Final report

Results of the bilateral supplementary comparison on pressure measurements in the range (60 to 350) kPa of gauge pressure in gas media
APMP.M.P-S4

T. Priruenrom [1], W. Sabuga [2] and T. Konczak [2]

March 2013

[1] National Institute of Metrology (Thailand) (NIMT), Thailand
[2] Physikalisch-Technische Bundesanstalt (PTB), Germany

1. INTRODUCTION

The objective of this bilateral supplementary comparison (SC) is to check equivalence of gas pressure standards of the two institutes, National Institute of Metrology (Thailand) (NIMT) and Physikalisch-Technische Bundesanstalt (PTB, Germany), in the pressure range 60 kPa to 350 kPa in gauge mode. The results of this comparison will be essential to support the calibration and measurement capabilities (CMC) of NIMT.

The pilot laboratory of this SC is NIMT, which has provided a transfer standard (TS) for the SC. The TS was a piston-cylinder assembly (PCA) with a nominal effective area of 10 cm^2. The TS properties are described in the Technical Protocol [1].

The measurements were started at NIMT during 26 – 28 November 2012. The TS was brought to PTB from NIMT on 7 December 2012 and the measurements at PTB were carried out in the time 10 – 12 December 2012. The TS was brought back to NIMT on 14 December 2012 and the measurements were done at NIMT again to control the transportation effect. All measurements were performed in accordance with the Technical Protocol [1] at pressures (60, 100, 150, 200, 250, 300 and 350) kPa.

This report presents the results of NIMT and PTB. All uncertainties in this report are standard ones (k = 1).

2. DESCRIPTION OF THE LABORATORY STANDARD

2.1 NIMT Laboratory Standard

The NIMT laboratory standard (LS) used in this comparison was a pressure balance with a PCA of 10 cm^2 manufactured by Fluke Corporation, DH Instruments Division (DHI), USA, and identified by serial number 0693. The properties of the NIMT LS are summarised in Tables 1 – 3.

Table 1: Details of the pressure balance used for the comparison

	Manufacturer	Model / Serial	Description
Base	DHI	PG-7601 / serial no. 867	-
Piston-cylinder	DHI	PC-7100/7600-10-TC / serial no. 0693	Operation mode[#1]: Simple Pressure range [MPa]: 0.35
Weights	DHI	MS-7002-35 / serial no. 2111, with carrying bell no. 349	Total mass [kg]: 35 Typical relative uncertainty of mass pieces (k=1) [ppm]: 2.5
Thermometer	DHI	PG-7601	Serial No.: U856

#1 for example: Simple or controlled-clearance, etc

Table 2: Details of the piston-cylinder

	Material	Linear thermal expansion coefficient (α) [°C^{-1}]
Piston	Tungsten carbide	4.5×10^{-6}
Cylinder	Tungsten carbide	4.5×10^{-6}

Table 3: Details of the effective area of the piston-cylinder

	Value	Uncertainty [k=1]	Traceability[#2]
Zero-pressure effective area [cm^2] at ref. temp., A_0 [#3] (Ref. temp.: t_0)	9.80528 (t_0 : 20 [°C])	$5.0\times10^{-6}\times A_0$	Dimensional measurement, Certificate No. 50078 PTB 10
Pressure distortion coefficient λ_1 [#3] [kPa^{-1}]	4.2×10^{-9}	7.5×10^{-10}	Manufacturer
Pressure distortion coefficient λ_2 [#3] [kPa^{-2}] (if applicable)	-	-	-

#2 for example: from PTB, Certificate number 1234, or mercury manometer, etc.

#3 $A_p = A_0\,(1 + \lambda_1\, p + \lambda_2\, p^2)$

Note: The zero-pressure effective area (A_0) was determined from dimensional measurements and from cross-float measurements against the other PCAs used as the primary gas pressure standards at NIMT, described in [2].

The value of pressure distortion coefficient (λ_1) has been taken from the manufacturer and its uncertainty is assumed to be 35% (k = 2).

2.2 PTB Laboratory Standard

The PTB LS used in this comparison was a pressure balance with a PCA of 10 cm^2 manufactured by Desgranges et Huot (DH) and identified by serial number 288. Its properties are described in [3] and are summarised in Tables 4 – 6.

Table 4: Details of the pressure balance used for the comparison

	Manufacturer	Model / Serial	Description
Base	PTB	-	
Piston-cylinder	DH	Serial no. 288	Operation mode#1: Simple Pressure range [MPa]: 0.6 - 1
Weights	DH	Serial no. 4138	Total mass [kg]: 100 Typical relative uncertainty of mass pieces (k=1) [ppm]: 0.5
Thermometer	Greisinger Elektronic	GTF 102	

#1 for example: Simple or controlled-clearance, etc

Table 5: Details of the piston-cylinder

	Material	Linear thermal expansion coefficient (α) [°C^{-1}]
Piston	tungsten carbide	4.5×10^{-6}
Cylinder	tungsten carbide	4.5×10^{-6}

Table 6: Details of the effective area of the piston-cylinder

	Value	Uncertainty [k=1]	Traceability#2
Zero-pressure effective area [cm^2] at ref. temp., A_0 #3 (Ref. temp.: t_0)	9.804904 (t_0 : 20 °C)	$1.68\times10^{-6} \times A_0$	PTB, dim. measurements and mercury manometer
Pressure distortion coefficient λ_1 #3 [kPa^{-1}]	4.0×10^{-9}	1.47×10^{-10}	PTB, elastic theory, dim. data, material properties
Pressure distortion coefficient λ_2 #3 [kPa^{-2}] (if applicable)	0	0	-

#2 for example: from PTB, Certificate number 1234, or mercury manometer, etc.

#3 $A_p = A_0 (1 + \lambda_1 p + \lambda_2 p^2)$

Note: The zero-pressure effective area (A_0) was determined from dimensional measurements and from measurements against a primary mercury manometer [3], the latter being described in [4].

