<u>Final Report</u>

Final report on EURAMET.M.P-K4.2010 – Key and Supplementary Comparison of National Pressure Standards in the Range 1 Pa to 15 kPa of Absolute and Gauge Pressure

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Abstract

This report describes a EURAMET comparison of five European National Metrology Institutes in low gauge and absolute pressure in gas (nitrogen), denoted as EURAMET.M.P-K4.2010. Its main intention is to state equivalence of the pressure standards, in particular those based on the technology of force-balanced piston gauges such as e.g. FRS by Furness Controls, UK and FPG8601 by DHI-Fluke, USA. It covers the range from 1 Pa to 15 kPa, both gauge and absolute. The comparison in absolute mode serves as a EURAMET Key Comparison which can be linked to CCM.P-K4 and CCM.P-K2 via PTB. The comparison in gauge mode is a supplementary comparison.

The comparison was carried out from September 2008 till October 2012. The participating laboratories were the following: CMI, INRIM, LNE, MIKES, PTB-Berlin (absolute pressure 1 kPa and below) and PTB-Braunschweig (absolute pressure 1 kPa and above and gauge pressure). CMI was the pilot laboratory and provided a transfer standard for the comparison. This transfer standard was also laboratory standard of CMI at the same time which resulted in a unique and logistically difficult star comparison.

Both in gauge and absolute pressures all the participating institutes successfully proved their equivalence with respect to the reference value and all also proved mutual bilateral equivalences in all the points. All the participating labs are also equivalent with the reference values of CCM.P-K4 and CCM.P-K2 in the relevant points. The comparison also proved ability of FPG8601 to serve as a transfer standard.

Content

1. Introduction

The digital non-rotating pressure balance FPG8601 manufactured by Fluke/DH-Instruments is based on a 10 cm^2 non-rotating tungsten-carbide piston-cylinder with a conical gap, see [1.1]. It is used for gauge and absolute pressures in the range from 1 Pa to 15 kPa. The claimed uncertainties of this instrument are rather low, so it is not easy to find a suitable transfer standard to prove them. To use this instrument itself for this purpose seemed the only solution. There was already some experience with such a solution gained during EURAMET.M.P-S2, see [1.2].

This comparison was originally initiated as a EURAMET Project No. 1047. At the EURAMET TCM meeting held in Malta in March 2009, it was agreed to be converted in a key/supplementary comparison in the range from 1 Pa to 15 kPa of absolute and gauge pressure. The comparison in absolute mode serves as a EURAMET Key Comparison (KC) which can be linked to CCM.P-K4 and CCM.P-K2 via PTB. The comparison in gauge mode is a supplementary comparison. The main intention of this comparison is to state equivalence of the National Metrology Institutes' (NMIs) pressure standards, in particular those based on the technology of force-balanced piston gauges such as e.g. FRS by Furness Controls, UK and FPG8601.

The Czech Metrology Institute (CMI) agreed to be the pilot laboratory and provide a transfer standard (TS) for the comparison. This TS is also laboratory standard (LS) of CMI at the same time which resulted in a star comparison. Each LS was evaluated in its own institute, so that they are considered to be independent.

The nominal pressure points p_n were 1 Pa (optional), 3 Pa, 10 Pa, 30 Pa, 100 Pa, 300 Pa, 1 kPa, 3 kPa, 10 kPa and 15 kPa both absolute and gauge. Measurements were performed in two cycles on two different days. Nitrogen was used as pressure transmitting medium.

2. Participants

For budgetary and practical reasons, the number of the participants had to be reduced (compared to the number of participants of Project No. 1047) to five, all from European Union plus Schengen states.

The participating laboratories were the following:

- Czech Metrology Institute (CMI) - pilot laboratory
- Istituto Nazionale di Ricerca Metrologica (INRIM)
- Laboratoire national de métrologie et d’essais (LNE)
- Mittatekniikan keskus (MIKES)
- Physikalisch-Technische Bundesanstalt (PTB)

The measurements at PTB were carried out in two laboratories:

1) in the Vacuum metrology laboratory in Berlin for absolute pressures between 1 Pa and 1 kPa, and
2) in the Pressure metrology laboratory in Braunschweig for absolute pressures between 1 kPa and 15 kPa as well as for gauge pressures between 3 Pa and 10 kPa.

The primary standards of PTB, mainly Hg-column and static expansion system are crucial, because they represent different physical principle of the primary standards. Up to 1 kPa the vacuum metrology section of PTB provides the respective National Standard, beyond 1 kPa the pressure laboratory of PTB.
Moreover, during the last comparison in October 2012, CMI and INRIM also managed a supplementary comparison (EURAMET.M.P-S12) with the same standards in the low negative gauge pressure from 300 Pa to 15 kPa.

Tab. 2.1: Comparison schedule

Measurement time	Institute	Place	Range
IX - X 2008	MIKES	CMI	gauge and absolute
X 2010	INRIM	INRIM	gauge
VI 2011	LNE	CMI	gauge and absolute
X 2011	PTB	PTB	gauge and absolute
X 2012	INRIM	CMI	absolute

3. Standard of CMI

The standard of CMI (serving in the same time as a transfer standard) was a digital non-rotating piston gauge FPG8601, manufactured by Fluke/DH-Instruments, USA and identified by serial number 107, in combination with a reference vacuum gauge 627B1TDD1B manufactured by MKS Instruments, USA, identified by serial number 000754687. The effective area was evaluated by the measurement of the piston-cylinder geometry and validated by the cross-floating techniques, see [3.1]. It is the same both for gauge and absolute modes. An intercomparison with the Slovak SMU was performed in 2002, with the Finnish MIKES in 2003, within EUROMET.M.P-S2 in 2006 and COOMET.M.P-K14 in 2009. It also takes part in CCM.P-K4.2012 and also in the negative gauge pressure range within EURAMET.M.P-S12.
Its uncertainty (for k = 1) in absolute mode equals 0.01 Pa + $1.4{\cdot}10^{-5}{\cdot}p$, where p is in pascals.
Its uncertainty (for k = 1) in gauge mode equals 0.01 Pa + $1.4{\cdot}10^{-5}{\cdot}p$, where p is in pascals.
A CDG (MKS Baratron of type 698A01TRA, identified by serial number 000043657, with control unit of type 270, identified by serial number 000042869) with a set of valves served as a zero indicator and as a separator between both standards. This instrument is capable of reading via a notebook with software FPG TOOLS 3.03e. It was provided by CMI with a calibration for both plus and minus indications with an emphasis on the range around zero. However, during the measurements the CDG indication was kept as near to zero as possible.

4. Standard of INRIM

The standard of INRIM was a digital non-rotating piston gauge FPG8601 manufactured by DH-Instruments, identified by serial number 132. It uses the different values of effective area for gauge and absolute modes.

Its uncertainty (for k = 1) in absolute mode equals 0.01 Pa + $1.5 \cdot 10^{-5} \cdot p$, where p is in pascals.

Its uncertainty (for k = 1) in gauge mode equals 0.01 Pa + $1.5 \cdot 10^{-5} \cdot p$, where p is in pascals.

The effective area was evaluated by the measurement of the piston-cylinder geometry and validated by the cross-floating techniques in gauge mode. In absolute mode the digital non-rotating piston gauge was compared with the Hg-manometer primary standard of INRIM. Five measurement cycles were carried out in the range from 7 kPa to 15 kPa with nitrogen. The effective cross sectional area of the piston agreed within the uncertainties.

It also takes part in EURAMET.M.P-S12 negative gauge pressure range.

5. Standard of LNE

The LNE pressure standard used for the comparison was a digital non-rotating piston gauge FPG8601 manufactured by DH-Instruments, identified by serial number 109. The effective area of the piston cylinder assembly is determined in gauge mode between 2500 Pa and 15 000 Pa by direct comparison with a PG 7607 pressure balance equipped with a 20 cm² piston-cylinder unit (serial number 205). In absolute mode, the FPG has been compared with the same pressure standard. The relative deviation between the two modes is 1.2×10^{-6}. A detailed metrological characterization of the standard is presented in [5.1].

Following the budget presented in table 5.1, the expanded uncertainty of the effective area is estimated to be $1.7 \times 10^{-5} \times S$. The uncertainty budget of the pressure measured by the FPG is presented in table 5.2. The standard uncertainty of the pressure measured has been estimated in the gauge mode to be 0.0050 Pa + $1.0 \times 10^{-5} \times p$ and in the absolute mode to be 0.010 Pa + $1.0 \times 10^{-5} \times p$, where p is in pascals.

In low absolute pressure the standard has been compared with a 100 Pa-capacitance diaphragm gauge and a spinning rotor gauge detailed in [5.2].

Table 5.1: Effective area uncertainty analysis.

Effective area at null pressure	
Type A . Uncertainty due to the modelling	$2{,}5 \times 10^{-6} \times S$
Type B . Uncertainty due to the standard	$8{,}0 \times 10^{-6} \times S$
Uncertainty due to the temperature (±0,2 °C)	$1{,}0 \times 10^{-6} \times S$
Uncertainty due to the head correction (±3 mm)	$1{,}1 \times 10^{-7} \times S$
Uncertainty due to the verticality of the piston	$7{,}0 \times 10^{-7} \times S$

Table 5.2: FPG pressure uncertainty budget

Parameter	Standard uncertainty mPa	Standard uncertainty $\times p$
type A		
Repeatability	4	4.5×10^{-6}
type B		
Resolution	0.289	
Effective area		8.5×10^{-6}
Calibration mass		1.2×10^{-6}
Calibration mass density		2.3×10^{-6}
Cell linearity		1.7×10^{-6}
PC Temperature		1.0×10^{-6}
Head correction		1.1×10^{-7}
Verticality		1.9×10^{-7}
Stability of the cell		1.0×10^{-6}
Cell temperature		1.4×10^{-6}
Force correction	0.467	
gravity		1.0×10^{-7}
Effective area stability		5.0×10^{-6}
In absolute mode		
vacuum	5	

6. Standard of MIKES

The standard of MIKES was a digital non-rotating piston gauge FPG8601 manufactured by Fluke/DH Instruments, USA, identified by serial number 105 (base) and 106 (piston cylinder unit), in combination with a reference vacuum gauge 627B1TDD1B manufactured by MKS Instruments, USA, identified by serial number 000661328. It uses the same value of effective area both for gauge and absolute modes. The effective area was determined by the cross-floating techniques, see [6.1]. During the comparison, the effective area was traceable to LNE. From the year 2012 the effective area is traceable to MIKES. The effective area values are in good agreement with both traceabilities. The reference vacuum is traceable to PTB. An intercomparison was performed in 2003 with CMI, within EURAMET 650 in 2002, EURAMET 676 in 2002 and EURAMET 1151 in 2010.

