High pressure comparisons between seven European National Laboratories Range 50 MPa to 500 MPa

Final Report on EUROMET Project 881 / EURAMET.M.P-K7

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Espoo, Finland 2007 (The original comparison report MIKES Publication J4/2007) and 2018 (The link between the comparisons EURAMET 881 / EURAMET.M.P.K7 and CCM.P.K13 added)

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Abstract

An inter-comparison in the high oil pressure range was arranged in 2005 – 2007. The participating laboratories were CMI/Czech Republic, METAS /Switzerland, MIKES/Finland, NMi-VSL/The Netherlands, PTB/Germany, SMD/Belgium and SP/Sweden. CMI, METAS, NMi-VSL and PTB are pressure laboratories of the primary level, and the three others are traceable to LNE/France.

The transfer standard was a Desgranges & Huot piston-cylinder unit with a nominal effective area of 1,96 mm^2, mounted in a D&H 5316 balance body. The participants determined the effective area at ten nominal pressures from 50 MPa to 500 MPa in steps of 50 MPa. All the results were in a good agreement with the reference values, calculated as weighted means of the results from the four primary level laboratories. The results fully support the uncertainties claimed in the CMC tables of the participants.

As the pressure distortion is the dominating source of uncertainty in this range, the claimed uncertainties were highest at 500 MPa, ranging from $5,6 \cdot 10^{-5}$ of PTB to $1,2 \cdot 10^{-4}$ of MIKES (expanded relative uncertainties, $k = 2$). Except for PTB, there were no big differences in the claimed uncertainties between the primary and the secondary level laboratories.

Some of the participants underestimated the uncertainties when giving their results in terms of the effective area at null pressure S_0 and the pressure distortion coefficient, λ. The uncertainties given by some others were unnecessarily high.

The transfer standard was not as stable as expected, and the uncertainties of the reference values were to some extent increased by the observed drift.

The comparison, registered as EUROMET Project #881, was started as an informal one between MIKES, METAS, NMi-VSL and CMI, and in the beginning the rules for EUROMET comparisons were not strictly followed.

No links to other comparisons were made as the latest EUROMET key comparisons in the high pressure range were carried out more than twelve years ago. Linking will be made as soon as results from newer comparisons are available.

Edited in 2018:

The link between this comparison (EUROMET 881 / EURAMET.M.P.K7) and the key comparison CCM.P.K13 was calculated, and the original EUROMET 881 report (MIKES Publication J4/2007) was updated accordingly in 2018.

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1 Introduction

A comparison on high pressures between MIKES, METAS, NMi-VSL and CMI was started in summer 2005.

At autumn 2005 PTB was asked to join in for better reference values. Later in 2006 SMD and SP joined in. The measurements were completed in January 2007.

The comparison was registered as EUROMET Project number 881.

Previous EUROMET comparison in the range 50 MPa to 500 MPa was arranged in 1993 – 1995 (EUROMET Project number 45), which later became a key comparison EUROMET.M.P.-K5 [1]. MIKES, NMi-VSL and SP participated in this comparison, coordinated by LNE, France.

Edited in 2018:

The link between this comparison (EUROMET 881 / EURAMET.M.P.K7) and the key comparison CCM.P.K13 was calculated, and the original EUROMET 881 report (MIKES Publication J4/2007) was updated accordingly in 2018.

2 Participants

2.1 Primary pressure laboratories

Physikalisch-Technische Bundesanstalt (PTB), Germany, is one of the leading pressure laboratories in the world. PTB has participated in several key comparisons in the high pressure range:

CCM.P-K7 (100 MPa)

APMP.M.P.K7 (100 MPa)
EUROMET.M.P-K4 (100 MPa)
CCM.P-K8 (500 MPa)
EUROMET.M.P-K6 (1000 MPa).

The PTB standards for high pressures are described in detail in References 2 to 5. Two piston-cylinder units were used in the present comparison: the first one with a nominal effective area of 8,4 mm^2, manufactured by Ruska, and the second with a nominal effective area of 4,9 mm^2, by DH-Budenberg.

Federal Institute of Metrology (METAS) is the national metrology institute of Switzerland. The standards used in this comparison were two piston cylinder units manufactured by Desgranges & Huot: up to 400 MPa one with a nominal effective area of 2 mm2 and above 400 MPa a unit with a nominal area of 4,9 mm2 with a pressure multiplier.

METAS has participated in the high pressure key comparison EUROMET.M.P-K4 (100 MPa).

Czech Metrology Institute (CMI) is the national metrology institute of Czech Republic. It used a tungsten-carbide piston-cylinder unit of nominal effective area 2 mm^2 for this comparison. The unit is of the type PC-7300-5 by DH Instruments. The primary standards for oil pressure covering the range from 100 kPa to 500 MPa are described (in Czech language) in Reference 7.

CMI has participated in the high pressure key comparison EUROMET.M.P-K4 (100 MPa) and in two bilateral comparisons: in 1999 with MIKES, Finland, in the range from 2 MPa to 500 MPa, and in 2006 with MIRS, Slovenia, in the range from 20 MPa to 200 MPa.

NMi-Van Swinden Laboratorium B.V (NMi-VSL), the national metrology institute of the Netherlands, used a Desgranges & Huot piston cylinder assembly with a nominal effective area of 2 mm^2. The piston cylinder assembly is traceable by a stepping-up calibration procedure to a primary pressure standard of NMi-VSL which consist of a piston cylinder assembly with a nominal effective area of 961 mm^2 and a pressure balance body of DH Instruments. The effective area of the primary pressure standard was calculated using the results of the dimensional calibration of this unit. The uncertainty of the effective area of the 2 mm^2 includes the uncertainty contribution due to the elastic distortion coefficient ($U = 0,1 \cdot \lambda$).

NMi-VSL has participated in high pressure key comparisons EUROMET.M.P-K4 (100 MPa) and EUROMET.M.P.-K5 (500 MPa)

2.2 Secondary level laboratories

The pressure laboratories of Service de la Métrologie (SMD), Belgium, Centre for Metrology and Accreditation (MIKES), Finland and SP Technical Research Institute of Sweden (SP) are all traceable to Laboratoire National de Métrologie et d'Essais (LNE), France. They all used a Desgranges & Huot piston cylinder assembly with a nominal effective area of 2 mm^2.

2.3 Measurement schedule

The measurements were made according to the following schedule:

MIKES 1 Early July 2005
METAS End of July 2005
CMI Early December 2005
PTB Early February 2006
MIKES 2 End of May 2006
SMD Early July 2006
NMi-VSL End of July 2006
SP End of August 2006
MIKES 3 Early January 2007

3 Transfer standard

The transfer standard was a DH-Budenberg piston-cylinder assembly No. 9080 with a nominal effective area of 2 mm^2. The piston-cylinder unit was mounted in a Desgranges & Huot pressure balance body model 5316 No. 5130, equipped with a load carrying bell No. 3154 and a Pt-100 temperature probe No. 1356. The transfer standard and the balance body were provided by MIKES. Each laboratory used its own weights set on the transfer standard.

The resistance of the Pt-100 probe at 0 °C was determined at MIKES as 99,9800 Ω.

According to the information provided by the manufacturer the piston was made of steel and the cylinder of tungsten carbide having the thermal expansion coefficients (1,05 ± 0,1) · 10^{-5} °C^{-1} and (0,45 ± 0,05) · 10^{-5} °C^{-1} respectively.

The true masses of the piston and the carrying bell were determined at MIKES before the circulation in July 2005 (Calibration certificate M-05M052, uncertainties with k = 2) as:

	Density (kg/m^3)	True mass (g)
Piston	7920 ± 100	200,0021 ± 0,0007
Carrying bell	7920 ± 30	800,008 ± 0,006

The density values were based on the manufacturer's data. Some of the laboratories re-determined the masses of the piston and the load carrying bell. The uncertainties of these mass values or their possible minor drift are not relevant to the uncertainty of the comparison results.

The pressure laboratory of CMI was the first to notice that the spirit level attached to balance body No. 5130 was not adjusted correctly. According to the geometrical measurements at CMI the levelling with the spirit level would generate an error of 0,18 degrees in the verticality of the piston.

Calculations and pressure measurements at CMI and MIKES showed that the magnitude of the relative error in pressure due to this verticality error would be less than 10^{-5}. Anyway, most of the laboratories followed a common practice and adjusted the verticality of the transfer standard using their own spirit levels placed on top of the piston. The spirit level of the balance body No. 5130 was re-adjusted at MIKES in May 2006.

Several laboratories had problems with the high fall rate of the transfer standard piston due to a leak at the O-ring gasket at the cylinder bottom. PTB used their own D&H balance body for their measurements. The O-ring was changed at MIKES in May 2006, and later at NMi-VSL and at SP.

4 Stability of the transfer standard

MIKES received the piston-cylinder unit s/n 9080 from the manufacturer DHBudenberg in April 2005.

The effective area of the unit was at first determined at MIKES in May 2005 using the MIKES reference standards with the nominal effective areas of 2 mm^2 and 4,9 mm^2. The second series of measurements was carried out in July and August 2005 using the same standards after the measurements at METAS.

The effective area of the transfer standard was again determined at MIKES in May 2006, when the instrument was returned from circulation at NMi-VSL, CMI and PTB.

Further, the measurements were made at MIKES in September and October 2006 and finally in January 2007.

The subsequent results from MIKES [8] show an increase in the effective area with time. The change in the effective area seems practically independent of the nominal pressure. If a linear drift is assumed for simplicity and the best fitting straight line is calculated for the result points, we obtain the following drift rates:

Nominal pressure MPa	Drift rate mm^2 /year	Uncertainty (k = 2) mm^2 /year
100	0,000095	0,000020
200	0,000103	0,000024
300	0,000096	0,000023
400	0,000087	0,000023
500	0,000086	0,000023
Average	0,000093	0,000022

The results at nominal pressures 100 MPa and 500 MPa are illustrated in Figures 1 and 2.

The stability of the transfer standard should have been confirmed more carefully before starting the comparison.

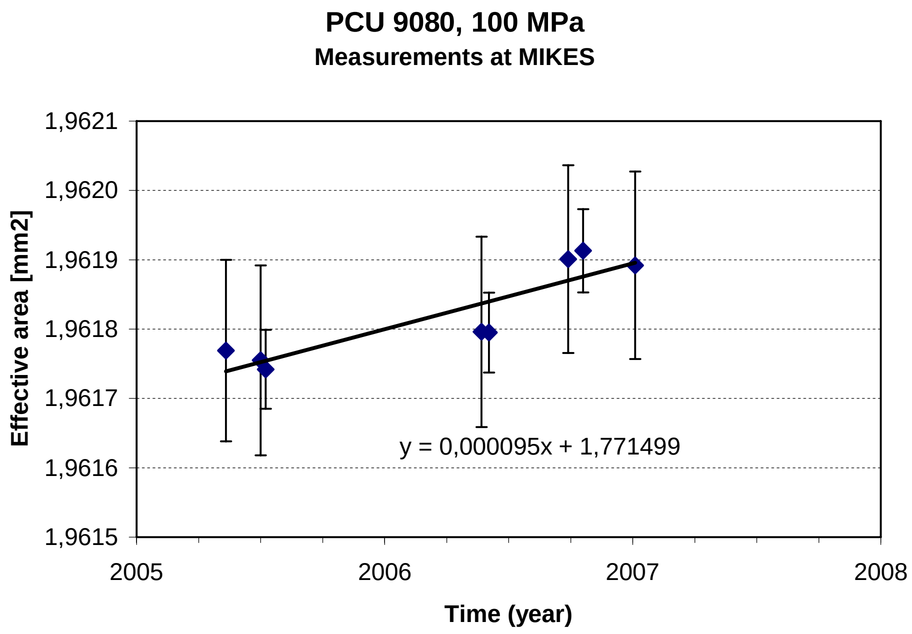

Figure 1. MIKES results on piston-cylinder unit s/n 9080 at 100 MPa.