The pressure distortion coefficient (λ) of the PCA was determined from its dimensions and the elastic constants of its materials using equation

$$\lambda = \frac{1}{2E}\left[\frac{R_2^2 + R_1^2}{R_2^2 - R_1^2} - \frac{R_1^2 - 3r_1^2}{R_1^2 - r_1^2} + 4\mu\right], \quad (1)$$

in which E and μ are Young's modulus and Poisson's coefficient of the piston-cylinder material, R_1 and R_2 are inner and outer cylinder radii, and r_1 is radius of the bore in the piston. Additionally, λ was calculated by the finite element method taking into account the real dimensions of the gap between the piston and cylinder [5].

3. DETAILS OF THE MEASUREMENT CONDITIONS

Details of the measurement conditions are given in Tables 7 – 9.

Table 7: Local gravity and height difference

	NIMT		PTB	
	Value [m/s^2]	Uncertainty (k=1) [mm]	Value [m/s^2]	Uncertainty (k=1) [mm]
Local gravity, g	9.783124	4.9×10^{-6}	9.812533	5.2×10^{-6}
Height difference, Δh *	0.0	1.0	-20.45	0.37

* It will be positive, if the level of the LS is higher.

Table 8: Piston rotation during measurement

	NIMT	PTB
LS	Rotate by hand, with speed 15 rpm	Rotate by hand, with speed 20 rpm
TS	Rotate by hand, with speed 15 rpm	Rotate by hand, with speed 20 rpm

Table 9: Instruments for measuring environmental condition

	Parameter	Manufacturer	Model	Uncertainty [k=1]
NIMT	Temperature	Lufft	8150.30	0.25 °C
	Humidity			1.25 %
	Ambient pressure			0.18 mbar
PTB	Temperature	Vaisala	PTU 300	0.5 °C
	Humidity			3 %
	Ambient pressure			0.016 mbar

4. CALIBRATION METHOD: TECHNICAL DETAILS

4.1 NIMT

The TS PCA was operated in a DHI platform PG 7601, serial no. 216. DHI mass carrying bell, serial no. 316, and DHI mass set, serial no. 2091, were used for operation. The direct comparison method (also called the fall-rate method) was used in the measurements, according to EURAMET cg 3: Calibration of Pressure Balances, Version 1.0 (03/2011). The pressure generated by LS at the reference level of TS and the effective area of TS were calculated with the formulas given in the Technical Protocol [1].

4.2 PTB

The TS PCA was operated in a DHI platform PG 7601, serial no. 135, belonging to PTB. Also DHI mass carrying bell, serial no. 235, and DHI mass set, serial no. 2067, used for operation of the TS are property of PTB. Pressure differences between TS and LS were measured using a differential pressure cell (DPC) MKS Baratron, type 698A11TRC, serial no. 016390809. DPC readings measured over the time of 60 s were averaged and then used in the calculation. The absolute values of pressure differences between TS and LS were always smaller than 0.64 Pa. The standard uncertainty of the DPC in this pressure range is smaller than 0.08 Pa.

The pressure generated by LS at the reference level of TS, p, was calculated with the well-known formula

$$p = \frac{g\sum_i m_i(1-\rho_\mathrm{a}/\rho_i) + \rho_{\mathrm{N_2}} gV(1-\rho_\mathrm{a}/\rho_{\mathrm{N_2}})}{A_0(1+\lambda p_\mathrm{nom})[1+2\alpha(t-t_0)]} + \rho_{\mathrm{N_2}} gh\,(1-\rho_\mathrm{a}/\rho_{\mathrm{N_2}}) + \Delta p \qquad (2)$$

where:
m_i are masses of the piston, the weight carrier and the mass pieces placed on the weight carrier;
ρ_i are densities of the parts with masses m_i;
ρ_a is air density;
ρ_{N2} is density of nitrogen at pressure p and temperature t;
g is local gravity acceleration;
V is free volume in the piston above the pressure reference level;
A_0 is zero-pressure effective area;
λ is pressure distortion coefficient;
p_nom is nominal pressure
α is thermal expansion coefficient of the piston and cylinder material;
t is temperature of the LS;
t_0 is reference temperature, t_0 = 20 °C;
h is height difference between the reference levels of the LS and the TS;
Δp is pressure difference between the TS and LS measured with the differential pressure cell.
The density of nitrogen was calculated by equations presented in [6].
The density of air that enters the calculation of the buoyancy effect was determined from the so-called BIPM formula [7] using values of room temperature and atmospheric pressure measured during the calibration process.

The effective area of the TS at pressure p and temperature 20 °C (A'_p) was calculated by formula

$$A_\mathrm{p}' = \frac{g\sum_i m_i'(1-\rho_\mathrm{a}/\rho_i')}{p\,[1+(\alpha_\mathrm{p}'+\alpha_\mathrm{c}')(t'-t_0)]} \qquad (3)$$

in which:

m'_i are masses of the piston, the weight carrier and the mass pieces placed on the weight carrier on the TS;
ρ'_i are densities of the parts with masses m'_i;
α'_p and α'_c are thermal expansion coefficients of the piston and cylinder materials of the TS;
t' is temperature of the TS.
The zero-pressure effective area and the pressure distortion coefficient of the TS, A'_0 and λ', were calculated by a linear fit of (A'_p; p) data using the model equation

$$A'_p = A'_0 \times (1 + \lambda' \cdot p)\,. \tag{4}$$

5. MEASUREMENTS RESULTS

The effective area results obtained in individual complete measuring series of each institute are presented in Table 10 – 15.

