COMPARISON IN GAS MEDIA (ABSOLUTE AND GAUGE MODE) IN THE RANGE FROM 25 kPa TO 200 kPa

EURAMET 1041 EURAMET.M.P-K8

COMPARISON FROM 25 kPa UP TO 200 kPa USING A PISTON CYLINDER AS TRANSFER STANDARD.

final report

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Abstract

It was decided at the EURAMET TC-M meeting in Torino in 2006 to realize a comparison in gauge and absolute pressure up to 200 kPa as it would allow establishing a link to the CCM.P-K6 and CCM.P-K2 comparisons. This project from the beginning interested a lot of laboratories with 23 participants, 22 of which have submitted results. The circulation of the transfer standard began on July 2009 and lasted until January 2012. No major problem occurred during the transport.

The mesurand of the comparison is the effective area of a piston-cylinder determined in gauge and absolute pressure from 25 kPa to 200 kPa with pressure steps of 25 kPa. The transfer standard is a gas lubricated tungsten carbide piston-cylinder with an effective area of ~9.8 cm^2, fabricated by DH Instruments and compatible with a PG-7601 pressure balance. Some participants used their own pressure balance while a pressure balance with a reference vacuum sensor has been circulated for the participants not equipped with this system.

One participant (SMU, Slovakia) has never provided the measurement results and another participant (FORCE Technology, Denmark) submitted a revised set of measurement results after the pilot laboratory mentioned that the equivalence was not met.

After the determination of the reference value, all the 22 participants who delivered the results in gauge pressure demonstrated equivalence respective to the reference value on most of the range. In absolute pressure the equivalence is demonstrated, for all nominal pressures, by all 17 participants who submitted results.

The comparison is linked to the CCM.P-K6 for gauge pressure and to CCM.P-K2 for absolute pressure. The link does not affect strongly the equivalence of the results and an excellent degree of equivalence is achieved in gauge and absolute pressure.

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1 Introduction

The calibration in the range 100 kPa, in absolute and gauge pressure is of great importance for the National Metrology Institutes because it covers many technical applications but also because this range of pressure is mostly used for the definition of all the pressure calibration chain in a laboratory.

This key comparison (KC) in the range 200 kPa was decided to be carried out at the EURAMET meeting in Torino in 2006. The motivation was the need for some EURAMET members, to provide basis for records in the Calibration and Measurement Capabilities database of the BIPM for their new equipment and, for some other participants, to improve their existing CMC. Following to MRA rules, this EURAMET KC had to be linked to the respective CCM KCs, CCM.P-K6 [1] and CCM.P-K2 [2], whose results were published few years ago.

Initially 16 laboratories decided to take part in the comparison followed then by KRISS (Republic of Korea) which is responsible for a similar comparison within APMP and intended, through participation in the present KC, to have a better link to the CCM comparisons mentioned above.

In March 2011, five more participants within EURAMET, decided to join the comparison, which had acquired new pressure standards or started activity in the pressure range of the comparison.

2 Participants

The list of the participants is given with the time of the measurement in table 1.

Table 1: List of the national metrology institutes which took part in the comparison, their contact persons, parts of the transfer standard used, time of their measurement, their traceability and availability of CMC in the comparison range.

NMI	Country	Responsible	Equipment	Date	Traceability	CMC
METAS	CH	Christian Wüthrich	PCU & Base	06.2009	primary	YES
LNE	FR	Pierre Otal	PCU	09.2009	primary	YES
PTB	DE	Wladimir Sabuga	PCU	10.2009	primary	YES
NSAI NML	EI	Paul Hetherington	PCU & Base	11.2009	PTB	YES
MIKES	FI	Markku Rantanen	PCU	12.2009	LNE	YES
VSL	NL	Inge van Andel	PCU	01.2010	primary	YES
NIS	EG	Alaaeldin A. Eltawil	PCU & Base	02.2010	primary	YES
INRIM	IT	Marina Sardi	PCU & Base	04.2010	primary	YES
UME	TR	Ilknur Kocas	PCU	05.2010	primary	YES
EIM	GR	Alexandros Lefkopoulos	PCU & Base	06.2010	PTB	YES
CMI	CZ	Dominik Prazak	PCU	07.2010	primary	YES
SMU	SK	Peter Faràr	PCU & Base	08.2010		YES
BEV	AT	Dietmar Steindl	PCU & Base	08.2010	PTB	YES
IMT	SI	Janez Setina	PCU & Base	09.2010	PTB	YES
LPM	HR	Lovorka Grgec-Bermanec	PCU & Base	10.2010	PTB	YES
IMBiH	BA	Sejla Alisic	PCU & Base	11.2010	PTB (IMT)	NO
CEM	ES	Ruiz Salustiano	PCU & Base	12.2010	primary	YES
KRISS	ROK	In-Mook Choi	PCU	04.2011	primary	YES
INM	RO	Ion Sandu	PCU & Base	08.2011	NPL	YES
Force Technology	DK	Aykurt Altintas	PCU & Base	09.2011	PTB	YES
IPQ	PT	Isabel Spohr	PCU & Base	10.2011	NPL	YES
MKEH	HU	Csilla Vámossy	PCU & Base	11.2011	Accr. Lab.	YES
MCCAA-SMI	MT	Nicola Testa	PCU & Base	12.2011	Accr. Lab.	NO

Among all the participants only SMU has not submitted results of the measurements. Most of the participants had already valid CMC for the range of the comparison, but two laboratories took the opportunity of the comparison to get recognition of their measurement capability.

2.1 Pilot laboratory: METAS

METAS is the national institute of metrology of Switzerland and has a primary definition of pressure through dimensional measurement of piston-cylinder, mass calibration and measurement of earth gravity acceleration. METAS took part in CCM.P-K2 and in CCM.P-K6, but unfortunately that participation was realized with a mercury manometer which is not in service anymore due to numerous failures of the electronics of the equipment.

As pilot of this comparison METAS characterized the piston-cylinder of the transfer standard (TS) by cross flotation but also by dimensional measurement to assess the stability of the effective area.

METAS performed the measurement by connecting the reference (DHI-PG7607) to the transfer standard (DHI-PG7601) with a membrane sensor as differential sensor (MKS Baratron 698A01TRA). This technique avoids making some assumption about the fall rate and avoids the difficult adjustment of the additional mass on the piston when working at absolute pressure. The differential sensor had been calibrated using a small absolute pressure and had been checked by observing the change of reading with known additional mass. A set of valves allows bypassing the differential sensor to adjust the pressure under the piston and adjust the position of the piston.

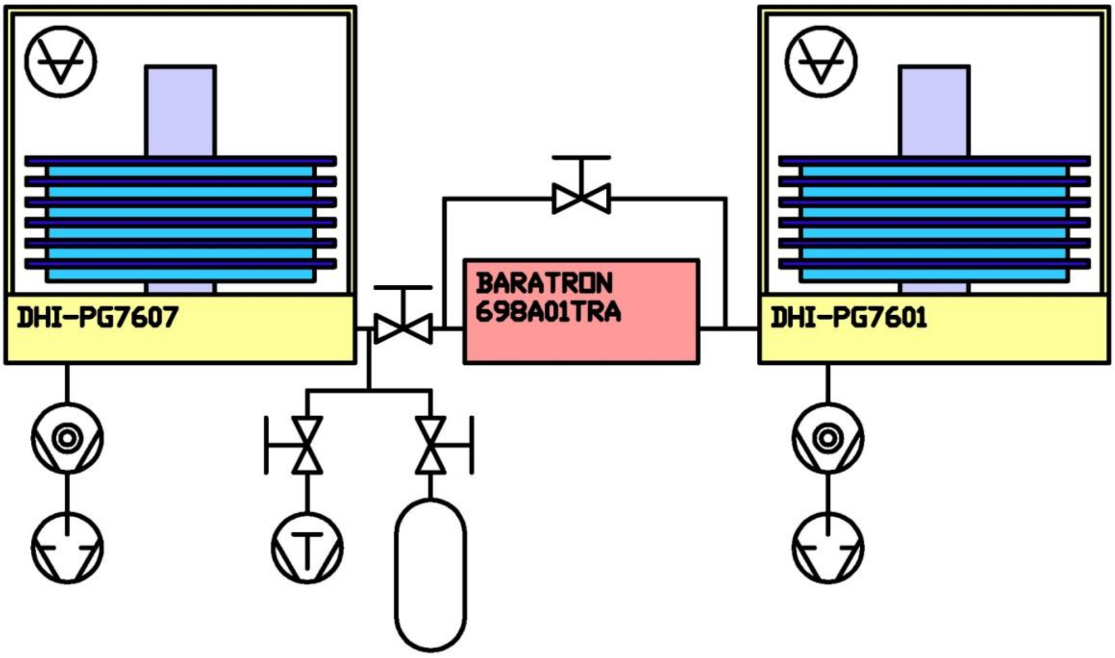

Figure 1: Schematic of the setup used by METAS for the determination of the effective area of the piston-cylinder.

The residual pressure above the piston of the reference pressure balance, in absolute mode, was measured using a membrane sensor (MKS Baratron 626A.1TDE). The pressure balance used for the transfer standard as well as the set of mass and the residual pressure sensor used by METAS have been circulated with the transfer standard.

2.2 Laboratories with link to CCM.P-K2 or CCM.P-K6

2.2.1 PTB

Two laboratory standards (LSs) were used in this KC as a reference – a primary mercury manometer for absolute and gauge pressure measurements (Hg manometer) and a primary pressure balance only for absolute pressure measurements.

2.2.1.1 PTB primary mercury manometer

The primary standard mercury manometer of PTB is basically a commercial dual cistern manometer manufactured by *Schwien Engineering*, Pomona, California, USA, around four decades ago. The instrument is operated in a specially designed enclosure protecting it from unavoidable fluctuations of the ambient temperature. The position of the mercury menisci in the cisterns, one of which is fixed and the other is movable, is detected with a capacitance system. In addition, the mercury manometer has been equipped with a laser interferometer to accurately measure the height position of the movable cistern. Hence, time-dependent, computer-controlled high-resolution measurements of the output signal of the capacitance sensing system allow exact adjustment of the position of the movable cistern whose height is exactly equal to the mercury column height.

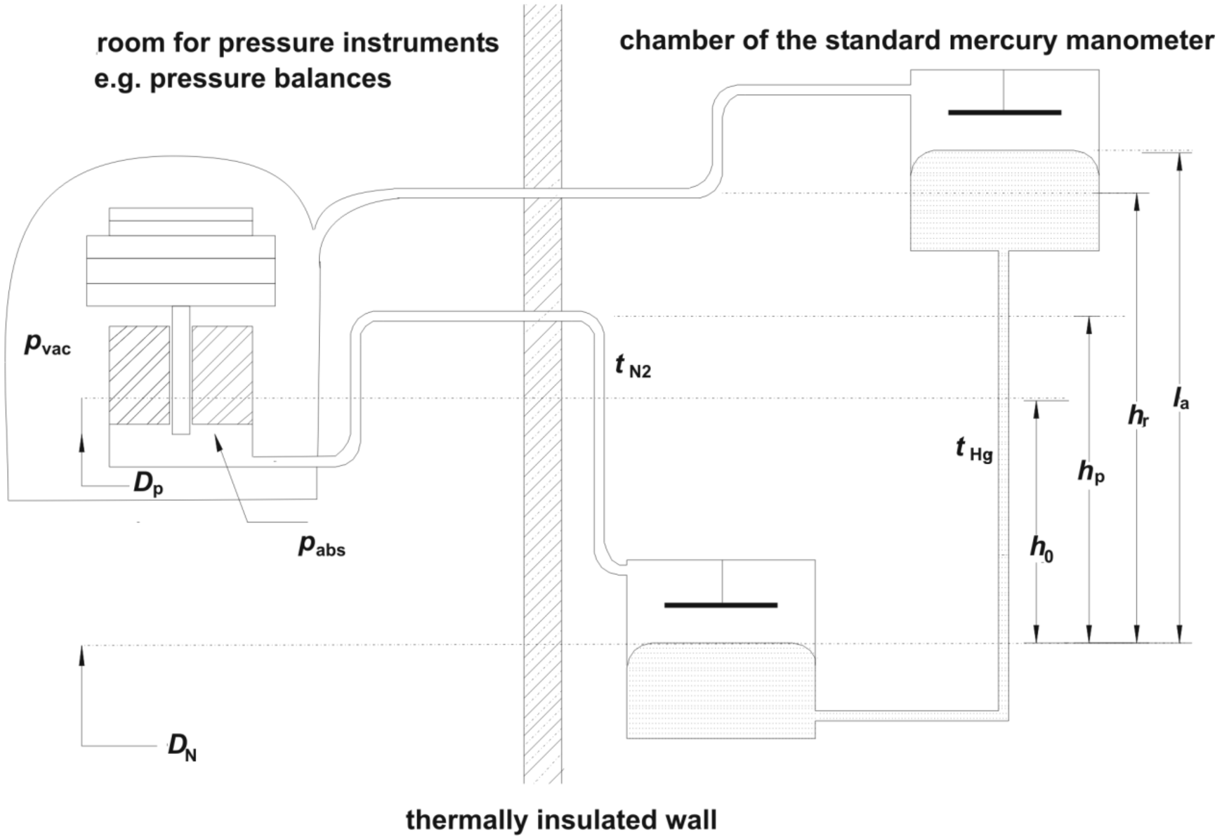

Figure 2: Schematic diagram of the experimental arrangement used to compare the standard mercury manometer and the pressure balance in absolute mode

2.2.1.2 PTB primary pressure balance

The primary pressure balance and piston cylinder assembly 1159 are part of the project of the definition of the Boltzmann constant [3, 4]. The piston cylinder assembly 1159 is of a cylinder-floating configuration and has a nominal effective area of 20 cm^2.

The zero-pressure effective area (A_0) of this assembly is based on dimensional and cross-float measurements performed on this and 4 further primary piston cylinder assemblies of 20 cm^2 and 2 cm^2 effective areas. The pressure distortion coefficient (λ) with the associated uncertainty was determined by finite element method using the approach used previously for oil lubricated piston-cylinders, and the elastic constants of the piston cylinder assembly materials were measured experimentally by the resonant ultrasound spectroscopy.

The pressure balance is equipped with an automated mass handling system (AMH) allowing loading the floating cylinder without breaking the vacuum in the bell jar. The smallest adjustable mass of the AMH is 100 g. The rest pressure difference between TS and LS was measured using an MKS Baratron differential pressure cell (DPC) type 698A11TRC serial no. 016390809 calibrated with an uncertainty smaller than 0.1 Pa.

The measurements were performed in absolute mode only.

2.2.2 INRIM

2.2.2.1 Mercury manometer

The primary mercury manometer of INRIM, used in the present comparison in absolute mode, is designated HG5 and works in a range from 1 kPa up to 120 kPa. It consists of two 60-mm bore, 1-m long glass tubes forming the U-tube, placed in a temperature-controlled water bath and filled with mercury. Two platinum resistance thermometers are installed coaxially at the base of the columns. The measurement of the vertical displacement of the mercury menisci is made by a He-Ne single-beam interferometer and cube corner reflectors mounted on very lightweight floats.

2.2.2.2 Pressure balance

The INRIM primary standard used in the comparison in relative mode is a Ruska (Model 2465) pressure-balance with piston-cylinder assembly TL-391 in tungsten carbide. The effective area, with a nominal value of 335.7 mm^2, is derived from dimensional measurements which are fully reported in the literature of the laboratory.

The primary standard was used in the pressure range from 25 kPa to 150 kPa and it was mounted on a Ruska base type 2465, fully equipped with weight set, temperature probe and appropriate instrumentations for measuring piston height level and fall rate.

2.2.3 VSL

VSL uses a PG-7601 with a 10 cm^2 piston-cylinder unit as reference standard. All the traceability is made by VSL for the mass and the effective area of the piston cylinder unit. The used effective area of the used piston (10 kg/kPa) was determined by dimensional calibration based upon measurements by VSL's Length department.

The PG bases needed for the measurement were unfortunately both borrowed, one is the base circulated with the transfer standard and the other was from DH instruments supplier Minerva as the drive mechanism of our pressure balance broke just before the measurement.

2.3 Laboratories with a primary definition

2.3.1 LNE

2.3.1.1 Reference standard

LNE primary pressure standard is the absolute pressure balance ***APX 50*** developed in cooperation with DH-Budenberg [5, 6] equipped with a 50 mm diameter piston-cylinder unit manufactured by DH Instruments. The main technical data of the pressure standard are listed in table 2.

Table 2: Characteristics of the LNE piston-cylinder standard.

Characteristics	LNE pressure standard
Measurement range in kPa	10 - 500
Material of piston	tungsten carbide
Material of cylinder	tungsten carbide
A_0, effective area at null pressure and reference temperature in mm^2	1961,0637
Relative standard uncertainty of A_0, in 10^{-6}	2,8
Pressure distortion coefficient λ in MPa^{-1}	7,15 x 10^{-6}
ρ_M, density of the weights in kg·m^{-3}	8000
Relative standard uncertainty of weight mass, in 10^{-6}	0,75
α_p and α_c, linear thermal expansion coefficients of the piston and the cylinder in °C^{-1}	4,5 x 10^{-6}
t_0, reference temperature in °C	20

Diameters, straightness and circularity measurements have been performed in the Length Laboratory of LNE. The standard uncertainties were 0.04 µm, 0.05 µm and 0.025 µm respectively for the 3 types of measurements. All the measurements were combined using the method used to perform the calculation in the EUROMET Project N° 740. The standard uncertainty of the effective area was estimated to be **2.8 x 10^{-6} x A_0**. Circular comparisons were also carried out with other piston-cylinder units of 35 mm diameters whose effective areas had been determined over the time using different methods [7]. The relative coherencies in the effective areas were within 2 x 10^{-6}.

The value of the pressure distortion coefficient λ has been calculated at LNE using the Lamé equation. The value of the linear thermal expansion coefficient of tungsten carbide α has been measured several times at LNE, by placing a pressure balance in a climatic chamber. This value has been confirmed by dimensional measurement on samples of the material made at NPL at the time of the CIPM comparison in the 20 - 100 MPa range [8].

The uncertainty budget for the LNE pressure standard operating in the range from 10 kPa to 500 kPa is detailed in [9, 10]. The standard uncertainty of the reference pressure was estimated to be:

$u(p') = 0.05 \text{ Pa} + 3.5\ 10^{-6}.p'$ in gauge mode

$u(p') = 0.10 \text{ Pa} + 3.5\ 10^{-6}.p'$ in absolute mode

2.3.1.2 Comparison procedure

The transfer standard assembly was mounted in the DH Instruments PG7601 pressure balance s/n 364 equipped with an automated mass handling system (AMH) with weight set s/n 2234.

In absolute mode, thanks to the automated mass handling system, the vacuum in the bell jar was never broken during the calibration. The reference pressure was measured by a 1 torr capacitance manometer MKS type 690A. The reference pressure was ranging from 0.3 Pa to 0.7 Pa.

