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Draft B report

Bell, Piston-Prover Bilateral-Comparison

EUROMET Project no. 852

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Introduction

This report describes the bilateral-comparison between Italian and Swiss NMIs (INRIM and METAS) of four primary standard gas provers carried out during year 2005: two bell provers and two piston provers were involved. The aim of the project was to ensure that there is good agreement between these four test facilities, and to test the relative merits of piston provers as compared to bell provers. An Instromet G25 rotary piston meter supplied by METAS was used as transfer standard and was repeatedly calibrated at (0.3, 0.5, 1, 2, 3, 4, 5, 6, 8, 9, 14, 16, 18, 20, and 25) m^3/h.

The project was registered as EUROMET project 852, as well as EUROMET.M.FF.S1 in the BIPM key comparison database. In 1998 three of the four provers (those existing at the time) had already taken part successfully in the EUROMET Projects 419 and 425 (comparisons among more than 12 European NMIs).

The participant persons in EUROMET 852 have been:

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The results of the project have also been presented by G. Cignolo, on behalf of both Institutes, at the 6th International Symposium on Fluid Flow Measurement at Querétaro (Mexico) in May 2006 [1].

1. Transfer standard (TS)

The transfer standard used was an Instromet G25 rotary piston meter, which was supplied by METAS. The meter had the following characteristics:

Manufacturer, type: INSTROMET IRM-A, G25, year 1995

Serial No: 304215

Minimum flowrate Q_{min}: 0.5 m^3/h

Maximum flowrate Q_{max}: 40 m^3/h

K-factor: 26723.7 pulses/m^3

The TS has been tested both in Switzerland and in Italy with its own upstream and downstream straight pipes (Fig.: 2.1).

Upstream pipe: the inlet bore is 53 mm, soon brought down to about 41 mm by means of a 115 mm long reduction cone. The next rectilinear stretch of pipe is 402 mm long (9.8 diameters). The size of the two end flanges is DN50.

Downstream pipe: another DN50 flange is fitted to the meter outlet port. The downstream pipe is 243 mm long with a diameter of 41 mm and it ends with a DN40 flange. The assembly discharges to atmosphere.

A fitting for radial insertion of a small-size temperature transducer is located close to the meter in both upstream and downstream pipes. The downstream location for thermometers and the upstream pressure port available on the meter body were used at both laboratories.

Fig. 2.1: Picture of the used transfer standard with the down and upstream pipes.

2. Facilities descriptions

Istituto Nazionale di Ricerca Metrologica (INRIM):

IT-BELL:

Bell prover:	0.16 m^3
Calibrated volume:	0.15 m^3
Displacement measure:	rotating encoder/pulse
Flow range:	(0.12 – 25) m^3/h
Uncertainty (CMC):	0.12 %

IT-PISTON:

Piston prover:	0.8 m^3
Calibrated volume:	0.8 m^3
Displacement measure:	rotating encoder/pulse
Flow range:	(1.8 - 160) m^3/h
Uncertainty (CMC):	0.05 % up to 65 m^3/h

Federal Office of Metrology (METAS):

CH-BELL:

Bell prover:	10 m^3
Calibrated volume:	10 m^3
Displacement measure:	electro-optic ruler
Flow range:	(1.0 – 1000) m^3/h
Uncertainty (CMC):	0.15 %

CH-PISTON:

Piston prover:	150 L
Calibrated volume:	150 L
Displacement measure:	encoder/pulse
Flow range:	(2.0 – 150) L/min
Uncertainty (CMC):	0.05 %

It can be seen that INRIM adopts a large piston prover together with a small bell prover, whereas METAS has just the opposite situation.

While both bell provers are quite traditional, the type of INRIM and METAS piston provers has seemingly never been adopted before in so large size. Their principle consists in forcing gas out from a chamber by introducing into it, at a constant speed, a precisely machined long piston through a fixed leak proof gasket. In addition to several practical advantages, the main asset of this type of piston is a metrological one: the volume-measuring body that has to be constructed and measured very accurately is the piston itself, instead of the cylinder that is the most important and critical part of a traditional piston-cylinder unit .

3. Test Procedure

Measurements at fifteen different flowrates have been made, ranging from 0.3 m^3/h to 25 m^3/h; the nominal test temperature was 21 °C.

