient (λ) in MPa^{-1}	7.2×10^{-7}
Uncertainty of λ in MPa^{-1}	2.5×10^{-7}
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	4.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.789 139 81
Relative uncertainty of g in 10^{-6}	0.047
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	107.6
Uncertainty of h in mm	0.6
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	CDG, MKS, 133 Pa
Piston rotation speed during measurement in rpm	30 to 40
Room Temperature during measurement in °C	23.0 ± 1.5
Traceability	PTB

Institute: MSL

Pressure Standard: Pressure balance

Manufacturer & Model	DH Instruments Inc, PC-7100/7600-10-TC
Measurement range in kPa	8 to 550
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Reference temperature (t_0) in °C	20
Zero-pressure effective area (A_0) at reference temperature in mm^2	980.524
Relative uncertainty of A_0 in 10^{-6}	4.6
Pressure distortion coefficient (λ) in MPa^{-1}	5.3×10^{-6}
Uncertainty of λ in MPa^{-1}	0.5×10^{-6} ($k = 2$)
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	4.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.802 789
Relative uncertainty of g in 10^{-6}	0.32
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0.08
Uncertainty of h in mm	0.10
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	Granville Phillips Stabil-Ion
Piston rotation speed during measurement in rpm	20~45
Room Temperature during measurement in °C	20.0±0.5
Traceability	MSL mass, length and temperature standards

Institute: National Metrology Institute of Japan (NMIJ), AIST

Pressure Standard: Pressure balance

Manufacturer & Model	DH Instruments, Inc.
Measurement range in kPa	2.5 to 175
Material of piston	Tungsten carbide
Material of cylinder	Ceramic
Reference temperature (t_0) in °C	23
Zero-pressure effective area (A_0) at reference temperature in mm^2	1961.153
Relative uncertainty of A_0 in 10^{-6}	6.5
Pressure distortion coefficient (λ) in MPa^{-1}	4.54×10^{-6}
Uncertainty of λ in MPa^{-1}	4.5×10^{-7}
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	4.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	5.5×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.799 480 8
Relative uncertainty of g in 10^{-6}	0.2
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	1.41
Uncertainty of h in mm	0.5
Operating gas (N_2/Dry air)	N_2
Gauge for residual pressure measurement	CDG, MKS, FS13.3 Pa
Piston rotation speed during measurement in rpm	20~30
Room Temperature during measurement in °C	22.9 ± 0.3
Traceability	Mercury manometer and Dimensional standard

Institute: National Institute of Metrology (Thailand)

Pressure Standard: Pressure balance

Manufacturer & Model	DH Instruments & PG7601
Measurement range in kPa	350
Material of piston	Tungsten carbide
Material of cylinder	Tungsten carbide
Reference temperature (*t*0) in °C	20
Zero-pressure effective area (*A*0) at reference temperature in mm^2	980.527 3
Relative uncertainty of *A*0 in 10^{-6}	8.1 (k = 1)
Additional volume of piston in cm^3	29.1
Relative uncertainty of *V* in cm3	3.0
Pressure distortion coefficient (λ) in MPa^{-1}	N/A
Uncertainty of λ in MPa^{-1}	N/A
Linear thermal expansion coefficient of piston (α_p) in $°C^{-1}$	4.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in $°C^{-1}$	4.5×10^{-6}
Local acceleration due to gravity (*g*) in m/s^2	9.783 124 3
Relative uncertainty of *g* in 10^{-6}	1.0
Height difference between laboratory standard (LS) and TS (*h*, positive if LS is higher than TS) in mm	0
Uncertainty of *h* in mm	0.5
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	1 × CDG 0.1 Torr (MKS) and 2 × Convectron Gauge (Granville-Phillips)
Piston rotation speed during measurement in rpm	20 ~ 40 rpm
Room Temperature during measurement in °C	(20.5 to 20.9) °C
Traceability	Dimensional measurement

Institute: Standards and Calibration Laboratory (SCL Hong Kong)

Pressure Standard: Pressure balance

Manufacturer & Model	Ruska 2465A-754A
Measurement range in kPa	3.5 to 175
Material of piston	440C stainless steel
Material of cylinder	Tungsten carbide
Reference temperature (t_0) in °C	20
Zero-pressure effective area (A_0) at reference temperature in mm^2	335.815
Relative uncertainty of A_0 in 10^{-6}	24×10^{-6}
Pressure distortion coefficient (λ) in MPa^{-1}	0
Uncertainty of λ in MPa^{-1}	N.A.
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	15×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	15×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.787 234 6
Relative uncertainty of g in 10^{-6}	0.5×10^{-6}
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0
Uncertainty of h in mm	30
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	Teledyne HPM 4/6-M
Piston rotation speed during measurement in rpm	2 ~ 26
Room temperature during measurement in °C	20 ± 1
Traceability	*NPL, UK