5.1 NIMT Results

Table 10: Measurement results of NIMT for series 1 of 3

Date:		26 Nov. 2012							
Meas. No.	Nom. Pres. [kPa]	Local Time	Amb. Temp. [°C]	Amb. R.H. [%]	Amb. Pres. [bar]	Temp. t [°C]	Temp. t' [°C]	Pressure p' [kPa]	Effective area A'_p [cm^2]
1	60	15:00	20.3	64.5	1.0074	21.16	22.04	60.00394	9.805286
2	100	15:10	20.3	64.0	1.0077	21.18	22.04	100.00673	9.805276
3	150	15:20	20.4	64.0	1.0077	21.19	22.03	150.03520	9.805277
4	200	15:30	20.4	64.0	1.0077	21.21	22.03	200.01376	9.805278
5	250	15:40	20.4	64.0	1.0077	21.22	22.03	249.99240	9.805276
6	300	15:50	20.5	64.0	1.0074	21.23	22.02	300.02066	9.805277
7	350	16:00	20.5	63.5	1.0074	21.23	22.04	349.99919	9.805273
8	350	16:10	20.5	64.0	1.0074	21.24	22.04	349.99916	9.805274
9	300	16:20	20.5	63.5	1.0074	21.26	22.04	300.02068	9.805275
10	250	16:30	20.5	63.5	1.0074	21.27	22.06	249.99251	9.805270
11	200	16:40	20.5	63.0	1.0078	21.29	22.06	200.01387	9.805270
12	150	16:50	20.5	63.0	1.0078	21.31	22.07	150.03519	9.805275
13	100	17:00	20.5	63.0	1.0078	21.32	22.10	100.00671	9.805273
14	60	17:10	20.5	62.5	1.0078	21.35	22.13	60.00398	9.805271

t is temperature of the institute's standard;

t' is temperature of the TS;

p' is the pressure measured with the institute standard at the local gravity g and the local air density ρ_a and calculated at the reference level of the TS;

A'_p is the effective area of TS at the reference temperature 20 °C.

Table 11: Measurement results of NIMT for series 2 of 3

Date:		27 Nov. 2012							
Meas. No.	Nom. Pres. [kPa]	Local Time	Amb. Temp. [°C]	Amb. R.H. [%]	Amb. Pres. [bar]	Temp. t [°C]	Temp. t' [°C]	Pressure p' [kPa]	Effective area A'_p [cm^2]
15	60	13:00	20.2	62.0	1.0089	21.16	22.01	60.00402	9.805273
16	100	13:10	20.2	62.0	1.0089	21.17	22.00	100.00671	9.805278
17	150	13:20	20.2	61.5	1.0089	21.18	22.00	150.03521	9.805276
18	200	13:30	20.3	62.0	1.0085	21.20	21.99	200.01384	9.805275
19	250	13:40	20.3	62.0	1.0085	21.21	22.00	249.99247	9.805273
20	300	13:50	20.4	61.5	1.0082	21.22	22.00	300.02072	9.805275
21	350	14:00	20.5	61.5	1.0082	21.23	22.00	349.99914	9.805277
22	350	14:10	20.5	61.5	1.0082	21.25	22.01	349.99927	9.805272
23	300	14:20	20.5	62.0	1.0078	21.26	22.02	300.02085	9.805270
24	250	14:30	20.5	61.5	1.0074	21.28	22.04	249.99258	9.805268
25	200	14:40	20.6	62.0	1.0074	21.30	22.04	200.01393	9.805270
26	150	14:50	20.6	61.5	1.0070	21.32	22.08	150.03525	9.805271
27	100	15:00	20.6	62.0	1.0070	21.36	22.11	100.00674	9.805271
28	60	15:10	20.6	62.0	1.0070	21.39	22.15	60.00397	9.805272

Table 12: Measurement results of NIMT for series 3 of 3

Date:		28 Nov. 2012							
Meas. No.	Nom. Pres. [kPa]	Local Time	Amb. Temp. [°C]	Amb. R.H. [%]	Amb. Pres. [bar]	Temp. t [°C]	Temp. t' [°C]	Pressure p' [kPa]	Effective area A'_p [cm^2]
29	60	13:00	20.5	60.5	1.0089	21.37	22.23	60.00386	9.805280
30	100	13:10	20.5	60.0	1.0089	21.39	22.24	100.00653	9.805277
31	150	13:20	20.5	60.5	1.0089	21.39	22.22	150.03490	9.805278
32	200	13:30	20.6	60.0	1.0086	21.39	22.22	200.01347	9.805274
33	250	13:40	20.6	60.0	1.0086	21.40	22.20	249.99198	9.805276
34	300	13:50	20.6	60.0	1.0086	21.40	22.20	300.02025	9.805273
35	350	14:00	20.6	60.5	1.0086	21.41	22.20	349.99866	9.805272
36	350	14:10	20.6	60.0	1.0086	21.42	22.20	349.99863	9.805273
37	300	14:20	20.6	60.5	1.0082	21.42	22.20	300.02041	9.805269
38	250	14:30	20.6	60.5	1.0078	21.44	22.20	249.99212	9.805272
39	200	14:40	20.6	60.5	1.0078	21.46	22.22	200.01357	9.805271
40	150	14:50	20.6	60.5	1.0082	21.48	22.23	150.03500	9.805272
41	100	15:00	20.7	60.5	1.0082	21.51	22.26	100.00659	9.805271
42	60	15:10	20.6	60.5	1.0078	21.54	22.30	60.00388	9.805272

5.2 PTB Results

Table 13: Measurement results of PTB for series 1 of 3

Date:		10 Dec. 2012							
Meas. No.	Nom. Pres. [kPa]	Local Time	Amb. Temp. [°C]	Amb. R.H. [%]	Amb. Pres. [bar]	Temp. t [°C]	Temp. t' [°C]	Pressure p' [kPa]	Effective area A'_p [cm^2]
1	60	9:05	20.12	26	0.99412	19.81	21.09	60.03761	9.805311
2	100	9:30	20.14	26	0.99465	19.84	21.11	100.06300	9.805309
3	150	9:55	20.15	26	0.99512	19.85	21.11	150.09442	9.805305
4	200	10:20	20.16	27	0.99552	19.86	21.10	200.12580	9.805296
5	250	10:45	20.18	27	0.99606	19.87	21.11	250.15715	9.805296
6	300	11:09	20.18	27	0.99651	19.87	21.11	300.18874	9.805292
7	350	11:41	20.20	28	0.99674	19.88	21.10	350.22045	9.805287
8	350	13:18	20.18	28	0.99806	19.90	21.12	350.22023	9.805289
9	300	13:35	20.17	28	0.99832	19.90	21.12	300.18833	9.805301
10	250	13:52	20.15	27	0.99860	19.89	21.13	250.15684	9.805303
11	200	14:09	20.14	27	0.99885	19.88	21.14	200.12552	9.805301
12	150	14:26	20.13	27	0.99912	19.88	21.13	150.09433	9.805303
13	100	14:44	20.13	27	0.99947	19.87	21.13	100.06290	9.805310
14	60	15:01	20.12	27	0.99990	19.86	21.13	60.03744	9.805328