In absolute mode, the temperature of the P/C assembly varied from 24°C to 25°C, and from 21°C to 22°C in gauge mode.

In both modes, the pressure difference between the standards was measured using a capacitance diaphragm gauge. The pressure difference measured was typically less than 1 Pa. An uncertainty of 0.5% for this pressure difference, which is certainly pessimistic, generates insignificant pressure measurement uncertainty.

For each pressure point, both standards were in equilibrium when the valve between the ports of the capacitance diaphragm gauge was closed.

The data acquired are:

- piston-cylinders temperature
- residual reference pressure (in absolute mode)
- position of the piston
- environmental conditions
- data from the differential transducer

The reference pressure was calculated at the reference level of the transfer standard.

2.3.2 NIS

2.3.2.1 Piston and cylinder

The primary standard piston cylinder assembly was measured dimensionally at PTB where the piston and cylinder diameters, straightness and roundness were measured using PTB state of the art comparators.

PTB certificates Reference No. 5.31 – 05-4019764 contains all the data used to generate the effective area of the primary piston cylinder assembly. Full description of the characterization has been published in the “PTB Mitteilungen” [11]

2.3.2.2 Mass measurements

Results of measurement are traceable to the SI system of units. NIS maintains a traceability chain for the standards used to the National Primary Standard Kilogram Pt–Ir No.58 calibrated at BIPM certificate No. 1, 2011.

2.3.3 CMI

CMI used its primary standard DHI PG 7601 for the comparison. It was equipped with 10 cm^2 piston-cylinder from DHI (serial number 248) with ceramic piston and tungsten-carbide cylinder.[12, 13, 14].

2.3.4 CEM

2.3.4.1 Gauge mode

We have used as reference standards two 0.01 MPa/kg DH piston - cylinder assemblies, which are traceable to our primary mercury column. These piston cylinder standards work in a Desgranges & Huot DH 5111 pressure balance. The results have been obtained by means of two measurement series with one of the piston cylinder assemblies and three measurement series with the other one. The calibration has been performed by cross-floating.

2.3.4.2 Absolute mode

We have used as reference standard a 0.01 MPa/kg piston cylinder assembly from DH Instruments, which is traceable to our primary mercury column. This piston cylinder assembly works in a DHi PG7601 pressure balance. This pressure balance has been modified to connect a CDG 690A01TRA, 1 Torr F.S., in order to measure the residual pressure. The calibration has been carried out using a differential CDG, 1 Torr F.S. MKS

690A11TRA, connected between both pressure balances to determine the residual pressure difference between them.

2.3.5 KRISS

KRISS has as reference standard a PG-7601 from DHI equipped with a piston cylinder unit of 9.8 cm^2. The traceability is internal to KRISS through dimensional measurement of the piston-cylinder and the characterisation of the mass. The residual pressure above the piston in absolute mode is measured using a membrane gauge from MKS Baratron with a full range of 13.3 Pa.

In spite of its primary definition; KRISS has not been included in the definition of the reference value of this comparison.

2.4 Laboratories with secondary definition

2.4.1 NSAI

The reference system of NSAI is a Ruska 2465 pressure balance with a number of piston-cylinder assemblies up to a range of 7MPa. Our standard’s effective area and uncertainty are taken from a PTB certificate. Oxygen-free nitrogen was used as the pressure medium.

2.4.2 MIKES

The reference standard used by MIKES is a DHI pressure balance PG-7607 (No 397) with a piston cylinder unit (No 451) from DHI. The effective area (about 19.6 cm^2) of the PCU is traceable to LNE. The transfer standard was installed in the base DHI PG-7601 (No 149). In absolute mode, the pressure difference was adjusted near zero by using small adjustment masses and measured with a CDG, type MKS Baratron 698A. The residual pressures were measured with vacuum gauges. In gauge mode, the traditional cross floating method was used.

2.4.3 EIM

EIM used as reference standard a pressure balance manufactured by RUSKA, model 2465-754, with a piston cylinder assembly, model 2465-725, made of stainless steel.

The traceability of EIM measurements to SI units is ensured through the German national standards (effective area) and Greek national standards (mass).

2.4.4 BEV

The measurements have been performed with a base PG-7601 from DHI for absolute measurement and a base PG-7102 for the measurement in gauge mode. Two piston-cylinder assemblies from DHI with an effective area of 9.8 cm^2 have been used.

The traceability of the effective area of the reference piston is made through the PTB while the mass have been calibrated by BEV. The residual pressure when working in absolute pressure is measured by a membrane sensor (CMR 364 from Pfeiffer)

2.4.5 IMT

The reference standard used by IMT is a PG-7601 pressure balance and the piston is made of ceramics while the cylinder is made of tungsten carbide, with an effective area of 9.8 cm^2. The effective area of the reference piston has been determined by PTB.

2.4.6 LPM

The reference standard is a DHI pressure balance equipped with a piston-cylinder made of tungsten carbide with an effective area of 9.80503 cm^2. The traceability is made through the PTB (Calibration certificate PTB 30006/12)

2.4.7 IMBiH

2.4.7.1 Reference standard

The determination of effective area of the METAS transfer standard has been performed by reference standard of Institute of metrology of Bosnia and Herzegovina, which is similar to the transfer standard. The characteristics of the reference standard are summarised in the following table 2

Table 3: Characteristics of the reference standard used by IMBiH.

Piston Cylinder Assembly 10kPa/kg	
Manufacturer:	DHI Instruments
Effective area A_o:	$9.8051286 \cdot 10^{-4}$ (m^2)
Expansion coefficient (αp+αc):	$9.00 \cdot 10^{-6}$ (K^{-1})
True mass:	0.40000503 (kg)
Density:	9363 (kg/m^3)
IMBiH inventory number	1865
Base	
Type:	PG 7601
Serial number	707
IMBiH inventory number	1863
Mass set 100(g) - 5(kg)	
Serial number	2532
IMBiH inventory number	1866

2.4.7.2 Calibration procedure

The transfer standard has been measured through a differential sensor. The ambient conditions (temperature, pressure and humidity) have been recorded during calibration.

2.4.7.3 Traceability

The piston - cylinder assembly 10 kPa/kg used is traceable to the standard of Laboratory for Pressure Metrology of the Institute of Metal and Technology Ljubljana, Slovenia. The traceability of set of free nominal masses weights is ensured by calibration in the Institute of Metrology of Bosnia and Herzegovina using reference measurement standards traceable to the international kilogram prototype kept at BIPM throughout national measurement standards for mass of Republic Slovenia kept at MIRS.

2.4.8 INM

The reference standard used by INM is a Ruska piston gauge, type 2465, up to 175 kPa. The traceability of effective area (3.36 cm2) is made through the NPL (Calibration Certificate 0478/07). The traceability of masses weight set is ensured by calibration in the INM, using reference measurement standards traceable to national kilogram prototype Nr. 2, periodically calibrated at BIPM.

2.4.9 FORCE Technology

The pressure balance used by FORCE Technology is a Budenberg with s/n 27245 and piston/cylinder assembly type 550 with s/n H425. The effective area, nominal 322 mm^2, and the weight set are traceable to PTB, Germany. The latest calibration was carried out in June 2011 (Certificate PTB 30260/11).

The measurements have been performed only in gauge mode.

2.4.10 IPQ

The reference standard is a Ruska 2465 pressure balance. The effective area of the piston cylinder assembly has been determined by the NPL and the mass have been calibrated by the mass laboratory of IPQ.

The measurements have been performed in gauge mode only.

2.4.11 MKEH

2.4.11.1 Reference standard in gauge mode

The reference standard, used for the comparison in gauge mode, was a Ruska 2465-725 piston-cylinder assembly with the nominal area 3.4 cm^2 (s/n: TL1703). The measuring range of the piston is (1.4...172) kPa. The piston was manufactured in 2010 and its calibration was performed by the GE Sensing (Houston). The calibration report includes the effective area A_0 (p=0 bar, t=23 °C) and the reported elastic distortion coefficient λ=0. The measurement results are traceable to the reference standards of the NIST. The piston/cylinder material is 440C Stainless Steel/Tungsten Carbide.

The base platform and the mass set were manufactured in 1998. The type of the base platform: 2465-753 (without rotating motor and bell jar). The type of the mass set: 2465-799 (s/n: 51410). The analytical weight set, used for balancing, was made by Troemner (USA) (s/n: 14440). All loading masses were measured and certified by the Mass Laboratory of MKEH.

The expanded uncertainty (k=2) of the pressure measurement is:
$U(p)$ = (0.22 Pa + 2.1· 10^{-5} p)

2.4.11.2 Reference standard in absolute mode

The reference standard, used for the comparison in absolute mode, was a DPG8-A02B Absolute Digital Piston Gauge assembly manufactured by DH-Budenberg. The measuring range of the instrument is (0...160) kPa. The nominal conversion coefficient of the piston-cylinder (s/n: 8830) is K_n =20 kPa/kg (nominal area 4.9 cm^2) and the maximum load of the built-in PR5002 Mettler Toledo electronic dynamometer (s/n: 8793) is 8 kg. The instrument was calibrated by the DH-Budenberg SA Cofrac accredited laboratory insured the traceability to the national standards of the BIPM. The K_n value (p=0 bar, t=20°C) was given in its calibration certificate. A pressure distortion coefficient of the P/C assembly is not reported (λ=0). For the calibration of the dynamometer we used a set of external standard masses manufactured and calibrated by DH-Budenberg. The DPG8 is equipped with an automatic pressure calculation system (software version: 3.25).

The expanded uncertainty (k=2) of the pressure measurement is: $U(p)$=(2.1 Pa+ 4.1·$10^{-5}$$p$)

2.4.11.3 Measurement in gauge pressure.

The measurements have been performed in the range 25 kPa to 175 kPa. To obtain the cross-float equilibrium, we always adjusted the masses by adding small analytical weights loaded on the transfer standard.

We used the fall rate method to control the equilibrium between the standards. The WinPrompt software has been used to control the piston position and piston fall rate of our Ruska 2465 reference standard. The determination of the temperature of the P/C assembly of our reference standard was carried out by a calibrated Pt100 thermosensors.

2.4.11.4 Measurement in absolute mode.

The measurements have been made in the range 25 kPa to 150 kPa. We used the base loads provided on the transfer standard according to the protocol and no additional loading weights were used.

The indication of the PG Terminal has been used to control the piston position of the transfer standard. A Varian SD91 oil seal rotary vane pump has been used to pump down under the PG-7601 bell jar.

The offset correction of the vacuum sensor (Pfeiffer TPG 261) has not been checked because we are unable to keep the required high vacuum for 12 hours. We read the parameters of the vacuum sensor as follow:

Filter: Slow
Cal: 0.987
Fsr: 1 mbar
OFS: 0E-3 Pa

2.4.11.5 General comments

Before the measurement we checked the deceleration of the rotation of the piston with a disc of 1 kg. As it took more than 85 seconds to decrease from 70 rpm to 40 rpm, no cleaning has been made. The fall rate at 200 kPa pressure was 0.08 mm/min.

2.4.12 MCCAA-SMI

The reference standard used was a DHI PG-7601 identical to the unit circulated. The piston and cylinder are of tungsten carbide with a nominal area of 980 mm^2. The residual pressure above the piston, in absolute mode, was measured with a vacuum sensor MKS 626A.1TDE. The traceability of all the main factors (mass, effective area, density) is made through the certificates delivered by the accredited laboratory Fluke DHI.

3 Transfer standard

The transfer standard that has been used consisted of a piston-cylinder unit manufactured by DH instruments and could be fitted on the base PG-7601 or PG-7101 produced by the same company. The piston-cylinder was made of tungsten carbide in order to achieve a good dimensional stability and a strong resistance to scratches.

Table 4: Characteristics of the piston-cylinder unit circulated.

Transfer Standard	Piston Cylinder
METAS inventory number	005712
Type	PC-7100/7600-10 TC
DH Instruments Part Number	401562
Serial Number	716
Nominal area	10 cm^2
True Mass	500.0030 g (u=0.8 mg)
Density	10080 kg/m^3(u=100 kg/m^3)
Fall rate at 200 hPa	< 0.15 mm/min
Deceleration from 70 rpm to 40 rpm with 1 kg disc	> 30 seconds
Pressure reference level respective to the low piston face	32.5 mm

A base PG-7601 produced by DHI equipped with a vacuum sensor and a set of mass has been circulated as well for the laboratories that did not have a PG-7601 to accommodate the piston-cylinder unit. The glass bell-jar of the system had been replaced by a steel bell-jar in order to avoid any damage during the transport or the manipulation.

The external vacuum sensor was based on ceramic membranes and it was possible to isolate it from atmospheric pressure thank to a valve. The vacuum sensor was chosen for its stability in time and its ability to remain calibrated after exposure to atmospheric pressure.

3.1 Properties of the transfer standard

Certificates have been provided by the pilot laboratory for the set of mass, the value of the mass of the piston, the value of the mass of the mass carrying bell and the response of the pressure sensor.

Table 5: Characteristics of the base circulated.

Base	
Type	DH-Instruments PG-7601
Part Number	400480-CE
Serial Number	328
METAS inventory number	005277
Vacuum Sensor	
Typ	Pfeiffer CMR 264
Serial Number	44240482
METAS inventory number	006246
Display	Pfeiffer TPG261
Serial Number	44242121
METAS inventory number	006245
Mass carrying bell	
Serial Number	754
True Mass	0.2999997 kg
Density	5013 kg/m^3
METAS inventory number	007265
Mass set	
Serial number	2159
Density	7975 kg/m^3
METAS inventory number	005275

Three weeks have been allocated to each participating laboratory for the measurement and one week was planned for the transport of the artefact. At some time in March 2010 the transfer standard was returned to METAS, mostly to renew the A.T.A. carnet. Unfortunately it was not possible at that time to make further measurement as the time allocated for it was used to compensate for accumulated delay. The base including the set of mass and the vacuum sensor has been circulated separately from the piston-cylinder as not all participants needed the base. There was no major incident during the circulation and all the participants had the opportunity to take part in the comparison according to the schedule. The equipment returned to METAS in December 2011 in good condition.

4 Measurement instructions

The measurement technique was precisely described in the protocol like the criterions that would need a new cleaning of the piston, and the fall rate that had to be achieved in a system leak tight.

4.1 Measurement points

The measurements had to be made from 25 kPa up to 200 kPa with steps of 25 kPa (8 steps), upward and downward. The measurements had to be repeated five times in gauge pressure and five times in absolute pressure for a total of 80 measurements in each mode.

The results have been collected by the pilot laboratory during the time of the comparison. A worksheet was provided for the collection of the results to facilitate the integration in the calculation of the reference value.

4.2 Calculation of the effective area in gauge pressure

The effective area is derived from the standard formula used to calculate the pressure measured by a gas-operated pressure balance at its reference level [16]:

$$p_e = \frac{\sum_i \left[m_i g (1 - \rho_a / \rho_{mi}) \right]}{A_p \left[1 + (\alpha_p + \alpha_c)(t - 20) \right]} \tag{1}$$

By reversing the formula and using the pressure measured by the laboratory standard at the reference level of the transfer standard, the effective area at a given pressure is given by:

$$A_p = \frac{\sum_i \left[m_i g (1 - \rho_a / \rho_{mi}) \right]}{p_e \left[1 + (\alpha_p + \alpha_c)(t - 20) \right]} \tag{2}$$

4.3 Calculation of the effective area in absolute pressure

The traditional formula for the piston manometer modified to take into account the residual pressure in the bell jar was used in absolute pressure:

$$p_{abs} = \frac{\sum_i \left[m_i g \right]}{A_p \left[1 + (\alpha_p + \alpha_c)(t - 20) \right]} + p_{vac} \tag{3}$$

The formula can be reversed to obtain the effective area at a given pressure:

$$A_p = \frac{\sum_i \left[m_i g \right]}{(p_{abs} - p_{vac}) \left[1 + (\alpha_p + \alpha_c)(t - 20) \right]} \tag{4}$$

5 Stability of the transfer standard

The transfer standard has been chosen for the well-known long term stability of a piston-cylinder made of tungsten carbide. Plastic deformation is not an issue while change of shape due to abrasion should be minimal.

In Table 6 the parameters of the piston-cylinder unit are shown, before and after the circulation. The effective area has been determined using a Dadson model [15] based on dimensional measurement performed at METAS.

The change of effective area is smaller than the uncertainty of this method and also much smaller than the uncertainty claimed by the participants of the comparison. The change of mass is 10 ppm relative to the total mass of the piston but is only 2 ppm respective to the mass used for the 25 kPa nominal pressure and much smaller for the other nominal pressures.

Table 6: Mass and dimensional parameters of the transfer standard before and after the circulation.

	True mass		**Effective area**		
Year	**value**	**Uncertainty (*k*=2)**	**gauge pressure**	**absolute pressure**	**Uncertainty (*k*=2)**
2007	500.00112 g	0.0008 g	980.5310 mm^2	980.5330 mm^2	0.0060 mm^2
2013	499.99639 g	0.0005 g	980.5312 mm^2	980.5349 mm^2	0.0060 mm^2

6 Calculation of the reference value and degree of equivalence

We used the weighted mean technique or procedure A as described by Cox [17].

6.1 Reference value

The reference value has been calculated based on the measurement of the participants having a primary definition of the pressure. We did not include the participants not member or associated to EURAMET (KRISS)

For each pressure step we have calculated the weighted mean of the effective area measurements by the participants with a primary definition:

$$A_i(EUR) = \frac{\sum_{j=1}^{m} \frac{A_{i,j}}{U^2(A_{i,j})}}{\sum_{j=1}^{m} \frac{1}{U^2(A_{i,j})}} \qquad (5)$$

Where:

$A_i(EUR)$	is the reference area A_p for the comparison for pressure step i
i	designates the index of the pressure step
j	designates the index of the participating laboratories
$A_{i,j}$	is the effective area A_p measured by participant j for pressure step i
$U^2(A_{i,j})$	is the expanded (k=2) uncertainty associated to the effective area

The expanded uncertainty (k=2) of the reference value is given by:

$$U\big(A_i(EUR)\big) = \sqrt{\frac{1}{\sum_{j=1}^{m} \frac{1}{U^2(A_{i,j})}}} \qquad (6)$$

The consistency of the determination of the reference value has been made using the chi squared test as described by Cox in [17].

6.2 Degree of equivalence

We are interested, in order to assess the equivalence of the measurements, to the difference respective to the reference value.

$$d_{i,j} = A_{i,j} - A_i(EUR) \qquad (7)$$

the uncertainty of $d_{i,j}$, for a laboratory contributing to the reference value, is given by:

$$U(d_{i,j}) = \sqrt{\Big(U(A_{i,j})\Big)^2 - \Big(U\big(A_i(EUR)\big)\Big)^2} \qquad (8)$$

while for a laboratory not contributing to the reference value it is given by :

$$U(d_{i,j}) = \sqrt{\Big(U(A_{i,j})\Big)^2 + \Big(U\big(A_i(EUR)\big)\Big)^2} \qquad (9)$$

7 Results of the participants

7.1 Results in gauge pressure

The results in gauge pressure include the 22 participants who provided results.