Its uncertainty (for k = 1) in absolute mode equals 0.035 Pa + $2\cdot10^{-5}\cdot p$, where p is in pascals.

Its uncertainty (for k = 1) in gauge mode equals 0.01 Pa + $2\cdot10^{-5}\cdot p$, where p is in pascals.

7. Standards of PTB

7.1 PTB Primary Hg-manometer

The Hg-manometer is a modified commercial dual-cistern Hg-manometer with properties and measurement conditions given in Table 1 (all uncertainties are standard ones).

Table 7.1. Details of the PTB primary Hg-manometer

Manufacturer & Model	*Schwien Engineering*, USA
Measurement range in kPa	0 – 180
Operating gas	N_2, other gases possible
Height measurement method	Laser interferometry & capacitance
Local gravity acceleration (g) in m/s^2	9.812533
Relative uncertainty of g in 10^{-6}	0.53
Height difference between LS and TS (h_0) in cm	-79.9
Uncertainty of h_0 in mm	0.5
Resid. pressure in the reference column (p_{vac}), Pa	0.1
Room temperature (t_R) in °C	19.96 – 20.28
Traceability	PTB

The position of the mercury menisci in the cisterns is detected with a capacitance system. The height position of the movable cistern is measured with a laser interferometer. Details of the Hg-manometer are presented in [7.1-7.3, 7.8]. It was employed in comparisons CCM.P-K10, CCM.P-K1.c, CCM.P-K2, CCM.P-K6 and EURAMET.M.P-K8 [7.4-7.9], among others.

The absolute pressure (p) in the reference level of the TS was calculated by:

$$p = \rho_{\mathrm{Hg}}\, g\, l_{\mathrm{a}} - \rho_{\mathrm{N_2}}(t_{\mathrm{N_2}}, p) h_{\mathrm{p}}\, g + \rho_{\mathrm{N_2}}(t_{\mathrm{R}}, p)(h_{\mathrm{p}} - h_0) g + p_{\mathrm{vac}} \text{ with} \tag{7.1}$$

ρ_{Hg} – mercury density, l_{a} – height of the mercury column, $\rho_{\mathrm{N_2}}$ – nitrogen density as a function of temperature and pressure, $t_{\mathrm{N_2}}$ – nitrogen temperature inside the manometer enclosure, h_{p} – height difference between the Hg-manometer reference level and the gas pressure line at the exit from the manometer enclosure, and other symbols as defined before. The mean mercury and nitrogen densities as functions of temperature and pressure were calculated according to [7.2] and [7.10], respectively.

The type B uncertainty contribution $u_{\mathrm{B}}(p)$ was calculated numerically using

$$u_{\mathrm{B}}(p) = \left\{ \sum_{l=1}^{n} \left[p(q_1, \ldots, q_l + u(q_l), \ldots, q_n) - p(q_1, \ldots, q_l, \ldots, q_n) \right]^2 \right\}^{0.5}, \tag{7.2}$$

where each of the n input quantities (q_l) entering the model equation (7.1) is consecutively varied by adding its uncertainty $u(q_l)$ to its value. These input quantities are listed in Table 2 together with the resulting contributions to the uncertainty of minimum and maximum pressure in the actual comparison. In addition, the instability of the Hg-manometer is considered as an uncertainty contribution (u_{instab}), which was

Table 2. Type B uncertainty budgets of the PTB Hg-manometer for 1 and 15 kPa.

Quantity	Uncertainty		$u_B(p)/p \times 10^6$ @ 1 kPa	$u_B(p)/p \times 10^6$ @ 15 kPa
Gravity acceleration variation in 0.8 m	$2.5 \cdot 10^{-5}$	m/s^2	0.26	0.26
Density of gas due to height difference	$1.0 \cdot 10^{-3}$	rel.	0.09	0.09
Residual pressure in LS	$8.3 \cdot 10^{-2}$	Pa	83.0	5.53
t of pressure line inside enclosure	0.44	°C	0.11	0.11
t of pressure line outside enclosure	0.78	°C	1.53	1.61
LS verticality	1.0	mm/m	0.50	0.50
Density of Hg	$0.5 \cdot 10^{-6}$	rel.	0.50	0.50
t of Hg	$2.3 \cdot 10^{-2}$	°C	3.11	3.79
h of Hg, interferometer, const. part	$1.2 \cdot 10^{-4}$	mm	15.4	1.02
h of Hg, interferometer, proport. part	$1.2 \cdot 10^{-7}$	rel.	0.12	0.12
h of Hg, interferometer, zero drift	$1.7 \cdot 10^{-4}$	mm	23.0	1.54
h of Hg, capacitance bridge sensitivity	$5.8 \cdot 10^{-5}$	mm	7.68	0.51
Air pressure → *h* of Hg, interferometer	14	Pa	0.04	0.04
Air temperat. → *h* of Hg, interferometer	$2.3 \cdot 10^{-2}$	°C	0.02	0.02
Air humidity → *h* of Hg, interferometer	10	%	0.09	0.09
Tilt of movable mercury cistern	$3.0 \cdot 10^{-4}$	rad	1.75	0.12
h of Hg, N_2 dielectric constant	0.1	rel.	0.07	0.07
Combined type B uncertainty			88	7.2

derived from results of repeated comparisons against the same pressure balances over more than 2 decades. The observed maximum changes are considered as the width of the rectangular distribution characterising the instability of the Hg manometer. The relative standard uncertainty associated with the instability, $u_{instab}(p)/p$, and the combined uncertainty, $u(p)$, are expressed by:

$$u_{instab}(p)/p = 4.3 \cdot 10^{-6} - 1 \cdot 10^{-8} \times (p/\text{kPa}), \tag{7.3}$$

$$u(p) = [u^2_B(p) + u^2_{instab}(p)]^{0.5} \tag{7.4}$$

with final uncertainties at the comparison's pressure points listed in Table 3.

Table 3. Type B (u_B) and combined (u) uncertainties of PTB Hg-manometer

p / kPa	$u_B / p \times 10^6$	$u / p \times 10^6$	u / Pa
1	88	88	0.088
3	30	30	0.090
10	9.8	11	0.11
15	7.2	8.4	0.13

7.2 PTB digital pressure balance (absolute mode)

The physical principle of the FRS5 was described in some detail in 1999 [7.11]. The range of the instrument in both gauge and absolute mode is 1 Pa to 11 kPa. Some improvements in the commercial instrument have been made since then: A so called “zero” setting allows the user to disconnect the piston from the balance and to put an internal mass artefact (1 kg) on the same. This allows recording any drift of the balance

during the measurements. Also, an additional turbomolecular pump was added on the test side in order to reach the base pressure more rapidly. At PTB some more dosing valves were added to the commercial instrument in order to get more stable gas flows into the system and therefore more stable pressures.
The effective cross sectional area of the piston was determined by comparison with the Hg-manometer primary standard of PTB in the range from 1 kPa up to 10 kPa both in absolute mode as well in the gauge mode. Both values agreed within the uncertainties. In absolute mode, helium and nitrogen were used to determine the effective area in order to check, if there would be any dependence of the effective area on the mean free path of the atom's respective molecules, which was not the case. Also, there was no significant dependence of the effective cross section area on pressure. In addition, the effective cross section area determined by comparison with the Hg-manometer agreed well within the uncertainties with the geometrical data obtained from measurements of piston and cylinder by a UKAS accredited laboratory. For these reasons, it was concluded that within the standard uncertainty the effective piston area does not depend on the flow around it, respectively the test pressure.
Standard uncertainty of the FRS5 in the absolute mode equals

$$u_{\mathrm{FRSa}}(p/\mathrm{Pa}) = \sqrt{1.73\cdot10^{-4} + 1.08\cdot10^{-8}\cdot p/\mathrm{Pa} + 5.54\cdot10^{-10}\cdot p^2/\mathrm{Pa}^2} \qquad (7.5)$$

7.3 PTB static expansion system

The pressure generator/primary standard is a static expansion system, called SE2, in which pressures are generated by expanding gas of known pressure from a small volume into a much larger volume. The system was described in detail in [7.11-7.13]. The regular operational range of SE2 is 0.1 Pa up to 1 kPa, by which the agreed comparison range could be covered.

7.4 PTB digital pressure balance (gauge mode)

The force compensated digital piston gauge is an FRS5 instrument manufactured by *Furness Controls*, UK [7.14] and has been operated at PTB for more than 10 years. The properties of the FRS5 are presented in Table 4. The effective area of the FRS5 is traceable to the PTB primary Hg-manometer described in section 7.1.
The gauge pressure (p_e) in the reference level of the CDG was calculated by:

$$p_e = \frac{F}{A_0\left[1+\left(\alpha_\mathrm{p}+\alpha_\mathrm{c}\right)\cdot\left(t-t_0\right)\right]} + g\left(\rho_\mathrm{l}-\rho_\mathrm{a}\right)h\,, \qquad (7.6)$$

where the parameters have the following meaning:
F is additional force measured with the mass balance when pressure p_e is applied;
A_0 is effective area of the piston-cylinder assembly;
α_p and α_c are thermal expansion coefficients of the piston and cylinder materials, respectively;
t_0 is reference temperature, t_0 = 20 °C;

g is local gravity acceleration;

ρ_1 is density of the pressure-transmitting gas;

ρ_a is air density;

h is the difference between FRS5 and CDG.