Table 14: Measurement results of PTB for series 2 of 3

Date:		11 Dec. 2012							
Meas. No.	Nom. Pres. [kPa]	Local Time	Amb. Temp. [°C]	Amb. R.H. [%]	Amb. Pres. [bar]	Temp. t [°C]	Temp. t' [°C]	Pressure p' [kPa]	Effective area A'_p [cm^2]
15	60	08:37:01	19.96	21	1.01301	19.73	20.98	60.03743	9.805321
16	100	08:51:01	19.97	21	1.01300	19.74	20.98	100.06275	9.805316
17	150	09:06:02	19.97	21	1.01300	19.97	20.97	150.09392	9.805323
18	200	09:21:01	19.96	21	1.01314	19.73	20.96	200.12534	9.805304
19	250	09:36:03	19.95	22	1.01338	19.73	20.95	250.15673	9.805300
20	300	09:52:01	19.96	21	1.01349	19.72	20.94	300.18813	9.805300
21	350	10:07:01	19.95	22	1.01356	19.72	20.93	350.21979	9.805294
22	350	12:24:09	20.10	20	1.01347	19.79	20.95	350.21986	9.805290
23	300	12:40:01	20.11	20	1.01355	19.80	20.96	300.18811	9.805299
24	250	12:55:01	20.09	21	1.01359	19.80	20.98	250.15688	9.805291
25	200	13:10:01	20.07	20	1.01366	19.80	20.98	200.12544	9.805296
26	150	13:27:01	20.06	20	1.01363	19.79	20.97	150.09418	9.805305
27	100	13:42:01	20.05	21	1.01366	19.79	20.98	100.06279	9.805312
28	60	13:57:01	20.04	20	1.01376	19.78	20.99	60.03747	9.805313

Table 15: Measurement results of PTB for series 3 of 3

Date:		12 Dec. 2012							
Meas. No.	Nom. Pres. [kPa]	Local Time	Amb. Temp. [°C]	Amb. R.H. [%]	Amb. Pres. [bar]	Temp. t [°C]	Temp. t' [°C]	Pressure p' [kPa]	Effective area A'_p [cm^2]
29	60	08:31:06	20.12	22	1.01107	19.86	21.09	60.03742	9.805318
30	100	08:46:02	20.10	22	1.01100	19.86	21.08	100.06284	9.805302
31	150	09:01:06	20.09	23	1.01095	19.86	21.07	150.09400	9.805312
32	200	09:17:04	20.08	23	1.01092	19.85	21.04	200.12547	9.805294
33	250	09:32:01	20.08	23	1.01098	19.84	21.03	250.15661	9.805302
34	300	09:48:05	20.07	21	1.01097	19.83	21.02	300.18799	9.805302
35	350	10:01:01	20.07	22	1.01105	19.83	21.00	350.21978	9.805292
36	350	13:13:01	20.16	23	1.01035	19.86	21.02	350.21980	9.805291
37	300	13:29:01	20.18	23	1.01013	19.88	21.03	300.18822	9.805295
38	250	13:44:08	20.17	23	1.01000	19.88	21.04	250.15679	9.805296
39	200	13:59:01	20.16	23	1.00998	19.88	21.05	200.12530	9.805303
40	150	14:14:03	20.15	23	1.00994	19.88	21.07	150.09421	9.805301
41	100	14:29:03	20.14	23	1.00983	19.87	21.08	100.06284	9.805304
42	60	14:41:03	20.13	23	1.00977	19.87	21.07	60.03743	9.805319

The results for all of three measuring series are plotted in Figure 1, in which S1, S2 and S3 represent the result from series 1, 2 and 3, respectively.