3.1 Tests at METAS

At METAS, the tests have been carried out in the first half of 2005 and repeated (as a closure check) in January 2006, when the TS was back to METAS. The fifteen flowrates cannot be covered by both Swiss provers, since CH-PISTON is only specified up to 9 m^3/h; however two test flowrates (14 m^3/h and 16 m^3/h) have been added, in order to improve the overlapping with CH-BELL. When using CH-PISTON a single measurement was repeated 5 times consecutively; this was done for all flowrates 4 times, by changing the test flowrate after each set of 5 measurements. The tests with CH-BELL were repeated 3 times consecutively at each test flowrate; this shorter procedure is justified by the long-dating knowledge of the performance and repeatability of both the TS and the bell prover, as well as by the very long duration of tests.

As shown by the Fig.: 4.1 for the piston prover, the final closure calibrations of the TS performed in January 2006 on both Swiss provers were very close to the initial ones (2005), thus demonstrating the remarkable performance, in terms of middle-term stability, of both the meter and the provers.

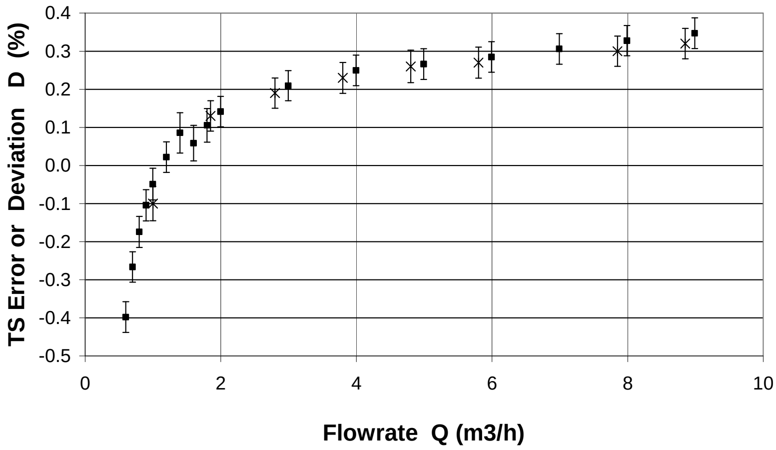

Fig.4.1: CH-PISTON closure calibration of the TS (x Calibration 2005, ▮ Calibration 2006)

3.2 Tests at INRIM

Calibrations started in September 2005 with IT-PISTON. The four test flowrates up to 2 m^3/h were repeated 5 times, whereas tests at larger flowrates were repeated 10 times each. Nominal flowrate was changed after each measurement, normally in an up-and-down sequence. Measured volumes ranged between 800 L and 320 L, the latter figure being used with higher flows that require a longer stabilization run.
During measurements with IT-BELL all flowrates were tested between 6 and 8 times, in up-and-down sequences. Measured volumes were larger than 110 L with flowrates up to 9 m^3/h, and half that value at higher flows.

4. Main calculations

The volume at the meter was calculated from the measured volume at the standard provers, bell or piston.

Reference Volume:

$$V_R = V_P \cdot \frac{P_P T_M}{P_M T_P} \tag{1}$$

Indicated Volume:

$$V_I = \frac{N}{K_{nom}} \tag{2}$$

Reference Flowrate:

$$Q_R = \frac{V_R}{t} \tag{4}$$

Indicated Flowrate:

$$Q_I = \frac{V_I}{t} \tag{5}$$

Reference K-Factor:

$$K_R = \frac{N}{V_R} \tag{6}$$

Error (%):

$$E = 100 \cdot \frac{V_I - V_R}{V_R} \tag{7}$$

Where

P_P: Absolute pressure at the provers, Bell or Piston (Pa)
P_M: Absolute pressure at the meter (Pa)
T_P: Absolute temperature at the provers, Bell or Piston (K)
T_M: Absolute temperature at the meter (K)
V_P: Volume at the provers, Bell or Piston (m^3)
N: Number of meter pulses
K_R: K-factor of the meter as obtained from the test (pulses/l)
K_{NOM}: K-Factor of the transfer standard (26.7237 pulses/l)
t: Measurement time (s)
Q: Volume flowrate (m^3/h)

5. Measurement results

5.1 Mean error of the Bell Provers

The table 5.1 and the graphic from the Fig. 5.1 summarize the obtained measurement with the two Bell provers.