Table 7: Effective area of the transfer standard and expanded uncertainty provided by the participants for gauge pressure.

	METAS		LNE		PTB		NSAI		MIKES		VSL	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5325	0.0186	980.5294	0.0140	980.5447	0.0124	980.5376	0.0693	980.5313	0.0167	980.5444	0.0294
50	980.5340	0.0137	980.5278	0.0114	980.5417	0.0104	980.5347	0.0327	980.5273	0.0147	980.5395	0.0294
75	980.5348	0.0121	980.5281	0.0103	980.5408	0.0106	980.5443	0.0242	980.5277	0.0141	980.5395	0.0294
100	980.5351	0.0113	980.5294	0.0098	980.5405	0.0094	980.5466	0.0217	980.5290	0.0137	980.5386	0.0294
125	980.5356	0.0108	980.5294	0.0096	980.5402	0.0090	980.5466	0.0229	980.5284	0.0135	980.5384	0.0294
150	980.5358	0.0105	980.5303	0.0096	980.5392	0.0080	980.5479	0.0245	980.5280	0.0134	980.5388	0.0294
175	980.5358	0.0102	980.5301	0.0093	980.5385	0.0071	980.5546	0.0227	980.5276	0.0133	980.5392	0.0294
200	980.5357	0.0101	980.5311	0.0092			980.5531	0.0219	980.5278	0.0133	980.5413	0.0294

	NIS		INRIM		UME		EIM		CMI		BEV	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5253	0.0198	980.5330	0.0239	980.5310	0.0103	980.5320	0.0220	980.5371	0.0157	980.5238	0.0300
50	980.5255	0.0198	980.5302	0.0190	980.5311	0.0105	980.5288	0.0210	980.5323	0.0137	980.5265	0.0250
75	980.5244	0.0199	980.5306	0.0168	980.5312	0.0103	980.5277	0.0200	980.5322	0.0118	980.5285	0.0240
100	980.5253	0.0198	980.5307	0.0158	980.5313	0.0095	980.5273	0.0200	980.5324	0.0108	980.5290	0.0240
125	980.5242	0.0198	980.5302	0.0158	980.5314	0.0092	980.5282	0.0200	980.5314	0.0108	980.5292	0.0240
150	980.5250	0.0198	980.5301	0.0158	980.5314	0.0094	980.5272	0.0200	980.5318	0.0108	980.5298	0.0240
175	980.5249	0.0198			980.5315	0.0097	980.5265	0.0200	980.5315	0.0108	980.5304	0.0240
200	980.5250	0.0198			980.5316	0.0100	980.5255	0.0210	980.5317	0.0108	980.5303	0.0240

	IMT		LPM		IMBiH		CEM		KRISS		INM	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5330	0.0094	980.5400	0.0278	980.5345	0.0387	980.5122	0.0290	980.5323	0.0180	980.5290	0.0252
50	980.5320	0.0075	980.5404	0.0280	980.5345	0.0380	980.5235	0.0290	980.5329	0.0180	980.5289	0.0252
75	980.5317	0.0068	980.5389	0.0279	980.5326	0.0385	980.5242	0.0160	980.5328	0.0180	980.5309	0.0252
100	980.5320	0.0065	980.5365	0.0280	980.5331	0.0392	980.5276	0.0170	980.5331	0.0180	980.5318	0.0253
125	980.5325	0.0063	980.5339	0.0271	980.5322	0.0403	980.5284	0.0170	980.5336	0.0180	980.5316	0.0252
150	980.5326	0.0062	980.5333	0.0270	980.5321	0.0416	980.5305	0.0170	980.5331	0.0180	980.5322	0.0252
175	980.5327	0.0061	980.5334	0.0269	980.5326	0.0431	980.5331	0.0170	980.5334	0.0180	980.5324	0.0252
200	980.5329	0.0060	980.5334	0.0268	980.5330	0.0448	980.5328	0.0160	980.5334	0.0180		

	Force Tech.		IPQ		MKEH		MSA	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5026	0.0784	980.5504	0.0271	980.5136	0.0224	980.5353	0.0160
50	980.4858	0.0490	980.5459	0.0271	980.5111	0.0212	980.5336	0.0110
75	980.4877	0.0490	980.5461	0.0270	980.5131	0.0210	980.5336	0.0100
100	980.4842	0.0490	980.5449	0.0270	980.5139	0.0210	980.5339	0.0092
125	980.4845	0.0490	980.5454	0.0271	980.5148	0.0208	980.5314	0.0086
150	980.4843	0.0490	980.5451	0.0271	980.5143	0.0208	980.5331	0.0083
175	980.4785	0.0490	980.5448	0.0271	980.5147	0.0208	980.5312	0.0081
200	980.4860	0.0490	980.5440	0.0271	0.0000	0.0000	980.5305	0.0077

7.2 Results in absolute pressure

A limited set of participants had the opportunity to measure in absolute pressure and sometime not on all the range of the comparison. It has to be mentioned that PTB took part with two reference standards, one mercury manometer which took part in the CCM.P-K2 project and a pressure balance with a piston of 20 cm^2 which is intended to the Boltzmann constant project for the new definition of the temperature scale [3, 4]. The pressure balance of the PTB has been included for the definition of the reference value but the mercury manometer is used only to establish the link to CCM.P-K2.

Table 8: Effective area of the transfer standard and expanded uncertainty provided by the participants for absolute pressure.

	METAS		LNE		PTB Hg mano.		MIKES		VSL		NIS	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5281	0.0206	980.5306	0.0175	980.5381	0.0096	980.5279	0.0245	980.5364	0.0294	980.5304	0.0201
50	980.5312	0.0147	980.5311	0.0127	980.5377	0.0090	980.5286	0.0186	980.5348	0.0294	980.5308	0.0199
75	980.5328	0.0127	980.5310	0.0112	980.5374	0.0092	980.5262	0.0167	980.5337	0.0294	980.5309	0.0198
100	980.5335	0.0118	980.5312	0.0105	980.5380	0.0086	980.5257	0.0157	980.5334	0.0294	980.5304	0.0199
125	980.5342	0.0112	980.5324	0.0103	980.5379	0.0080	980.5251	0.0151	980.5324	0.0294	980.5308	0.0199
150	980.5348	0.0108	980.5311	0.0098	980.5372	0.0073	980.5248	0.0147	980.5329	0.0294	980.5302	0.0199
175	980.5351	0.0105	980.5309	0.0096	980.5364	0.0067	980.5247	0.0144	980.5326	0.0294	980.5302	0.0198
200	980.5354	0.0103	980.5310	0.0094			980.5241	0.0143	980.5336	0.0294	980.5306	0.0199

	INRIM		UME		CMI		BEV		IMT		LPM	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5336	0.0192	980.5301	0.0103	980.5322	0.0226	980.5447	0.0410	980.5311	0.0128	980.5412	0.0458
50	980.5307	0.0125	980.5305	0.0105	980.5337	0.0167	980.5400	0.0360	980.5310	0.0099	980.5430	0.0462
75	980.5294	0.0094	980.5312	0.0103	980.5349	0.0147	980.5421	0.0340	980.5314	0.0089	980.5427	0.0449
100	980.5306	0.0090	980.5317	0.0095	980.5346	0.0137	980.5394	0.0330	980.5308	0.0084	980.5410	0.0453
125			980.5317	0.0092	980.5344	0.0127	980.5387	0.0330	980.5312	0.0081	980.5390	0.0447
150			980.5320	0.0094	980.5336	0.0127	980.5371	0.0330	980.5314	0.0079	980.5384	0.0441
175			980.5321	0.0097	980.5333	0.0127	980.5407	0.0330	980.5316	0.0078	980.5389	0.0438
200			980.5322	0.0100	980.5331	0.0127	980.5379	0.0330	980.5318	0.0077	980.5386	0.0440

	IMBiH		CEM		KRISS		MKEH		MSA		PTB press. Bal.	
P	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$	A_i	$U(A_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5360	0.0396	980.5357	0.0240	980.5327	0.0180	980.5661	0.1220	980.5339	0.0260		
50	980.5342	0.0390	980.5310	0.0200	980.5327	0.0180	980.5699	0.0804	980.5298	0.0150		
75	980.5326	0.0374	980.5292	0.0180	980.5330	0.0180	980.5692	0.0668	980.5319	0.0120	980.5281	0.0049
100	980.5326	0.0373	980.5201	0.0180	980.5334	0.0180	980.5656	0.0602	980.5328	0.0110	980.5283	0.0045
125	980.5320	0.0372	980.5190	0.0180	980.5337	0.0180	980.5632	0.0562	980.5307	0.0097	980.5284	0.0043
150	980.5324	0.0372	980.5223	0.0180	980.5338	0.0180	980.5465	0.0536	980.5318	0.0091	980.5287	0.0039
175	980.5322	0.0372	980.5199	0.0170	980.5335	0.0180			980.5312	0.0085	980.5291	0.0037
200	980.5322	0.0372	980.5204	0.0170	980.5338	0.0180			980.5306	0.0081	980.5293	0.0035

8 Reference value and consistency check

8.1 Reference value for gauge pressure

The reference value of the effective area in gauge pressure is displayed in table 9. The reference value is determined by using a weighted mean between all the participants having a primary definition of the pressure as expressed in Eq.5. The participants contributing to the reference value are: METAS, LNE, PTB, VSL, NIS, INRIM, CMI and CEM. The number of contributors to the reference value at different pressure steps, as shown in column 2 of table 9, is not always the same because some contributors did not provide measurement at all the pressure steps.

The change of the effective area with pressure is very small as expected. It has to be mentioned that the uncertainty of the reference value is less than one third of the best uncertainty found within the participants.

The observed chi-squared is always at least half the value of the maximum chi-squared calculated for a probability of 5% according to the number of contributing participants, which demonstrates the validity of the reference value [17].

Table 9: Reference value and associated expanded uncertainty for the different nominal gauge pressures. The number of laboratories contributing to the reference value, the observed chi-squared and the maximal allowable value for the chi-squared are also provided.

	Number of	Reference	Uncertainty	chi-squared	chi-squared
Nominal	contributors	Value	k=2	observed	maximal
Pressure		A(ref)	U(A(ref))		Pr<0.05
kPa		mm^2	mm^2		
25	8	980.5347	0.0031	7.10	14.07
50	8	980.5333	0.0027	4.96	14.07
75	8	980.5324	0.0024	5.35	14.07
100	8	980.5333	0.0023	4.44	14.07
125	8	980.5333	0.0022	4.75	14.07
150	8	980.5339	0.0021	3.89	14.07
175	7	980.5344	0.0021	3.57	12.59
200	6	980.5325	0.0026	1.44	11.07

8.2 Reference value for absolute pressure

The reference value of the effective area in absolute pressure is displayed in table 10. The reference value has been calculated by a weighted mean among the participant with a primary definition and members of EURAMET (Eq.5). The contributors to the reference value are METAS, LNE, PTB (20 cm^2 pressure balance), VSL, NIS, INRIM, CMI and CEM. The reference value of the effective area shows a trend to a decrease while the pressure increases. This trend remains within the expanded uncertainty. The uncertainty of the reference value is better than half the best uncertainty found within the participants.

The chi-squared observed remains safely within the limit of the chi-squared for 5% probability, as seen in table 10, which confirm the validity of the reference value [17].

Table 10: Reference value and associated expanded uncertainty for the different nominal absolute pressures. The number of laboratories contributing to the reference value, the chi-squared observed and the maximal allowable value for the chi-squared are also provided.

Nominal Pressure kPa	Number of contributors	Reference Value A(ref) mm²	Uncertainty k=2 U(A(ref)) mm²	chi-squared observed	chi-squared maximal Pr<0.05
25	7	980.5319	0.0040	0.41	12.59
50	7	980.5315	0.0030	0.15	12.59
75	8	980.5296	0.0018	1.29	14.07
100	8	980.5295	0.0017	2.63	14.07
125	7	980.5296	0.0017	3.31	12.59
150	7	980.5297	0.0016	2.34	12.59
175	7	980.5298	0.0015	2.92	12.59
200	7	980.5300	0.0015	2.88	12.59

9 Degree of equivalence

The degree of equivalence is the offset respective to the reference value and the associated uncertainty.

9.1 Degree of equivalence for gauge pressure

The degrees of equivalence for all the participants in gauge pressure are displayed in table 11. All the participants have an offset much smaller than the uncertainty except for two laboratories (FORCE Technology and MKEH) where the offset is sometimes slightly outside the uncertainty.

On the figures 3a to 3h it is shown that the agreement is well within the uncertainty for most of the participants from 25 kPa up to 200 kPa and the participant with offset larger than the uncertainty are outside only by a small amount.

Table 11: Degree of equivalence of all the participants in gauge mode.

	METAS		LNE		PTB		NSAI		MIKES		VSL	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0022	0.0175	-0.0053	0.0127	0.0100	0.0106	0.0029	0.0523	-0.0034	0.0178	0.0097	0.0287
50	0.0007	0.0127	-0.0055	0.0100	0.0084	0.0089	0.0014	0.0318	-0.0060	0.0156	0.0062	0.0289
75	0.0024	0.0111	-0.0043	0.0091	0.0084	0.0094	0.0119	0.0237	-0.0047	0.0149	0.0071	0.0290
100	0.0017	0.0103	-0.0040	0.0087	0.0072	0.0083	0.0133	0.0220	-0.0043	0.0144	0.0053	0.0291
125	0.0023	0.0098	-0.0039	0.0086	0.0069	0.0079	0.0133	0.0227	-0.0049	0.0142	0.0051	0.0291
150	0.0019	0.0096	-0.0035	0.0086	0.0053	0.0068	0.0140	0.0233	-0.0059	0.0141	0.0049	0.0291
175	0.0014	0.0093	-0.0043	0.0085	0.0041	0.0057	0.0202	0.0226	-0.0068	0.0139	0.0048	0.0291
200	0.0032	0.0086	-0.0014	0.0077			0.0206	0.0226	-0.0047	0.0143	0.0088	0.0289

	NIS		INRIM		UME		EIM		CMI		BEV	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0094	0.0188	-0.0017	0.0222	-0.0037	0.0121	-0.0027	0.0229	0.0024	0.0144	-0.0109	0.0307
50	-0.0078	0.0191	-0.0031	0.0174	-0.0022	0.0118	-0.0045	0.0217	-0.0010	0.0126	-0.0068	0.0256
75	-0.0080	0.0193	-0.0018	0.0158	-0.0012	0.0114	-0.0047	0.0206	-0.0002	0.0108	-0.0039	0.0245
100	-0.0080	0.0193	-0.0026	0.0151	-0.0020	0.0105	-0.0060	0.0205	-0.0009	0.0098	-0.0043	0.0244
125	-0.0091	0.0193	-0.0031	0.0150	-0.0019	0.0102	-0.0051	0.0205	-0.0019	0.0099	-0.0041	0.0244
150	-0.0089	0.0194	-0.0038	0.0151	-0.0025	0.0103	-0.0067	0.0204	-0.0021	0.0099	-0.0041	0.0244
175	-0.0095	0.0194			-0.0029	0.0106	-0.0079	0.0204	-0.0029	0.0099	-0.0040	0.0244
200	-0.0075	0.0191			-0.0009	0.0112	-0.0070	0.0216	-0.0008	0.0095	-0.0022	0.0245

	IMT		LPM		IMBiH		CEM		KRISS		INM	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0017	0.0113	0.0053	0.0286	-0.0002	0.0392	-0.0225	0.0283	-0.0024	0.0191	-0.0057	0.0260
50	-0.0013	0.0091	0.0071	0.0290	0.0012	0.0384	-0.0098	0.0285	-0.0004	0.0188	-0.0044	0.0258
75	-0.0007	0.0083	0.0065	0.0284	0.0002	0.0388	-0.0082	0.0153	0.0004	0.0186	-0.0015	0.0257
100	-0.0013	0.0079	0.0032	0.0279	-0.0002	0.0395	-0.0057	0.0164	-0.0002	0.0186	-0.0015	0.0256
125	-0.0008	0.0077	0.0006	0.0274	-0.0011	0.0405	-0.0049	0.0164	0.0003	0.0185	-0.0017	0.0256
150	-0.0013	0.0075	-0.0006	0.0273	-0.0018	0.0418	-0.0034	0.0165	-0.0008	0.0185	-0.0017	0.0256
175	-0.0017	0.0074	-0.0010	0.0272	-0.0018	0.0433	-0.0013	0.0165	-0.0010	0.0185	-0.0020	0.0255
200	0.0004	0.0079	0.0009	0.0273	0.0005	0.0451	0.0003	0.0151	0.0009	0.0187		

	Force Tech.		IPQ		MKEH		MSA	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0321	0.0787	0.0157	0.0278	-0.0211	0.0233	0.0006	0.0172
50	-0.0475	0.0493	0.0126	0.0276	-0.0222	0.0219	0.0003	0.0122
75	-0.0447	0.0493	0.0137	0.0275	-0.0193	0.0215	0.0012	0.0111
100	-0.0492	0.0492	0.0116	0.0274	-0.0194	0.0215	0.0006	0.0102
125	-0.0487	0.0492	0.0121	0.0274	-0.0185	0.0213	-0.0019	0.0097
150	-0.0496	0.0492	0.0112	0.0274	-0.0196	0.0212	-0.0008	0.0093
175	-0.0559	0.0492	0.0104	0.0274	-0.0197	0.0212	-0.0032	0.0091
200	-0.0465	0.0493	0.0115	0.0275	0.0000	0.0000	-0.0020	0.0093

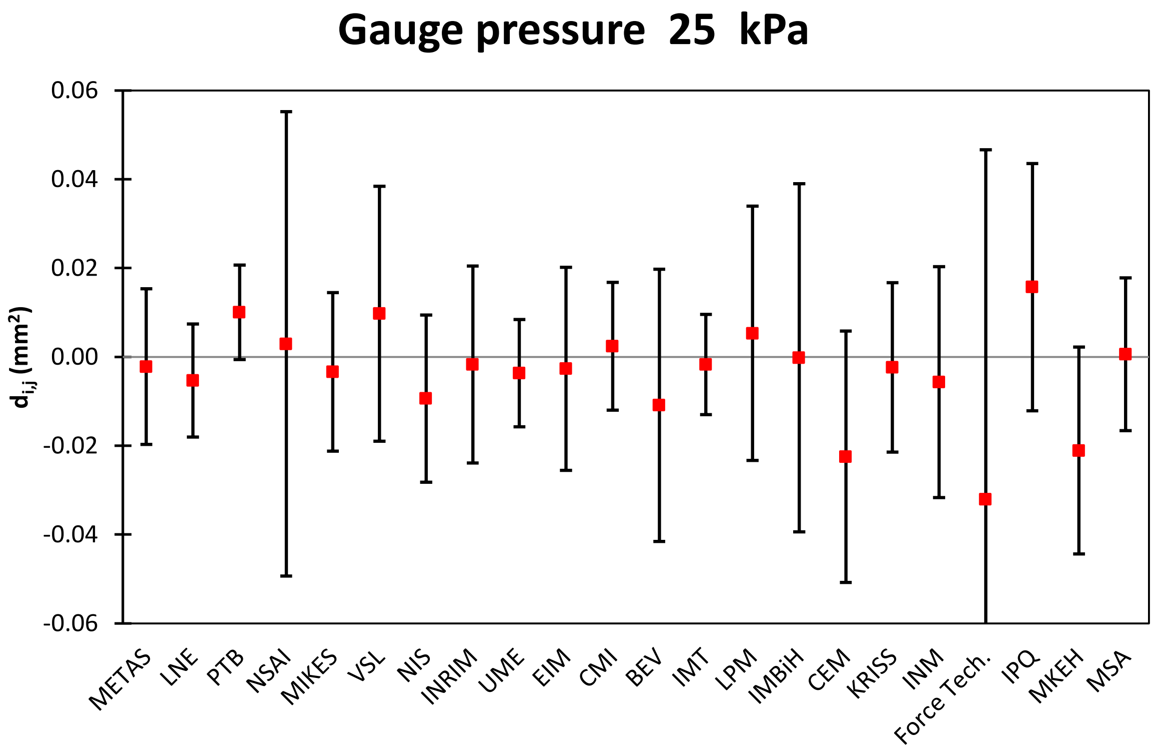

Figure 3a: Offset respective to the reference value and associated expanded uncertainty at 25 kPa for gauge mode.