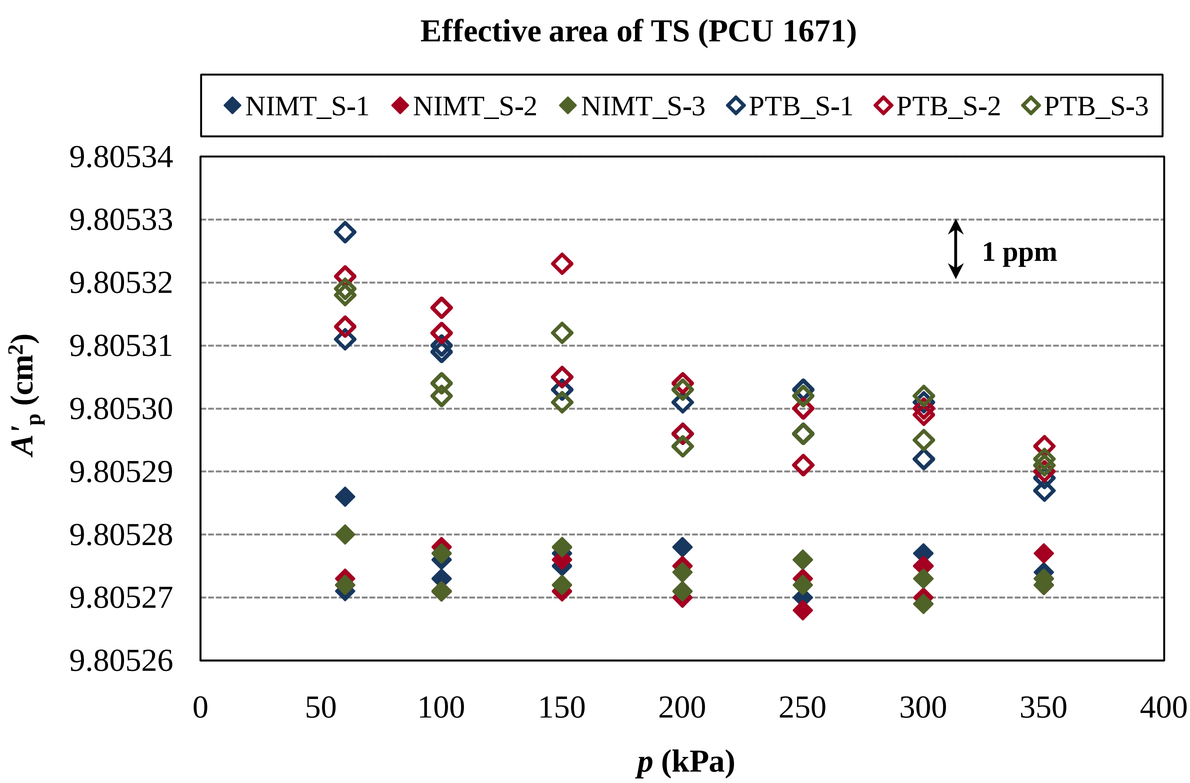

Figure 1: Distorted effective area results for all of the measuring points, NIMT and PTB

The summary of all three measuring series of each institute are given in Tables 16 – 17.

Table 16: Summary results of NIMT

Period:		26 Nov. 2012 – 28 Nov. 2012				
Nom. Pres. [kPa]	Typical min. adjusted mass [mg] 1)	Average of A'_p, $< A'_p >$ [cm^2] 2)	Rel. standard deviation of $< A'_p >$ [10^{-6}] 3)	Rel. standard uncertainty of p' [10^{-6}] 4)	Standard uncertainty of t' [°C] 5)	Rel. standard uncertainty of $< A'_p >$ [10^{-6}] 6)
60	10	9.805276	0.62	5.8	0.25	6.6
100	10	9.805274	0.32	5.8	0.25	6.6
150	10	9.805275	0.28	5.8	0.25	6.6
200	10	9.805273	0.33	5.8	0.25	6.6
250	20	9.805273	0.33	5.8	0.25	6.6
300	20	9.805273	0.34	5.8	0.25	6.6
350	20	9.805273	0.18	5.8	0.25	6.6

Table 17: Summary results of PTB

Period:		10 Dec. 2012 – 12 Dec. 2012				
Nom. Pres. [kPa]	Typical standard uncert. of Δp [kPa] 1)	Average of A'_p, $< A'_p >$ [cm^2] 2)	Rel. standard deviation of $< A'_p >$ [10^{-6}] 3)	Rel. standard uncertainty of p' [10^{-6}] 4)	Standard uncertainty of t' [°C] 5)	Rel. standard uncertainty of $< A'_p >$ [10^{-6}] 6)
60	0.17	9.805318	0.8	4.5	0.1	4.8
100	0.17	9.805309	0.7	3.1	0.1	3.4
150	0.17	9.805308	1.1	2.7	0.1	3.2
200	0.18	9.805299	0.6	2.5	0.1	2.9
250	0.19	9.805298	0.6	2.4	0.1	2.8
300	0.19	9.805298	0.5	2.4	0.1	2.8
350	0.19	9.805290	0.3	2.3	0.1	2.7

1) the smallest mass adjusted on the piston of the TS to reach the equilibrium between it and the institute's standard, if the classical fall rate method is used. If a differential pressure cell was applied to measure the pressure difference between the laboratory and transfer standard, the typical uncertainty of the pressure difference between the reference standard and TS due to this method should be given. In this case the heading of this column shall be changed to "Typical uncertainty of Δp [kPa]";
2) average of the A'_p values measured at the same nominal pressure;
3) standard deviation of the mean value;
4) type B uncertainty of the pressure at the reference level of TS, which includes uncertainty of pressure generated by the institute's standard, of the height difference between the institute standard and TS, of the density of the pressure transmitting medium, etc.;
5) type B uncertainty of the temperature measurement on TS;
6) combined uncertainty of the mean value in 2).

All the uncertainties are expressed as the standard ones.

The average of effective area values measured at the same nominal pressure with its uncertainty for each nominal pressure is plotted in Figure 2. In this figure the scale of pressure (in x-axis) has been slightly shifted for a better resolution of the NIMT and PTB mean values.