Table 4. Details of the PTB force compensated digital piston gauge and measurement conditions

Manufacturer & Model	*Furness Controls*, FRS5
Measurement range in kPa	0 – 11
Operating gas	N_2, other gases possible
Material of piston	Invar
Material of cylinder	Invar
Operation mode	absolute and gauge
Zero-pressure effective area (A_0) at ref. temperature in cm^2	45.36038
Relative uncertainty of A_0 in 10^{-6}	13
Mass balance resolution in mg	1
Linear thermal expansion coefficient of PCA ($\alpha_p + \alpha_c$) in $°C^{-1}$	$\leq 4 \cdot 10^{-6}$
Reference temperature (t_0) in °C	20
Local gravity (g) in m/s^2	9.812533
Relative uncertainty of g in 10^{-6}	0.53
Height difference between laboratory standard (LS) and TS (h, positive if LS is higher than TS)* in cm	12.19
Uncertainty of h in mm	0.5
Piston-cylinder temperature during measurements in °C	20.43 – 21.43
Ambient pressure during measurements in hPa	1000.35 – 1003.66
Traceability	PTB

* *The value of 12.19 cm presents the difference between the PTB FRS and the CDG (Baratron) of the transfer standard. The difference between the CMI FPG8601 and the CDG (Baratron) was 32.60 cm.*

The uncertainty of the pressure measured with the FRS5 was determined from the uncertainty of A_0, uncertainty of the mass balance and an experimental uncertainty contribution derived from comparison measurements between the actual FRS5 and another FRS5 operated in the PTB Vacuum laboratory in Berlin in the range 1 Pa to 10 kPa [7.15]. In particular this last uncertainty contribution is the biggest at pressures below 1 kPa. (Note: As the time and extent of the pressure measurements between the FRS5 of Braunschweig and Berlin was limited, a rather conservative uncertainty estimation of the results was performed which, presumably, led to an overestimated uncertainty.)

Finally, the combined standard uncertainty of the FRS5 is expressed by equation:

$$u(p) = 7\ \text{mPa} + 1.3 \cdot 10^{-5} p + 3.33 \cdot 10^{-2} \times \lg(p/\text{Pa})\ \text{Pa} - 6.89 \cdot 10^{-3} \times \lg^2(p/\text{Pa})\ \text{Pa}. \qquad (7.7)$$

8. Procedures of the comparison

8.1 Comparisons of the digital pressure balances FPG

The nominal pressure points p_n were 1 Pa (optional), 3 Pa, 10 Pa, 30 Pa, 100 Pa, 300 Pa, 1 kPa, 3 kPa, 10 kPa and 15 kPa both absolute and gauge. Measurements were made in 2 cycles for absolute pressure and 2 cycles for gauge pressure. Each cycle was performed on a different day. The pressure transmitting medium was dry nitrogen (dry is the gas entering FPG stand, however the FPG adjusts relative humidity of the gas to approximately 50 % via its internal reservoir of water).

The two standards to be compared were located close to each other to keep the pressure line between the two instruments as short as possible. There was no height difference between the reference levels of both standards within an uncertainty of about 1 mm. (Pressure uncertainty of small pressure head is included in the declared uncertainty of the FPG of the CMI.) Horizontality of both the TS and the LS were checked with the built-in spirit levels. Both TS and LS were switched on at least 24 h before the start of the comparison. Linearity of the mass comparators of both the TS and the LS were checked before the start of the comparison measurements.

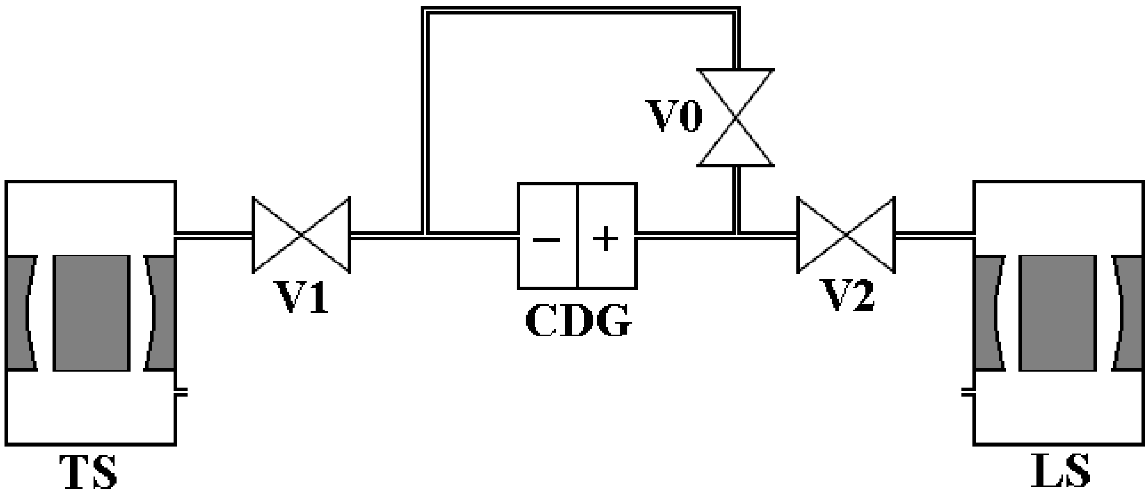

Fig. 8.1: Arrangement of the TS and LS in the gauge mode.

The comparison measurements were performed using a differential 1 torr (133 Pa) fullscale CDG as a zero indicator, see Fig. 8.1 and 8.2. A bypass line with a valve V0 connected the two sides of the zero pressure indicator to control its zero pressure reading. The zero indicating CDG was heated during absolute mode measurements, but not heated (but long term stabilized) during gauge mode measurements. The CDG was connected to both standards via tubings (bellows) that were as similar to each other as possible concerning their diameters and volumes. The by-pass valve V0 of the CDG did not induce large changes of pressure. For gauge mode measurements, both reference ports of TS and LS were left fully open to atmosphere, i.e. nothing connected to KF16 flanges. For absolute mode measurements; it was recommended to check (calibrate) the reference vacuum gauges by a vacuum meter at real working reference pressure value. It was performed by an SRG or another suitable vacuum gauge mounted between interconnected reference ports of TS and LS. The same gauge was used for zero checking of both TS and LS.

Before the start of the comparison measurements both standards were zeroed and then calibrated internally. (Check of the internal calibration was repeated every four hours.) Then both instruments were zeroed again and the zero was checked and recorded. Then the isolation valve (V1 or V2) between both standards was closed (but with CDG by-pass valve V0 remaining open). Only after this, the target nominal pressure was set by an FPG that was not connected to the CDG at the moment. Then the generated target pressure was set by the other FPG (filling also CDG). After stabilization, the zero of the CDG was read at the open by-pass valve V0. Then the by-pass valve V0 was closed and the isolating valve (V1 or V2) opened. After a stabilization of reading, 5 successive readings were taken by averaging outputs of FPGs and CDG during at least 1 min. After measuring a point, a check of the CDG zero drift (if sufficiently stable this checking did not need to be performed after every point) and check of the zero drifts of both standards were done. The results were corrected for these drifts.

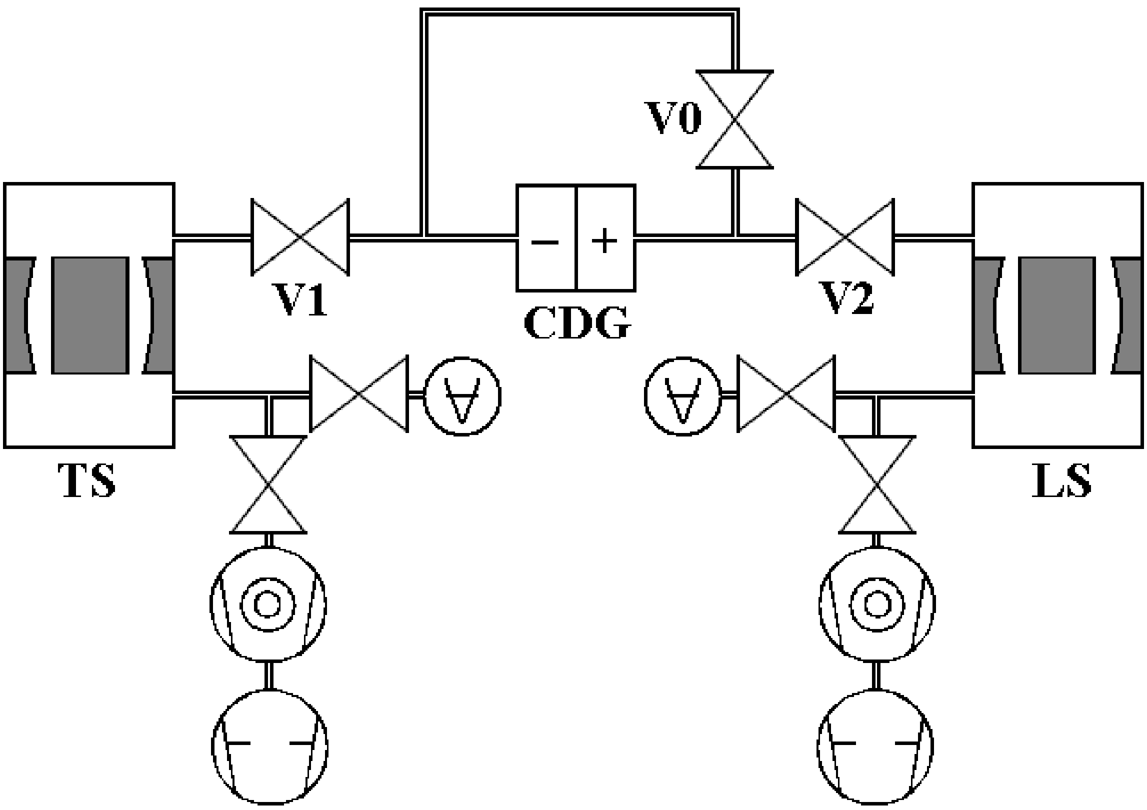

Fig. 8.2: Arrangement of the TS in the absolute mode.