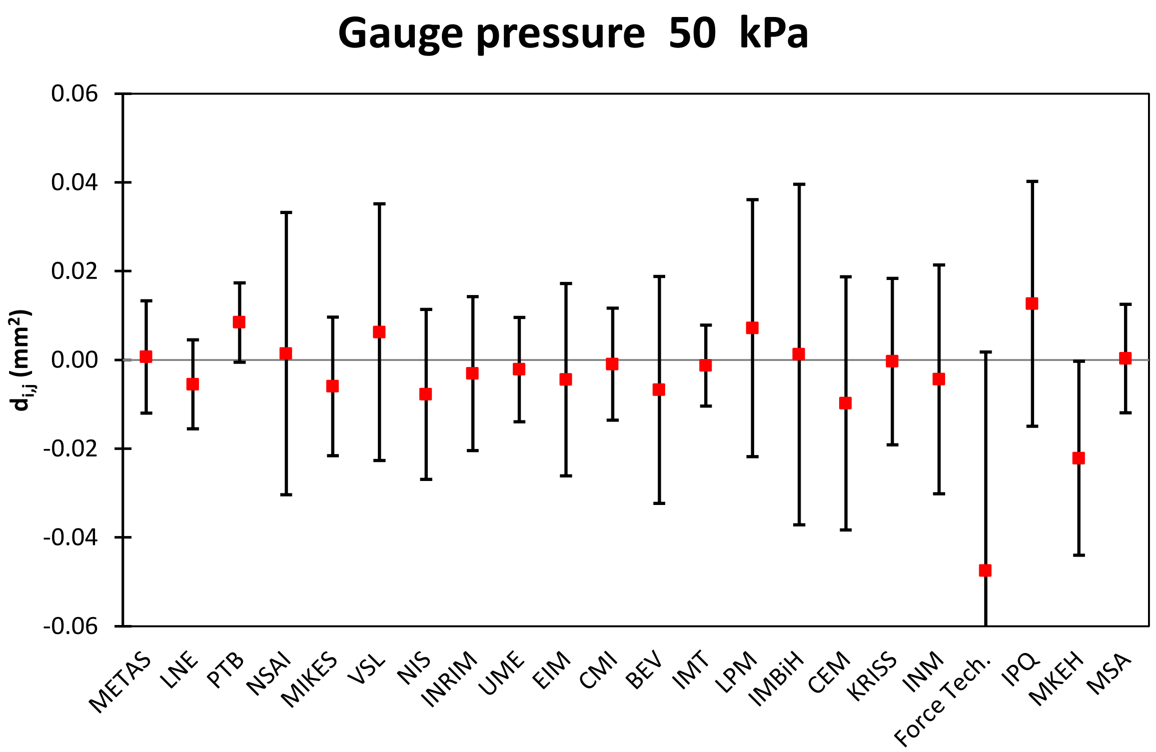

Figure 3b: Offset respective to the reference value and associated expanded uncertainty at 50 kPa for gauge mode.

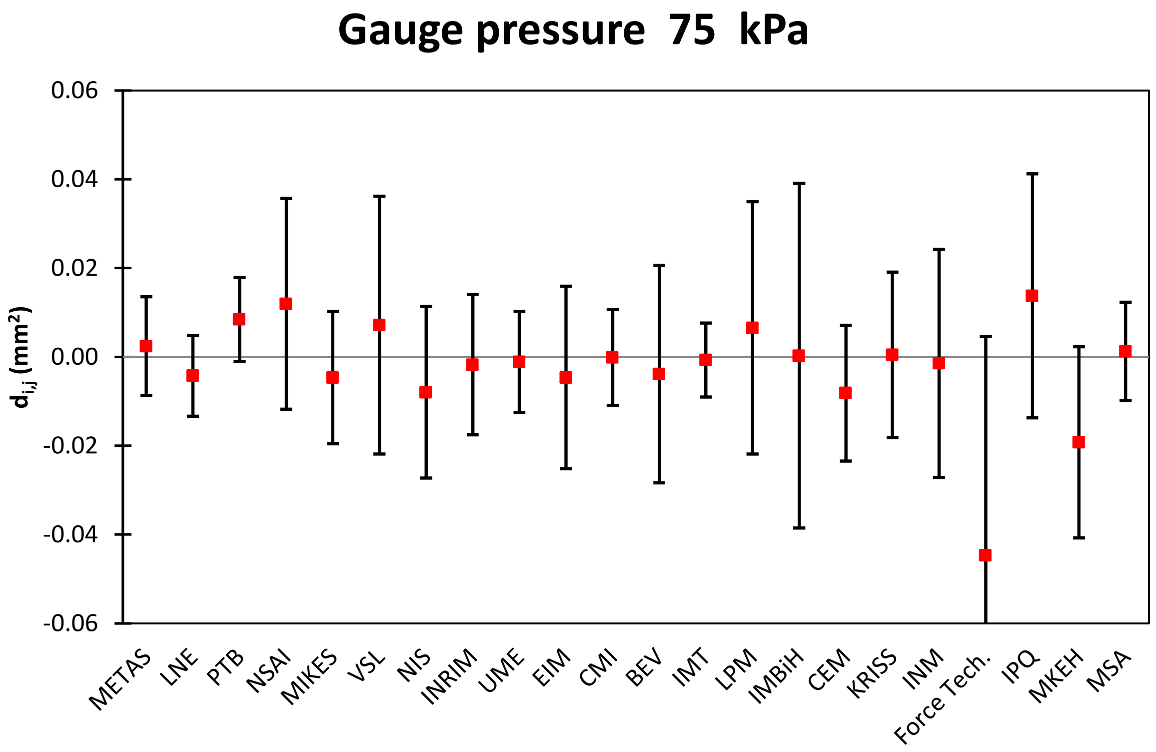

Figure 3c: Offset respective to the reference value and associated expanded uncertainty at 75 kPa for gauge mode.

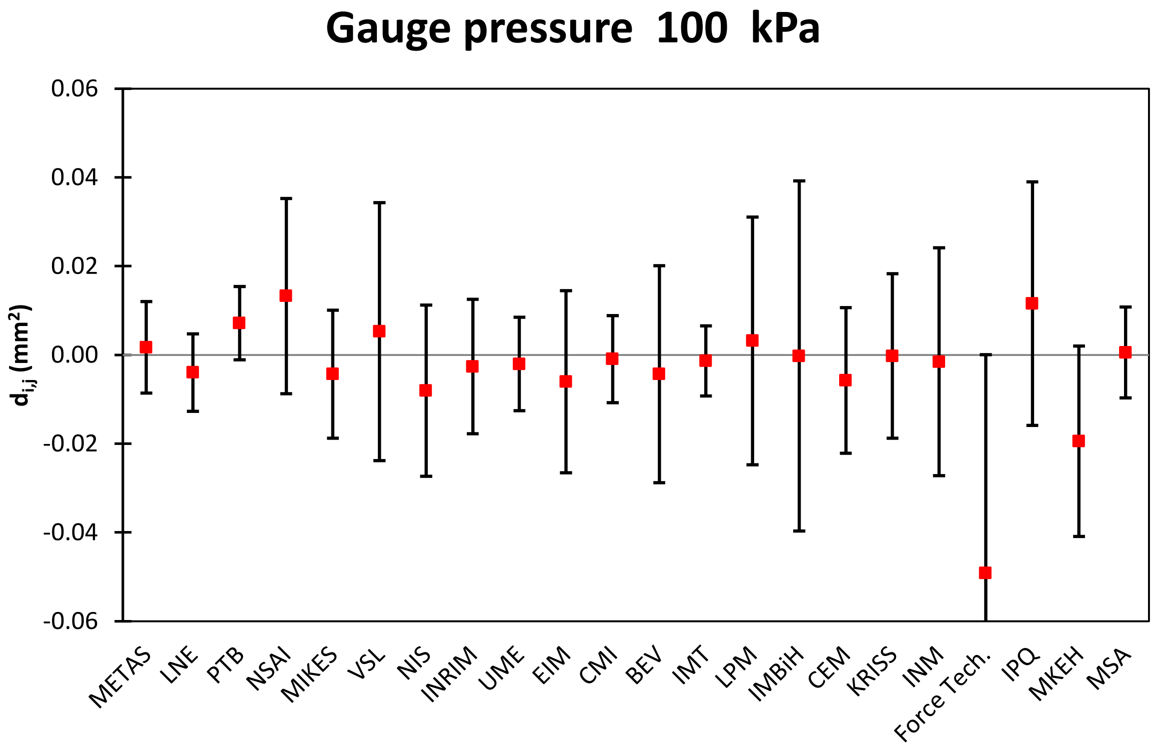

Figure 3d: Offset respective to the reference value and associated expanded uncertainty at 100 kPa for gauge mode.

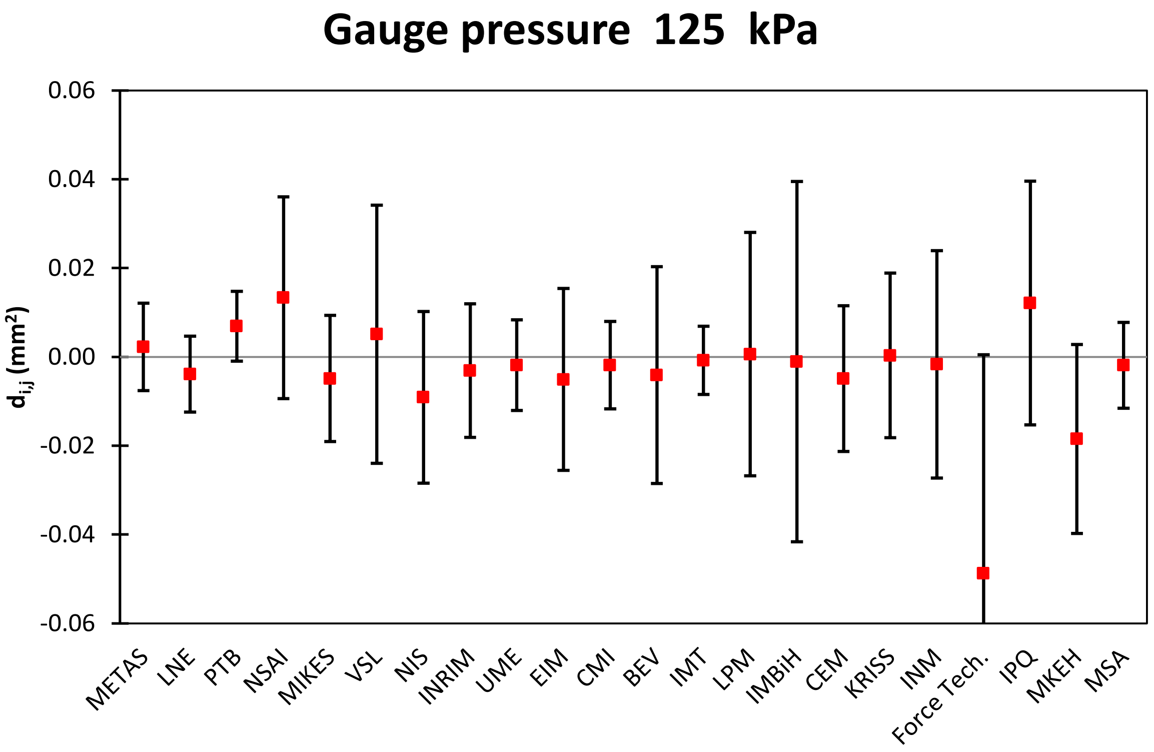

Figure 3e: Offset respective to the reference value and associated expanded uncertainty at 125 kPa for gauge mode.

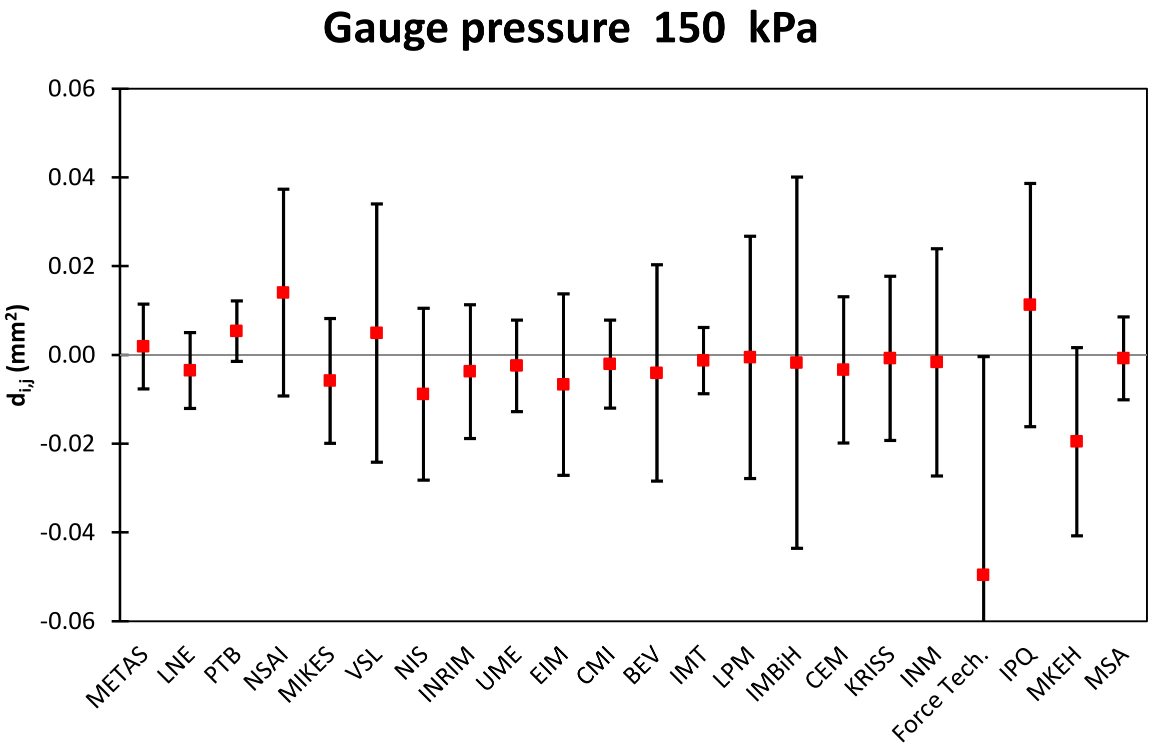

Figure 3f: Offset respective to the reference value and associated expanded uncertainty at 150 kPa for gauge mode.

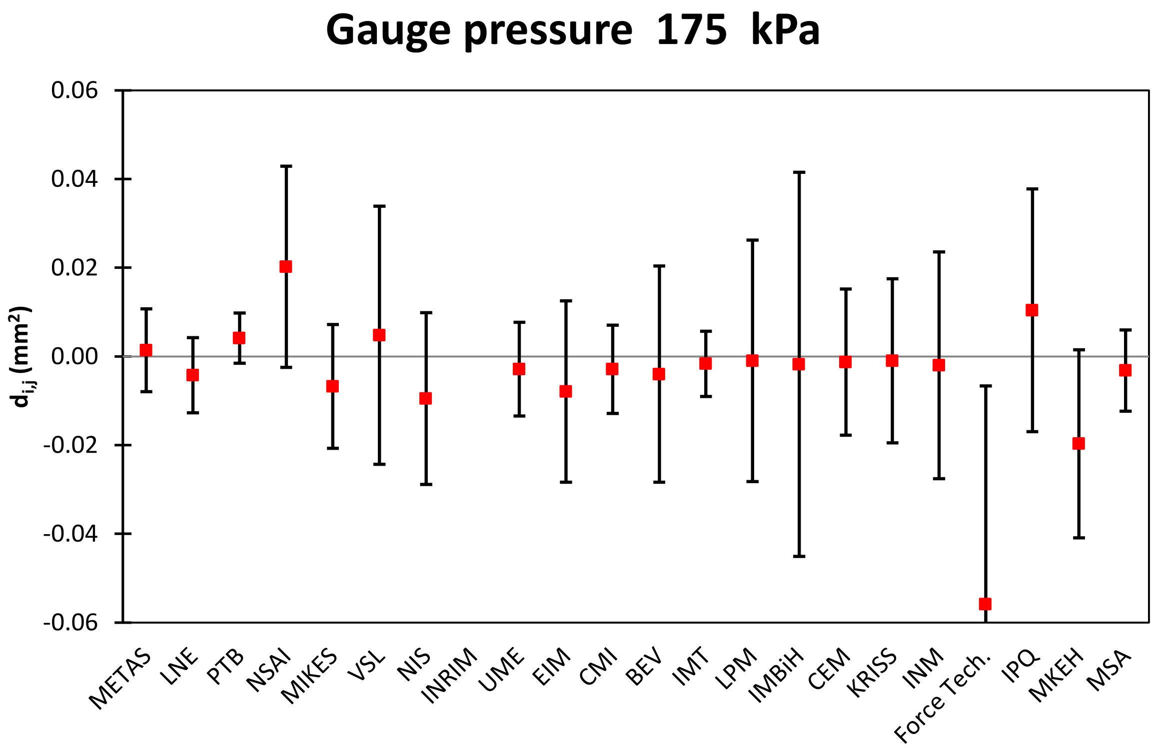

Figure 3g: Offset respective to the reference value and associated expanded uncertainty at 175 kPa for gauge mode.