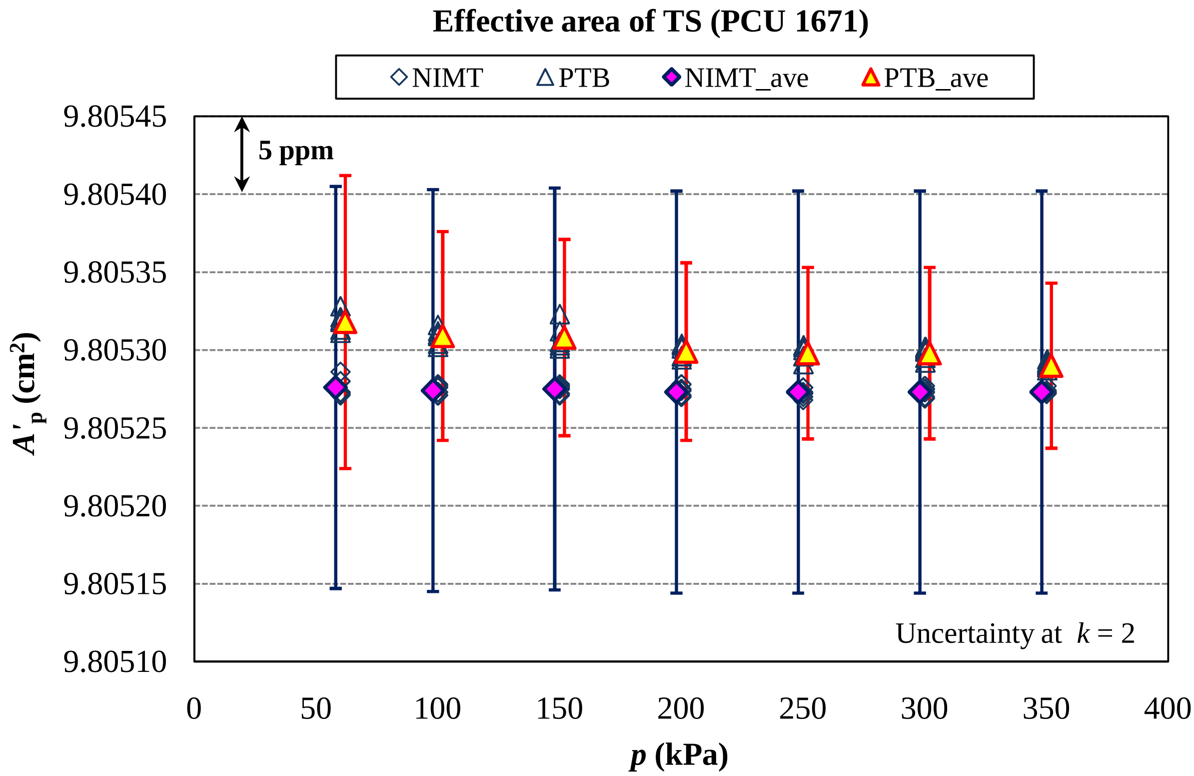

Figure 2: Average values of the effective areas measured at the same nominal pressure with their expanded uncertainties (k = 2), NIMT and PTB

Table 18 shows the relative difference of the effective area values between NIMT and PTB, using the data from Tables 16 and 17, the expanded uncertainties of A'_p (U) and the normalized error (E_n) that was calculated by the equation below.

$$E_n = \frac{|[<A'_p>_{NIMT} - <A'_p>_{PTB}]| / <A'_p>_{PTB}}{[U^2(<A'_p>_{NIMT}) + U^2(<A'_p>_{PTB})]^{0.5}} \qquad (5)$$

Table 18: Relative difference of the effective areas and E_n

Nom. Pres. [kPa]	Rel. difference of $<A'_p>$, $[<A'_p>_{NIMT} - <A'_p>_{PTB}] / <A'_p>_{PTB}$ $[10^{-6}]$	Rel. uncertainty of $<A'_p>$ (k=2) $[10^{-6}]$		E_n
		$U(<A'_p>_{NIMT})$	$U(<A'_p>_{PTB})$	
60	-4.3	13.2	9.6	0.26
100	-3.6	13.2	6.8	0.24
150	-3.4	13.2	6.4	0.23
200	-2.7	13.2	5.8	0.18
250	-2.5	13.2	5.6	0.18
300	-2.5	13.2	5.6	0.18
350	-1.7	13.2	5.4	0.12

The maximum difference of the effective area values between NIMT and PTB occurs at the minimum pressure. It is about 4.3 ppm, which corresponds to E_n = 0.26. At higher pressure the difference becomes smaller. At pressure 350 kPa, the difference is only 1.7 ppm, which corresponds to E_n = 0.12. The uncertainty claimed by NIMT is almost the same for all nominal pressures, whereas that by PTB decreases with increasing pressure.

By a linear fit of (A'_p; p) data using the model equation $A'_p = A'_0 \cdot (1+\lambda' \cdot p)$, the zero-pressure effective area and the pressure distortion coefficient of the TS, A'_0 and λ', can be obtained as given in Table 19.

Table 19: Zero-pressure effective area (A'_0) and pressure distortion coefficient (λ') of TS with their uncertainties

	NIMT		PTB	
	Value	Uncertainty [k=1]	Value	Uncertainty [k=1]
A'_0 [cm^2] at ref. temp., 20 °C	9.805266	0.000064 ($6.5 \cdot 10^{-6} \times A'_0$)	9.805320	0.000039 ($4.0 \cdot 10^{-6} \times A'_0$)
λ' [kPa^{-1}]	$4.2 \cdot 10^{-9}$	$7.4 \cdot 10^{-10}$	$-8.5 \cdot 10^{-9}$	$9.4 \cdot 10^{-9}$

Note: The value of pressure distortion coefficient (λ') reported by NIMT was taken from the manufacturer certificate and its uncertainty was assumed to be 35% (k = 2).

PTB explains that the result for λ' cannot be considered as a realistic distortion coefficient because the pressure range of the measurement was too short for an experimental determination of λ'. This is expressed by the rather big uncertainty of λ'.

The distorted effective areas A'_p from all measurements, the zero-pressure effective areas A'_0, which were calculated using the model equation $A'_0 = A'_p / (1+\lambda' \cdot p)$ with λ given in Table 19, and the average values of A'_0 with their uncertainties are plotted in Figure 3.