8.2 Notes to comparison with the FRS5

In the gauge mode, the measurements included two measurement series at (3, 10, 30, 100, 300, 1000, 3000, 10000) Pa of gauge pressure. The arrangement of the TS and the LS was an analogy to Figure 8.1. The pressure ports of both instruments were separated by a CDG belonging to the TS. A bypass line with a valve connected both sides of the

CDG indicator to check its zero pressure reading. Several tests were carried out with different configuration of the reference ports of the TS and the LS to minimise instability of their readings caused by the ambient pressure fluctuations. Finally, following the prescriptions of the Technical protocol, it was decided to let the reference ports of both instruments opened to atmosphere. However, in this configuration, the instability of readings was considerable. As recommended in the Technical protocol, the TS was operated with moist nitrogen, whereas dry nitrogen was used in the LS. The installation of the TS, its operation and its data acquisition during the comparison was performed by the CMI staff. PTB reported its values at the level of CDG, see 7.4. A level difference between CDG and TS was taken into account by final evaluation, see chap. 9, eq. (9.1).
In the absolute mode, the measurements included two measurement series at (30, 100, 300, 1000) Pa of absolute pressure. As recommended in the Technical protocol, the TS was operated with moist nitrogen, whereas dry nitrogen was used in the LS. Influence of a level difference between CDG and TS was negligible.

8.3 Notes to comparison with the Hg-manometer

The measurements included two measurement series at (1, 3, 10, 15) kPa of absolute pressure. The measurement pressure lines of both instruments were connected with each other directly, and their reference lines were separated and evacuated independently. Consequently, their residual pressures could be different and were measured individually.

8.4 Notes to comparison with the static expansion system

In this case the recommended point of the comparison protocol, utilising a spinning rotor gauge (SRG) for zeroing the reference vacuum gauges could not be fulfilled for TS. There were some vibrations due to the construction works at PTB-Berlin at the time of comparison. It caused too high scatter of measurement at point 1 Pa. We tried to reduce it by doing some measurements with opened by-pass of the differential CDG. It helped a little, but in this way it was possible to reach only cca 1.5 Pa and the measurement set-up was hard to interpret. Therefore the pilot decided not to include the optional point 1 Pa in this case.

9. Evaluation of the comparison

The pressure defined from the TS (based on the CMI data and corrected for TS zero drift) in combination with the CDG reading was used to predict the pressure of the LS. This predicted value p_{Lp} was compared to the value p_{L} evaluated from the LS itself (also corrected for its zero drift).

Let p_{T} denote the pressure as determined by the TS (based on the CMI data) and p_{CDG} the pressure reading of the CDG.

Then for gauge mode and for absolute mode and nominal pressure p_{n} = 100 Pa and higher, where no thermal transpiration effect exists, the predicted pressure in the LS is given by [1.2]:

$$p_{\mathrm{Lp}} = p_{\mathrm{T}} - \left(p_{\mathrm{CDG}} - (p_0 + p_0')/2\right) \cdot C_{\mathrm{CDG}} + p_{\mathrm{h}}\,, \tag{9.1}$$

where is

p_0 zero reading of the CDG before the measurement,

p_0' zero reading of the CDG after the measurement,

C_{CDG} calibration factor of the CDG,

p_{h} head pressure, if relevant.

The head pressure had a significant value only in the comparison with FRS5 in gauge mode. (In all other cases it was lower than the relevant part of uncertainty budget of the TS.) In this case it was calculated as:

$$p_{\mathrm{h}} = h\left(\rho_{\mathrm{g}} - \rho_{\mathrm{a}}\right)g\,, \tag{9.2}$$

where is

h the level difference between TS and CDG,

ρ_{g} density of gas medium,

ρ_{a} density of air,

g acceleration due to gravity.

Because of unknown humidity of nitrogen and a slight difference between temperatures in the TS and the surrounding atmosphere (i.e. tubing walls) we took uncertainty of p_{h} as 1 %, but still it remained a minor component of the total uncertainty.

For nominal pressures lower than 100 Pa in absolute mode, the pressure in the LS can be predicted as [1.2]:

$$p_{\mathrm{Lp}} = \frac{p_{\mathrm{T}}(1+c_1) - \left(p_{\mathrm{CDG}} - (p_0 + p_0')/2\right)\cdot C_{\mathrm{CDG}}}{1+c_2}, \tag{9.3}$$

where c_1 and c_2 are thermal transpiration corrections. (Head pressure was always irrelevant here).

$$c_1 = f\,(p_{\mathrm{t}})\left(\sqrt{\frac{T_{\mathrm{CDG}}}{T_{\mathrm{T}}}} - 1\right), \tag{9.4}$$

where is

$f(p_{\mathrm{t}})$ thermal transpiration correction factor (between 0 and 1),
T_{CDG} absolute temperature of the CDG (about 318 K),
T_{T} absolute temperature of the TS.

$$c_2 = f\,(p_{\mathrm{t}})\left(\sqrt{\frac{T_{\mathrm{CDG}}}{T_{\mathrm{L}}}} - 1\right), \tag{9.5}$$

where T_{L} is absolute temperature of the LS.

For each measurement i (i = 1…5) on day j (j = 1, 2) at the defined target pressure the difference d_{ij} between the two systems is calculated as:

$$d_{ij} = p_{\mathrm{L}ij} - p_{\mathrm{Lp}ij}\,. \tag{9.6}$$

For each nominal pressure a single value of d is calculated by taking the mean of all measurements of the two days:

$$d = \frac{1}{10}\cdot\sum_{j=1}^{2}\sum_{i=1}^{5} d_{ij}\ . \tag{9.7}$$

The uncertainty u_d of d is determined by the uncertainties of p_{T}, p_{L}, p_{h}, p_{CDG}, p_0, p_0', C_{CDG}. The uncertainties of p_{T}, p_{L}, p_{h} and p_{CDG} (denoted as u_{T}, u_{L}, u_{h} and $u_{C_{\mathrm{CDG}}}$) were already listed in Sections 3 to 8. Since the sensitivity coefficient for $u_{C_{\mathrm{CDG}}}$ varied significantly with pressure, the maximum value was used. Because the CDG was calibrated by the FPG8601 of CMI, we assume a full correlation between u_{C} and $u_{C_{\mathrm{CDG}}}$. The uncertainties of p_{CDG}, p_0, p_0', are inaccurate by the scatter and short term instabilities which are revealed in the scatter of repeat calibrations. Therefore these uncertainties are being considered in the experimental standard deviation of the mean of d. Since n = 10 measurements were taken with an effective degree of freedom of 9, the square of the standard deviation of the mean of the repeated measurements $s_{d_{ij}}$ was multiplied by $(n-1)/(n-3)$, as suggested by Kacker and Jones [9.1].

Hence the total uncertainty u_d of d (determined by (9.1) and (9.6)) for each nominal pressure is then given by:

$$u_d = \sqrt{u_\mathrm{L}^2 + \left(u_\mathrm{T} + \left|p_\mathrm{CDG} - \frac{p_0 + p_0'}{2}\right| u_{C_\mathrm{CDG}}\right)^2 + \frac{n-1}{n-3}\left(s_{d_{ij}}\right)^2 + u_\mathrm{h}^2}\,. \quad (9.8)$$

And the total uncertainty u_d of d (determined by (9.3) and (9.6)) for each nominal pressure is then given by:

$$u_d = \left[u_\mathrm{L}^2 + \left(\frac{1+c_1}{1+c_2}u_\mathrm{T} + \left|p_\mathrm{CDG} - \frac{p_0 + p_0'}{2}\right|\frac{1}{1+c_2}u_{C_\mathrm{CDG}}\right)^2 + \frac{n-1}{n-3}\left(s_{d_{ij}}\right)^2 + \right.$$
$$\left. + \left(\frac{p_\mathrm{T}}{1+c_2}\right)^2 u_{c_1}^2 + \left(-p_\mathrm{T}\frac{(1+c_1)}{(1+c_2)^2} + \left(p_\mathrm{CDG} - \frac{p_0 + p_0'}{2}\right)\frac{C_\mathrm{CDG}}{(1+c_2)^2}\right)^2 u_{c_2}^2\right]^{1/2}. \quad (9.9)$$

We assumed the uncertainties of c_1 and c_2 as 10 % because of the high uncertainty of temperatures. Because their sensitivity coefficients vary slightly we took their maximum values.

The degree of equivalence of the bilateral comparison between CMI and institute x is:

$$E_{\mathrm{C}x} = \frac{d}{U_d}, \quad (9.10)$$

where $U_d = 2u_d$.

The problem in searching a reference value of the comparison is that the TS was also the LS of CMI. For each point in gauge or absolute mode there are k pairs of values d and U_d, as well as k declared uncertainties U, where k is the number of the LS, which took part in the comparison. Number k can differ for each point, because there were different numbers of LS measuring each point. Let us denote them by index x when they appear in a sum. Or by indexes $_\mathrm{I}$ (INRIM), $_\mathrm{L}$ (LNE), $_\mathrm{M}$ (MIKES), $_\mathrm{P}$ (PTB-FRS5 in gauge mode), $_\mathrm{Pm}$ (PTB-Hg-column), $_\mathrm{Pf}$ (PTB-FRS5 in absolute mode) and $_\mathrm{Ps}$ (PTB-static expansion), when they appear in a Table.