	CH-BELL		IT-BELL	
Q_n (m^3/h)	e (%)	U (%)	e (%)	U (%)
0.3	-	-	**-1.18**	0.250
0.5	-	-	**-0.34**	0.140
1.0	**0.01**	0.274	**0.23**	0.078
2.0	**0.14**	0.090	**0.31**	0.068
3.0	**0.23**	0.114	**0.31**	0.068
4.0	**0.30**	0.113	**0.31**	0.069
5.0	**0.26**	0.085	**0.31**	0.067
6.0	**0.31**	0.088	**0.31**	0.066
8.0	**0.25**	0.082	**0.31**	0.066
9.0	**0.31**	0.088	**0.29**	0.079
14.0	**0.34**	0.077	**0.31**	0.102
16.0	**0.35**	0.090	**0.33**	0.080
18.0	**0.37**	0.087	**0.28**	0.107
20.0	**0.33**	0.093	**0.29**	0.108
25.0	**0.34**	0.092	**0.29**	0.114

Tab. 5.1: Arithmetic mean error ‘e’ and expanded uncertainty U for the Italian IT-BELL and Swiss CH-BELL bell provers.

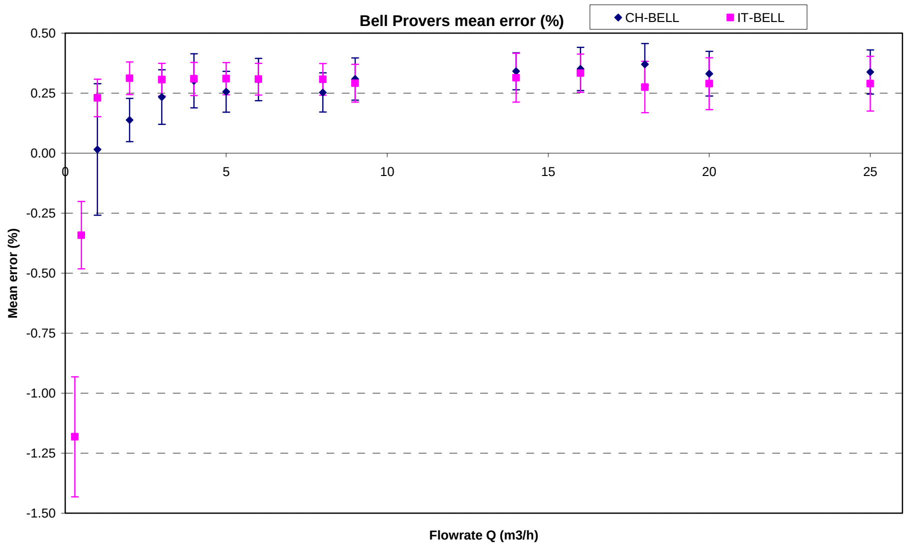

Fig. 5.1: Arithmetic mean error ‘e’ and expanded uncertainty U four the Italian IT-BELL and Swiss CH-BELL bell provers

The error plot from the figure Fig. 5.1 shows in general a very good agreement between the two facilities and only one measurement point at Q = 2 m^3/h reveals a difference higher than it can be covered by the claimed uncertainty.

5.2 Mean error of the Piston Provers

The table 5.2 and the graphic from the Fig. 5.2 summarize the measurements obtained with the two Piston provers.

	CH-PISTON		IT-PISTON	
Q_n (m^3/h)	e (%)	U (%)	e (%)	U (%)
0.3	**-1.21**	0.072	**-2.12**	0.192
0.5	**-0.58**	0.044	**-0.82**	0.064
1.0	**-0.10**	0.045	**-0.09**	0.071
2.0	**0.13**	0.040	**0.14**	0.049
3.0	**0.19**	0.040	**0.19**	0.060
4.0	**0.23**	0.041	**0.23**	0.056
5.0	**0.26**	0.043	**0.27**	0.050
6.0	**0.27**	0.041	**0.31**	0.052
8.0	**0.30**	0.040	**0.31**	0.051
9.0	**0.32**	0.040	**0.34**	0.057
14.0	**0.36**	0.041	**0.29**	0.056
16.0	**0.37**	0.041	**0.32**	0.055
18.0	-	-	**0.31**	0.054
20.0	-	-	**0.33**	0.053
25.0	-	-	**0.36**	0.055

Tab. 5.2: Arithmetic mean error ‘e’ and expanded uncertainty U four the Italian IT-PISTON and Swiss CH-PISTON piston provers.