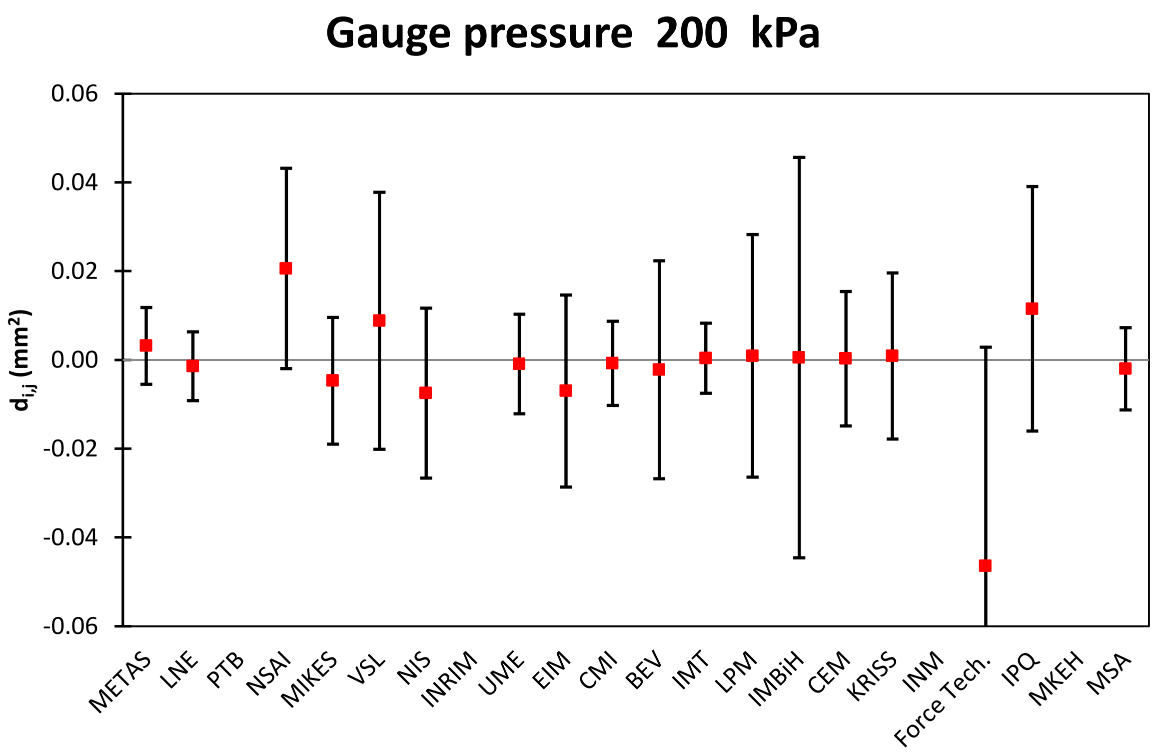

Figure 3h: Offset respective to the reference value and associated expanded uncertainty at 200 kPa for gauge mode.

9.2 Degree of equivalence for absolute pressure

The offset respective to the reference value and the expanded uncertainty of all the participants is displayed in table 12. It has to be mentioned that all the participants have offsets smaller than the expanded uncertainty.

The good agreement of the laboratories from 25 kPa up to 200 kPa is shown in the figures 4a to 4h.

Table 12: Degree of equivalence of all the participants in absolute mode.

	METAS		LNE		PTB Hg mano.		MIKES		VSL		NIS	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0038	0.0190	-0.0013	0.0154	0.0062	0.0125	-0.0040	0.0258	0.0045	0.0283	-0.0015	0.0185
50	-0.0003	0.0134	-0.0004	0.0111	0.0062	0.0109	-0.0029	0.0196	0.0033	0.0288	-0.0007	0.0189
75	0.0032	0.0122	0.0014	0.0107	0.0078	0.0099	-0.0034	0.0171	0.0041	0.0292	0.0013	0.0195
100	0.0040	0.0113	0.0016	0.0100	0.0085	0.0093	-0.0038	0.0161	0.0039	0.0292	0.0009	0.0196
125	0.0046	0.0106	0.0028	0.0096	0.0083	0.0087	-0.0045	0.0155	0.0028	0.0292	0.0012	0.0196
150	0.0051	0.0103	0.0014	0.0093	0.0075	0.0079	-0.0049	0.0150	0.0032	0.0292	0.0005	0.0196
175	0.0053	0.0100	0.0011	0.0091	0.0066	0.0073	-0.0051	0.0147	0.0028	0.0292	0.0004	0.0196
200	0.0054	0.0099	0.0010	0.0089			-0.0059	0.0146	0.0036	0.0293	0.0006	0.0197

	INRIM		UME		CMI		BEV		IMT		LPM	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	0.0017	0.0175	-0.0018	0.0130	0.0003	0.0211	0.0128	0.0418	-0.0008	0.0151	0.0093	0.0458
50	-0.0008	0.0109	-0.0010	0.0121	0.0022	0.0156	0.0085	0.0365	-0.0005	0.0116	0.0115	0.0460
75	-0.0002	0.0087	0.0016	0.0109	0.0053	0.0143	0.0125	0.0342	0.0018	0.0096	0.0131	0.0449
100	0.0011	0.0084	0.0022	0.0101	0.0051	0.0133	0.0099	0.0332	0.0013	0.0091	0.0115	0.0447
125			0.0021	0.0098	0.0048	0.0122	0.0091	0.0332	0.0016	0.0088	0.0094	0.0444
150			0.0023	0.0099	0.0039	0.0123	0.0074	0.0332	0.0017	0.0086	0.0087	0.0440
175			0.0023	0.0102	0.0035	0.0123	0.0109	0.0331	0.0018	0.0084	0.0091	0.0439
200			0.0022	0.0104	0.0031	0.0124	0.0079	0.0331	0.0018	0.0082	0.0086	0.0440

	IMBiH		CEM		KRISS		MKEH		MSA		PTB press. Bal.	
P	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$	$d_{i,j}$	$U(d_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	0.0041	0.0404	0.0038	0.0226	0.0008	0.0197	0.0342	0.1223	0.0020	0.0272		
50	0.0027	0.0395	-0.0005	0.0191	0.0012	0.0190	0.0384	0.0806	-0.0017	0.0162		
75	0.0030	0.0376	-0.0004	0.0176	0.0034	0.0184	0.0396	0.0669	0.0023	0.0125	-0.0015	0.0034
100	0.0031	0.0374	-0.0094	0.0177	0.0039	0.0183	0.0361	0.0603	0.0033	0.0115	-0.0012	0.0030
125	0.0024	0.0374	-0.0106	0.0177	0.0041	0.0183	0.0336	0.0563	0.0011	0.0103	-0.0012	0.0026
150	0.0027	0.0373	-0.0074	0.0177	0.0041	0.0183	0.0168	0.0537	0.0021	0.0097	-0.0010	0.0023
175	0.0024	0.0373	-0.0099	0.0167	0.0037	0.0183			0.0014	0.0090	-0.0007	0.0021
200	0.0022	0.0373	-0.0096	0.0167	0.0038	0.0182			0.0006	0.0086	-0.0007	0.0019

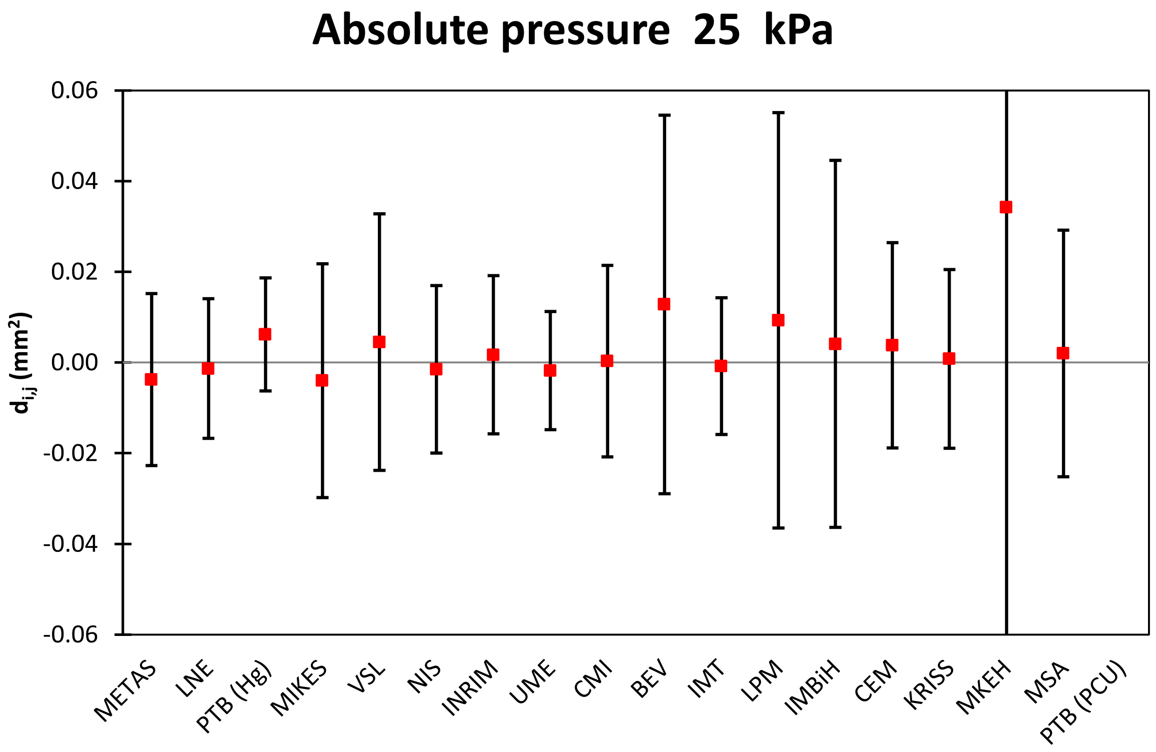

Figure 4a: Offset respective to the reference value and associated expanded uncertainty at 25 kPa for absolute pressure.

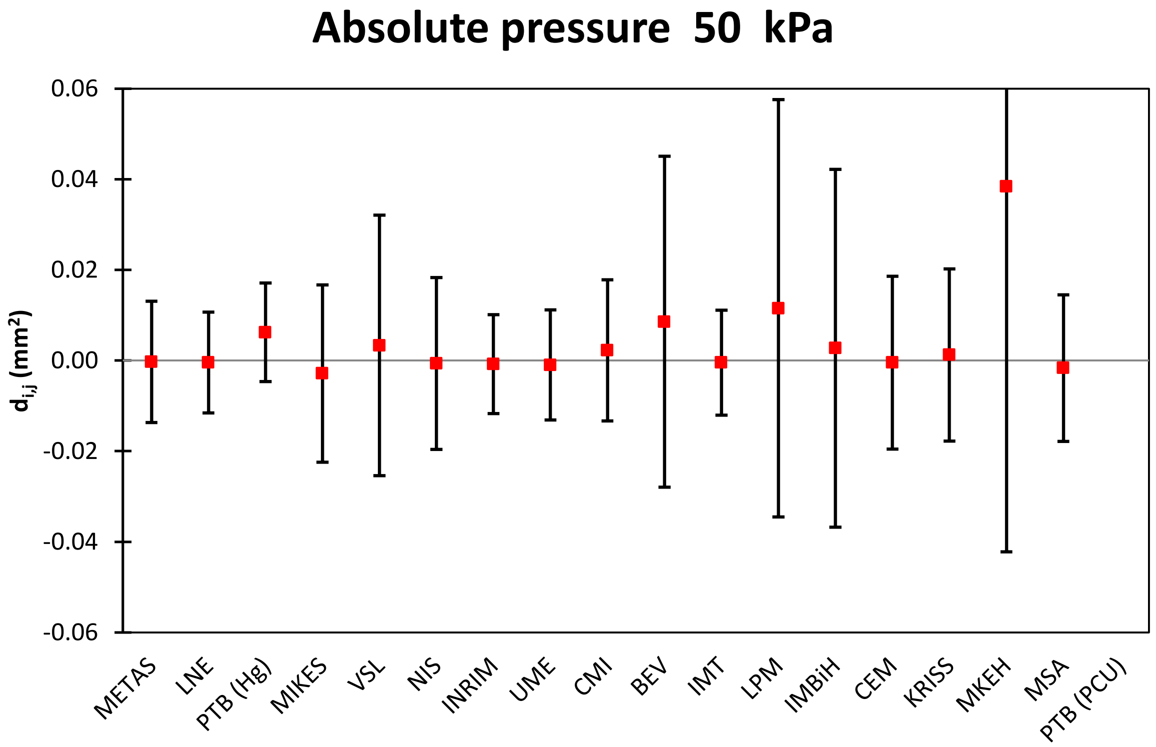

Figure 4b: Offset respective to the reference value and associated expanded uncertainty at 50 kPa for absolute pressure.

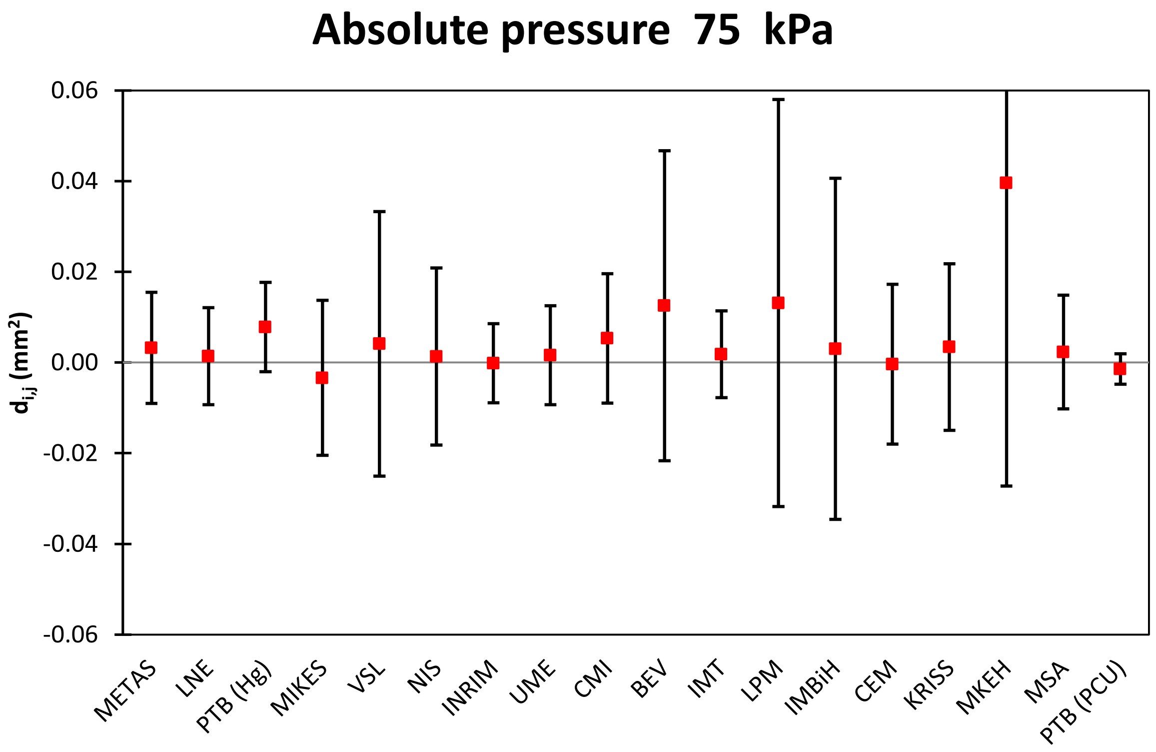

Figure 4c: Offset respective to the reference value and associated expanded uncertainty at 75 kPa for absolute pressure.

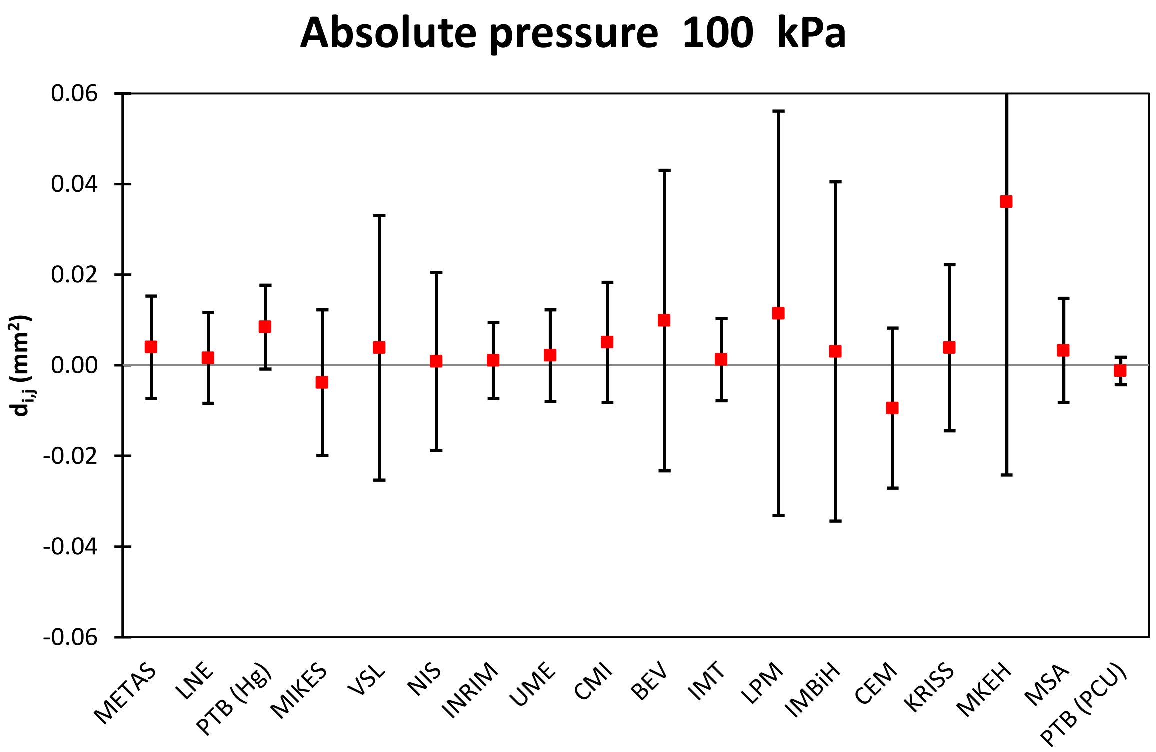

Figure 4d: Offset respective to the reference value and associated expanded uncertainty at 100 kPa for absolute pressure.