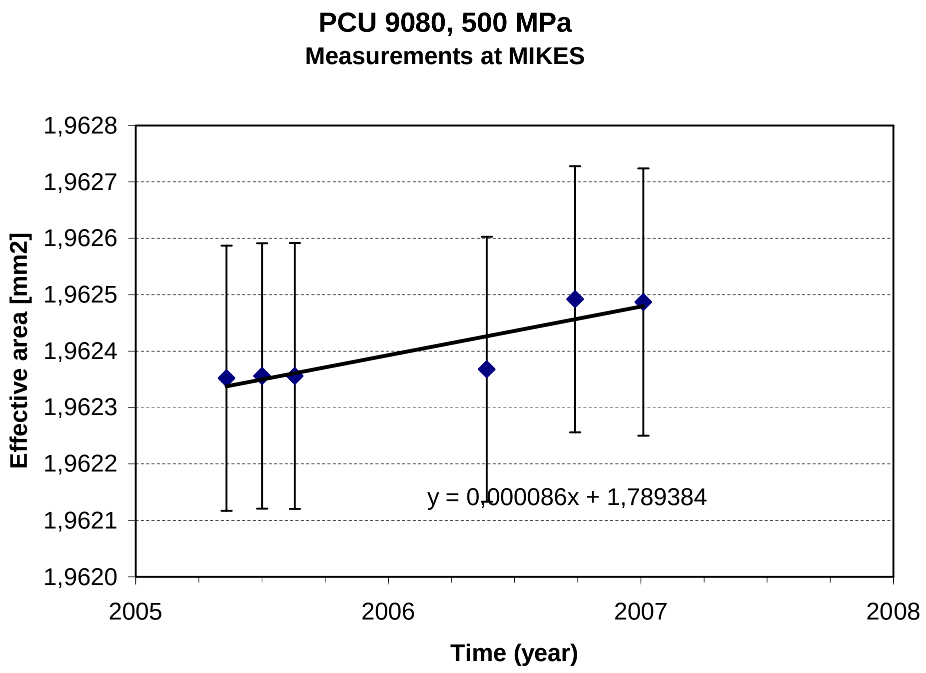

Figure 2. MIKES results on piston-cylinder unit s/n 9080 at 500 MPa.

5 Measurement instructions

The measurement instructions were similar to those of EUROMET 45 [1] in 1993 – 95, and very short and straightforward:

The participants were asked to determine the effective area of the transfer standard at the nominal pressures from 50 MPa to 500 MPa at 20 °C in steps of 50 MPa. Further, they were asked to determine the effective area at null pressure at 20 °C plus the pressure distortion coefficient.

As the background information the participants were asked to give a description of the laboratory standards and their traceability, measurement method and conditions and other information relevant to the results.

The number of measurement cycles was left to be decided by each laboratory.

The rules for the acceptance and use of measurement protocols specified in the EUROMET Guidelines [9] were not strictly followed.

6 Calculation of the reference values in the range 50 MPa to 500 MPa

The reference values for the comparison were calculated applying the Procedure A described in Ref. [10] with minor modifications.

Only the results from the laboratories of primary level were included in calculating the weighted mean for the effective area at each nominal pressure in the range from 50 MPa to 500 MPa.

As the first step the results of each laboratory were corrected for drift to correspond the situation of the 1st of January 2006. This date was selected because two primary laboratories made their measurements before and two after that date. The measurements at PTB were made in early February, and the corrections to their results with the lowest uncertainties were small. The uncertainties of the drift corrections were added to the original uncertainties as the square root of the sum of squares.

The weighted mean y of the effective area results x at each nominal pressure was calculated as

$$y = \frac{x_1/u^2(x_1) + \cdots + x_N/u^2(x_N)}{1/u^2(x_1) + \cdots + 1/u^2(x_N)}$$

where x_i is the result and $u^2(x_i)$ the variance of the result from laboratory i.

The standard deviation u(y) associated with y was calculated from

$$\frac{1}{u^2(y)} = \frac{1}{u^2(x_1)} + \cdots + \frac{1}{u^2(x_N)}$$

The consistency check specified in Procedure A of Ref. [10] using a chi squared test was carried out on all of the effective area results, and they were accepted as reference values.

The reference values as effective areas corresponding to the 1st of January 2006 for each nominal pressure and their uncertainties are presented in Table 1 and illustrated in Figure 3.

Table 1. The reference values as effective areas at nominal pressures 50 MPa to 500 MPa.

Nominal pressure MPa	Reference value mm^2	Uncertainty of reference value mm^2 (k = 2)	Relative uncertainty of reference value $/10^{-6}$, (k = 2)
50	1,961755	0,000034	17,3
100	1,961804	0,000044	22,4
150	1,961866	0,000050	25,5
200	1,961933	0,000051	26,0
250	1,962005	0,000056	28,5
300	1,962076	0,000059	30,1
350	1,962152	0,000063	32,1
400	1,962219	0,000067	34,1
450	1,962318	0,000085	43,3
500	1,962403	0,000088	44,8

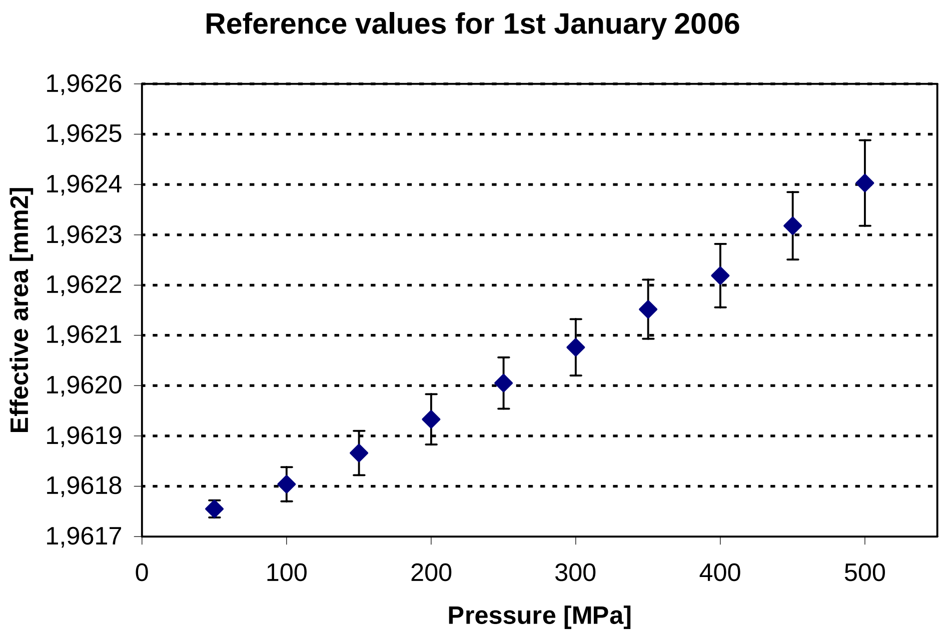

Figure 3. The reference values and their uncertainties in the range 50 MPa to 500 MPa.

7 Results in the range 50 MPa to 500 MPa

The effective area results from each laboratory were corrected for the observed drift in the transfer standard to correspond to the 1st of January 2006.

The uncertainty of the drift correction for each laboratory was added to the uncertainties of the reference values as the square root of the sum of the squares. Now the uncertainty values given by the laboratories remain unchanged, the reference values are constant for all the participating laboratories, and the uncertainties of the reference values increase with the interval from the date of the measurements to the reference date. Figures 4 to 6 illustrate the procedure.

The results, including the original and corrected values, the uncertainties as well as the deviations from the reference values are shown in Tables 2a-c. A summary of the relative deviations from the reference values are shown in Figure 7.

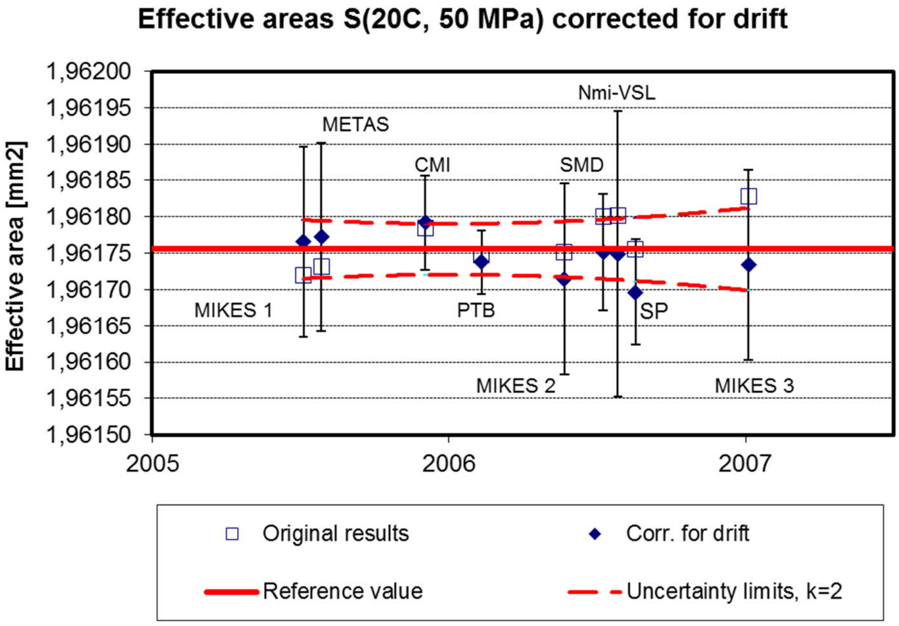

Figure 4. Results at nominal pressure 50 MPa.

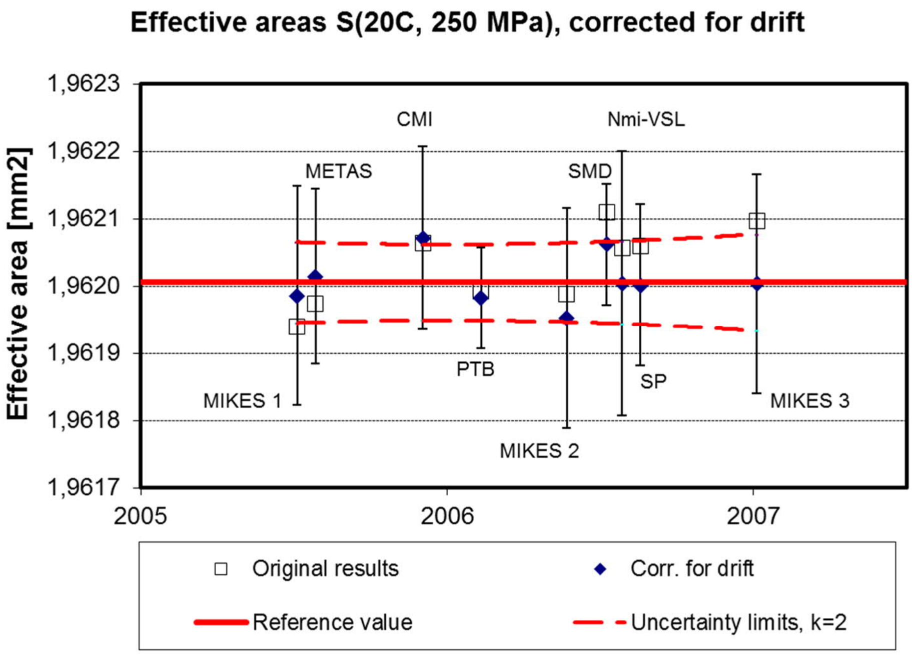

Figure 5. Results at nominal pressure 250 MPa.

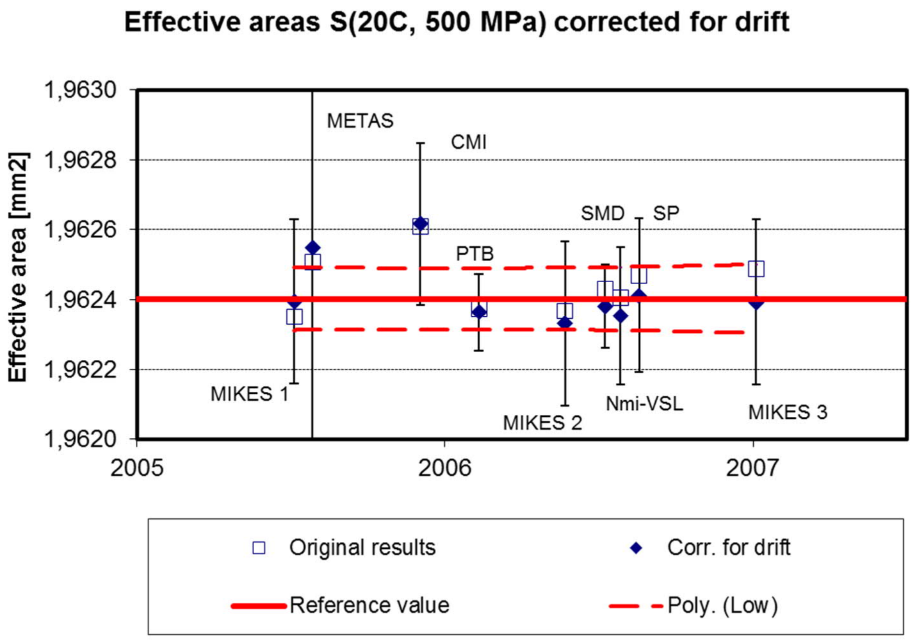

Figure 6. Results at nominal pressure 500 MPa.