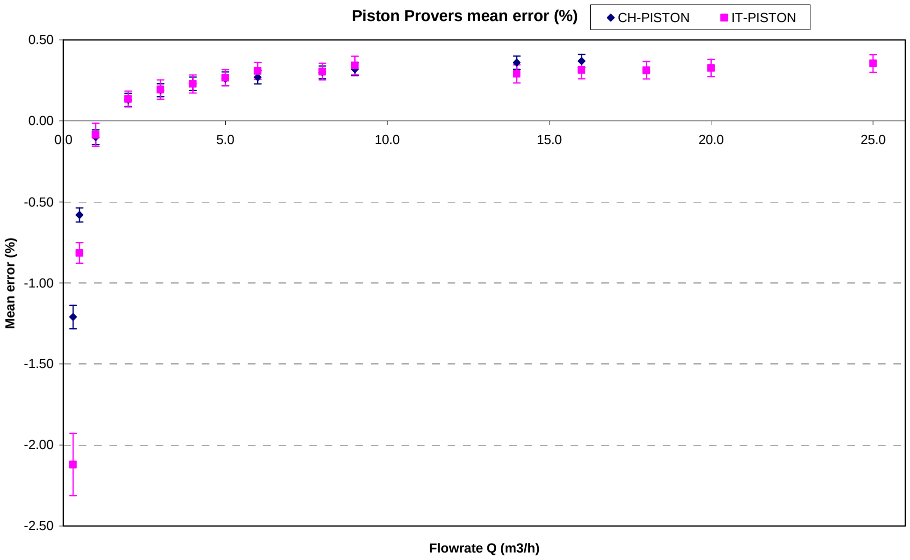

Fig. 5.2: Arithmetic mean error ‘e’ and expanded uncertainty U four the Italian IT-PISTON and Swiss CH-PISTON piston provers

As well as for the Bell provers, the agreement between the Italian and the Swiss Piston provers is very good from the maximum flowrate down to 1 m^3/h. For the points 0.5 m^3/h and 0.3 m^3/h, it seems that a problem occurs during the tests. This will be analyzed in details in the next chapter. It is also interesting to reveal that, even if the measurement points 14 m^3/h and 16 m^3/h are outside of the specified range of the CH-Piston prover, the agreement between the two provers is excellent.

6. Evaluation of the measurement results

As mentioned in the previous chapter, there are some measurements where the registered difference between the provers can't be covered by their claimed uncertainties. The origin of these differences can be attributed to various sources that are extremely difficult to localize and tell apart. However, at least the three following causes do not refer to the provers themselves, but to the transfer standard:

a) the repeatability of the transfer standard, although very good (generally better than 0.1%, as demonstrated by the closure checks), is not perfect as it has been implicitly assumed when looking for consistency of results and when calculating (see next paragraph) the compatibility factor;
b) given the very steep slope of the characteristic curve of the transfer standard below 2 m^3/h, the existing and tolerated differences in actual test flowrates at a same nominal point (although not larger than a few tenths of a m^3/h) generate large differences in meter errors;
c) flowrate no.1 (0.3 m^3/h) lies below the minimum rated flowrate of the transfer standard, where its repeatability and linearity are comparatively poorer.

Because it is not the goal of a comparison to find out the sources of the measurement discrepancies we will only figure out which facility seemed to have a problem during part of the tests.

6.1 Compatibility index En

The compatibility index E_n being defined by,

$$E_n = \frac{x_i - x_j}{\sqrt{u^2(x_i) + u^2(x_j)}} \qquad (8)$$

it defines the ratio between the difference of two estimated values and the uncertainty of the difference. An E_n factor larger then one means, that the difference between the values can not be covered by the uncertainty. With a perfectly repeatable transfer standard, this implies that either at least one of the two values is corrupted, or the claimed uncertainties are too small.

Table 6.1 summarizes the estimated E_n factors between al provers used during the tests.