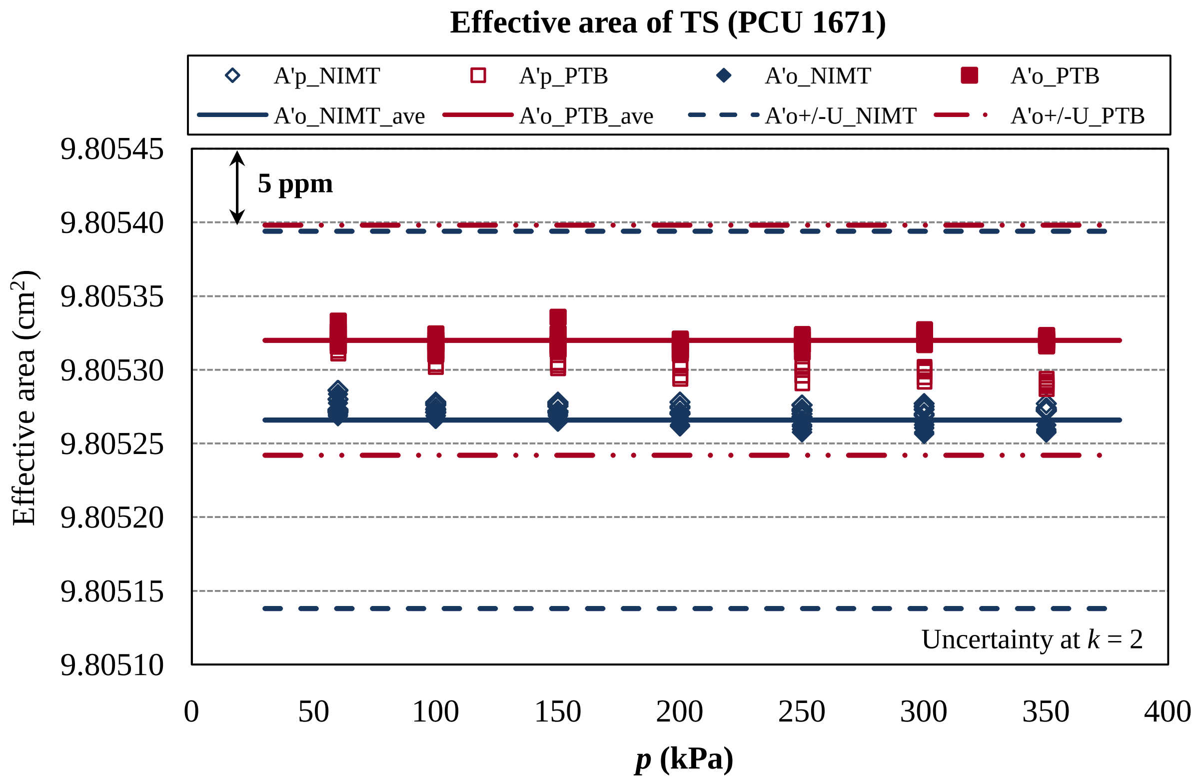

Figure 3: Plot of the effective areas, A'_p and A'_0, and the average values of A'_0 with their uncertainties (k = 2)

The difference in the zero-pressure effective area of NIMT and PTB is 0.000054 cm^2 or 5.5 ppm, whereas the value of NIMT is lower than of PTB. The expanded uncertainty (k = 2) of A'_0 claimed by NIMT is 13 ppm and by PTB is 8 ppm.

Due to the fact that the pressure range of the measurement is too short for an experimental determination of λ'; the result for λ' cannot be considered as a realistic value. Therefore, its value should not be compared.

6. UNCERTAINTY ESTIMATION

6.1 NIMT

The measurement uncertainty of $\langle A'_p \rangle$ is determined in accordance with “EURAMET cg 3” [8] and the ISO GUM [9]. The uncertainty budget of the $\langle A'_p \rangle$ calculated at the minimum and the maximum pressure range, 60 and 350 kPa, are shown in Tables 20 – 21.

Table 20: Uncertainty budget of the $<A'_p>$ at 60 kPa

Symbol	Source of Uncertainties	Value	Prob. Dist.	Divisor	Sensitivity	Standard Uncer. (m^2)			DOF
						p	const.	1/p	
u_A_0,std	Uncertainty of A_0 standard (m^2)	9.8E-09	N	2	1.0E+00		4.9E-09		∞
u_m,std	Uncertainty of STD mass (kg)	3.0E-05	N	2	1.6E-04		2.5E-09		∞
u_ρ_m,std	Uncertainty of STD mass density (kg m^{-3})	5.0E+01	R	√3	6.1E-12		1.8E-10		∞
u_t,std	Uncertainty of STD temp. (^oC)	2.5E-01	R	√3	8.8E-09		1.3E-09		∞
u_m,uuc	Uncertainty of UUC mass (kg)	3.0E-05	N	2	1.6E-04		2.5E-09		∞
u_ρ_m,uuc	Uncertainty of UUC mass density (kg m^{-3})	5.0E+01	R	√3	6.1E-12		1.8E-10		∞
u_t,uuc	Uncertainty of UUC temp. (^oC)	2.5E-01	R	√3	8.8E-09		1.3E-09		∞
u_(α_p+α_c)	Uncertainty of thermal exp. ($^oC^{-1}$)	9.0E-07	R	√3	2.3E-03		1.2E-09		∞
u_ρ_a	Uncertainty of air density (kg m^{-3})	5.9E-03	N	2	1.2E-07		3.6E-10		∞
u_Δh	Uncertainty of head corr. (m)	2.0E-03	R	√3	6.3E-03			7.2E-06	∞
u_ρ_f	Uncertainty of fluid density (kg m^{-3})	3.7E-03	N	2	0.0E+00			0.0E+00	∞
u_θ	Uncertainty of verticality (mm/m)	4.0E-01	R	√3	3.9E-10		9.1E-11		∞
u_V	Uncertainty of volume UUC (m^3)	1.0E-06	R	√3	6.4E+00			3.7E-06	∞
u_sens	Uncertainty of sensitivity of UUC (kg)	5.0E-06	R	√3	1.6E-04		4.7E-10		∞
u_λ,std	Uncertainty of STD distortion coeff. (Pa^{-1})	1.5E-12	N	2	9.8E-04	7.2E-16			∞
u_B	Type B uncertainty					7.2E-16	6.4E-09	8.1E-06	
u_A	Type A uncertainty						5.9E-10		
u_c	Combined uncertainty					7.2E-16	6.4E-09	8.1E-06	
						m^2			ppm
	Standard uncertainty (k=1)						**6.4E-09**		**6.6**