Moreover, during each comparison the target nominal pressure p_{n} was met with a different precision. Hence, we shifted all the $p_{\mathrm{Lpg}ijx}$ and $p_{\mathrm{Lpa}ijx}$ values to p_{n}. (Gauge mode is denoted by index $_{\mathrm{g}}$ and absolute mode is denoted by index $_{\mathrm{a}}$.) This also means a shift of all $p_{\mathrm{Lg}ijx}$ and $p_{\mathrm{La}ijx}$ values to the new values:

$$p_{\mathrm{Lng}ijx} = p_{\mathrm{n}} + d_{\mathrm{g}ijx}, \tag{9.11}$$

$$p_{\mathrm{Lna}ijx} = p_{\mathrm{n}} + d_{\mathrm{a}ijx}. \tag{9.11a}$$

Resulting in the mean value:

$$p_{\mathrm{Lng}x} = p_{\mathrm{n}} + \frac{1}{10} \cdot \sum_{j=1}^{2} \sum_{i=1}^{5} d_{\mathrm{g}ijx} = p_{\mathrm{n}} + d_{\mathrm{g}x}, \tag{9.12}$$

$$p_{\mathrm{Lna}x} = p_{\mathrm{n}} + \frac{1}{10} \cdot \sum_{j=1}^{2} \sum_{i=1}^{5} d_{\mathrm{a}ijx} = p_{\mathrm{n}} + d_{\mathrm{a}x}. \tag{9.12a}$$

It also means that $d_{\mathrm{gC}} = d_{\mathrm{aC}} = 0$.

So the reference values (accounting also CMI) for each mode can be calculated as:

$$p_{\mathrm{rg}} = \frac{1}{k+1} \cdot \left(p_{\mathrm{n}} + \sum_{x=1}^{k} p_{\mathrm{Lng}x} \right) = p_{\mathrm{n}} + \frac{1}{k+1} \cdot \sum_{x=1}^{k} d_{\mathrm{g}x} = p_{\mathrm{n}} + d_{\mathrm{g}}, \tag{9.13}$$

$$p_{\mathrm{ra}} = \frac{1}{k+1} \cdot \left(p_{\mathrm{n}} + \sum_{x=1}^{k} p_{\mathrm{Lna}x} \right) = p_{\mathrm{n}} + \frac{1}{k+1} \cdot \sum_{x=1}^{k} d_{\mathrm{a}x} = p_{\mathrm{n}} + d_{\mathrm{a}}. \tag{9.13a}$$

Let us also denote CMI by index $_{\mathrm{C}}$, the uncertainties of $d_{\mathrm{g}x}$ and $d_{\mathrm{a}x}$, i.e. u_d as defined by appropriate equation (9.8) or (9.9), as $u_{d\mathrm{g}x}$ and $u_{d\mathrm{a}x}$. The uncertainties of the reference values are (taking into account that each u_{dx} includes also u_{C}):

$$u_{\mathrm{rg}} = \frac{1}{k+1} \sqrt{\sum_{x=1}^{k} u_{d\mathrm{g}x}^{\ 2} - (k-1) u_{\mathrm{gC}}^{\ 2}}, \tag{9.14}$$

$$u_{\mathrm{ra}} = \frac{1}{k+1} \sqrt{\sum_{x=1}^{k} u_{d\mathrm{a}x}^{\ 2} - (k-1) u_{\mathrm{aC}}^{\ 2}}. \tag{9.14a}$$

Or, as the expanded uncertainties:

$$U_{\mathrm{rg}} = 2u_{\mathrm{rg}}, \tag{9.15}$$

$$U_{\mathrm{ra}} = 2u_{\mathrm{ra}}. \tag{9.15a}$$

Now we can determine the differences of the LSs from the reference values:

$$D_{\mathrm{g}x} = p_{\mathrm{Lng}x} - p_{\mathrm{rg}} = d_{\mathrm{g}x} - d_{\mathrm{g}}, \tag{9.16}$$

$$D_{\mathrm{a}x} = p_{\mathrm{Lna}x} - p_{\mathrm{ra}} = d_{\mathrm{a}x} - d_{\mathrm{a}}. \tag{9.16a}$$

For the TS, they simplify to:

$$D_{\mathrm{gC}} = -d_{\mathrm{g}}\,, \tag{9.17}$$

$$D_{\mathrm{aC}} = -d_{\mathrm{a}}\,. \tag{9.17a}$$

Hence we have the evaluation numbers:

$$E_{\mathrm{g}x} = \frac{D_{\mathrm{g}x}}{\sqrt{U_{\mathrm{g}x}{}^{2} + U_{\mathrm{rg}}{}^{2}}}\,. \tag{9.18}$$

$$E_{\mathrm{a}x} = \frac{D_{\mathrm{g}x}}{\sqrt{U_{\mathrm{a}x}{}^{2} + U_{\mathrm{ra}}{}^{2}}}\,. \tag{9.18a}$$

Mutual bilateral equivalences are:

$$E_{\mathrm{g}x\mathrm{y}} = \frac{D_{\mathrm{g}x} - D_{\mathrm{g}y}}{\sqrt{U_{d\mathrm{g}x}{}^{2} + U_{d\mathrm{g}y}{}^{2} - 2U_{\mathrm{gC}}{}^{2}}}\,, \tag{9.19}$$

$$E_{\mathrm{a}x\mathrm{y}} = \frac{D_{\mathrm{a}x} - D_{\mathrm{a}y}}{\sqrt{U_{d\mathrm{a}x}{}^{2} + U_{d\mathrm{a}y}{}^{2} - 2U_{\mathrm{aC}}{}^{2}}}\,. \tag{9.19a}$$

10. Results of the comparison

10.1 Results of the bilateral comparisons in gauge mode

Tab. 10.1 gives the bilateral differences d_X, their expanded (k = 2) uncertainties Ud_X and bilateral degrees of equivalence E_{CX} for the set of the bilateral comparisons of CMI and laboratory X in the gauge mode.

p_n/Pa	d_I/Pa	d_L/Pa	d_M/Pa	d_P/Pa	Ud_I/Pa	Ud_L/Pa	Ud_M/Pa	Ud_P/Pa	E_{CI}	E_{CL}	E_{CM}	E_{CP}
1	0,008	-0,001	-0,002		0,029	0,023	0,029		0,28	-0,02	-0,07	
3	0,004	-0,015	-0,010	0,009	0,029	0,023	0,030	0,083	0,16	-0,65	-0,32	0,11
10	0,003	-0,010	-0,014	-0,001	0,029	0,023	0,031	0,107	0,11	-0,44	-0,43	-0,01
30	0,003	-0,007	-0,007	0,013	0,030	0,024	0,032	0,104	0,11	-0,28	-0,23	0,13
100	0,006	-0,009	-0,002	0,023	0,033	0,026	0,035	0,114	0,19	-0,34	-0,06	0,20
300	0,006	-0,005	0,005	0,021	0,042	0,034	0,044	0,136	0,14	-0,13	0,11	0,15
1000	0,020	0,002	0,008	0,090	0,070	0,060	0,078	0,160	0,28	0,03	0,11	0,56
3000	0,055	0,007	0,016	0,125	0,154	0,142	0,184	0,237	0,36	0,05	0,09	0,53
10000	0,256	0,156	0,031	-0,094	0,461	0,402	0,525	0,490	0,55	0,39	0,06	-0,19
15000	0,371	0,186	0,041		0,656	0,571	0,766		0,56	0,33	0,05	

Tab. 10.1: Results of the bilateral comparisons in gauge mode.

10.2 Results to reference value in gauge mode

Tab. 10.2 gives the expanded (k = 2) uncertainty of the reference value U_g, differences D_{gX} of laboratory X from this reference value and the degrees of equivalence E_{gX} in the gauge mode. See also Fig. 10.1.

p_n/Pa	p_{rg}/Pa	U_{rg}/Pa	D_{gC}/Pa	D_{gI}/Pa	D_{gL}/Pa	D_{gM}/Pa	D_{gP}/Pa	E_{gC}	E_{gI}	E_{gL}	E_{gM}	E_{gP}
1	1,001	0,009	-0,001	0,007	-0,002	-0,003		-0,06	0,30	-0,14	-0,16	
3	2,998	0,018	0,002	0,007	-0,013	-0,007	0,011	0,08	0,25	-0,63	-0,27	0,23
10	9,996	0,022	0,004	0,007	-0,006	-0,009	0,003	0,14	0,24	-0,23	-0,31	0,05
30	30,000	0,022	0,000	0,003	-0,007	-0,008	0,013	-0,01	0,09	-0,30	-0,25	0,15
100	100,004	0,024	-0,004	0,003	-0,012	-0,006	0,019	-0,11	0,08	-0,46	-0,17	0,20
300	300,005	0,029	-0,005	0,000	-0,010	-0,001	0,016	-0,13	0,01	-0,30	-0,01	0,15
1000	1000,024	0,036	-0,024	-0,004	-0,022	-0,015	0,066	-0,40	-0,07	-0,47	-0,22	0,54
3000	3000,040	0,064	-0,040	0,015	-0,034	-0,025	0,084	-0,33	0,11	-0,36	-0,16	0,50
10000	10000,070	0,158	-0,070	0,186	0,086	-0,039	-0,164	-0,21	0,52	0,33	-0,09	-0,46
15000	15000,149	0,244	-0,149	0,221	0,037	-0,109		-0,30	0,42	0,09	-0,16	

Tab. 10.2: Results to reference value in gauge mode.