Compatibility index E_n						
Qn	**CH_{Piston}-CH_{Bell}**	**CH_{Piston}-IT_{Bell}**	**CH_{Piston}-IT_{Piston}**	**CH_{Bell}-IT_{Bell}**	**CH_{Bell}-IT_{Piston}**	**IT_{Bell}-IT_{Piston}**
(m^3/h)	(%)	(%)	(%)	(%)	(%)	(%)
0.30	-	0.11	**4.44**	-	-	**2.98**
0.50	-	**1.62**	**3.03**	-	-	**3.07**
1.00	0.41	**3.66**	0.18	0.75	0.35	**2.99**
2.00	0.08	**2.31**	0.09	**1.55**	0.02	**2.10**
3.00	0.36	**1.47**	0.06	0.55	0.31	**1.24**
4.00	0.59	0.98	0.01	0.06	0.57	0.90
5.00	0.05	0.63	0.11	0.50	0.12	0.51
6.00	0.38	0.49	0.59	0.01	0.02	0.01
8.00	0.52	0.09	0.08	0.52	0.54	0.02
9.00	0.12	0.33	0.33	0.15	0.33	0.53
14.00	0.22	0.42	0.99	0.21	0.53	0.20
16.00	0.20	0.41	0.80	0.14	0.34	0.19
18.00	-	-	-	0.69	0.55	0.32
20.00	-	-	-	0.29	0.03	0.32
25.00	-	-	-	0.33	0.16	0.52
					En < 1:	**84%**

Tab. 6.1: Estimated compatibility index factor E_n between the four provers.

Form the estimated E_n factors in table 6.1, we can see that with 84% of the values lying below 1, a large majority of the measures are absolutely correct. It can also be observed that all non-consistent results lie in the low-flowrate region, where the transfer standard is less performing, whereas most provers are working in optimum conditions.

6.2 Evaluation of the reference values

As described by M. G. Cox [2], the reference values at each flowrate are determined by the weighted mean yi.

$$y_i = \frac{x_{i1} \big/ u^2(x_{i1}) + \cdots + x_{iN} \big/ u^2(x_{iN})}{1 \big/ u^2(x_{i1}) + \cdots + 1 \big/ u^2(x_{iN})} \qquad (9)$$

where:
yi : weighted mean value for the florate i

xij : estimated error by the prover j at florate i
u2ij: uncertainty of the prover j at florate i

To be able to identify systematic errors, it is useful to carry out a statistical test like a χ^2 test like described by M. G. Cox [1].

$$\chi^2_{i_{obs}} = \frac{(x_{i1} - y_i)^2}{u^2(x_{i1})} + \cdots + \frac{(x_{iN} - y_i)^2}{u^2(x_{iN})} \qquad (10)$$

where:

$\chi^2_{i_{obs}}$: chi-squared value for the flowrate i
yi : weighted mean value for the flowrate i

xij : estimated error by the prover j at flowrate i
u2ij : uncertainty of the prover j at flowrate i

To estimate the consistency of the observed chi-squared value, this value has to be compared with the theoretical value of chi-squared which is dependant of the degree of freedom $\nu = n - 1$. From the tables [3], we can extract the value that chi-squared shall have to be sure at 95% that the estimated reference value is admissible.
Table 6.2 and 6.3 summarize the complete processing, from the estimation of the weighted mean values to the chi-squared tests.
After the first test, we can see that the test failed for the first flowrates from 0.3 m^3/h to 1.0 m^3/h. Once, for these three flows the provers with the largest influence onto the chi-squared value have been canceled, the corrected test, Test$_{cor}$, is satisfied over the al range.