Institute: RCM-LIPI

Pressure Standard: Pressure balance

Manufacturer & Model	DH Instruments & PG 7601-AMH
Measurement range in kPa	10 to 350
Material of piston	Tungsten Carbide
Material of cylinder	Tungsten Carbide
Reference temperature (t_0) in °C	20
Zero-pressure effective area (A_0) at reference temperature in mm^2	980,509
Relative uncertainty of A_0 in 10^{-6}	14
Pressure distortion coefficient (λ) in MPa^{-1}	$4,2 \times 10^{-6}$
Uncertainty of λ in MPa^{-1}	$1,0 \times 10^{-6}$
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	$4,5 \times 10^{-6}$
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	$4,5 \times 10^{-6}$
Local acceleration due to gravity (g) in m/s^2	9,78137
Relative uncertainty of g in 10^{-6}	5
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0,5
Uncertainty of h in mm	0,03
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	Internal sensor of PG7000
Piston rotation speed during measurement in rpm	30~50
Room Temperature during measurement in °C	20,0 ± 1,0
Traceability	PTB

Institute: KRISS

Pressure Standard: Pressure balance

Manufacturer & Model	DH Instruments & PG 7601
Measurement range in kPa	10 to 350
Material of piston	Tungsten Carbide
Material of cylinder	Tungsten Carbide
Reference temperature (t_0) in °C	23
Zero-pressure effective area (A_0) at reference temperature in mm^2	980.5612
Relative uncertainty of A_0 in 10^{-6}	14
Pressure distortion coefficient (λ) in MPa^{-1}	4.6×10^{-6}
Uncertainty of λ in MPa^{-1}	0.5×10^{-6}
Linear thermal expansion coefficient of piston (α_p) in °C^{-1}	4.5×10^{-6}
Linear thermal expansion coefficient of cylinder (α_c) in °C^{-1}	4.5×10^{-6}
Local acceleration due to gravity (g) in m/s^2	9.798 310
Relative uncertainty of g in 10^{-6}	0.5
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS) in mm	0
Uncertainty of h in mm	0.3
Operating gas (N_2)	Yes
Gauge for residual pressure measurement	CDG, MKS 0.1 Torr
Piston rotation speed during measurement in rpm	20 to 40
Room Temperature during measurement in °C	(20.0 ± 1.0) & (23.00 ± 1.0)
Traceability	KRISS

Appendix II. Participant’s correction values and corresponding uncertainties as reported

The correction values and corresponding uncertainties used for the comparison in the report was highlighted

Nominal Pressure	NMIA				NSCL				PTB				NIM			
	TS-A1(HIGH)		**TS-A1(LOW)**		**TS-A1(HIGH)**		TS-A1(LOW)		**TS-A2(HIGH)**		TS-A2(LOW)		**TS-A2(HIGH)**		TS-A2(LOW)	
P_n kPa	$\langle C_H \rangle$ kPa	$u(C_H)$ $\times10^{-6}$	**$\langle C_L \rangle$ kPa**	**$u(C_L)$ $\times10^{-6}$**	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times10^{-6}$	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times10^{-6}$	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times10^{-6}$
110	0.0004	3.1	**0.0025**	**3.0**	**-0.0029**	**27**	0.0008	27	**0.0011**	**5.8**	-0.0025	6.0	**0.0028**	**5.3**	0.0002	5.3
100	0.0010	3.1	**0.0029**	**3.1**	**-0.0010**	**28**	0.0021	27	**0.0012**	**5.9**	-0.0023	6.0	**0.0029**	**5.3**	0.0004	5.3
90	0.0012	3.3	**0.0030**	**3.2**	**0.0003**	**27**	0.0025	27	**0.0012**	**5.9**	-0.0020	5.8	**0.0029**	**5.4**	0.0006	5.3
70	0.0011	4.0	**0.0028**	**3.7**	**0.0009**	**27**	0.0023	27	**0.0016**	**5.9**	-0.0009	5.7	**0.0033**	**5.7**	0.0014	5.7
50	0.0011	5.7	**0.0025**	**5.8**	**0.0012**	**27**	0.0022	27	**0.0023**	**5.8**	0.0002	5.9	**0.0038**	**5.4**	0.0022	5.3
30	0.0011	8.4	**0.0027**	**8.9**	**0.0013**	**27**	0.0024	27	**0.0028**	**6.0**	0.0009	6.7	**0.0042**	**6.0**	0.0027	6.0
10	0.0015	26	**0.0039**	**26**	**0.0019**	**57**	0.0036	56	**0.0030**	**13**	0.0017	18	**0.0041**	**12**	0.0030	12
10	0.0017	24	**0.0040**	**26**	**0.0022**	**59**	0.0038	56	**0.0029**	**11**	0.0017	18	**0.0042**	**11**	0.0030	11
30	0.0018	6.9	**0.0033**	**7.1**	**0.0034**	**30**	0.0032	27	**0.0022**	**6.6**	0.0012	6.8	**0.0037**	**6.8**	0.0029	6.0
50	0.0018	5.1	**0.0028**	**5.1**	**0.0029**	**27**	0.0027	27	**0.0018**	**6.0**	0.0004	5.6	**0.0033**	**5.4**	0.0023	5.3
70	0.0019	4.0	**0.0028**	**4.2**	**0.0015**	**27**	0.0023	27	**0.0013**	**6.3**	-0.0007	5.9	**0.0029**	**5.7**	0.0014	5.8
90	0.0019	3.2	**0.0027**	**3.2**	**0.0004**	**27**	0.0026	27	**0.0010**	**6.1**	-0.0018	6.0	**0.0026**	**5.4**	0.0007	5.6
100	0.0016	3.3	**0.0028**	**3.2**	**-0.0003**	**27**	0.0028	27	**0.0010**	**6.2**	-0.0022	6.3	**0.0027**	**5.3**	0.0004	5.5
110	0.0011	3.0	**0.0026**	**3.0**	**-0.0017**	**27**	0.0024	27	**0.0010**	**6.2**	-0.0025	6.1	**0.0027**	**5.3**	0.0002	5.5