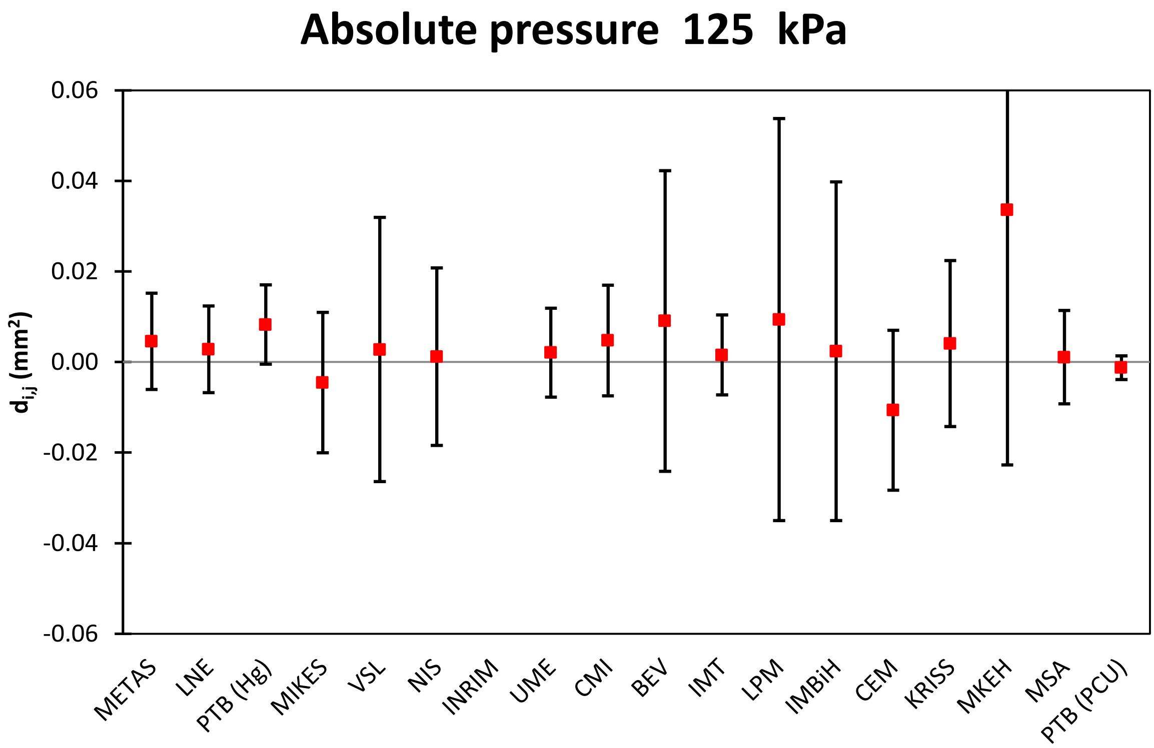

Figure 4e: Offset respective to the reference value and associated expanded uncertainty at 125 kPa for absolute pressure.

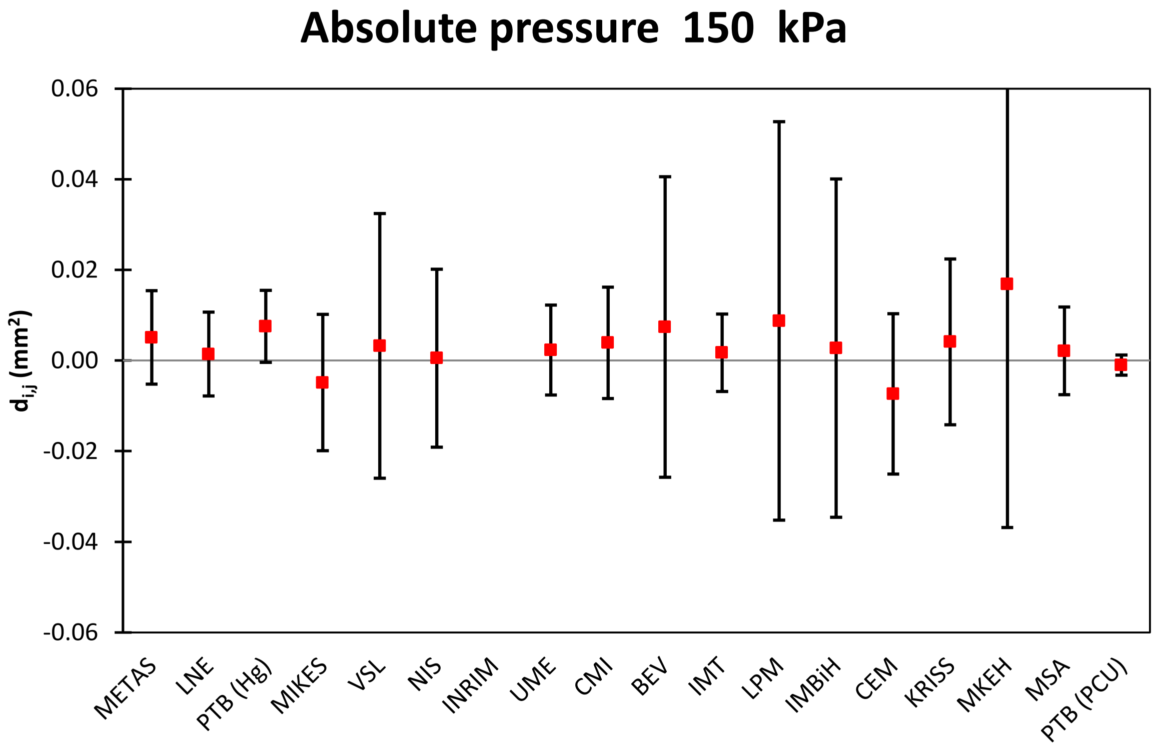

Figure 4f: Offset respective to the reference value and associated expanded uncertainty at 150 kPa for absolute pressure.

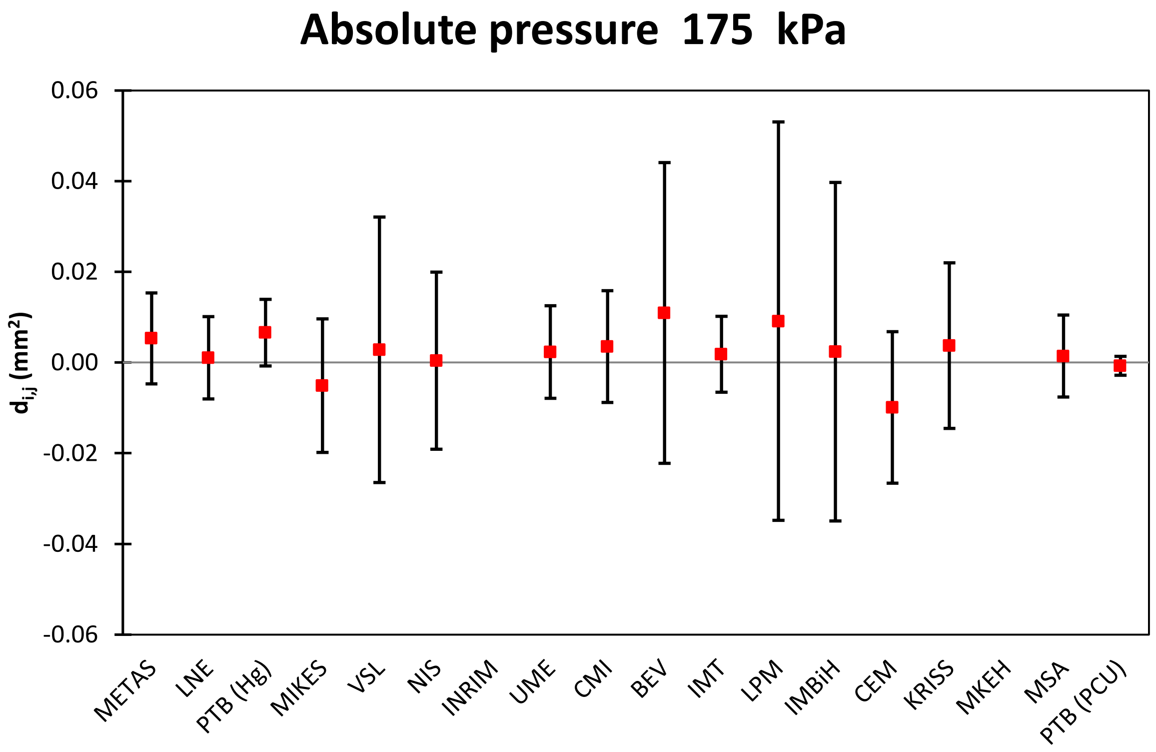

Figure 4g: Offset respective to the reference value and associated expanded uncertainty at 175 kPa for absolute pressure.

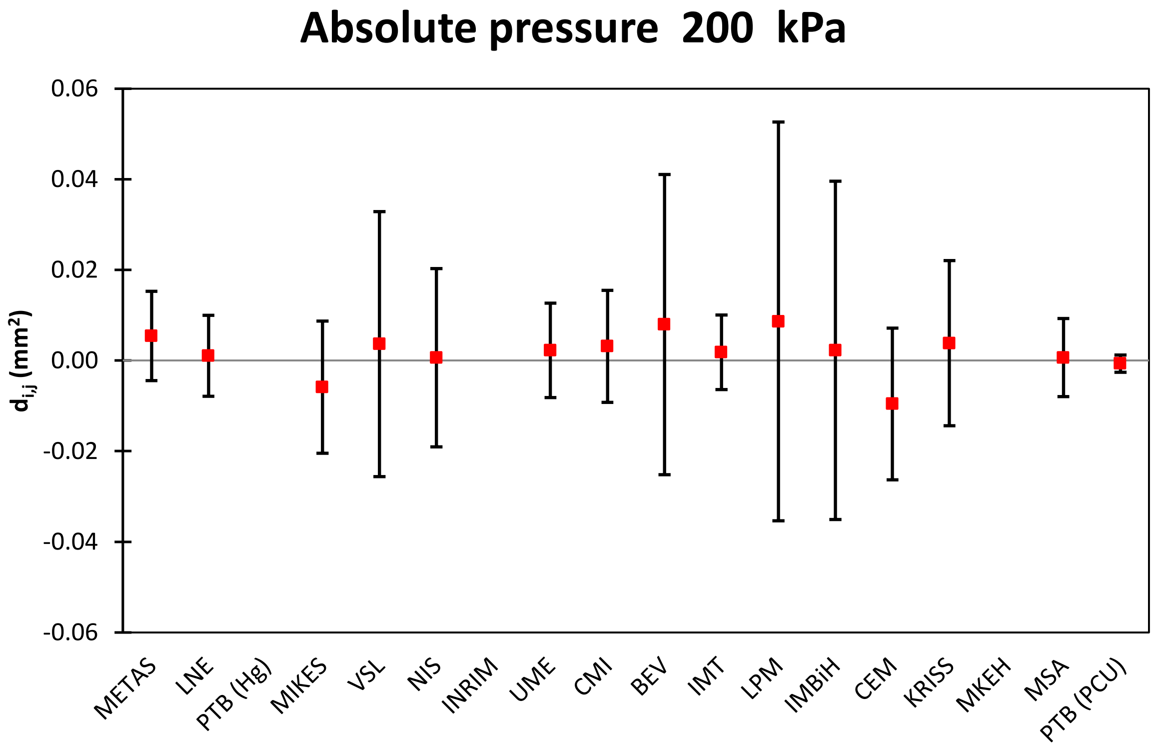

Figure 4h: Offset respective to the reference value and associated expanded uncertainty at 200 kPa for absolute pressure.

10 Degree of equivalence between the participants

Due to the high number of laboratories and as it is not compulsory anymore to provide the table of the degree of equivalence between the participants [18], no table of degree of equivalence between the participants will be provided. We will however explain how to calculate the degree of equivalence between two participants based on the value given in table 9 and 11 for gauge pressure and table 10 and 12 for absolute pressure.

The offset $d_{i,j,k}$ for the nominal pressure i, for a participant labelled j respective to a participant labelled k is easily calculated:

$$d_{i,j,k} = d_{i,j} - d_{i,k} \quad (10)$$

The uncertainty $U(d_{i,j,k})$ is then given by:

$$U\left(d_{i,j,k}\right) = \sqrt{U^2\left(d_{i,j}\right) + U^2\left(d_{i,k}\right) - U^2\left(A_i\left(EUR\right)\right)} \quad (11)$$

where $U(d_{i,j})$ and $U(d_{,i,k})$ are given by Eq. 8 or 9 and $U(A_i(EUR))$ is given by Eq. 6.

Even if we will not publish the pair-wise degrees of equivalence, we did the calculation of the $d_{i,j,k}$ and the consistency check with the associated uncertainty. The non-equivalence was almost exclusively visible for the results where the equivalence is also a problem respective to the reference value.

11 Link to CCM key comparisons

According to the document CIPM MRA-D-05 [19] the RMO key comparisons must be linked to the corresponding CCM key comparison.

In this comparison we have the opportunity to be linked to the following key comparisons from the CCM:

- CCM.P-K6 for gauge pressure through VSL and PTB up to 100 kPa.
- CCM.P-K2 for absolute pressure through INRIM and PTB (Hg manometer) up to 100 kPa

In each case we have the chance to have two participants to establish the link which fulfills the requirements of the BIPM.

11.1 Mathematics used for linking to the CCM comparisons

In absolute pressure as well as in gauge pressure we have a similar situation with two participants used for linking the EURAMET comparison to the CCM comparison. We will use a technique similar to [20] and the linking laboratories will be labeled with the indices 1 and 2.

In a first time we calculated the weighted mean of the offset respective to the reference value of the CCM comparison:

$$X_i = \frac{\sum_{j=1}^{2} \frac{x_j(p_i)}{U^2\left(x_j(p_i)\right)}}{\sum_{j=1}^{2} \frac{1}{U^2\left(x_j(p_i)\right)}} \tag{12}$$

where :

i	designates the index of the pressure step
j	designates the index of the participating laboratories
X_i	is the offset of the weighted mean of the laboratories used for the link, respective to the reference value of the CCM comparison, for target pressure i
$x_j(p_i)$	is the offset respective to the CCM comparison reference value for laboratory j at target pressure i
$U(x_j(p_i))$	is the expanded uncertainty (k=2) associated to the deviation

and the expanded uncertainty (k=2) of the weighted mean is given by:

$$U(X_i) = \frac{1}{\sum_{j=1}^{2} \frac{1}{U^2\left(x_j(p_i)\right)}} \tag{13}$$

We calculate then a similar way the weighted mean of the offset respective to the reference value for the EURAMET comparison:

$$Y_i = \frac{\sum_{j=1}^{2} \frac{y_j(p_i)}{U^2\left(y_j(p_i)\right)}}{\sum_{j=1}^{2} \frac{1}{U^2\left(y_j(p_i)\right)}} \tag{14}$$

Y_i	is the offset of the weighted mean of the laboratories used for the link, respective to the reference value of the EURAMET comparison, for target pressure i
$y_j(p_i)$	is the offset respective to the EURAMET comparison reference value for laboratory j at target pressure i
$UI(y_j(p_i))$	is the expanded uncertainty (k=2) associated to the deviation

and the expanded uncertainty (k=2) of the weighted mean is given by:

$$U(Y_i) = \frac{1}{\sum_{j=1}^{2} \frac{1}{U^2\left(y_j(p_i)\right)}} \tag{15}$$

The reference values are expressed in terms of area of piston-cylinders in both comparisons but the areas are not similar in the CCM comparison (~335 mm^2) and EURAMET comparison. (~980 mm^2). In order to be able to go further in the calculation we need to translate the offset and uncertainties obtained for the EURAMET comparison in offset and uncertainties expressed for the CCM comparison. For this purpose we simply multiply the values (offset and uncertainties) of the EURAMET for a pressure p by a ratio which is given by the ratio of the reference value obtained at the given pressure p for the CCMT and EURAMET comparison:

$$Z_i = Y_i \frac{A_i(CCM)}{A_i(EUR)} \tag{16}$$

where $A_i(EUR)$ is the reference value of the EURAMET comparison as given by Eq. 5 and $A_i(CCM)$ is the reference value of the CCM comparison given by the report of the respective comparison [1, 2].

We are then able to define the expanded uncertainty associated to the offset of EURAMET values expressed in terms of CCM values:

$$U(Z_i) = U(Y_i) \frac{A_i(CCM)}{A_i(EUR)} \tag{17}$$

and we can also express the expanded uncertainty of the reference value of the EURAMET comparison to be compatible with the effective area of the CCM comparison:

$$U_{CCM}\left(A_i(EUR)\right) = U\left(A_i(EUR)\right) \frac{A_i(CCM)}{A_i(EUR)} \tag{18}$$

The reference value obtained for the EURAMET laboratories is then translated the following way once it is representative of the reference value of the CCM comparison:

$$A_i(EUR, linked) = A_i(CCM) + X_i - Z_i \tag{19}$$

and the associated expanded uncertainty is:

$$U\left(A_i(EUR, linked)\right) = \sqrt[2]{\left(U\left(A_i(CCM)\right)\right)^2 + \left(U_{CCM}\left(A_i(EUR)\right)\right)^2 + \left(U(X_i)\right)^2 + \left(U(Z_i)\right)^2} \tag{20}$$

In the equation 20 we made the assumption that there is no correlation, for the laboratories contributing to the link, in the measurement made at the time of the CCM comparison and at the time of the EURAMET comparison. This is motivated by the fact that a lot of the uncertainty contributions are not correlated (temperature, residual vacuum, atmospheric pressure,…) and the few contributions that could be correlated (Hg density, piston area, offset of temperature calibration) have only a limited correlation due to the time since the CCM comparisons when the EURAMET work was made.

We are then able to evaluate the offset of each laboratory respective to the reference value of the EURAMET comparison calculated in Eq. 7 in terms of the reference value obtained in the CCM comparison

We are then able to calculate the offset expressed for the reference value of the CCM, based on the offset obtained in the EURAMET work that had been calculated by Eq. 7:

$$D_{i,j} = d_{i,j} \frac{A_i(CCM)}{A_i(EUR)} + X_{CCM}(p_i) - Z_{CCM}(p_i) \tag{21}$$

where $D_{i,j}$ represents the offset respective to the CCM reference value, for the laboratory j and for the target pressure i.

Finally we can express the expanded uncertainty on the $D_{i,j}$, for the laboratories not contributing to the linking process:

$$U(D_{i,j}) = \sqrt[2]{\left(U(d_{i,j})\frac{A_i(CCM)}{A_i(EUR)}\right)^2 + \left(U\left(A_i(CCM)\right)\right)^2 + \left(U(X_i)\right)^2 + \left(U(Z_i)\right)^2} \tag{22}$$

while for the two laboratories contributing to the link we obtain [17]:

$$U(D_{i,j}) = \sqrt[2]{\left(U(d_{i,j})\frac{A_i(CCM)}{A_i(EUR)}\right)^2 + \left(U\left(A_i(CCM)\right)\right)^2 + \left(U(X_i)\right)^2 - \left(U(Z_i)\right)^2} \tag{23}$$

11.2 Link to CCM.P-K6

The link to the comparison CCM.P-K6 is made through the mercury manometer of PTB and the pressure balance of VSL. This link is relevant only to the measurements performed in gauge pressure.