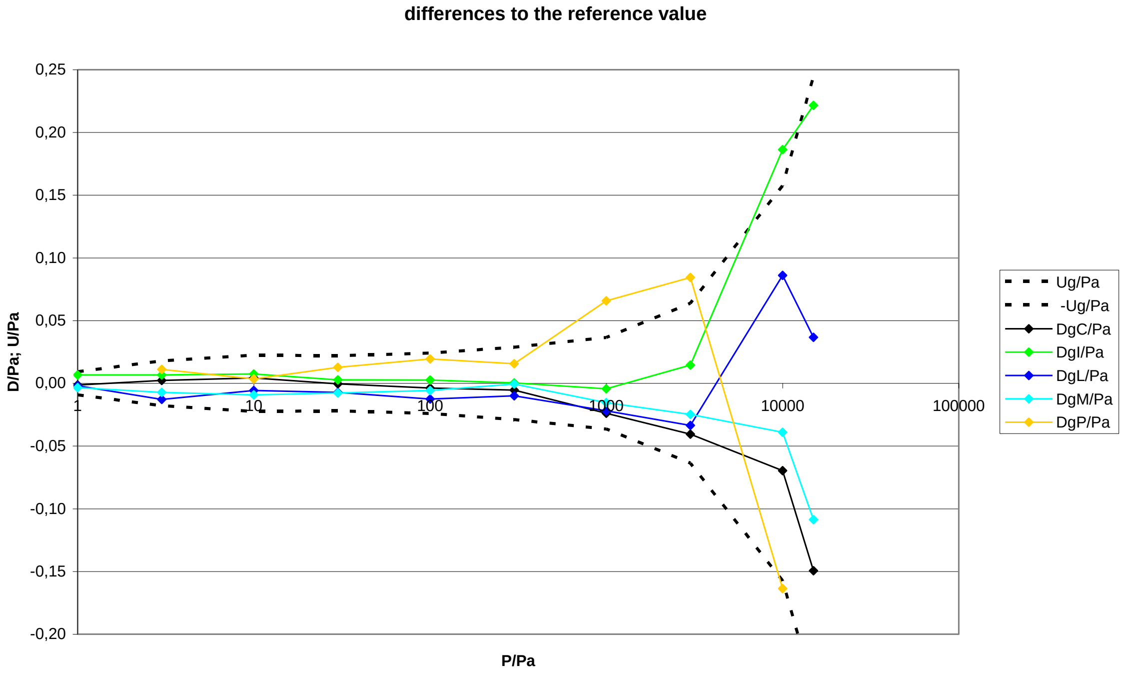

Fig. 10.1: Results to the reference value in gauge mode.

10.3 Bilateral equivalences in gauge mode

Tab. 10.3 to 10.6 show the bilateral equivalences of the participants with INRIM E_{gIX}, LNE E_{gLX}, MIKES E_{gMX} and PTB E_{gPX} (with CMI these are already in Tab. 10.1) in gauge mode.

p_n/Pa	E_{gIL}	E_{gIM}	E_{gIP}
1	0,37	0,35	
3	0,83	0,47	-0,05
10	0,56	0,53	0,04
30	0,41	0,32	-0,10
100	0,57	0,24	-0,15
300	0,29	0,02	-0,11
1000	0,28	0,14	-0,44
3000	0,32	0,21	-0,29
10000	0,23	0,41	0,67
15000	0,30	0,42	

Tab. 10.3: Mutual bilateral equivalences with INRIM.

p_n/Pa	E_{gLI}	E_{gLM}	E_{gLP}
1	-0,37	0,07	
3	-0,83	-0,22	-0,29
10	-0,56	0,13	-0,09
30	-0,41	0,02	-0,19
100	-0,57	-0,23	-0,28
300	-0,29	-0,24	-0,19
1000	-0,28	-0,09	-0,56
3000	-0,32	-0,05	-0,50
10000	-0,23	0,25	0,53
15000	-0,30	0,20	

Tab. 10.4: Mutual bilateral equivalences with LNE.

p_n/Pa	E_{gMI}	E_{gML}	E_{gMP}
1	-0,35	-0,07	
3	-0,47	0,22	-0,22
10	-0,53	-0,13	-0,12
30	-0,32	-0,02	-0,19
100	-0,24	0,23	-0,22
300	-0,02	0,24	-0,12
1000	-0,14	0,09	-0,49
3000	-0,21	0,05	-0,42
10000	-0,41	-0,25	0,21
15000	-0,42	-0,20	

Tab. 10.5: Mutual bilateral equivalences with MIKES.

p_n/Pa	E_{gPI}	E_{gPL}	E_{gPM}
3	0,05	0,29	0,22
10	-0,04	0,09	0,12
30	0,10	0,19	0,19
100	0,15	0,28	0,22
300	0,11	0,19	0,12
1000	0,44	0,56	0,49
3000	0,29	0,50	0,42
10000	-0,67	-0,53	-0,21

Tab. 10.6: Mutual bilateral equivalences with PTB.

10.4 Results of the bilateral comparisons in absolute mode

Tab. 10.7a gives the bilateral differences d_X and their expanded (k = 2) uncertainties Ud_X for the set of the bilateral comparisons of CMI and laboratory X in the absolute mode.

p_n/Pa	d_I/Pa	d_L/Pa	d_M/Pa	d_{Ps}/Pa	d_{Pf}/Pa	d_{Pm}/Pa	Ud_I/Pa	Ud_L/Pa	Ud_M/Pa	Ud_{Ps}/Pa	Ud_{Pf}/Pa	Ud_{Pm}/Pa
1	0,002	-0,009	0,018				0,030	0,030	0,027			
3	0,002	-0,005	0,014	-0,009			0,033	0,032	0,035	0,026		
10	0,007	0,000	0,011	0,005			0,038	0,038	0,055	0,036		
30	0,012	0,002	0,008	0,018	-0,009		0,036	0,036	0,078	0,055	0,052	
100	0,022	0,002	0,022		-0,005		0,033	0,033	0,078		0,052	
300	0,039	0,009	0,007		-0,010		0,042	0,040	0,087		0,058	
1000	0,041	0,030	0,020		-0,009	-0,001	0,071	0,064	0,121		0,090	0,184
3000	0,077	0,049	0,033			-0,017	0,153	0,132	0,217			0,208
10000	0,204	0,172	0,100			0,076	0,443	0,376	0,562			0,374
15000	0,272	0,290	0,226			0,124	0,647	0,547	0,807			0,512

Tab. 10.7a: Results of the bilateral comparisons in absolute mode.

Tab. 10.7b gives the bilateral degrees of equivalence E_{CX} for the set of the bilateral comparisons of CMI and laboratory X in the absolute mode.

p_n/Pa	E_{CI}	E_{CL}	E_{CM}	E_{CPs}	E_{CPf}	E_{CPm}
1	0,06	-0,31	0,64			
3	0,07	-0,16	0,39	-0,36		
10	0,18	-0,01	0,19	0,14		
30	0,33	0,06	0,11	0,32	-0,17	
100	0,66	0,05	0,28		-0,09	
300	0,92	0,23	0,08		-0,18	
1000	0,59	0,47	0,16		-0,10	-0,01
3000	0,51	0,37	0,15			-0,08
10000	0,46	0,46	0,18			0,20
15000	0,42	0,53	0,28			0,24

Tab. 10.7b: Results of the bilateral comparisons in absolute mode.

10.5 Results to reference value in absolute mode

Tab. 10.8 gives the expanded (k = 2) uncertainty of the reference value U_a, differences D_{aX} of laboratory X from this reference value and the degrees of equivalence E_{aX} in the absolute mode. See also Fig. 10.2.

p_n/Pa	p_{ra}/Pa	U_{ra}/Pa	D_{aC}/Pa	D_{aI}/Pa	D_{aL}/Pa	D_{aM}/Pa	D_{aPs}/Pa	D_{aPf}/Pa	D_{aPm}/Pa	E_{aC}	E_{aI}	E_{aL}	E_{aM}	E_{aPs}	E_{aPf}	E_{aPm}
1	1,003	0,020	-0,003	-0,001	-0,012	0,015				-0,09	-0,02	-0,42	0,21			
3	3,000	0,017	0,000	0,002	-0,005	0,013	-0,010			-0,01	0,08	-0,21	0,18	-0,81		
10	10,004	0,019	-0,004	0,002	-0,005	0,006	0,001			-0,16	0,09	-0,17	0,09	0,03		
30	30,005	0,019	-0,005	0,007	-0,003	0,003	0,013	-0,014		-0,18	0,24	-0,11	0,04	0,26	-0,30	
100	100,008	0,019	-0,008	0,014	-0,007	0,014		-0,013		-0,27	0,45	-0,22	0,18		-0,27	
300	300,009	0,022	-0,009	0,030	0,000	-0,002		-0,019		-0,25	0,82	0,00	-0,02		-0,38	
1000	1000,013	0,040	-0,013	0,028	0,016	0,006		-0,023	-0,015	-0,22	0,44	0,29	0,06		-0,30	-0,08
3000	3000,028	0,063	-0,028	0,049	0,020	0,004			-0,045	-0,23	0,38	0,20	0,02			-0,24
10000	10000,111	0,145	-0,111	0,093	0,062	-0,010			-0,034	-0,33	0,26	0,24	-0,02			-0,13
15000	15000,182	0,205	-0,182	0,090	0,107	0,043			-0,059	-0,38	0,18	0,28	0,06			-0,18

Tab. 10.8: Results to reference value in absolute mode.