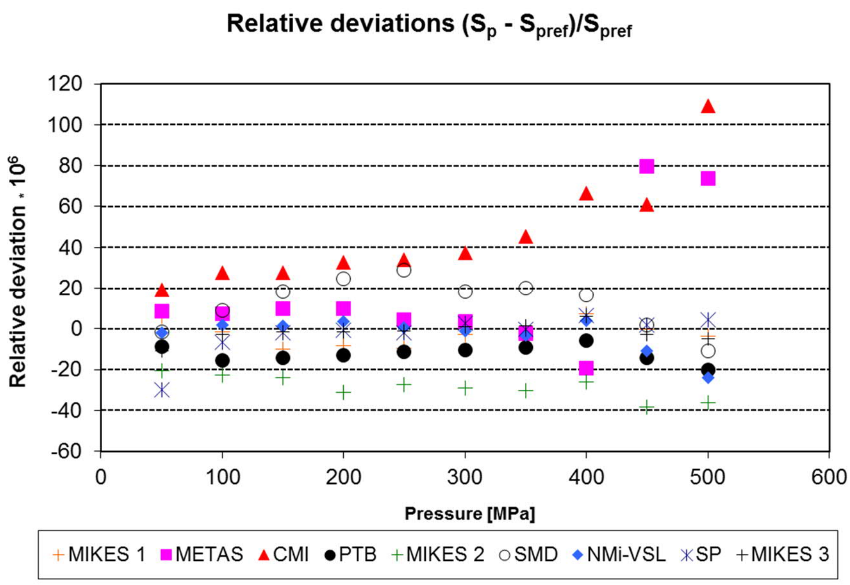

Figure 7. Results $S_{p,20C}$ as relative deviations from the reference values $S_{p,20C,ref}$.

Table 2a. Results from MIKES 1 and METAS at nominal pressures from 50 MPa to 500 MPa.

MIKES 1	July 2005						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result		deviation d (k=2)			
Nominal pressure	Original result	Uncert. k=2	Drift correction	Corrected result	Reference value	Uncert. of ref. k=2	from ref. value abs.	rel.	U(d) abs.	U(d) rel.		
MPa	mm²	mm²	mm²	mm²	mm²	mm²	mm²	/10⁻⁶	mm²	/10⁻⁶	d/U(d)	E(n)
50	1,961721	0,000131	0,000046	1,961767	1,961755	0,000041	0,000012	5,9	0,000131	67	0,09	0,08
100	1,961755	0,000137	0,000046	1,961801	1,961804	0,000049	-0,000003	-1,7	0,000137	70	-0,03	-0,02
150	1,961801	0,000144	0,000046	1,961847	1,961866	0,000054	-0,000019	-9,9	0,000144	73	-0,13	-0,13
200	1,961871	0,000152	0,000046	1,961917	1,961933	0,000056	-0,000016	-8,4	0,000152	77	-0,11	-0,10
250	1,961941	0,000163	0,000046	1,961987	1,962005	0,000060	-0,000018	-9,4	0,000163	83	-0,11	-0,11
300	1,962025	0,000175	0,000046	1,962071	1,962076	0,000063	-0,000005	-2,8	0,000175	89	-0,03	-0,03
350	1,962104	0,000189	0,000046	1,962150	1,962152	0,000067	-0,000002	-1,2	0,000189	96	-0,01	-0,01
400	1,962188	0,000203	0,000046	1,962234	1,962219	0,000070	0,000015	7,4	0,000203	103	0,07	0,07
450	1,962272	0,000219	0,000046	1,962318	1,962318	0,000087	0,000000	-0,2	0,000219	112	0,00	0,00
500	1,962350	0,000235	0,000046	1,962396	1,962403	0,000090	-0,000007	-3,8	0,000235	120	-0,03	-0,03

METAS	August 2005						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result		deviation d (k=2)			
Nominal pressure	Original result	Uncert. k=2	Drift correction	Corrected result	Reference value	Uncert. of ref. k=2	from ref. value abs.	rel.	U(d) abs.	U(d) rel.		
MPa	mm²	mm²	mm²	mm²	mm²	mm²	mm²	/10⁻⁶	mm²	/10⁻⁶	d/U(d)	E(n)
50	1,961732	0,000130	0,000040	1,961772	1,961755	0,000039	0,000017	8,7	0,000124	63	0,14	0,13
100	1,961778	0,000130	0,000040	1,961818	1,961804	0,000048	0,000014	7,1	0,000121	62	0,12	0,10
150	1,961845	0,000130	0,000040	1,961885	1,961866	0,000053	0,000019	9,7	0,000119	61	0,16	0,14
200	1,961912	0,000130	0,000040	1,961952	1,961933	0,000055	0,000019	9,7	0,000118	60	0,16	0,13
250	1,961974	0,000130	0,000040	1,962014	1,962005	0,000059	0,000009	4,6	0,000116	59	0,08	0,06
300	1,962043	0,000130	0,000040	1,962083	1,962076	0,000062	0,000007	3,6	0,000114	58	0,06	0,05
350	1,962107	0,000130	0,000040	1,962147	1,962152	0,000066	-0,000005	-2,6	0,000112	57	-0,04	-0,03
400	1,962141	0,000130	0,000040	1,962181	1,962219	0,000070	-0,000038	-19,4	0,000110	56	-0,35	-0,26
450	1,962434	0,000590	0,000040	1,962474	1,962318	0,000087	0,000156	79,5	0,000584	297	0,27	0,26
500	1,962508	0,000590	0,000040	1,962548	1,962403	0,000090	0,000145	73,9	0,000583	297	0,25	0,24

Table 2b. Results from CMI, PTB, MIKES 2 and SMD at nominal pressures from 50 MPa to 500 MPa.

CMI	December 2005						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure MPa	Original result mm²	Uncert. k=2 mm²	Drift correction mm²	Corrected result mm²	Reference value mm²	Uncert. of ref. k=2 mm²	abs. mm²	rel. /10^{-6}	U(d) abs. mm²	U(d) rel. /10^{-6}	d/U(d)	E(n)
50	1,961785	0,000065	0,000007	1,961792	1,961755	0,000034	0,000037	19,1	0,000055	28	0,68	0,51
100	1,961851	0,000084	0,000007	1,961858	1,961804	0,000044	0,000054	27,7	0,000072	36	0,76	0,57
150	1,961913	0,000101	0,000007	1,961920	1,961866	0,000050	0,000054	27,7	0,000088	45	0,62	0,48
200	1,961990	0,000118	0,000007	1,961997	1,961933	0,000051	0,000064	32,8	0,000106	54	0,61	0,50
250	1,962064	0,000136	0,000007	1,962071	1,962005	0,000056	0,000066	33,9	0,000124	63	0,54	0,45
300	1,962142	0,000154	0,000007	1,962149	1,962076	0,000059	0,000073	37,4	0,000142	72	0,52	0,45
350	1,962234	0,000173	0,000007	1,962241	1,962152	0,000063	0,000089	45,6	0,000161	82	0,56	0,49
400	1,962342	0,000195	0,000007	1,962349	1,962219	0,000067	0,000130	66,5	0,000183	93	0,71	0,63
450	1,962430	0,000213	0,000007	1,962437	1,962318	0,000085	0,000119	60,9	0,000195	100	0,61	0,52
500	1,962610	0,000231	0,000007	1,962617	1,962403	0,000088	0,000214	109,3	0,000214	109	1,00	0,87

PTB	February 2006						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure MPa	Original result mm²	Uncert. k=2 mm²	Drift correction mm²	Corrected result mm²	Reference value mm²	Uncert. of ref. k=2 mm²	abs. mm²	rel. /10^{-6}	U(d) abs. mm²	U(d) rel. /10^{-6}	d/U(d)	E(n)
50	1,961748	0,000043	-0,000010	1,961738	1,961755	0,000035	-0,000017	-8,8	0,000025	13	-0,69	-0,31
100	1,961784	0,000059	-0,000010	1,961774	1,961804	0,000044	-0,000030	-15,4	0,000039	20	-0,77	-0,41
150	1,961848	0,000067	-0,000010	1,961838	1,961866	0,000050	-0,000028	-14,4	0,000045	23	-0,63	-0,34
200	1,961918	0,000067	-0,000010	1,961908	1,961933	0,000051	-0,000025	-12,9	0,000043	22	-0,58	-0,30
250	1,961993	0,000075	-0,000010	1,961983	1,962005	0,000056	-0,000022	-11,3	0,000050	25	-0,45	-0,24
300	1,962066	0,000078	-0,000010	1,962056	1,962076	0,000059	-0,000020	-10,3	0,000051	26	-0,40	-0,21
350	1,962144	0,000086	-0,000010	1,962134	1,962152	0,000063	-0,000018	-9,3	0,000059	30	-0,31	-0,17
400	1,962218	0,000094	-0,000010	1,962208	1,962219	0,000067	-0,000011	-5,7	0,000066	34	-0,17	-0,10
450	1,962300	0,000106	-0,000010	1,962290	1,962318	0,000085	-0,000028	-14,4	0,000063	32	-0,45	-0,21
500	1,962374	0,000110	-0,000010	1,962364	1,962403	0,000088	-0,000039	-20,0	0,000066	34	-0,59	-0,28

MIKES 2	May 2006						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure MPa	Original result mm²	Uncert. k=2 mm²	Drift correction mm²	Corrected result mm²	Reference value mm²	Uncert. of ref. k=2 mm²	abs. mm²	rel. /10^{-6}	U(d) abs. mm²	U(d) rel. /10^{-6}	d/U(d)	E(n)
50	1,961751	0,000132	-0,000036	1,961715	1,961755	0,000038	-0,000040	-20,5	0,000132	67	-0,31	-0,29
100	1,961796	0,000137	-0,000036	1,961760	1,961804	0,000047	-0,000044	-22,6	0,000137	70	-0,32	-0,31
150	1,961855	0,000145	-0,000036	1,961819	1,961866	0,000053	-0,000047	-24,1	0,000145	74	-0,33	-0,31
200	1,961908	0,000152	-0,000036	1,961872	1,961933	0,000054	-0,000061	-31,2	0,000152	77	-0,40	-0,38
250	1,961988	0,000163	-0,000036	1,961952	1,962005	0,000059	-0,000053	-27,2	0,000163	83	-0,33	-0,31
300	1,962055	0,000175	-0,000036	1,962019	1,962076	0,000061	-0,000057	-29,2	0,000175	89	-0,33	-0,31
350	1,962129	0,000189	-0,000036	1,962093	1,962152	0,000065	-0,000059	-30,2	0,000189	96	-0,31	-0,30
400	1,962204	0,000204	-0,000036	1,962168	1,962219	0,000069	-0,000051	-26,1	0,000204	104	-0,25	-0,24
450	1,962279	0,000219	-0,000036	1,962243	1,962318	0,000086	-0,000075	-38,4	0,000219	112	-0,34	-0,32
500	1,962368	0,000235	-0,000036	1,962332	1,962403	0,000089	-0,000071	-36,3	0,000235	120	-0,30	-0,28

SMD	July 2006						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure MPa	Original result mm²	Uncert. k=2 mm²	Drift correction mm²	Corrected result mm²	Reference value mm²	Uncert. of ref. k=2 mm²	abs. mm²	rel. /10^{-6}	U(d) abs. mm²	U(d) rel. /10^{-6}	d/U(d)	E(n)
50	1,961800	0,000080	-0,000048	1,961752	1,961755	0,000041	-0,000003	-1,7	0,000080	41	-0,04	-0,04
100	1,961870	0,000080	-0,000048	1,961822	1,961804	0,000050	0,000018	9,0	0,000080	41	0,22	0,19
150	1,961950	0,000080	-0,000048	1,961902	1,961866	0,000055	0,000036	18,2	0,000080	41	0,45	0,37
200	1,962030	0,000080	-0,000048	1,961982	1,961933	0,000056	0,000049	24,8	0,000080	41	0,61	0,50
250	1,962110	0,000090	-0,000048	1,962062	1,962005	0,000061	0,000057	28,9	0,000090	46	0,63	0,52
300	1,962160	0,000090	-0,000048	1,962112	1,962076	0,000063	0,000036	18,2	0,000090	46	0,40	0,32
350	1,962240	0,000100	-0,000048	1,962192	1,962152	0,000067	0,000040	20,2	0,000100	51	0,40	0,33
400	1,962300	0,000110	-0,000048	1,962252	1,962219	0,000071	0,000033	16,6	0,000110	56	0,30	0,25
450	1,962370	0,000120	-0,000048	1,962322	1,962318	0,000088	0,000004	1,9	0,000120	61	0,03	0,02
500	1,962430	0,000120	-0,000048	1,962382	1,962403	0,000091	-0,000021	-10,9	0,000120	61	-0,18	-0,14

Table 2c. Results from NMi-VSL, SP and MIKES 3 at nominal pressures from 50 MPa to 500 MPa.