Table 21: Uncertainty budget of the $\langle A'_p \rangle$ at 350 kPa

Symbol	Source of Uncertainties	Value	Prob. Dist.	Divisor	Sensitivity	Standard Uncer. (m^2)			DOF
						p	const.	1/p	
u_A_0,std	Uncertainty of A_0 standard (m^2)	9.8E-09	N	2	1.0E+00		4.9E-09		∞
u_m,std	Uncertainty of STD mass (kg)	1.8E-04	N	2	2.8E-05		2.5E-09		∞
u_ρ_m,std	Uncertainty of STD mass density (kg m^{-3})	5.0E+01	R	√3	6.1E-12		1.8E-10		∞
u_t,std	Uncertainty of STD temp. (^oC)	2.5E-01	R	√3	8.8E-09		1.3E-09		∞
u_m,uuc	Uncertainty of UUC mass (kg)	1.8E-04	N	2	2.8E-05		2.5E-09		∞
u_ρ_m,uuc	Uncertainty of UUC mass density (kg m^{-3})	5.0E+01	R	√3	6.1E-12		1.8E-10		∞
u_t,uuc	Uncertainty of UUC temp. (^oC)	2.5E-01	R	√3	8.8E-09		1.3E-09		∞
u_(α_p+α_c)	Uncertainty of thermal exp. ($^oC^{-1}$)	9.0E-07	R	√3	2.3E-03		1.2E-09		∞
u_ρ_a	Uncertainty of air density (kg m^{-3})	5.9E-03	N	2	1.2E-07		3.6E-10		∞
u_Δh	Uncertainty of head corr. (m)	2.0E-03	R	√3	3.8E-02			4.4E-05	∞
u_ρ_f	Uncertainty of fluid density (kg m^{-3})	1.0E-02	N	2	0.0E+00			0.0E+00	∞
u_θ	Uncertainty of verticality (mm/m)	4.0E-01	R	√3	3.9E-10		9.1E-11		∞
u_V	Uncertainty of volume UUC (m^3)	1.0E-06	R	√3	3.9E+01			2.2E-05	∞
u_sens	Uncertainty of sensitivity of UUC (kg)	1.0E-05	R	√3	2.8E-05		1.6E-10		∞
u_λ,std	Uncertainty of STD distortion coeff. (Pa^{-1})	1.5E-12	N	2	9.8E-04	7.2E-16			∞
u_B	Type B uncertainty					7.2E-16	6.4E-09	4.9E-05	
u_A	Type A uncertainty						5.9E-10		
u_c	Combined uncertainty					7.2E-16	6.4E-09	4.9E-05	
						m^2			ppm
	Standard uncertainty (*k*=1)					**6.4E-09**			**6.6**

6.2 PTB

The calculation of the measurement uncertainty of <A'_p> is based on the ISO GUM [9]. The list of the main uncertainty quantities, X, their standard uncertainties, u(X), and their contributions to relative uncertainties of <A'_p>, u(<A'_p>)/<A'_p>, at the minimum and maximum pressures are given in Table 22. The contributions of smaller than 1×10^{-8} are omitted. The values of the outputs were calculated by a numerical method (variation of parameters). A computer program calculated the uncertainty in the values of the output quantities (effective areas) from the uncertainty in the input quantities.

Table 22: List of principal uncertainty components (u) for the effective area <A'_p> determined at pressures of 60 kPa and 350 kPa

Quantity (X)	***u*(X)**	***u*(<A'_p>)/<A'_p>**	
		60 kPa	**350 kPa**
Gravity acceleration change in 0.5 m	$1.6\cdot10^{-3}$ X	$1.6\cdot10^{-7}$	$1.6\cdot10^{-7}$
Height difference	0.37 mm	$4.0\cdot10^{-8}$	$4.1\cdot10^{-8}$
Temperature of LS	0.1 °C	$9.0\cdot10^{-7}$	$9.0\cdot10^{-7}$
Temperature of TS	0.1 °C	$9.0\cdot10^{-7}$	$9.0\cdot10^{-7}$
Thermal expansion coefficient of LS	$9\cdot10^{-7}$ K^{-1}	$1.3\cdot10^{-7}$	$1.1\cdot10^{-7}$
Thermal expansion coefficient of TS	$5\cdot10^{-7}$ K^{-1}	$5.5\cdot10^{-7}$	$5.5\cdot10^{-7}$
DPC reading	0.08 Pa	$1.3\cdot10^{-6}$	$2.3\cdot10^{-7}$
Standard deviation of DPC	0.26 Pa	$3.5\cdot10^{-6}$	$6.3\cdot10^{-7}$
Pressure distortion coefficient of LS	$1.5\cdot10^{-7}$ MPa^{-1}	$8.8\cdot10^{-9}$	$5.1\cdot10^{-8}$
Free volume in piston of LS	3 cm^3	$3.3\cdot10^{-7}$	$3.4\cdot10^{-7}$
Non-verticality of NPS	1 mm/m	$5.0\cdot10^{-7}$	$5.0\cdot10^{-7}$
Non-verticality of TS	1 mm/m	$5.0\cdot10^{-7}$	$5.0\cdot10^{-7}$
Const. mass parts (piston, etc.) on LS	7.5 mg	$1.3\cdot10^{-6}$	$2.1\cdot10^{-7}$
Const. mass parts (piston, etc.) on TS	3.8 mg	$6.3\cdot10^{-7}$	$1.1\cdot10^{-7}$
Density of const. mass parts on LS	54 kg/m^3	$2.7\cdot10^{-7}$	$4.5\cdot10^{-8}$
Density of const. mass parts on TS	51 kg/m^3	$1.5\cdot10^{-7}$	$2.6\cdot10^{-8}$
Additional mass (deadweights) on LS	max. 17 mg	$4.2\cdot10^{-7}$	$4.2\cdot10^{-7}$
Additional mass (deadweights) on TS	max. 28 mg	$6.9\cdot10^{-7}$	$7.9\cdot10^{-7}$
Density of additional mass on LS	25 kg/m^3	$3.2\cdot10^{-7}$	$4.4\cdot10^{-7}$
Density of additional mass on TS	20 kg/m^3	$3.2\cdot10^{-7}$	$4.0\cdot10^{-7}$
Effective area of LS	$1.7\cdot10^{-6}$ X	$1.7\cdot10^{-6}$	$1.7\cdot10^{-6}$
Type B relative uncertainty of <A'_p>		$\mathbf{4.7\cdot10^{-6}}$	$\mathbf{2.7\cdot10^{-6}}$
Type A relative uncertainty of <A'_p>		$\mathbf{8.0\cdot10^{-7}}$	$\mathbf{3.2\cdot10^{-7}}$
Combined relative uncertainty of <A'_p>		$\mathbf{4.8\cdot10^{-6}}$	$\mathbf{2.7\cdot10^{-6}}$

7. CONCLUSION

The relative difference of A'_p in this bilateral supplementary comparison varies from 1.7 ppm to 4.3 ppm, which corresponds to E_n = 0.12 to 0.26, respectively. Therefore, it confirms that the gas pressure standards maintained by the two institutes, NIMT and PTB, in the pressure range 60 kPa to 350 kPa in gauge mode are equivalent. The results of this bilateral supplementary comparison support the calibration and measurement capabilities (CMC) of NIMT in the pressure range 60 kPa to 350 kPa.

8. REFERENCES

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