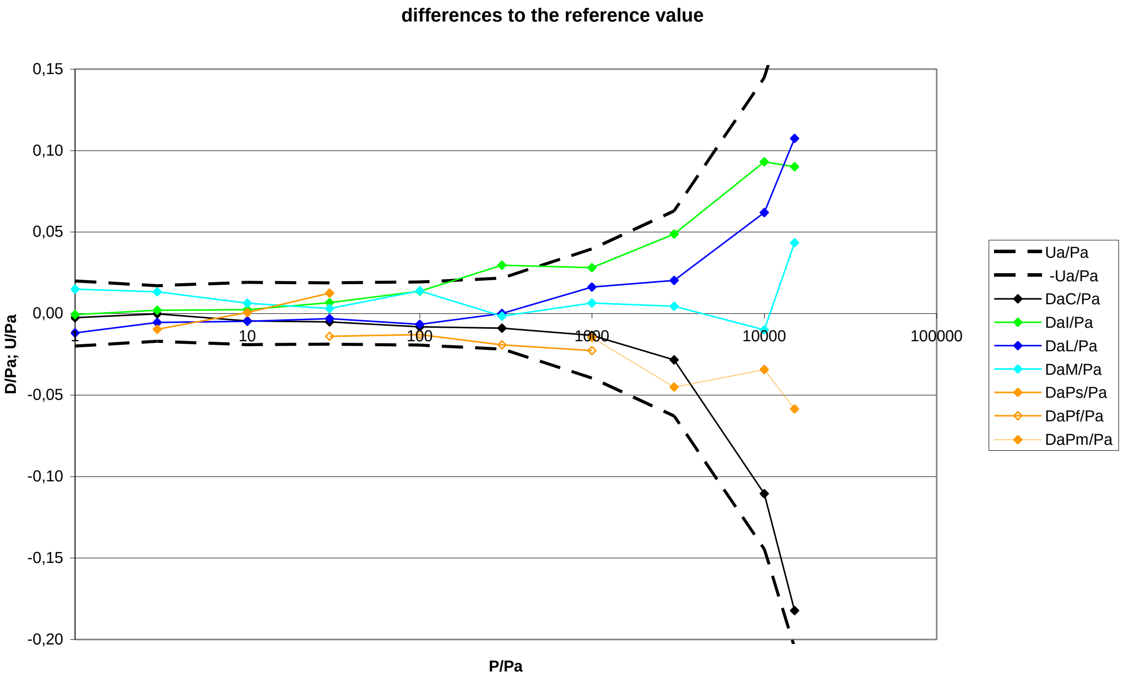

Fig. 10.2: Results to the reference value in absolute mode.

10.6 Bilateral equivalences in absolute mode

Tab. 10.9 to 10.14 show the bilateral equivalences of the participants with INRIM E_{aIX}, LNE E_{aLX}, MIKES E_{aMX}, PTB static expansion E_{aPsX}, PTB FRS E_{aPfX} and PTB Hg-column E_{aPmX} (with CMI these are already in Tab. 10.7b) in absolute mode.

p_n/Pa	E_{aIL}	E_{aIM}	E_{aIPs}	E_{aIPf}	E_{aIPm}
1	0,36	-0,54			
3	0,21	-0,29	0,38		
10	0,16	-0,06	0,04		
30	0,23	0,04	-0,10	0,37	
100	0,61	0,00		0,51	
300	0,71	0,36		0,83	
1000	0,18	0,18		0,55	0,23
3000	0,21	0,20			0,44
10000	0,08	0,18			0,32
15000	-0,03	0,06			0,27

Tab. 10.9: Mutual bilateral equivalences with INRIM.

p_n/Pa	E_{aLI}	E_{aLM}	E_{aLPs}	E_{aLPf}	E_{aLPm}
1	-0,36	-0,93			
3	-0,21	-0,49	0,14		
10	-0,16	-0,18	-0,13		
30	-0,23	-0,08	-0,27	0,19	
100	-0,61	-0,26		0,12	
300	-0,71	0,02		0,34	
1000	-0,18	0,08		0,45	0,17
3000	-0,21	0,08			0,33
10000	-0,08	0,14			0,30
15000	0,03	0,09			0,40

Tab. 10.10: Mutual bilateral equivalences with LNE.

p_n/Pa	E_{aMI}	E_{aML}	E_{aMPs}	E_{aMPf}	E_{aMPm}
1	0,54	0,93			
3	0,29	0,49	0,70		
10	0,06	0,18	0,09		
30	-0,04	0,08	-0,10	0,19	
100	0,00	0,26		0,31	
300	-0,36	-0,02		0,18	
1000	-0,18	-0,08		0,22	0,10
3000	-0,20	-0,08			0,19
10000	-0,18	-0,14			0,05
15000	-0,06	-0,09			0,14

Tab. 10.11: Mutual bilateral equivalences with MIKES.

p_n/Pa	E_{aPsI}	E_{aPsL}	E_{aPsM}	E_{aPsPf}
3	-0,38	-0,14	-0,70	
10	-0,04	0,13	-0,09	
30	0,10	0,27	0,10	0,38

Tab. 10.12: Mutual bilateral equivalences with PTB – static expansion.

p_n/Pa	E_{aPfI}	E_{aPfL}	E_{aPfM}	E_{aPfPs}	E_{aPfPm}
30	-0,37	-0,19	-0,19	-0,38	
100	-0,51	-0,12	-0,31		
300	-0,83	-0,34	-0,18		
1000	-0,55	-0,45	-0,22		-0,04

Tab. 10.13: Mutual bilateral equivalences with PTB – FRS5 absolute.

p_n/Pa	E_{aPmI}	E_{aPmL}	E_{aPmM}	E_{aPmPf}
1000	-0,23	-0,17	-0,10	0,04
3000	-0,44	-0,33	-0,19	
10000	-0,32	-0,30	-0,05	
15000	-0,27	-0,40	-0,14	

Tab. 10.14: Mutual bilateral equivalences with PTB – Hg-column.

11. Linking to the reference value of the CCM key comparisons

Now the link for the results in absolute mode to CCM.P-K4 and CCM.P-K2 can be determined. (The comparison in gauge mode is a supplementary comparison.) Such points can be utilised which share the same LS for their determination. There are four such points: 3 Pa, 10 Pa and 30 Pa for CCM.P-K4 and 10000 Pa for CCM.P-K2. Let us take the differences D_{aX} of laboratory X from the reference value in the absolute mode in these points, see Tab. 10.8 and Tab. 11.1.

p_n/Pa	p_{ra}/Pa	D_{aC}/Pa	D_{aI}/Pa	D_{aL}/Pa	D_{aM}/Pa	D_{aPs}/Pa	D_{aPm}/Pa
3	3,0002	0,000	0,002	-0,005	0,013	-0,010	
10	10,0045	-0,004	0,002	-0,005	0,006	0,001	
30	30,0052	-0,005	0,007	-0,003	0,003	0,013	
10000	10000,1105	-0,111	0,093	0,062	-0,010		-0,034

Tab. 11.1: The differences to the reference value in absolute mode.

Let us also take the differences of PTB from the reference values of the CCM.P-K4 and CCM.P-K2 which can be denoted as $\Delta_{\text{CCM-PTB}}$ and listed together with their expanded uncertainties $U(\Delta_{\text{CCM-PTB}})$ in Tab. 11.2. The differences of PTB from the reference values of this EURAMET comparison can be denoted as $\Delta_{\text{EM-PTB}}$ and are equal either D_{aPs} or D_{aPm}. Then their difference can be calculated:

$$\Delta_{\text{C-E-PTB}} = \Delta_{\text{CCM-PTB}} - \Delta_{\text{EM-PTB}}\,. \tag{11.1}$$

p_n/Pa	$\Delta_{CCM\text{-}PTB}$/Pa	$U(\Delta_{CCM\text{-}PTB})$/Pa	$\Delta_{EM\text{-}PTB}$/Pa	$\Delta_{C\text{-}E\text{-}PTB}$/Pa
3	-0,0013	0,0075	-0,010	0,008
10	-0,0050	0,025	0,001	-0,006
30	0,0020	0,062	0,013	-0,011
10000	0,0179	0,19	-0,034	0,052

Tab. 11.2: The differences of the linking laboratory.

Now the values D_{aPs} and D_{aPm} can be substituted by $\Delta_{CCM\text{-}PTB}$ and all the remaining values D_{aX} can be calculated by

$$\Delta_{aX} = D_{aX} + \Delta_{C\text{-}E\text{-}PTB} \, . \qquad (11.2)$$

The expanded uncertainties of D_{aPs} and D_{aPm} can be substituted by $U(\Delta_{CCM\text{-}PTB})$ and the expanded uncertainties of all the remaining values D_{aX} can be calculated from uncertainties of the reference value and the claimed uncertainties:

$$U(\Delta_{aX}) = \sqrt{U_{ra}^{\ 2} + U_X^{\ 2}} \, . \qquad (11.3)$$

These values are listed in Tab. 11.3 and in Fig. 11.1 to 11.4. It can be easily seen that all the participating labs are also equivalent with reference values of CCM.P-K4 and CCM.P-K2.

p_n/Pa	Δ_{aC}/Pa	Δ_{aI}/Pa	Δ_{aL}/Pa	Δ_{aM}/Pa	Δ_{aP}/Pa	$U(\Delta_{aC})$/Pa	$U(\Delta_{aI})$/Pa	$U(\Delta_{aL})$/Pa	$U(\Delta_{aM})$/Pa	$U(\Delta_{aP})$/Pa
3	0,008	0,010	0,003	0,022	-0,001	0,026	0,026	0,026	0,072	0,008
10	-0,010	-0,003	-0,010	0,001	-0,005	0,028	0,028	0,028	0,073	0,025
30	-0,016	-0,004	-0,014	-0,007	0,002	0,028	0,028	0,028	0,074	0,062
10000	-0,058	0,145	0,114	0,042	0,018	0,333	0,351	0,263	0,492	0,194

Tab. 11.3: The differences to the CCM reference values and their uncertainties.