(Continued)

Nominal Pressure	VMI				CMS-ITRI				MSL				NMIJ			
	TS-A2(HIGH)		TS-A2(LOW)		**TS-A2(HIGH)**		TS-A2(LOW)		**TS-A2(HIGH)**		TS-A2(LOW)		TS-B1(HIGH)		TS-B1(LOW)	
P_n kPa	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times 10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times 10^{-6}$	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times 10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times 10^{-6}$	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times 10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times 10^{-6}$	**$\langle C_H \rangle$ kPa**	**$u(C_H)$ $\times 10^{-6}$**	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times 10^{-6}$
110	**0.0022**	**15**	-0.0010	15	**0.0033**	**7.4**	0.0020	7.4	**0.0029**	**5.0**	0.0001	5.0	0.0017	7.1	**0.0020**	**7.1**
100	**0.0022**	**14**	-0.0010	14	**0.0033**	**7.5**	0.0022	7.5	**0.0031**	**5.0**	0.0002	5.0	0.0016	7.1	**0.0019**	**7.1**
90	**0.0022**	**15**	-0.0008	15	**0.0034**	**7.6**	0.0024	7.6	**0.0030**	**5.0**	0.0005	5.0	0.0017	7.1	**0.0021**	**7.1**
70	**0.0027**	**16**	0.0005	16	**0.0037**	**7.9**	0.0027	7.9	**0.0034**	**5.0**	0.0014	5.0	0.0015	7.2	**0.0021**	**7.2**
50	**0.0034**	**16**	0.0017	16	**0.0044**	**8.4**	0.0029	8.4	**0.0041**	**5.1**	0.0025	5.0	0.0014	7.3	**0.0024**	**7.3**
30	**0.0038**	**17**	0.0028	17	**0.0049**	**9.7**	0.0031	9.7	**0.0046**	**5.1**	0.0029	5.1	0.0015	7.8	**0.0030**	**7.8**
10	**0.0035**	**31**	0.0028	31	**0.0051**	**16**	0.0037	16	**0.0047**	**5.6**	0.0035	5.6	0.0022	12	**0.0040**	**13**
10	**0.0038**	**30**	0.0032	30	**0.0050**	**16**	0.0037	16	**0.0047**	**5.4**	0.0035	5.4	0.0024	13	**0.0043**	**13**
30	**0.0037**	**17**	0.0034	17	**0.0044**	**9.7**	0.0034	9.7	**0.0041**	**5.0**	0.0032	5.1	0.0019	7.9	**0.0039**	**7.8**
50	**0.0031**	**16**	0.0021	16	**0.0038**	**8.4**	0.0032	8.4	**0.0035**	**5.0**	0.0029	5.0	0.0018	7.3	**0.0037**	**7.4**
70	**0.0024**	**16**	0.0008	16	**0.0033**	**7.9**	0.0029	7.9	**0.0030**	**5.0**	0.0017	5.0	0.0020	7.2	**0.0035**	**7.2**
90	**0.0021**	**14**	-0.0004	15	**0.0032**	**7.6**	0.0027	7.6	**0.0028**	**5.0**	0.0007	5.0	0.0023	7.1	**0.0034**	**7.1**
100	**0.0020**	**14**	-0.0007	14	**0.0033**	**7.5**	0.0025	7.5	**0.0029**	**5.0**	0.0003	5.0	0.0022	7.1	**0.0031**	**7.1**
110	**0.0019**	**15**	-0.0012	15	**0.0032**	**7.4**	0.0021	7.4	**0.0028**	**5.0**	0.0001	5.0	0.0020	7.1	**0.0027**	**7.1**