NMi-VSL	July 2006						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure	Original result	Uncert. k=2	Drift correction	Corrected result	Reference value	Uncert. of ref. k=2	abs.	rel.	U(d) abs.	U(d) rel.		
MPa	mm²	mm²	mm²	mm²	mm²	mm²	mm²	/10⁻⁶	mm²	/10⁻⁶	d/U(d)	E(n)
50	1,961802	0,000196	-0,000051	1,961751	1,961755	0,000042	-0,000004	-2,1	0,000191	98	-0,02	-0,02
100	1,961859	0,000196	-0,000051	1,961808	1,961804	0,000051	0,000004	2,0	0,000189	96	0,02	0,02
150	1,961920	0,000196	-0,000051	1,961869	1,961866	0,000056	0,000003	1,5	0,000188	96	0,02	0,01
200	1,961991	0,000196	-0,000051	1,961940	1,961933	0,000057	0,000007	3,5	0,000188	96	0,04	0,03
250	1,962057	0,000196	-0,000051	1,962006	1,962005	0,000062	0,000001	0,4	0,000186	95	0,00	0,00
300	1,962125	0,000196	-0,000051	1,962074	1,962076	0,000064	-0,000002	-1,1	0,000185	94	-0,01	-0,01
350	1,962197	0,000196	-0,000051	1,962146	1,962152	0,000068	-0,000006	-3,1	0,000184	94	-0,03	-0,03
400	1,962278	0,000196	-0,000051	1,962227	1,962219	0,000072	0,000008	4,0	0,000182	93	0,04	0,04
450	1,962348	0,000196	-0,000051	1,962297	1,962318	0,000088	-0,000021	-10,8	0,000175	89	-0,12	-0,10
500	1,962407	0,000196	-0,000051	1,962356	1,962403	0,000091	-0,000047	-24,0	0,000174	88	-0,27	-0,22

SP	August 2006						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure	Original result	Uncert. k=2	Drift correction	Corrected result	Reference value	Uncert. of ref. k=2	abs.	rel.	U(d) abs.	U(d) rel.		
MPa	mm²	mm²	mm²	mm²	mm²	mm²	mm²	/10⁻⁶	mm²	/10⁻⁶	d/U(d)	E(n)
50	1,961755	0,000073	-0,000059	1,961696	1,961755	0,000044	-0,000059	-29,9	0,000073	37,2	-0,80	-0,69
100	1,961850	0,000078	-0,000059	1,961791	1,961804	0,000052	-0,000013	-6,4	0,000078	40	-0,16	-0,13
150	1,961921	0,000090	-0,000059	1,961862	1,961866	0,000057	-0,000004	-1,8	0,000090	46	-0,04	-0,03
200	1,961990	0,000110	-0,000059	1,961931	1,961933	0,000058	-0,000002	-0,8	0,000110	56	-0,01	-0,01
250	1,962060	0,000120	-0,000059	1,962001	1,962005	0,000063	-0,000004	-1,8	0,000120	61	-0,03	-0,03
300	1,962140	0,000140	-0,000059	1,962081	1,962076	0,000065	0,000005	2,8	0,000140	71	0,04	0,04
350	1,962210	0,000160	-0,000059	1,962151	1,962152	0,000069	-0,000001	-0,3	0,000160	82	0,00	0,00
400	1,962290	0,000180	-0,000059	1,962231	1,962219	0,000073	0,000012	6,3	0,000180	92	0,07	0,06
450	1,962380	0,000200	-0,000059	1,962321	1,962318	0,000089	0,000003	1,7	0,000200	102	0,02	0,02
500	1,962470	0,000220	-0,000059	1,962411	1,962403	0,000092	0,000008	4,3	0,000220	112	0,04	0,04

MIKES 3	January 2007						Deviation d		Uncertainty of			
	Effective area at 20 C						of corrected result from ref. value		deviation d (k=2)			
Nominal pressure	Original result	Uncert. k=2	Drift correction	Corrected result	Reference value	Uncert. of ref. k=2	abs.	rel.	U(d) abs.	U(d) rel.		
MPa	mm²	mm²	mm²	mm²	mm²	mm²	mm²	/10⁻⁶	mm²	/10⁻⁶	d/U(d)	E(n)
50	1,961828	0,000131	-0,000094	1,961734	1,961755	0,000056	-0,000021	-10,7	0,000131	67	-0,16	-0,15
100	1,961892	0,000135	-0,000094	1,961798	1,961804	0,000063	-0,000006	-3,0	0,000135	69	-0,04	-0,04
150	1,961957	0,000142	-0,000094	1,961863	1,961866	0,000067	-0,000003	-1,5	0,000142	72	-0,02	-0,02
200	1,962024	0,000151	-0,000094	1,961930	1,961933	0,000068	-0,000003	-1,5	0,000151	77	-0,02	-0,02
250	1,962097	0,000162	-0,000094	1,962003	1,962005	0,000072	-0,000002	-1,0	0,000162	83	-0,01	-0,01
300	1,962172	0,000175	-0,000094	1,962078	1,962076	0,000074	0,000002	1,1	0,000175	89	0,01	0,01
350	1,962249	0,000189	-0,000094	1,962155	1,962152	0,000077	0,000003	1,6	0,000189	96	0,02	0,02
400	1,962325	0,000203	-0,000094	1,962231	1,962219	0,000080	0,000012	6,2	0,000203	103	0,06	0,06
450	1,962406	0,000219	-0,000094	1,962312	1,962318	0,000096	-0,000006	-3,0	0,000219	112	-0,03	-0,02
500	1,962487	0,000237	-0,000094	1,962393	1,962403	0,000098	-0,000010	-5,1	0,000237	121	-0,04	-0,04

7.1 Equivalence with reference values

The degree of equivalence of the results and the reference values was again calculated according to the procedure A of Ref [9]. The degree of equivalence of each laboratory result and the reference value is expressed by two terms: The deviation d_i of the laboratory result x_i from the reference value x_{ref}

$$d_i = x_i - x_{ref}$$

and the uncertainty $U(d_i)$ of the deviation d_i defined as

$$U(d_i) = 2u(d_i)$$

where $u(d_i)$ for the primary level laboratories METAS, CMI, PTB and NMi-VSL whose results were used in calculating the reference values is given by

$$u^2(d_i) = u^2(x_i) - u^2(x_{ref})$$

and by

$$u^2(d_i) = u^2(x_i)$$

for the secondary level laboratories MIKES, SMD and SP.

The values of deviations d_i and their uncertainties $U(d_i)$ for the results from all laboratories were calculated and are shown in Table 2. For easier comparison the calculated relations d_i / $U(d_i)$ are also included.

Further, the traditional normalised error E_n - values for each result are shown in Table 2. The disadvantage of the normalised error is the fact that it does not take into account the correlation between the reference value and the laboratory results which it is based on.

A summary of the results as relations d_i / $U(d_i)$ and normalised error values E_n are shown in Table 3. Figure 8 illustrates the relations d_i / $U(d_i)$ and Figure 9 the E_n – values.

Table 3. Summary of the deviations d_i as relations d_i / $U(d_i)$ and the normalised errors E_n in the range 50 MPa to 500 MPa.

Laboratory	Range of relations d_i / $U(d_i)$	Range of normalised errors E_n
MIKES 1	-0,13 ... +0,09	-0,13 ... +0,08
METAS	-0,35 ... +0,27	-0,26 ... +0,26
CMI	+0,52 ... +1,00	+0,50 ... +0,87
PTB	-0,77 ... -0,17	-0,41 ... -0,17
MIKES 2	-0,40 ... -0,25	-0,38 ... -0,24
SMD	-0,18 ... +0,63	-0,14 ... +0,52
NMi-VSL	-0,27 ... +0,04	-0,22 ... +0,04
SP	-0,80 ... +0,07	-0,69 ... +0,06
MIKES 3	-0,16 ... +0,06	-0,15 ... +0,06

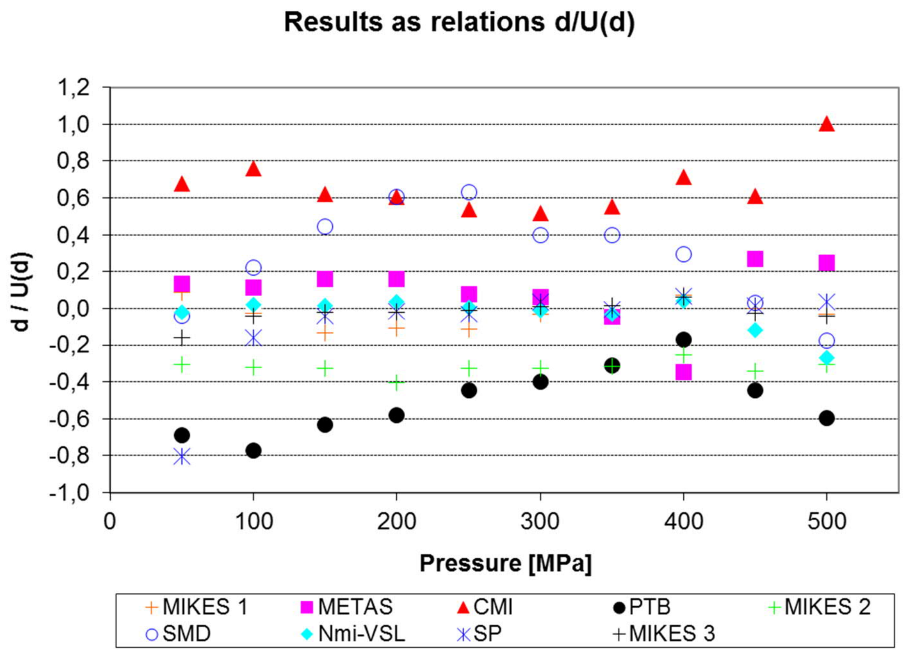

Figure 8. Summary of the deviations d_i in the range 50 MPa to 500 MPa as relations d_i / $U(d_i)$.

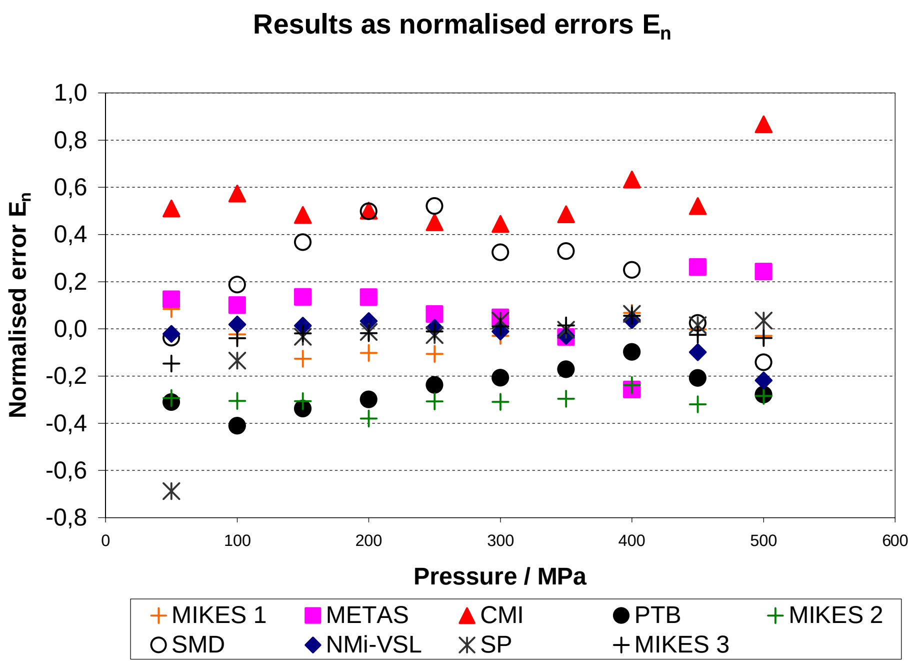

Figure 9. Results as normalised errors E_n.