In Tab. 11.4, there are the equivalences of each lab to the CCM reference values:

$$\varepsilon_X = \Delta_{aX} / U(\Delta_{aX}) . \qquad (11.4)$$

p_n/Pa	ε_C/Pa	ε_I/Pa	ε_L/Pa	ε_M/Pa	ε_P/Pa
3	0,31	0,39	0,11	0,30	-0,17
10	-0,36	-0,12	-0,38	0,01	-0,20
30	-0,56	-0,14	-0,49	-0,10	0,03
10000	-0,18	0,41	0,43	0,09	0,09

Tab. 11.4: The equivalences with the CCM reference values.

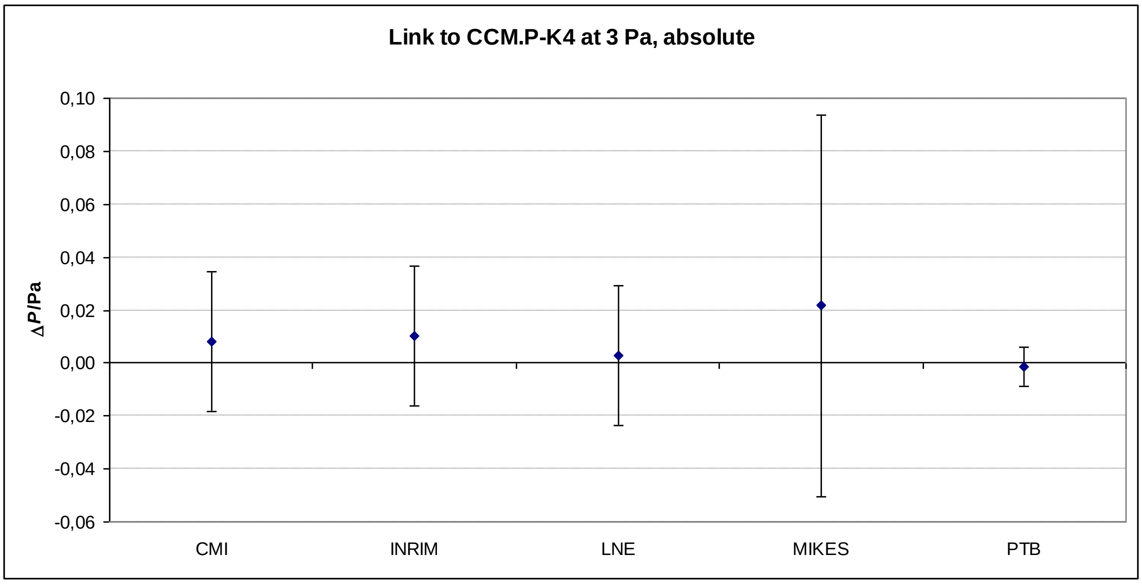

Fig. 11.1: The differences to the CCM.P-K4 reference value at 3 Pa.

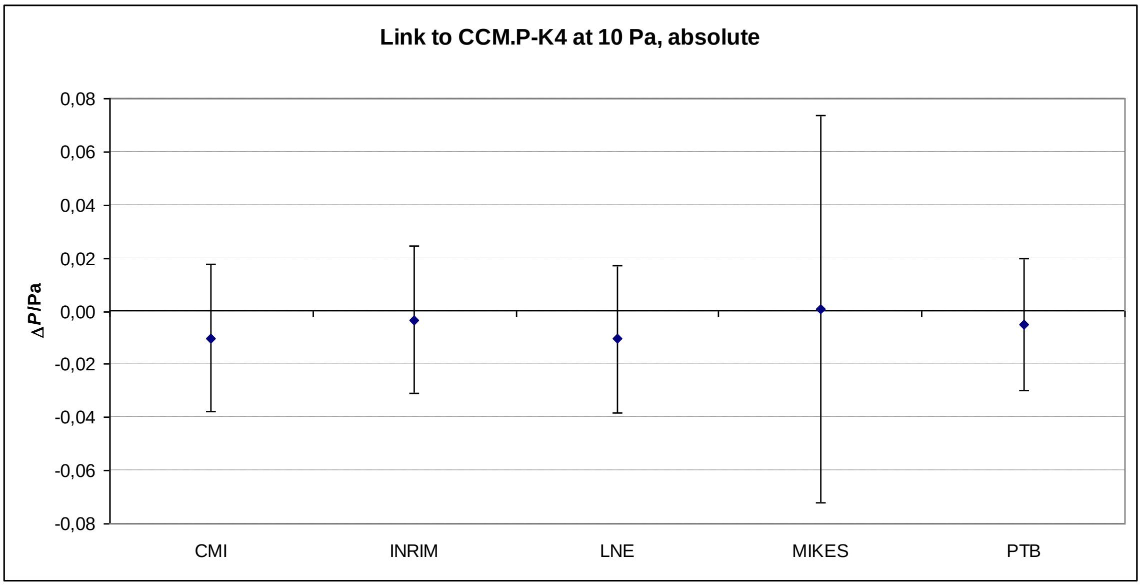

Fig. 11.2: The differences to the CCM.P-K4 reference value at 10 Pa.

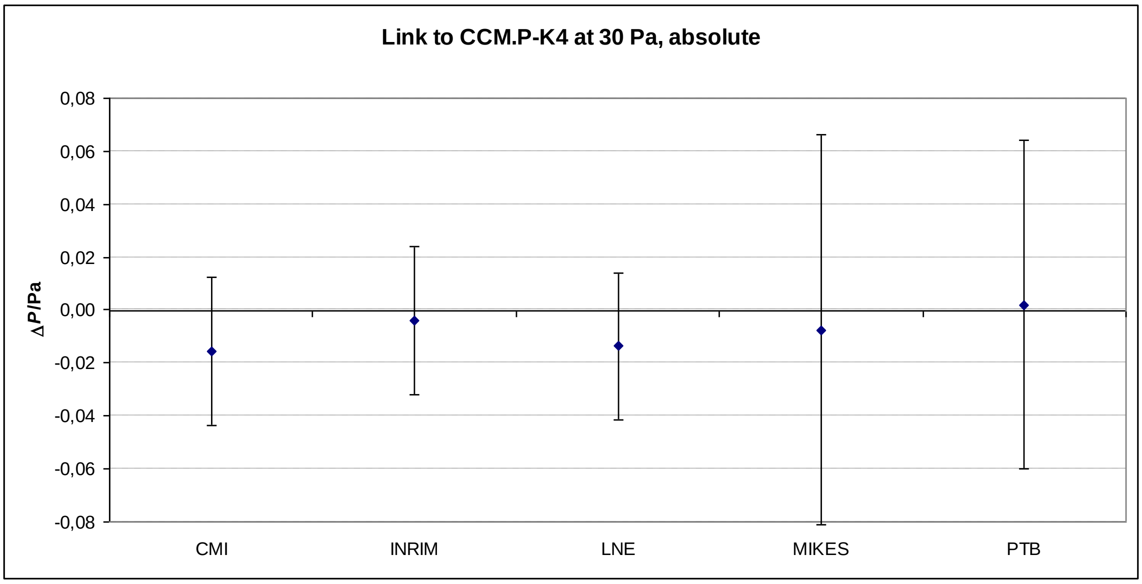

Fig. 11.3: The differences to the CCM.P-K4 reference value at 30 Pa.

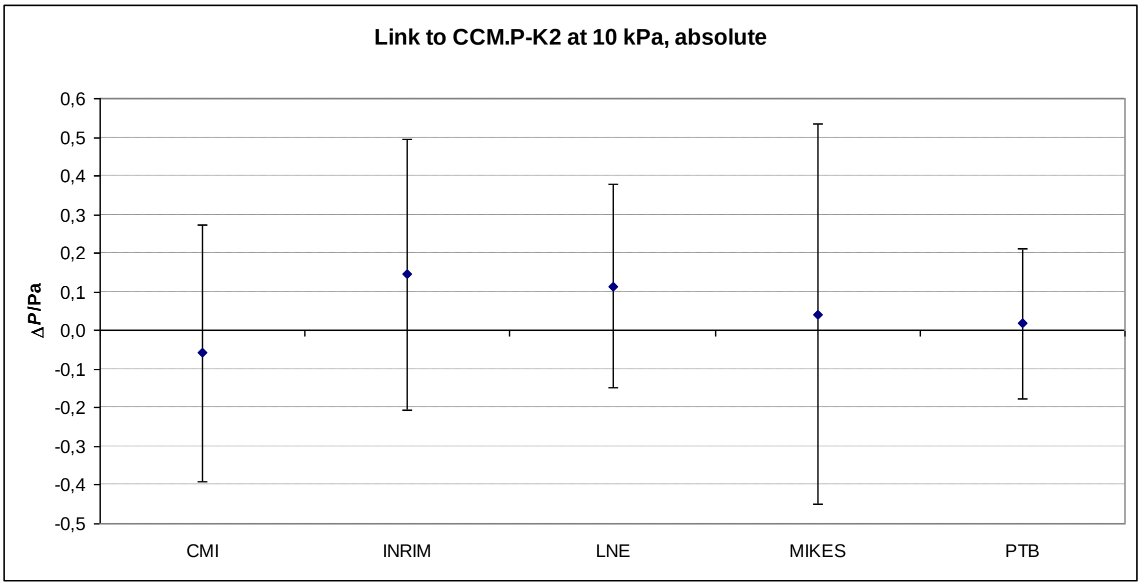

Fig. 11.4: The differences to the CCM.P-K2 reference value at 10 kPa.

12. Conclusions

Both in gauge and absolute pressures all the participating institutes successfully proved their equivalence in bilateral comparisons with CMI and also with respect to the reference value. They all also proved mutual bilateral equivalences in all the points. All the participating labs are also equivalent with the reference values of CCM.P-K4 and CCM.P-K2 in the relevant points.

The comparison was demanding and unique from the logistical point of view and proved ability of FPG8601 to serve as a transfer standard.

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