(Continued)

Nominal Pressure	NIMT				SCL				RCM-LIPI				KRISS			
	TS-B2(HIGH)		**TS-B2(LOW)**		TS-B2(HIGH)		**TS-B2(LOW)**		TS-B2(HIGH)		**TS-B2(LOW)**		**TS-B1(HIGH)**		TS-B1(LOW)	
P_n kPa	$\langle C_H \rangle$ kPa	$u(C_H)$ $\times 10^{-6}$	**$\langle C_L \rangle$ kPa**	**$u(C_L)$ $\times 10^{-6}$**	$\langle C_H \rangle$ kPa	$u(C_H)$ $\times 10^{-6}$	**$\langle C_L \rangle$ kPa**	**$u(C_L)$ $\times 10^{-6}$**	$\langle C_H \rangle$ kPa	$u(C_H)$ $\times 10^{-6}$	**$\langle C_L \rangle$ kPa**	**$u(C_L)$ $\times 10^{-6}$**	$\langle C_H \rangle$ kPa	$u(C_H)$ $\times 10^{-6}$	$\langle C_L \rangle$ kPa	$u(C_L)$ $\times 10^{-6}$
110	0.0007	9.2	**-0.0039**	**9.2**	0.0028	36	**-0.0020**	**36**	**-0.0007**	**8.5**	-0.0066	8.5	-	7.3	-	7.3
100	0.0006	9.2	**-0.0040**	**9.2**	0.0024	35	**-0.0025**	**35**	**-0.0012**	**7.9**	-0.0070	7.9	-	7.3	-	7.3
90	0.0003	9.2	**-0.0038**	**9.2**	0.0021	33	**-0.0023**	**33**	**-0.0011**	**7.8**	-0.0064	7.8	-	7.3	-	7.3
70	0.0004	9.4	**-0.0032**	**9.3**	0.0021	36	**-0.0019**	**36**	**-0.0014**	**7.9**	-0.0060	7.9	-	7.5	-	7.5
50	0.0006	9.6	**-0.0024**	**9.6**	0.0025	40	**-0.0009**	**40**	**-0.0009**	**9.0**	-0.0051	9.0	-	7.7	-	7.7
30	0.0003	11	**-0.0021**	**11**	0.0016	52	**-0.0011**	**52**	**-0.0012**	**10**	-0.0049	10	-	8.2	-	8.2
10	0.0006	22	**-0.0021**	**21**	0.0002	102	**-0.0028**	**102**	**-0.0007**	**15**	-0.0046	15	-	13	-	13
10	0.0005	21	**-0.0021**	**21**	0.0000	103	**-0.0030**	**103**	**-0.0007**	**14**	-0.0045	14	-	13	-	13
30	0.0005	11	**-0.0026**	**10**	0.0025	50	**-0.0008**	**50**	**-0.0007**	**8.9**	-0.0049	8.9	-	8.2	-	8.2
50	0.0005	9.6	**-0.0030**	**9.6**	0.0028	40	**-0.0011**	**40**	**-0.0006**	**8.7**	-0.0053	8.7	-	7.7	-	7.7
70	0.0003	9.3	**-0.0035**	**9.3**	0.0025	36	**-0.0017**	**36**	**-0.0010**	**8.5**	-0.0058	8.5	-	7.5	-	7.5
90	0.0002	9.2	**-0.0038**	**9.2**	0.0021	33	**-0.0023**	**33**	**-0.0009**	**8.6**	-0.0060	8.6	-	7.3	-	7.3
100	0.0004	9.2	**-0.0040**	**9.2**	0.0023	35	**-0.0025**	**35**	**-0.0015**	**7.7**	-0.0067	7.7	-	7.3	-	7.3
110	0.0004	9.2	**-0.0040**	**9.2**	0.0022	36	**-0.0024**	**36**	**-0.0011**	**7.7**	-0.0063	7.7	-	7.3	-	7.3