All results from all participating laboratories are equivalent with the reference values as the values d_i / $U(d_i)$ are all in the range from -1,00 to +1,00. The same conclusion can be drawn from the normalised error values E_n.

7.2 Mutual equivalence

The degree of the mutual equivalence of the results from each pair of laboratories is similarly expressed by two terms: The difference D_{ij} between the result x_i from laboratory i and the result x_j from laboratory j and the uncertainty $U(D_{ij})$ of the difference. D_{ij} is defined as

$$D_{ij} = x_i - x_j$$

and

$$U(D_{ij}) = 2u(D_{ij}),$$

where $u(D_{ij})$ is given by

$$u^2(D_{ij}) = u^2(x_i) - u^2(x_j).$$

Tables 4a and 4b show the comparison of all the results in pairs. As

$| D_{ij} | < U(D_{ij})$

for all the observed differences at each nominal pressure, the results can be regarded as mutually equivalent. The result set 2 of the three from MIKES was selected for this comparison as its measurement date was closest to the reference one.

Table 4a. Mutual equivalence of the results at nominal pressures from 50 MPa and 100 MPa.

50 MPa		Lab j	METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
Lab i	d_i /10^{-6}	$U(d)_i$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}
METAS	8,7	66			-10,4	74	17,5	70	29,2	94	10,4	78	10,8	120	38,6	76
CMI	19,1	33	10,4	74			27,9	40	39,6	75	20,8	53	21,2	105	49,0	50
PTB	-8,8	22	-17,5	70	-27,9	40			11,7	70	-7,1	46	-6,7	102	21,1	43
MIKES 2	-20,5	67	-29,2	94	-39,6	75	-11,7	70			-18,8	79	-18,4	120	9,4	77
SMD	-1,7	41	-10,4	78	-20,8	53	7,1	46	18,8	79			0,4	108	28,2	55
NMi-VSL	-2,1	100	-10,8	120	-21,2	105	6,7	102	18,4	120	-0,4	108			27,8	107
SP	-29,9	37	-38,6	76	-49,0	50	-21,1	43	-9,4	77	-28,2	55	-27,8	107		

100 MPa		Lab j	METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
Lab i	d_i /10^{-6}	$U(d)_i$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}	D_{ij} /10^{-6}	$U(D_{ij})$ /10^{-6}
METAS	7,1	66			-20,6	79	22,5	73	29,7	96	-1,9	78	5,1	120	13,5	77
CMI	27,7	43	20,6	79			43,1	52	50,3	82	18,7	59	25,7	109	34,1	59
PTB	-15,4	30	-22,5	73	-43,1	52			7,2	76	-24,4	51	-17,4	104	-9,0	50
MIKES 2	-22,6	70	-29,7	96	-50,3	82	-7,2	76			-31,6	81	-24,6	122	-16,2	81
SMD	9,0	41	1,9	78	-18,7	59	24,4	51	31,6	81			7,0	108	15,4	57
NMi-VSL	2,0	100	-5,1	120	-25,7	109	17,4	104	24,6	122	-7,0	108			8,4	108
SP	-6,4	40	-13,5	77	-34,1	59	9,0	50	16,2	81	-15,4	57	-8,4	108		

Table 4b. Mutual equivalence of the results at nominal pressures from 150 MPa and 400 MPa.

150 MPa	Lab j		METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	9,7	66			-18,0	84	-4,7	75	33,8	99	-8,5	78	8,2	117	11,5	81
CMI	27,7	52	18,0	84			13,3	62	51,8	90	9,5	66	26,2	109	29,5	69
PTB	14,4	34	4,7	75	-13,3	62			38,5	82	-3,8	53	12,9	102	16,2	57
MIKES 2	-24,1	74	-33,8	99	-51,8	90	-38,5	82			-42,3	85	-25,6	121	-22,3	87
SMD	18,2	41	8,5	78	-9,5	66	3,8	53	42,3	85			16,7	104	20,0	62
NMi-VSL	1,5	96	-8,2	117	-26,2	109	-12,9	102	25,6	121	-16,7	104			3,3	106
SP	-1,8	46	-11,5	81	-29,5	69	-16,2	57	22,3	87	-20,0	62	-3,3	106		

200 MPa	Lab j		METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	9,7	66			-23,1	89	22,6	75	40,9	102	-15,1	78	6,2	120	10,5	87
CMI	32,8	60	23,1	89			45,7	69	64,0	98	8,0	73	29,3	117	33,6	82
PTB	-12,9	34	-22,6	75	-45,7	69			18,3	84	-37,7	53	-16,4	106	-12,1	66
MIKES 2	-31,2	77	-40,9	102	-64,0	98	-18,3	84			-56,0	87	-34,7	126	-30,4	95
SMD	24,8	41	15,1	78	-8,0	73	37,7	53	56,0	87			21,3	108	25,6	69
NMi-VSL	3,5	100	-6,2	120	-29,3	117	16,4	106	34,7	126	-21,3	108			4,3	115
SP	-0,8	56	-10,5	87	-33,6	82	12,1	66	30,4	95	-25,6	69	-4,3	115		

250 MPa	Lab j		METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	4,6	66			-29,3	96	15,9	77	31,8	106	-24,3	81	4,2	120	6,4	90
CMI	33,9	69	29,3	96			45,2	79	61,1	108	5,0	83	33,5	122	35,7	92
PTB	-11,3	38	-15,9	77	-45,2	79			15,9	91	-40,2	60	-11,7	107	-9,5	72
MIKES 2	-27,2	83	-31,8	106	-61,1	108	-15,9	91			-56,1	95	-27,6	130	-25,4	103
SMD	28,9	46	24,3	81	-5,0	83	40,2	60	56,1	95			28,5	110	30,7	76
NMi-VSL	0,4	100	-4,2	120	-33,5	122	11,7	107	27,6	130	-28,5	110			2,2	117
SP	-1,8	61	-6,4	90	-35,7	92	9,5	72	25,4	103	-30,7	76	-2,2	117		

300 MPa	Lab j		METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	3,6	66			-33,8	103	13,9	77	32,8	111	-14,6	81	4,7	120	0,8	97
CMI	37,4	79	33,8	103			47,7	88	66,6	119	19,2	91	38,5	127	34,6	106
PTB	-10,3	40	-13,9	77	-47,7	88			18,9	97	-28,5	61	-9,2	108	-13,1	81
MIKES 2	-29,2	89	-32,8	111	-66,6	119	-18,9	97			-47,4	100	-28,1	134	-32,0	114
SMD	18,2	46	14,6	81	-19,2	91	28,5	61	47,4	100			19,3	110	15,4	85
NMi-VSL	-1,1	100	-4,7	120	-38,5	127	9,2	108	28,1	134	-19,3	110			-3,9	123
SP	2,8	71	-0,8	97	-34,6	106	13,1	81	32,0	114	-15,4	85	3,9	123		

350 MPa	Lab j		METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	-2,6	66			-48,2	110	6,7	79	27,6	117	-22,8	84	0,5	120	-2,3	105
CMI	45,6	88	48,2	110			54,9	98	75,8	130	25,4	102	48,7	133	45,9	120
PTB	-9,3	44	-6,7	79	-54,9	98			20,9	106	-29,5	67	-6,2	109	-9,0	93
MIKES 2	-30,2	96	-27,6	117	-75,8	130	-20,9	106			-50,4	109	-27,1	139	-29,9	126
SMD	20,2	51	22,8	84	-25,4	102	29,5	67	50,4	109			23,3	112	20,5	97
NMi-VSL	-3,1	100	-0,5	120	-48,7	133	6,2	109	27,1	139	-23,3	112			-2,8	129
SP	-0,3	82	2,3	105	-45,9	120	9,0	93	29,9	126	-20,5	97	2,8	129		

400 MPa	Lab j		METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	-19,4	66			-85,9	119	-13,7	82	6,7	123	-36,0	87	-23,4	120	-25,7	113
CMI	66,5	99	85,9	119			72,2	110	92,6	144	49,9	114	62,5	141	60,2	135
PTB	-5,7	48	13,7	82	-72,2	110			20,4	115	-22,3	74	-9,7	111	-12,0	104
MIKES 2	-26,1	104	-6,7	123	-92,6	144	-20,4	115			-42,7	118	-30,1	144	-32,4	139
SMD	16,6	56	36,0	87	-49,9	114	22,3	74	42,7	118			12,6	115	10,3	108
NMi-VSL	4,0	100	23,4	120	-62,5	141	9,7	111	30,1	144	-12,6	115			-2,3	136
SP	6,3	92	25,7	113	-60,2	135	12,0	104	32,4	139	-10,3	108	2,3	136		

Table 4c. Mutual equivalence of the results at nominal pressures from 450 MPa and 500 MPa.

450 MPa		Lab j	METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	79,5	301			18,6	320	93,9	305	118	321	77,6	307	90,3	317	77,8	317
CMI	60,9	109	-18,6	320			75,3	121	99,3	156	59,0	124	71,7	147	59,2	149
PTB	-14,4	54	-93,9	305	-75,3	121			24,0	124	-16,3	81	-3,6	114	-16,1	115
MIKES 2	-38,4	112	-118	321	-99,3	156	-24,0	124			-40,3	128	-27,6	150	-40,1	151
SMD	1,9	61	-77,6	307	-59,0	124	16,3	81	40,3	128			12,7	117	0,2	119
NMi-VSL	-10,8	100	-90,3	317	-71,7	147	3,6	114	27,6	150	-12,7	117			-12,5	143
SP	1,7	102	-77,8	317	-59,2	149	16,1	115	40,1	151	-0,2	119	12,5	143		

500 MPa		Lab j	METAS		CMI		PTB		MIKES 2		SMD		NMi-VSL		SP	
	d_i	$U(d)_i$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$	D_{ij}	$U(D_{ij})$
Lab i	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$	$/10^{-6}$
METAS	73,9	306			-35,4	328	93,9	311	110	329	84,8	312	97,9	322	69,6	326
CMI	109,3	118	35,4	328			129	130	146	168	120	133	133	154	105	162
PTB	-20,0	56	-93,9	311	-129	130			16,3	132	-9,1	83	4,0	115	-24,3	125
MIKES 2	-36,3	120	-110	329	-146	168	-16,3	132			-25,4	135	-12,3	156	-40,6	164
SMD	-10,9	61	-84,8	312	-120	133	9,1	83	25,4	135			13,1	117	-15,2	128
NMi-VSL	-24,0	100	-97,9	322	-133	154	-4,0	115	12,3	156	-13,1	117			-28,3	150
SP	4,3	112	-69,6	326	-105	162	24,3	125	40,6	164	15,2	128	28,3	150		

8 Effective area S_0 and the pressure distortion coefficient λ

The results of the effective area S0 at null pressure and 20 °C and the pressure distortion coefficient λ were, as agreed, supplementary information for the comparison. However, these results are interesting because these quantities are usually reported in calibration certificates for pressure balances. $S_{0,20C}$ and the pressure distortion coefficient λ are typically calculated as fitting a straight line to the result points obtained on higher pressures.

Again, the effective area results from each laboratory were corrected for the observed drift in the transfer standard to correspond to the 1st of January 2006. The uncertainty of the drift correction for each laboratory and the uncertainties of the reference values were combined as the square root of the sum of the squares.

No correction was made on the values for the pressure distortion coefficient λ as there were practically no changes.

The reference values for the effective area S0 at 20 °C and null pressure for the comparison were calculated as weighted averages in the manner described in the previous chapter, based on the results from the laboratories of primary level. The weighted averages were accepted as reference values for the comparison based on the results of the performed chi squared check.