The values of CCM.P-K6 used for achieving the link are given on table 13. The measurement at 50 kPa and 100 kPa of the EURAMET comparison are easily linked with the measurement at the same nominal pressure from the CCM comparison. The measurements of EURAMET.M.P-K8 at the nominal pressure 25 kPa are linked with the averaged value of the 20 kPa and 30 kPa measurements of the CCM comparison. The measurements of EURAMET.M.P-K8 at 75 kPa are linked with the averaged value of the measurements of the CCM.P-K6 at 70 kPa and 80 kPa. This averaging is made possible by the fact that the reference value (effective area) is not strongly dependent of the pressure.

The reference values of EURAMET.P.K-8 adapted to the nominal pressure of CCM.P-K6 are given in table 14. The same table provides the coefficient used for establishing the link, based on the measurement of VSL and PTB.

Table 13: Reference value and offset for VSL and PTB extracted from table 5 of the report of CCM.P-K6 [1]. The two last columns give respectively the weighted mean of the offsets from VSL and PTB and the related expanded uncertainty.

	Reference value CCM.P.K-6		**VSL**		**PTB**		**Weighted mean**	
Pressure	x_{ref}	$U(x_{ref})$	x_i-x_{ref}	$U(x_i$-$x_{ref})$	x_i-x_{ref}	$U(x_i$-$x_{ref})$	X_i	$U(X_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
10	335.7442	0.0015			0.0002	0.0056	0.0002	0.0056
20	335.7444	0.0007	0.0010	0.0110	0.0000	0.0041	0.0001	0.0038
30	335.7442	0.0010	0.0015	0.0110	0.0000	0.0038	0.0002	0.0036
40	335.7441	0.0009	0.0017	0.0110	0.0005	0.0033	0.0006	0.0032
50	335.7443	0.0008	0.0012	0.0110	0.0005	0.0032	0.0006	0.0031
60	335.7443	0.0005	0.0011	0.0110	0.0006	0.0032	0.0006	0.0031
70	335.7443	0.0008	0.0010	0.0110	0.0010	0.0037	0.0010	0.0035
80	335.7445	0.0006	0.0007	0.0110	0.0008	0.0038	0.0008	0.0036
90	335.7445	0.0007	0.0006	0.0110	0.0009	0.0039	0.0009	0.0037
100	335.7445	0.0009	0.0005	0.0110	0.0008	0.0032	0.0008	0.0031

Table 14: Reference values of CCM.P-K6 adapted to the nominal pressures of EURAMET.M.P-K8 and the corresponding correction factor needed to establish the link. The values of the weighted mean are obtained using the data from VSL and PTB.

	Reference value CCM.P.K-6		EURAMET. M.P.K-8	Weighted mean CCM.P.K-6		Weighted mean EURAMET.M.P.K-8	
Pressure	x_{ref}	$U(x_{ref})$	$U_{CCM}(A_i(EUR))$	X_i	$U(X_i)$	Z_i	$U(Z_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	335.7443	0.0009	0.0011	0.0001	0.0037	0.0034	0.0034
50	335.7443	0.0008	0.0009	0.0006	0.0031	0.0028	0.0029
75	335.7444	0.0007	0.0008	0.0009	0.0035	0.0028	0.0031
100	335.7445	0.0009	0.0008	0.0008	0.0031	0.0024	0.0027

11.3 Link to CCM.P-K2

The link to CCM.P-K2 is made through the mercury barometer of the PTB and the mercury barometer of INRIM as both instruments took part to the CCM.P-K2 and to the EURAMET.M.P-K8.

The reference values of CCM.P-K2 as well as the degree of equivalence for INRIM and PTB (mercury manometer) are given on table 15. The nominal pressure 50 kPa and 100 kPa are similar in both comparisons and are straightforward to link. The nominal pressure 25 kPa of EURAMET.M.P-K8 is linked with the averaged value of 20 kPa and 30 kPa in CCM.P-K2 and the nominal pressure 75 kPa of EURAMET.M.P-K8 is linked with the averaged value of 70 kPa and 80 kPa of CCM.P-K2. The reason why this is possible is the almost negligible change of the effective area with the pressure.

The reference values of EURAMET.M.P-K8 adapted to the nominal pressure of CCM.P-K2 are given in table 16. The same table provides the coefficient used for establishing the link, based on the measurements of INRIM and the PTB.

Table 15: Reference value and offset for INRIM and PTB extracted from table 4 and 5 of the report of CCM.P-K2 [2]. The two last columns give respectively the weighted mean of the offsets from INRIM and PTB and the related expanded uncertainty.

	Reference value CCM.P.K-2		INRIM		PTB		Weighted mean	
Pressure	x_{ref}	$U(x_{ref})$	x_i-x_{ref}	$U(x_i$-$x_{ref})$	x_i-x_{ref}	$U(x_i$-$x_{ref})$	X_i	$U(X_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
10	335.7444	0.0009	-0.0003	0.0085	0.0006	0.0065	-0.0001	0.0052
21	335.7448	0.0017	0.0027	0.0057	0.0007	0.0048	0.0011	0.0037
30	335.7455	0.0010	0.0012	0.0041	0.0000	0.0038	0.0006	0.0028
40	335.7442	0.0008	0.0000	0.0038	0.0011	0.0034	0.0000	0.0025
50	335.7440	0.0008	0.0019	0.0035	0.0017	0.0034	0.0009	0.0024
60	335.7451	0.0009	-0.0017	0.0040	0.0010	0.0042	-0.0009	0.0029
70	335.7453	0.0005	0.0006	0.0040	0.0009	0.0042	0.0003	0.0029
80	335.7446	0.0009	0.0003	0.0044	0.0014	0.0047	0.0002	0.0032
90	335.7448	0.0009	0.0004	0.0043	0.0013	0.0047	0.0002	0.0032
100	335.7451	0.0007	0.0000	0.0050	0.0008	0.0053	0.0000	0.0036

Table 16: Reference value of EURAMET.M.P-K8 adapted to the nominal pressures of CCM.P-K2 and the corresponding correction factor needed to establish the link. The values of the weighted mean are obtained using the data from INRIM and PTB.

	Reference value CCM.P.K-2		**Euramet. M.P.K-8**	**Weighted mean CCM.P.K-2**		**Weighted mean EURAMET.M.P.K-8**	
Pressure	x_{ref}	$U(x_{ref})$	$U_{CCM}(A_i(EUR))$	X_i	$U(X_i)$	Z_i	$U(Z_i)$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	980.5319	0.0040	0.0014	0.0008	0.0032	0.0002	0.0035
50	980.5315	0.0030	0.0010	0.0009	0.0024	-0.0001	0.0026
75	980.5296	0.0018	0.0006	0.0002	0.0031	0.0000	0.0022
100	980.5295	0.0017	0.0006	0.0000	0.0036	0.0002	0.0021

12 Degree of equivalence of EURAMET.M.P-K8 linked to CCM.P-K6

The degree of equivalence is given in table 17 and the figures 5a to 5d show the respective deviation and uncertainties.

The offset and uncertainties of the linked values are expressed respective to the 335 mm2 piston used in the CCM.P-K6 comparison. In absolute numbers the values look smaller but there is not that much change in relative numbers.

The equivalence is not very affected by the link and only FORCE Metrology and MKEH are outside of the uncertainty, by only a small amount, for some nominal pressures.

Table 17: Degree of equivalence of the results for gauge pressure of EURAMET.M.P-K8 linked to CCM.P-K6.

	METAS		LNE		PTB		NSAI		MIKES		VSL	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0040	0.0079	-0.0051	0.0067	0.0002	0.0040	-0.0023	0.0186	-0.0044	0.0080	0.0001	0.0100
50	-0.0020	0.0061	-0.0041	0.0055	0.0006	0.0033	-0.0018	0.0117	-0.0043	0.0069	-0.0001	0.0100
75	-0.0011	0.0061	-0.0034	0.0057	0.0009	0.0038	0.0021	0.0094	-0.0035	0.0070	0.0005	0.0101
100	-0.0010	0.0055	-0.0030	0.0052	0.0008	0.0033	0.0029	0.0086	-0.0031	0.0065	0.0002	0.0101

	NIS		INRIM		UME		EIM		CMI		BEV	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0065	0.0082	-0.0039	0.0092	-0.0045	0.0066	-0.0042	0.0094	-0.0024	0.0071	-0.0070	0.0117
50	-0.0049	0.0078	-0.0033	0.0073	-0.0030	0.0059	-0.0038	0.0086	-0.0026	0.0061	-0.0046	0.0098
75	-0.0047	0.0081	-0.0026	0.0072	-0.0023	0.0061	-0.0035	0.0085	-0.0020	0.0060	-0.0033	0.0096
100	-0.0044	0.0078	-0.0025	0.0067	-0.0023	0.0055	-0.0037	0.0082	-0.0019	0.0054	-0.0031	0.0094

	IMT		LPM		IMBiH		CEM		KRISS		INM	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0039	0.0064	-0.0015	0.0111	-0.0033	0.0144	-0.0110	0.0110	-0.0041	0.0083	-0.0052	0.0103
50	-0.0027	0.0053	0.0002	0.0108	-0.0018	0.0138	-0.0056	0.0107	-0.0024	0.0077	-0.0038	0.0098
75	-0.0022	0.0055	0.0003	0.0108	-0.0019	0.0141	-0.0047	0.0071	-0.0018	0.0080	-0.0025	0.0100
100	-0.0021	0.0050	-0.0005	0.0104	-0.0017	0.0141	-0.0036	0.0070	-0.0017	0.0076	-0.0022	0.0097

	Force Tech.		IPQ		MKEH		MSA	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0143	0.0274	0.0021	0.0108	-0.0105	0.0095	-0.0031	0.0078
50	-0.0185	0.0174	0.0021	0.0104	-0.0099	0.0086	-0.0022	0.0060
75	-0.0173	0.0175	0.0028	0.0105	-0.0085	0.0088	-0.0015	0.0061
100	-0.0185	0.0174	0.0023	0.0103	-0.0083	0.0085	-0.0014	0.0055

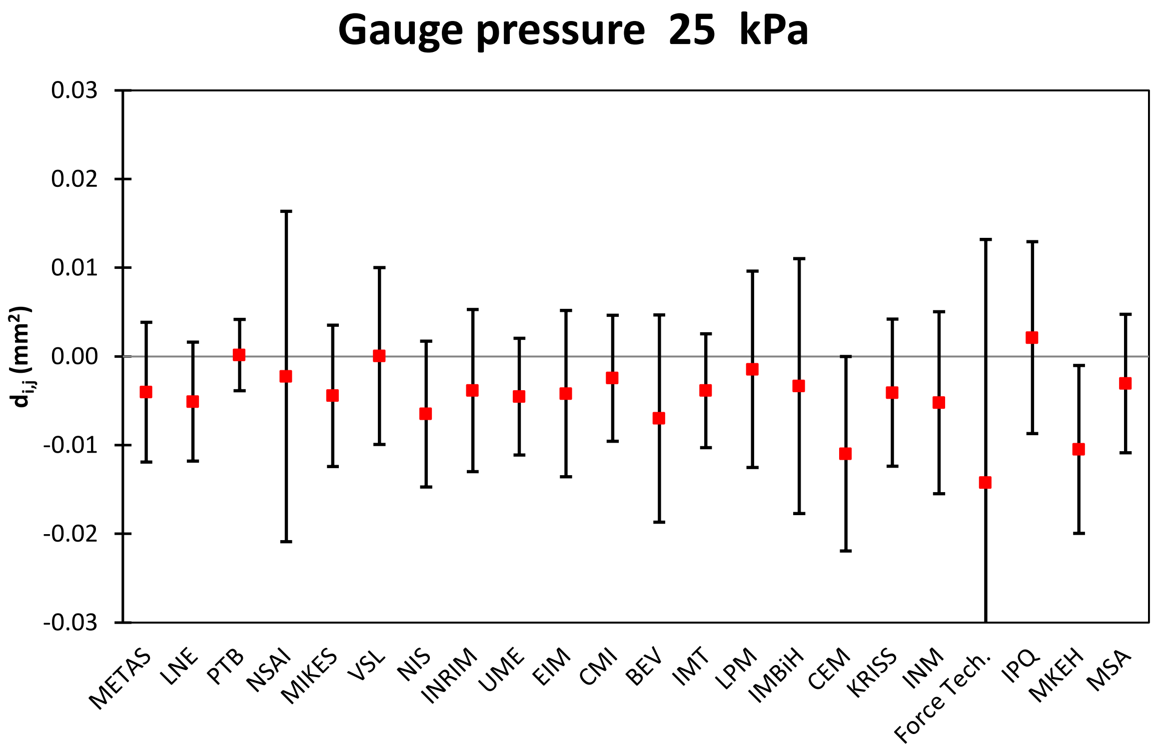

Figure 5a: Offset respective to the reference value of CCM.P-K6 and associated expanded uncertainty at 25 kPa for gauge pressure.

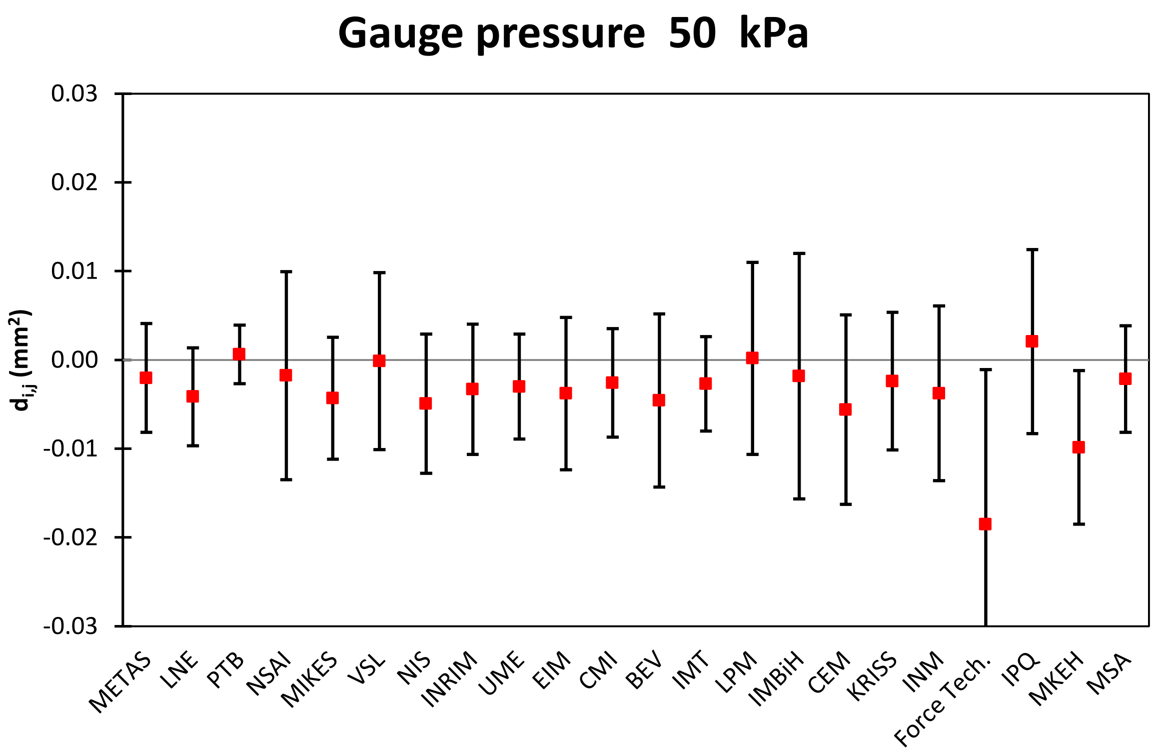

Figure 5b: Offset respective to the reference value of CCM.P-K6 and associated expanded uncertainty at 50 kPa for gauge pressure.

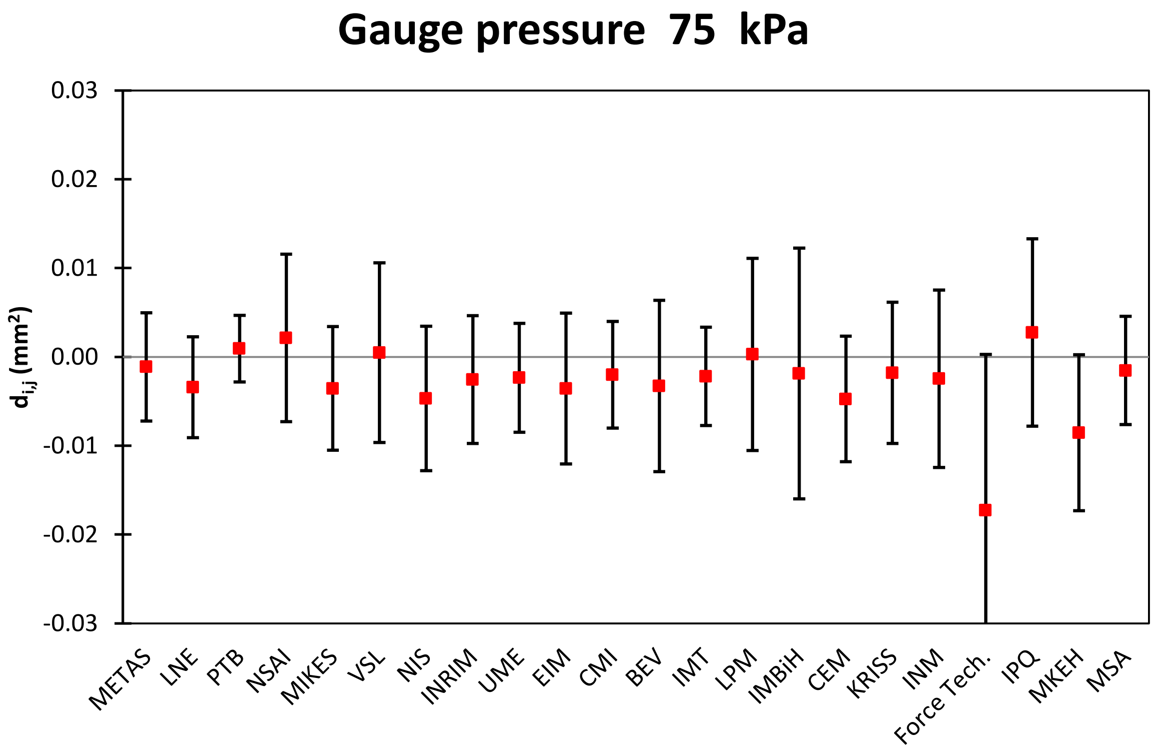

Figure 5c: Offset respective to the reference value of CCM.P-K6 and associated expanded uncertainty at 75 kPa for gauge pressure.