The reference values for S_0 results and the results from the participating laboratories are shown in Table 5 and illustrated in Figure 10. For the pressure distortion coefficient λ the results are presented in Table 6 and Figure 11.

Table 5. The results at nominal pressure p = 0.

Lab.	Effective area at p = 0 and 20 C Original result mm^2	Uncert. k=2 mm^2	Drift correction mm^2	Corrected result mm^2	Reference value mm^2	Uncert. of ref. k=2 mm^2	Deviation d of corrected result from ref. value abs. mm^2	rel. $/10^{-6}$	Uncertainty of deviation d (k=2) U(d) abs. mm^2	U(d) rel. $/10^{-6}$	d/U(d)	E(n)
MIKES 1	1,961600	0,000131	0,000046	1,961646	1,961634	0,000049	0,000012	5,9	0,000131	67	0,09	0,08
METAS	1,961660	0,000130	0,000040	1,961700	1,961634	0,000048	0,000066	33,6	0,000121	62	0,55	0,48
CMI	1,961655	0,000069	0,000007	1,961662	1,961634	0,000044	0,000028	14,5	0,000053	27	0,54	0,35
PTB	1,961641	0,000067	-0,000010	1,961631	1,961634	0,000044	-0,000003	-1,6	0,000050	26	-0,06	-0,04
MIKES 2	1,961650	0,000128	-0,000036	1,961614	1,961634	0,000047	-0,000020	-10,3	0,000128	65	-0,16	-0,15
SMD	1,961740	0,000078	-0,000048	1,961692	1,961634	0,000050	0,000058	29,4	0,000078	40	0,74	0,62
NMi-VSL	1,961731	0,000196	-0,000051	1,961680	1,961634	0,000050	0,000046	23,4	0,000189	97	0,24	0,23
SP	1,961680	0,000230	-0,000059	1,961621	1,961634	0,000052	-0,000013	-6,4	0,000230	117	-0,05	-0,05
MIKES 3	1,961740	0,000125	-0,000094	1,961646	1,961634	0,000062	0,000012	6,2	0,000125	64	0,10	0,09

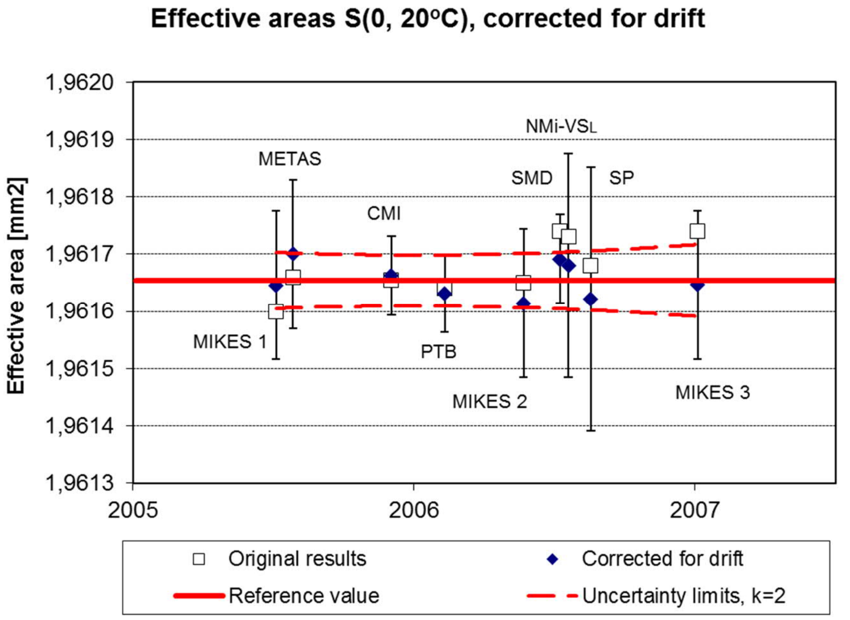

Figure 10. The results at nominal pressure p = 0.

Table 6. The results on the pressure distortion coefficient λ. The uncertainty value of the NMi-VSL result consists of the uncertainty from calculating the regression line only.

Lab.	Lambda Result 1/MPa	Unc. (k=2) 1/MPa
MIKES 1	7,4E-07	1,5E-07
METAS	6,3E-07	1,2E-07
CMI	8,9E-07	1,3E-07
PTB	7,4E-07	1,4E-07
MIKES 2	7,0E-07	1,5E-07
SMD	7,1E-07	1,0E-07
NMI-VSL	7,0E-07	1,4E-11
SP	7,9E-07	1,6E-07
MIKES 3	7,5E-07	1,5E-07

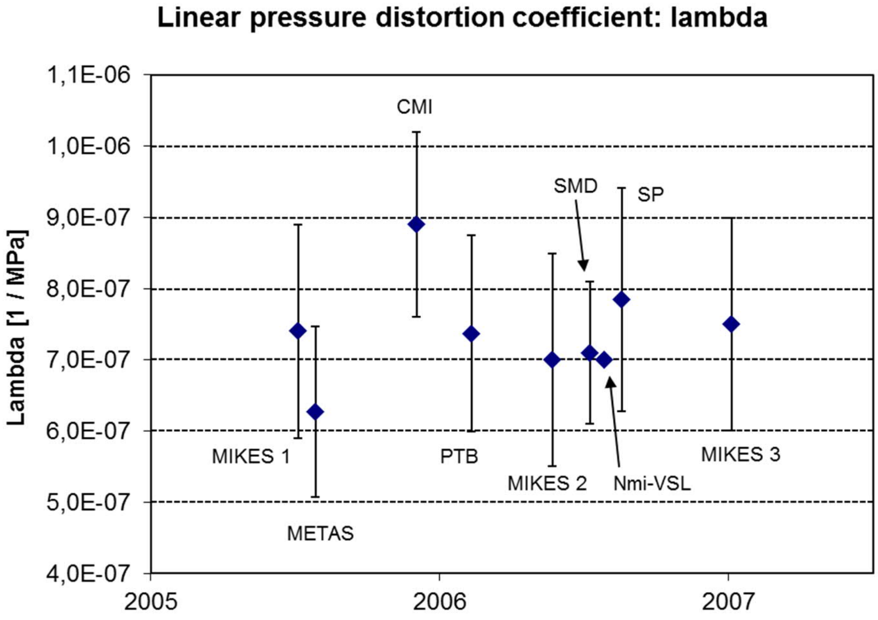

Figure 11. The results for the pressure distortion coefficient λ.

Figures 12 to 18 illustrate the comparison of the effective areas calculated from S_0 and λ to the areas determined at each nominal pressure. The uncertainties of S0 and λ were combined as the square root of the sum of the squares.

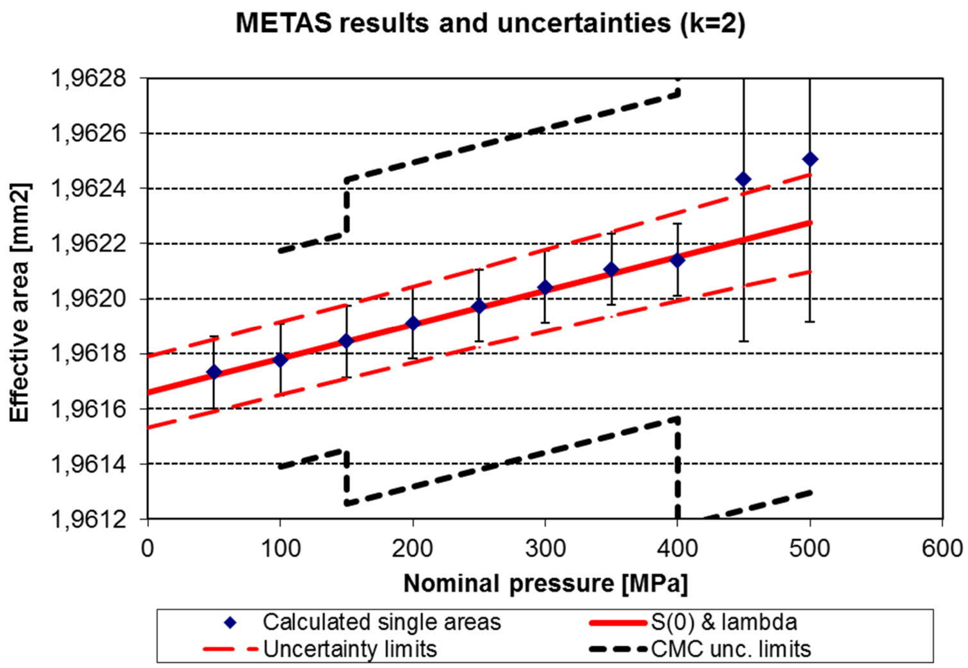

Figure 12. Results from METAS. The value of λ was calculated from measurements in the range 50 MPa to 400 MPa and extrapolated up to 500 MPa. The single areas at 450 MPa and 500 MPa are based on measurements using a pressure multiplier.

In addition to the comparison results Figures 12 to 18 illustrate the uncertainty values from the CMC-tables for the range 100 MPa to 500 MPa for each laboratory (Calibration and Measurement Capabilities in the BIPM key comparison database, situation 11th of June 2007).

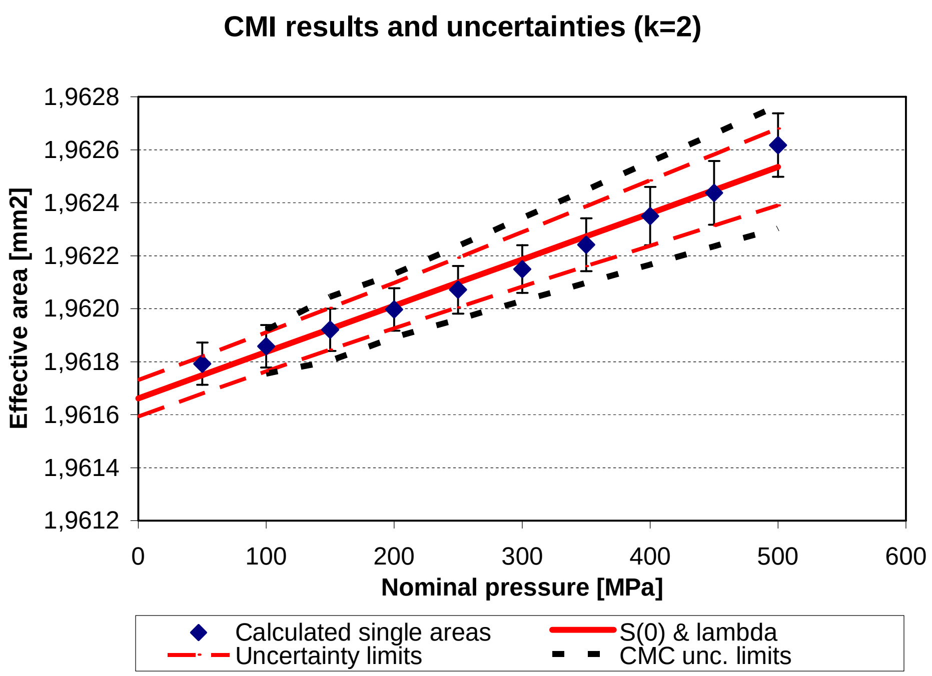

Figure 13. Results from CMI.

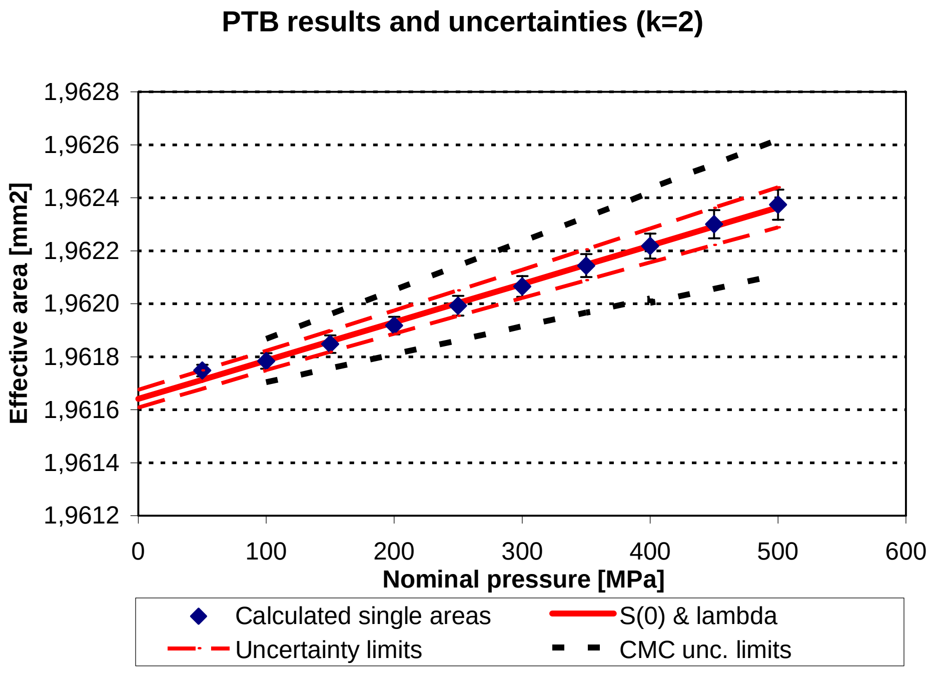

Figure 14. Results from PTB.

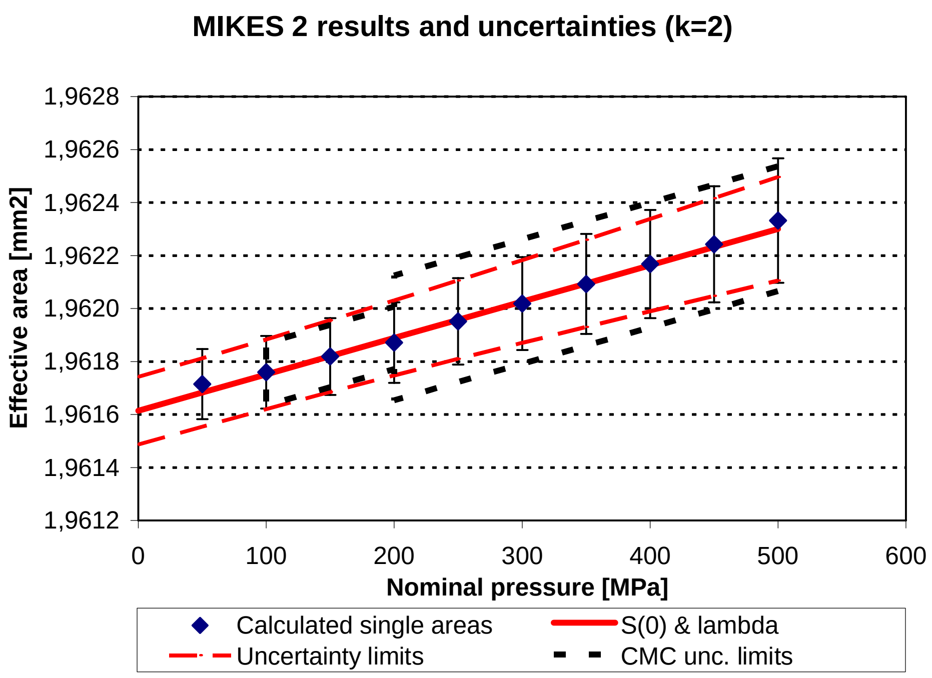

Figure 15. Results from MIKES (measurement 2).

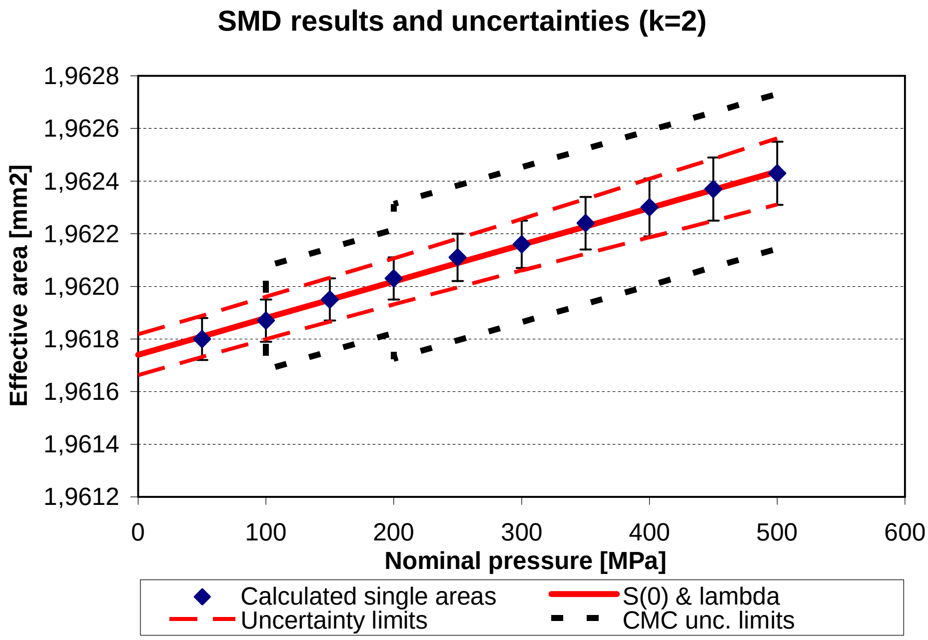

Figure 16. Results from SMD.

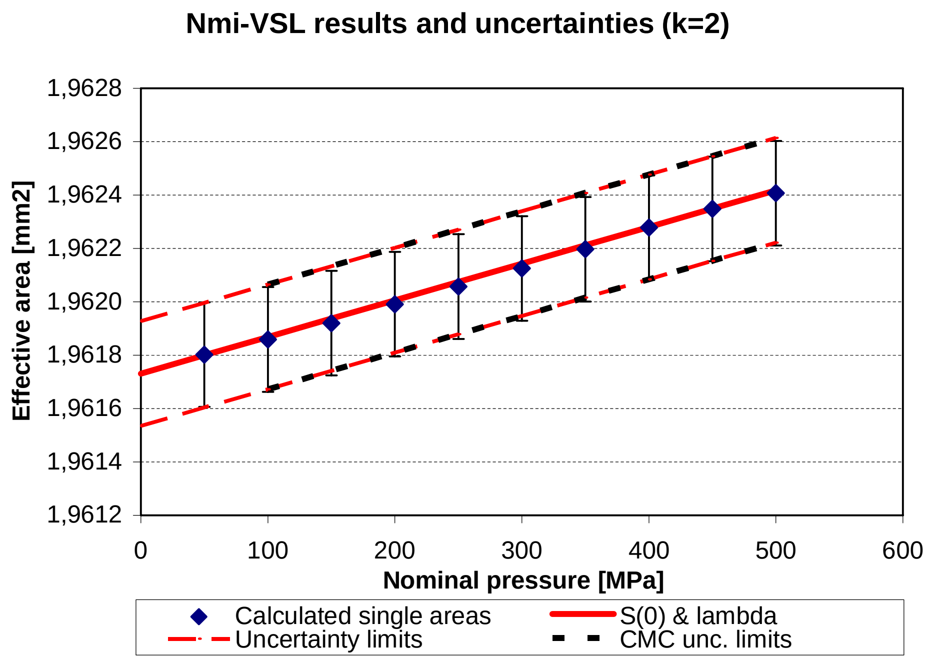

Figure 17. Results from NMi-VSL.

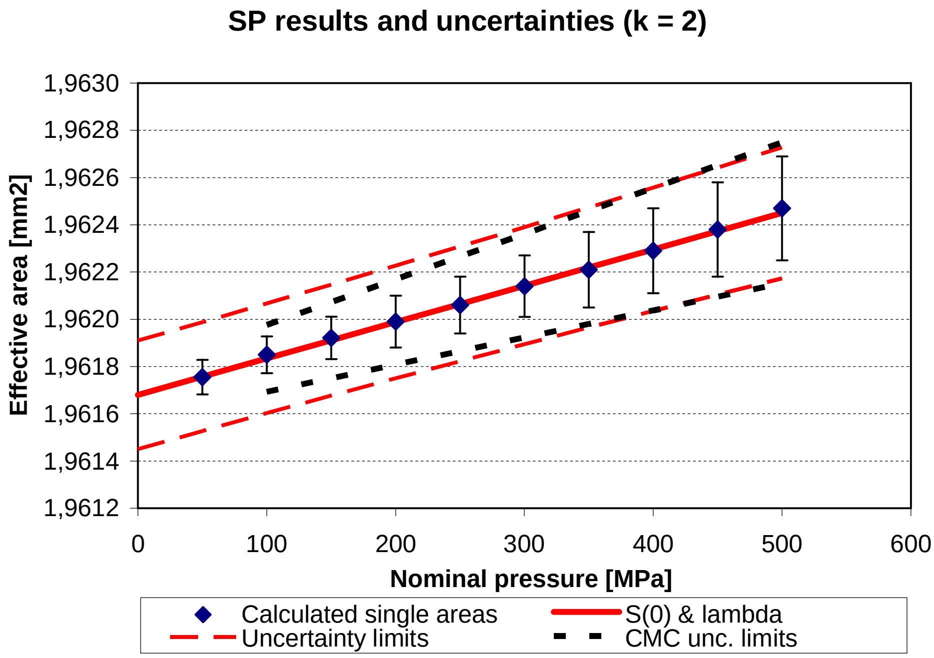

Figure 18. Results from SP.

The participating laboratories seem to have various approaches in giving the uncertainties for S_0 and λ.

Obviously the combined uncertainties of S_0 and λ from each laboratory should be high enough to make an envelope to the uncertainty bars of the results obtained at each nominal pressure. The combined uncertainties from CMI and MIKES seem to be too low. The extrapolated results from METAS at 450 MPa and 500 MPa lead to very much lower uncertainties than actual measurements with another standard. Further, a part of the uncertainty bar of the result from PTB measurement at 50 MPa falls outside the combined uncertainty of S_0 and λ due to the non-linearity of the transfer standard.

The uncertainty for λ given by NMi-VSL was only the (very small) uncertainty from calculating the regression line. The physical uncertainty of λ corresponding to the highest nominal pressure is included in the uncertainty of S_0. The results are consistent with the results obtained separately at each nominal pressure but obviously the uncertainties are overestimated at lower pressures. The results from NMi-VSL are shown in Figure 17.

METAS and SP give a large uncertainty for S_0 similar to NMi-VSL in combination with an additional realistic uncertainty for λ. MIKES, too, gives the uncertainties for S_0 and λ in this manner in their certificates for routine calibrations. Figure 18 shows the results from SP. It is easy to see that the uncertainties for the effective area based on S_0 and λ are overestimated at all nominal pressures.

The uncertainties given by NMi-VSL were exactly the same as their uncertainties in the CMC tables. From METAS, PTB and SMD the uncertainties were much lower than the CMC uncertainties.

9 Links to key comparisons

Many years have passed since the latest key comparisons in the high pressure range. EUROMET.M.P-K6 was carried out in 1992 – 1994 and EUROMET.M.P-K5 in 1993 – 1995. In principle it would have been possible to link the present comparison to the combination of these two key comparisons. As most of the old data is no longer relevant, it was decided to wait and make links to new comparisons that are in progress or in planning.

Edited in 2018:

The results of the comparison can be linked to the results of the key comparison CCM.P-K13 [11] using the results of PTB, who participated in both comparisons. The PTB uncertainties in both comparisons are practically the same.

U_i of the participants are calculated by adding (geometrically) $U(x_{ref,EURAMET})$ to $U(D_i)$. That is because, in the original report (MIKES Publication J4/2007), $U(D_i) = U_i - U(x_{ref,EURAMET})$ (geometrically) was used. Further, $U(x_{ref,EURAMET})$ are taken from the original report, Table 1, and $u(x_{ref,CCM})$ are from the final report of the comparison CCM.P-K13 [11], Table 16. U_PTB_stability is taken with 10 ppm relatively conservatively because of an observation made in the time between the two comparisons, see the final report of the comparison CCM.P-K13, Table 1, Note 1. U_CCM_drift is 4,4 ppm as stated in the final report of the comparison EURAMET.M.P-K13. U_EURAMET_drift is taken as 10 ppm (estimated from Figures 1 and 2 in the original report MIKES Publication J4/2007).