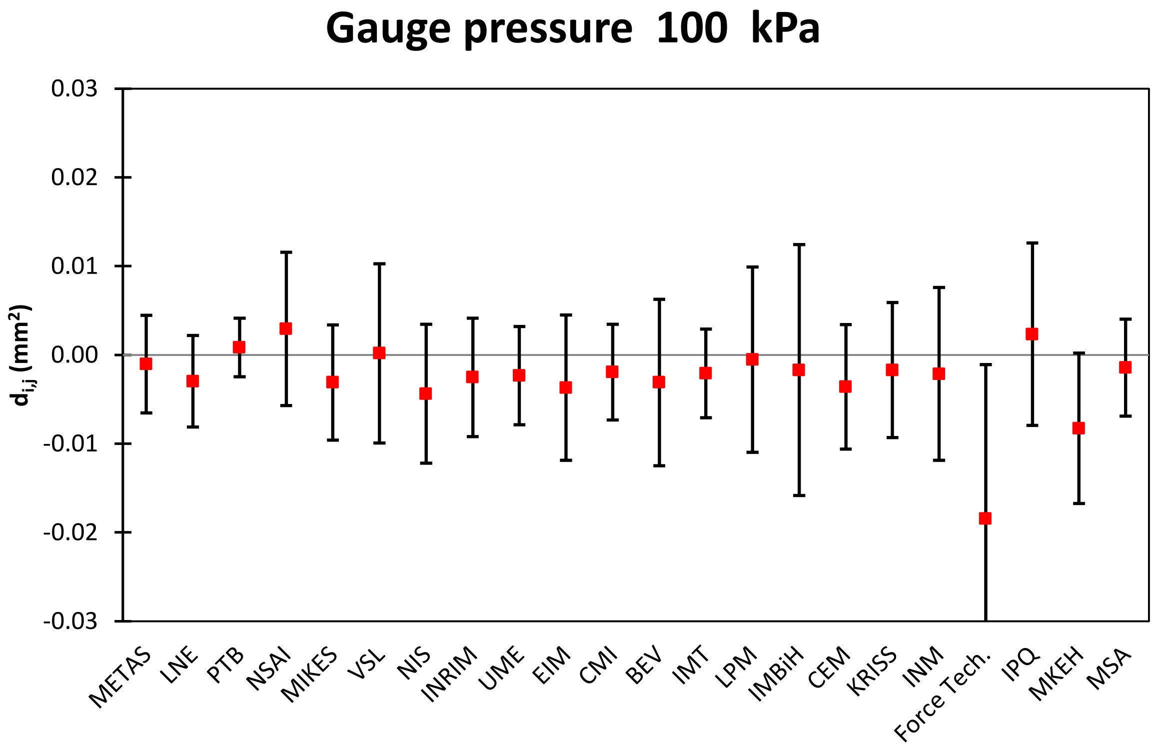

Figure 5d: Offset respective to the reference value of CCM.P-K6 and associated expanded uncertainty at 100 kPa for gauge pressure.

13 Degree of equivalence of EURAMET.M.P-K8 linked to CCM.P-K2

The degree of equivalence is given in table 18 and the figures 6a to 6d show the respective deviation and uncertainties.

The offset and uncertainties of the linked values are expressed respective to the 335 mm^2 piston used in the CCM.P-K2 comparison. In absolute numbers the values look smaller but there is not that much change in relative numbers.

The equivalence is not very affected by the link and all the laboratories are in agreement with the CCM.P-K2 reference value at all nominal pressures.

Table 18: Degree of equivalence of the results for absolute pressure of EURAMET.M.P-K8 linked to CCM.P-K2.

	METAS		LNE		PTB Hg mano.		MIKES		VSL		NIS	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	-0.0007	0.0082	0.0002	0.0072	0.0028	0.0043	-0.0007	0.0101	0.0022	0.0109	0.0001	0.0080
50	0.0009	0.0059	0.0009	0.0053	0.0032	0.0037	0.0001	0.0076	0.0022	0.0105	0.0008	0.0075
75	0.0014	0.0057	0.0007	0.0053	0.0029	0.0040	-0.0009	0.0070	0.0017	0.0107	0.0007	0.0077
100	0.0012	0.0058	0.0004	0.0055	0.0027	0.0044	-0.0015	0.0070	0.0011	0.0109	0.0001	0.0080
	INRIM		UME		CMI		BEV		IMT		LPM	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	0.0012	0.0060	0.0000	0.0067	0.0007	0.0088	0.0050	0.0151	0.0004	0.0071	0.0038	0.0164
50	0.0008	0.0037	0.0007	0.0056	0.0018	0.0065	0.0040	0.0130	0.0009	0.0054	0.0050	0.0162
75	0.0002	0.0037	0.0008	0.0054	0.0021	0.0062	0.0046	0.0123	0.0009	0.0051	0.0048	0.0159
100	0.0002	0.0042	0.0005	0.0055	0.0015	0.0062	0.0032	0.0121	0.0002	0.0053	0.0037	0.0159
	IMBiH		CEM		KRISS		MKEH		MSA		PTB press. Bal.	
P	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
kPa	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2	mm^2
25	0.0020	0.0147	0.0019	0.0092	0.0009	0.0084	0.0123	0.0422	0.0013	0.0105		
50	0.0020	0.0140	0.0009	0.0075	0.0015	0.0075	0.0142	0.0279	0.0005	0.0067		
75	0.0013	0.0134	0.0001	0.0072	0.0014	0.0074	0.0138	0.0232	0.0011	0.0058	-0.0002	0.0040
100	0.0008	0.0135	-0.0034	0.0074	0.0011	0.0076	0.0121	0.0211	0.0009	0.0058	-0.0006	0.0044

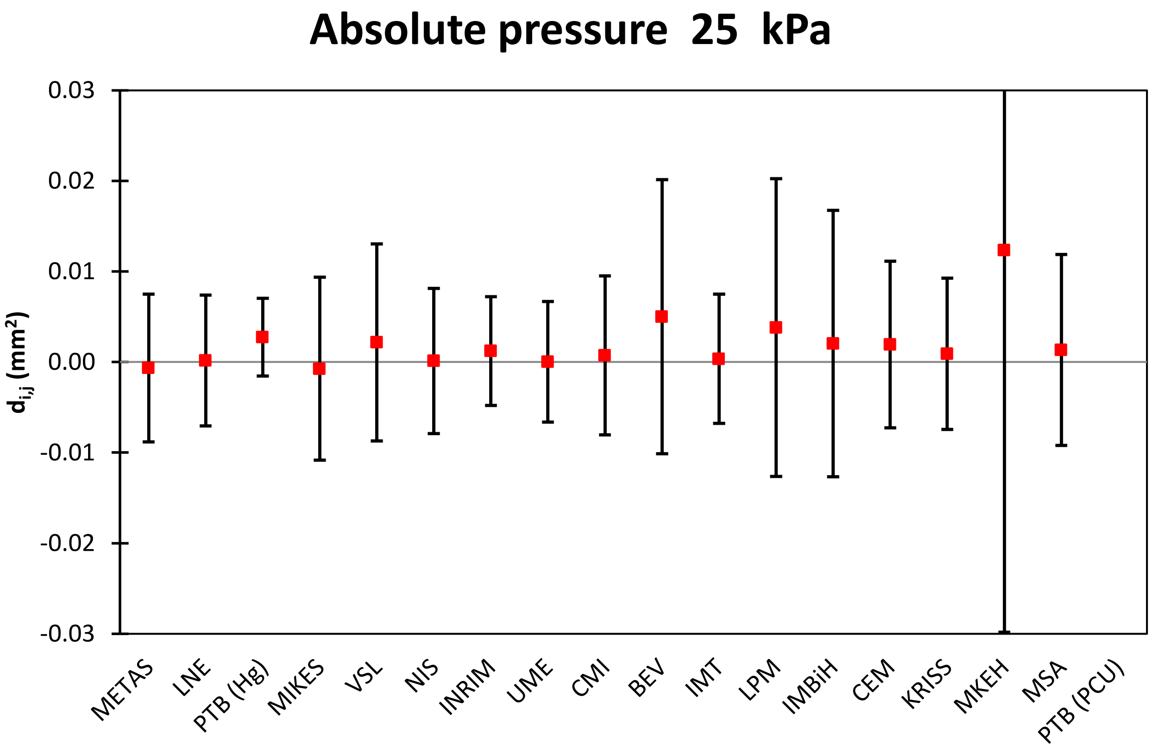

Figure 6a: Offset respective to the reference value of CCM.P-K2 and associated expanded uncertainty at 25 kPa for absolute pressure.

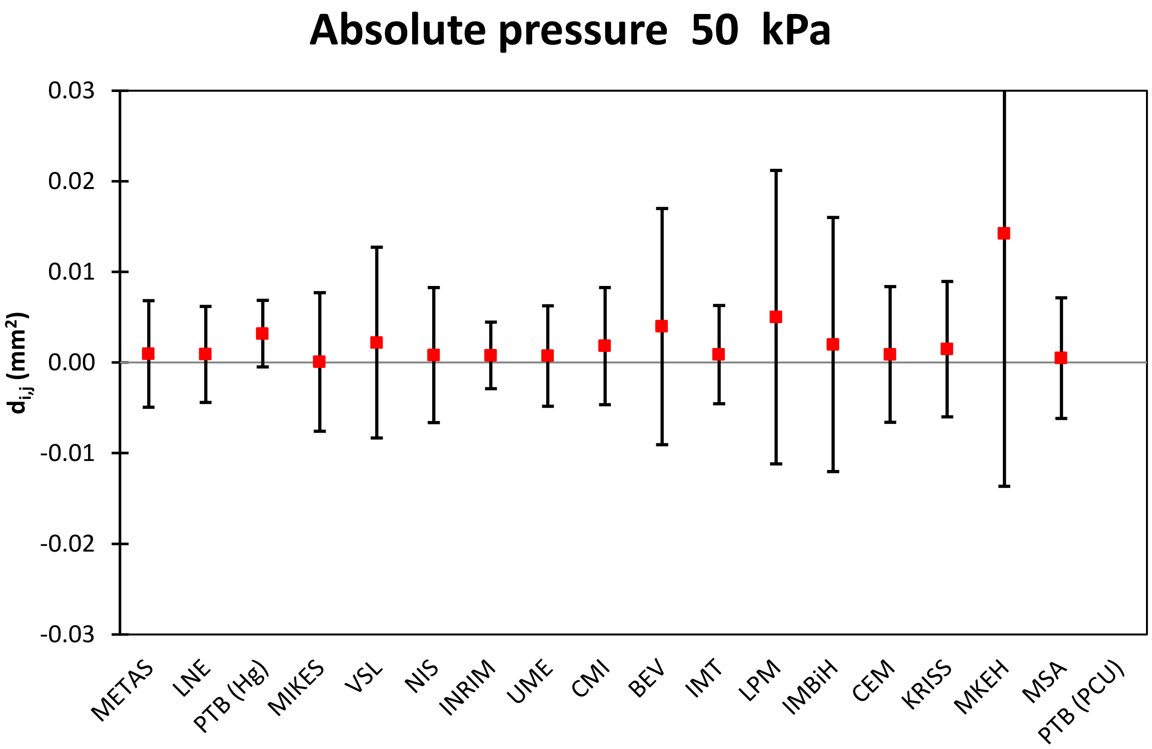

Figure 6b: Offset respective to the reference value of CCM.P-K2 and associated expanded uncertainty at 50 kPa for absolute pressure.

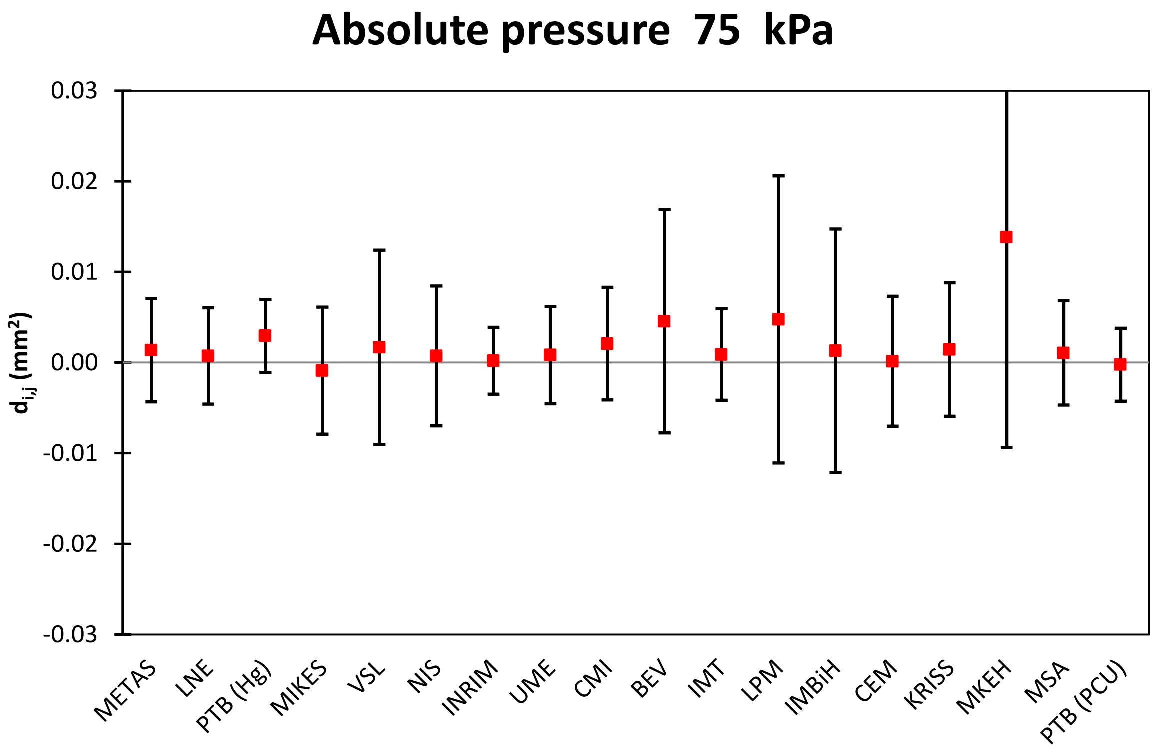

Figure 6c: Offset respective to the reference value of CCM.P-K2 and associated expanded uncertainty at 75 kPa for absolute pressure.

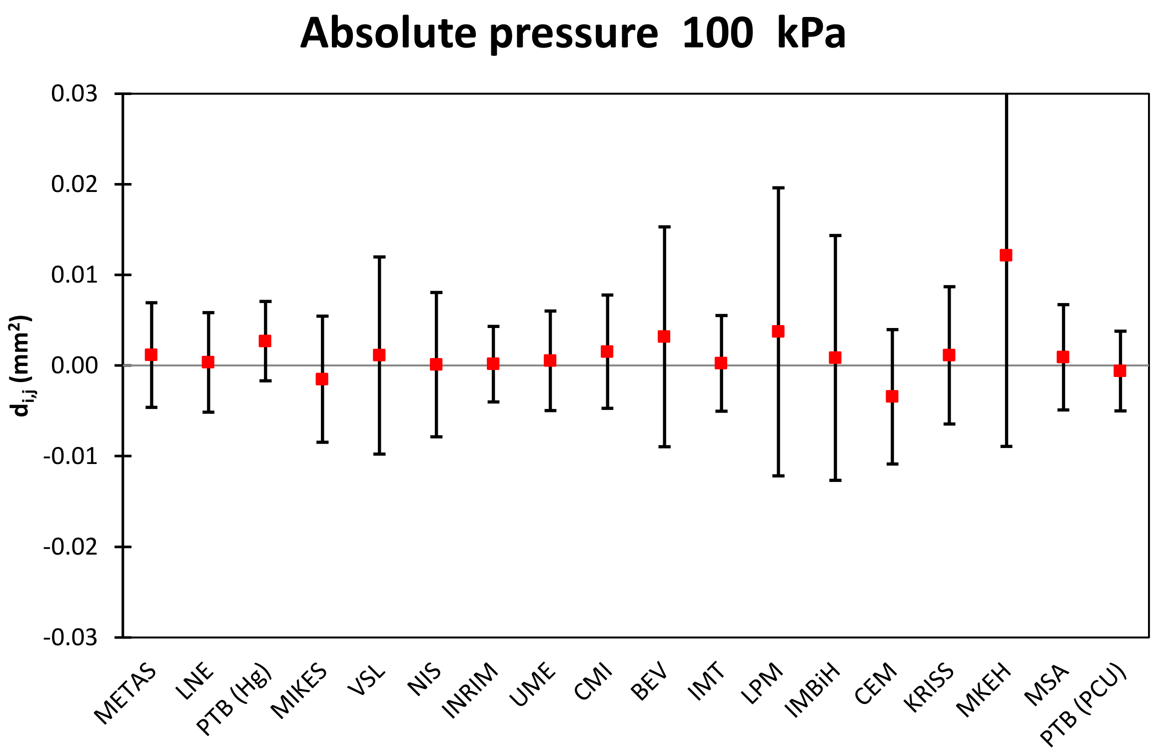

Figure 6d: Offset respective to the reference value of CCM.P-K2 and associated expanded uncertainty at 100 kPa for absolute pressure.

14 Conclusion

The project EURAMET 1041 which is the comparison EURAMET.M.P-K8 attracted a lot of interest within the EURAMET community with 23 participants for gauge pressure and 17 participants for absolute pressure. Only one participant, SMU, never provided the results.

The transfer standard was a piston-cylinder of 9.8 cm^2 and was circulated without major problems from June 2009 to January 2012.

The transfer standard has demonstrated an excellent stability with a change of mass that has an influence of less than 2 ppm on the first nominal pressure and an effective area determined by dimensional measurement in agreement within 2 ppm before and after circulation.

The reference value, for gauge as well as absolute pressure, has been determined based on the weighted mean of the measurements provided by the participants, with a primary definition, and members of EURAMET. The consistency check has demonstrated the validity of the reference value according to the uncertainty provided by the laboratories.

The equivalence of the participants with the reference value, in gauge pressure, is realized at all nominal pressure by 20 participants out of 22. For the two remaining participants the equivalence is not realized on only a limited number of nominal pressures.

The equivalence respective to the reference value, in absolute pressure, is realized by the 17 participants, on all nominal pressures.

The pair-wise degree of equivalence has been defined through an equation. The calculation of the effective value has shown that the equivalence is realized as long as there is no problem with the equivalence respective to the reference value.

The link to the comparison CCM.P-K6 in gauge pressure has been made through the measurement of VSL and PTB. The equivalence, on most of the nominal pressures, with the reference value of the CCM.P-K6, has been demonstrated by the 22 participants who provided results.

The link to the comparison CCM.P-K2 has been made through the measurements of INRIM and of the PTB with the mercury manometer. The equivalence of all the results of the 17 participants has been demonstrated with the reference value of CCM.P-K2.

15 References

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