The difference between the EURAMET and the CCM KCRVs is taken as:

$$D_{\text{EURAMET, CCM}} = D_{\text{PTB, CCM}} - D_{\text{PTB,EURAMET}}$$

Deviation of EURAMET participant number i from the CCM KCRV ($D_{i,\text{CCM}}$) is:

$$D_{i,\text{CCM}} = D_{i,\text{EURAMET}} + D_{\text{EURAMET,CCM}}$$

Relations of EURAMET.M.P-K7 to CCM.P-K13 are presented in the tables 7a to 7d.

Table 7a. Relation of EURAMET.M.P-K7 to CCM.P-K13 (relative deviations and their relative expanded uncertainties) in the range 50 MPa to 150 MPa.

p_n / MPa	50			100			150		
	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i
$D_{PTB,EURAMET}$	-8,8	13	-0,68	-15,4	20	-0,77	-14,4	23	-0,63
$D_{PTB,CCM}$	-2,0	40	-0,05	0,0	31	0,00	0,7	33	0,02
$D_{EURAMET,CCM}$	6,8			15,4			15,1		

p_n / MPa	50			100			150		
	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i
$D_{MIKES1,EURAMET}$	5,9	67	0,09	-1,7	70	-0,02	-9,9	73	-0,14
$D_{METAS,EURAMET}$	8,7	63	0,14	7,1	62	0,11	9,7	61	0,16
$D_{CMI,EURAMET}$	19,1	28	0,68	27,7	36	0,77	27,7	45	0,62
$D_{MIKES2,EURAMET}$	-20,5	67	-0,31	-22,6	70	-0,32	-24,1	74	-0,33
$D_{SMD,EURAMET}$	-1,7	41	-0,04	9,0	41	0,22	18,2	41	0,44
$D_{NMi\text{-}VSL,EURAMET}$	-2,1	98	-0,02	2,0	96	0,02	1,5	96	0,02
$D_{SP,EURAMET}$	-29,9	37	-0,80	-6,4	40	-0,16	-1,8	46	-0,04
$D_{MIKES3,EURAMET}$	-10,7	67	-0,16	-3,0	69	-0,04	-1,5	72	-0,02
$D_{PTB,EURAMET}$	-8,8	13	-0,68	-15,4	20	-0,77	-14,4	23	-0,63
$D_{MIKES1,CCM}$	12,7	76	0,17	13,7	76	0,18	5,2	79	0,07
$D_{METAS,CCM}$	15,5	72	0,21	22,5	68	0,33	24,8	68	0,36
$D_{CMI,CCM}$	25,9	45	0,57	43,1	46	0,94	42,8	54	0,79
$D_{MIKES2,CCM}$	-13,7	76	-0,18	-7,2	76	-0,10	-9,0	80	-0,11
$D_{SMD,CCM}$	5,1	54	0,09	24,4	50	0,49	33,3	51	0,65
$D_{NMi\text{-}VSL,CCM}$	4,7	104	0,05	17,4	100	0,17	16,6	101	0,16
$D_{SP,CCM}$	-23,1	51	-0,45	9,0	49	0,18	13,3	55	0,24
$D_{MIKES3,CCM}$	-3,9	76	-0,05	12,4	75	0,17	13,6	78	0,17
$D_{PTB,CCM}$	-2,0	38	-0,05	0,0	35	0,00	0,7	38	0,02

Table 7b. Relation of EURAMET.M.P-K7 to CCM.P-K13 (relative deviations and their relative expanded uncertainties) in the range 200 MPa to 300 MPa.

p_n / MPa	200			250			300		
	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i
$D_{PTB,EURAMET}$	-12,9	22	-0,59	-11,3	25	-0,45	-10,3	26	-0,40
$D_{PTB,CCM}$	0,0	35	0,00	-0,4	38	-0,01	-1,6	42	-0,04
$D_{EURAMET,CCM}$	12,9			10,9			8,7		

p_n / MPa	200			250			300		
	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i
$D_{MIKES1,EURAMET}$	-8,4	77	-0,11	-9,4	83	-0,11	-2,8	89	-0,03
$D_{METAS,EURAMET}$	9,7	60	0,16	4,6	59	0,08	3,6	58	0,06
$D_{CMI,EURAMET}$	32,8	54	0,61	33,9	63	0,54	37,4	72	0,52
$D_{MIKES2,EURAMET}$	-31,2	77	-0,41	-27,2	83	-0,33	-29,2	89	-0,33
$D_{SMD,EURAMET}$	24,8	41	0,60	28,9	46	0,63	18,2	46	0,40
$D_{NMi-VSL,EURAMET}$	3,5	96	0,04	0,4	95	0,00	-1,1	94	-0,01
$D_{SP,EURAMET}$	-0,8	56	-0,01	-1,8	61	-0,03	2,8	71	0,04
$D_{MIKES3,EURAMET}$	-1,5	77	-0,02	-1,0	83	-0,01	1,1	89	0,01
$D_{PTB,EURAMET}$	-12,9	22	-0,59	-11,3	25	-0,45	-10,3	26	-0,40
$D_{MIKES1,CCM}$	4,5	83	0,05	1,5	90	0,02	5,9	96	0,06
$D_{METAS,CCM}$	22,6	67	0,34	15,5	68	0,23	12,3	68	0,18
$D_{CMI,CCM}$	45,7	62	0,74	44,8	72	0,63	46,1	80	0,57
$D_{MIKES2,CCM}$	-18,3	83	-0,22	-16,3	90	-0,18	-20,5	96	-0,21
$D_{SMD,CCM}$	37,7	51	0,74	39,8	57	0,70	26,9	58	0,46
$D_{NMi-VSL,CCM}$	16,4	101	0,16	11,3	101	0,11	7,6	101	0,08
$D_{SP,CCM}$	12,1	64	0,19	9,1	70	0,13	11,5	79	0,14
$D_{MIKES3,CCM}$	11,4	83	0,14	9,9	90	0,11	9,8	96	0,10
$D_{PTB,CCM}$	0,0	38	0,00	-0,4	42	-0,01	-1,6	44	-0,04

Table 7c. Relation of EURAMET.M.P-K7 to CCM.P-K13 (relative deviations and their relative expanded uncertainties) in the range 350 MPa to 450 MPa.

p_n / MPa	350			400			450		
	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i
$D_{PTB,EURAMET}$	-9,3	30	-0,31	-5,7	34	-0,17	-14,4	32	-0,45
$D_{PTB,CCM}$	-1,2	47	-0,03	-1,2	50	-0,02	-1,0	55	-0,02
$D_{EURAMET,CCM}$	8,1			4,5			13,4		

p_n / MPa	350			400			450		
	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i	D_i / ppm	U_i / ppm	D_i/U_i
$D_{MIKES1,EURAMET}$	-1,2	96	-0,01	7,4	103	0,07	-0,2	112	0,00
$D_{METAS,EURAMET}$	-2,6	57	-0,05	-19,4	56	-0,35	79,5	297	0,27
$D_{CMI,EURAMET}$	45,6	82	0,56	66,5	93	0,72	60,9	100	0,61
$D_{MIKES2,EURAMET}$	-30,2	96	-0,31	-26,1	104	-0,25	-38,4	112	-0,34
$D_{SMD,EURAMET}$	20,2	51	0,40	16,6	56	0,30	1,9	61	0,03
$D_{NMi-VSL,EURAMET}$	-3,1	94	-0,03	4,0	93	0,04	-10,8	89	-0,12
$D_{SP,EURAMET}$	-0,3	82	0,00	6,3	92	0,07	1,7	102	0,02
$D_{MIKES3,EURAMET}$	1,6	96	0,02	6,2	103	0,06	-3,0	112	-0,03
$D_{PTB,EURAMET}$	-9,3	30	-0,31	-5,7	34	-0,17	-14,4	32	-0,45
$D_{MIKES1,CCM}$	6,9	103	0,07	11,9	110	0,11	13,2	122	0,11
$D_{METAS,CCM}$	5,5	69	0,08	-14,9	69	-0,22	92,9	301	0,31
$D_{CMI,CCM}$	53,7	91	0,59	71,0	101	0,70	74,3	111	0,67
$D_{MIKES2,CCM}$	-22,1	103	-0,21	-21,6	111	-0,19	-25,0	122	-0,20
$D_{SMD,CCM}$	28,3	64	0,44	21,1	69	0,31	15,3	78	0,20
$D_{NMi-VSL,CCM}$	5,0	102	0,05	8,5	101	0,08	2,6	102	0,03
$D_{SP,CCM}$	7,8	91	0,09	10,8	100	0,11	15,1	113	0,13
$D_{MIKES3,CCM}$	9,7	103	0,09	10,7	110	0,10	10,4	122	0,09
$D_{PTB,CCM}$	-1,2	49	-0,02	-1,2	52	-0,02	-1,0	59	-0,02

Table 7d. Relation of EURAMET.M.P-K7 to CCM.P-K13 (relative deviations and their relative expanded uncertainties) at 500 MPa.

p_n / MPa	500		
	D_i / ppm	U_i / ppm	D_i/U_i
$D_{PTB,EURAMET}$	-20,0	34	-0,59
$D_{PTB,CCM}$	-0,2	61	0,00
$D_{EURAMET,CCM}$	19,8		

p_n / MPa	500		
	D_i / ppm	U_i / ppm	D_i/U_i
$D_{MIKES1,EURAMET}$	-3,8	120	-0,03
$D_{METAS,EURAMET}$	73,9	297	0,25
$D_{CMI,EURAMET}$	109,3	109	1,00
$D_{MIKES2,EURAMET}$	-36,3	120	-0,30
$D_{SMD,EURAMET}$	-10,9	61	-0,18
$D_{NMi\text{-}VSL,EURAMET}$	-24	88	-0,27
$D_{SP,EURAMET}$	4,3	112	0,04
$D_{MIKES3,EURAMET}$	-5,1	121	-0,04
$D_{PTB,EURAMET}$	-20,0	34	-0,59
$D_{MIKES1,CCM}$	16,0	131	0,12
$D_{METAS,CCM}$	93,7	302	0,31
$D_{CMI,CCM}$	129,1	121	1,07
$D_{MIKES2,CCM}$	-16,5	131	-0,13
$D_{SMD,CCM}$	8,9	80	0,11
$D_{NMi\text{-}VSL,CCM}$	-4,2	102	-0,04
$D_{SP,CCM}$	24,1	124	0,20
$D_{MIKES3,CCM}$	14,7	132	0,11
$D_{PTB,CCM}$	-0,2	62	0,00

10 Conclusions

The participants determined the effective area values at ten nominal pressures from 50 MPa to 500 MPa in steps of 50 MPa. The results of the participants are consistent with their uncertainty (k = 2) claims in the comparison EUROMET 881 / EURAMET.M.P.K7. In a great majority, the results of the participants are consistent with their uncertainty (k = 2) claims in the linked comparison CCM.P.K13, too, with only one minor exception (CMI result at 500 MPa, whose deviation from the CCM.P-K13 key comparison reference value is slightly higher than the uncertainty of the deviation). The link between this comparison (EUROMET 881 / EURAMET.M.P.K7) and the key comparison CCM.P.K13 was calculated and the original EUROMET 881 report (MIKES Publication J4/2007) was updated accordingly in 2018.

As the pressure distortion is the dominating source of uncertainty in this range, the claimed uncertainties were highest at 500 MPa, ranging from $5{,}6 \cdot 10^{-5}$ of PTB to $1{,}2 \cdot 10^{-4}$ of MIKES (expanded relative uncertainties). Except for PTB, there were no big differences in the claimed uncertainties between the primary and the secondary level laboratories. The uncertainties given by METAS for the nominal pressures 450 MPa and 500 MPa were higher due to using a pressure multiplier. Their uncertainty at 500 MPa was $3{,}01 \cdot 10^{-4}$.

Some of the participants gave unnecessarily high uncertainties when giving their results in terms of the effective area at null pressure S_0 and the pressure distortion coefficient λ. On the other hand some of them underestimated the uncertainty of the pressure distortion coefficient which was inconsistent with the uncertainty of the effective area S_p at high pressures. Whereas all participants' results demonstrate full mutual agreement for effective areas S_p and S_0, the differences between their pressure distortion coefficients sometimes exceed the uncertainties of these differences. As a consequence, the effective areas S_p based on reported S_0 and λ values do not always agree at the highest pressure.

The transfer standard was not as stable as expected, and the uncertainties of the reference values were to some extent increased by the observed drift.

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