	CH-PISTON			CH-BELL			IT-BELL			IT-PISTON			Weighted mean y	std(y)	Chi^2	Chi$_{95}$^{2}	Test
Qn (m^3/h)	**D$_1$** (%)	**U$_1$** (%)	**Chi^2**	**D$_2$** (%)	**U$_2$** (%)	**Chi^2**	**D$_3$** (%)	**U$_3$** (%)	**Chi^2**	**D$_4$** (%)	**U$_4$** (%)	**Chi^2**	(%)	(%)			**Chi^2 < Chi$_{95}$^{2}**
0.30	-1.21	0.07	2.04	-	-	-	-1.18	0.25	0.27	-2.12	0.19	**17.72**	-1.31	0.004	**20.03**	5.99	**?**
0.50	-0.58	0.04	1.60	-	-	-	-0.34	0.14	4.40	-0.82	0.06	**7.85**	-0.64	0.001	**13.85**	5.99	**?**
1.00	-0.10	0.05	2.25	0.01	0.27	0.03	0.23	0.08	**11.32**	-0.09	0.07	0.55	-0.03	0.001	**14.15**	7.81	**?**
2.00	0.13	0.04	0.60	0.14	0.09	0.07	0.31	0.07	4.93	0.14	0.05	0.26	0.16	0.001	5.86	7.81	ok
3.00	0.19	0.04	0.38	0.23	0.11	0.03	0.31	0.07	1.80	0.19	0.06	0.12	0.21	0.001	2.33	7.81	ok
4.00	0.23	0.04	0.20	0.30	0.11	0.22	0.31	0.07	0.78	0.23	0.06	0.12	0.25	0.001	1.31	7.81	ok
5.00	0.26	0.04	0.06	0.26	0.09	0.03	0.31	0.07	0.35	0.27	0.05	0.00	0.27	0.001	0.44	7.81	ok
6.00	0.27	0.04	0.26	0.31	0.09	0.03	0.31	0.07	0.07	0.31	0.05	0.12	0.29	0.001	0.48	7.81	ok
8.00	0.30	0.04	0.00	0.25	0.08	0.30	0.31	0.07	0.02	0.31	0.05	0.02	0.30	0.001	0.35	7.81	ok
9.00	0.32	0.04	0.00	0.31	0.09	0.02	0.29	0.08	0.14	0.34	0.06	0.15	0.32	0.001	0.31	7.81	ok
14.00	0.36	0.04	0.38	0.34	0.08	0.01	0.31	0.10	0.04	0.29	0.06	0.61	0.33	0.001	1.04	7.81	ok
16.00	0.37	0.04	0.29	0.35	0.09	0.00	0.33	0.08	0.04	0.32	0.06	0.36	0.35	0.001	0.68	7.81	ok
18.00	-	-	-	0.37	0.09	0.32	0.28	0.11	0.18	0.31	0.05	0.02	0.32	0.002	0.52	5.99	ok
20.00	-	-	-	0.33	0.09	0.01	0.29	0.11	0.09	0.33	0.05	0.01	0.32	0.002	0.11	5.99	ok
25.00	-	-	-	0.34	0.09	0.00	0.29	0.11	0.21	0.36	0.06	0.06	0.34	0.002	0.27	5.99	ok

Tab. 6.2: Analysis overview of the first chi-squared test. By taking in account each prover the test fails at Q = 0.3 m^3/h, 0.5 m^3/h and 1 m^3/h.

	CH-PISTON			CH-BELL			IT-BELL			IT-PISTON			Weighted mean y_{cor}	std(y_{cor})	Chi_{cor}^2	Chi_{95}^2	$Test_{cor}$
Qn (m^3/h)	D_1 (%)	U_1 (%)	Chi^2	D_2 (%)	U_2 (%)	Chi^2	D_3 (%)	U_3 (%)	Chi^2	D_4 (%)	U_4 (%)	Chi^2	(%)	(%)			$Chi_{cor}^2 < Chi_{95}^2$
0.30	-1.21	0.07	0.00	-	-	-	-1.18	0.25	0.01	-2.12	0.19	-	-1.21	0.00	0.01	3.84	ok
0.50	-0.58	0.04	0.24	-	-	-	-0.34	0.14	2.39	-0.82	0.06	-	-0.56	0.00	2.63	3.84	ok
1.00	-0.10	0.05	0.02	0.01	0.27	0.16	0.23	0.08	-	-0.09	0.07	0.01	-0.09	0.00	0.19	5.99	ok
2.00	0.13	0.04	0.60	0.14	0.09	0.07	0.31	0.07	4.93	0.14	0.05	0.26	0.16	0.00	5.86	7.81	ok
3.00	0.19	0.04	0.38	0.23	0.11	0.03	0.31	0.07	1.80	0.19	0.06	0.12	0.21	0.00	2.33	7.81	ok
4.00	0.23	0.04	0.20	0.30	0.11	0.22	0.31	0.07	0.78	0.23	0.06	0.12	0.25	0.00	1.31	7.81	ok
5.00	0.26	0.04	0.06	0.26	0.09	0.03	0.31	0.07	0.35	0.27	0.05	0.00	0.27	0.00	0.44	7.81	ok
6.00	0.27	0.04	0.26	0.31	0.09	0.03	0.31	0.07	0.07	0.31	0.05	0.12	0.29	0.00	0.48	7.81	ok
8.00	0.30	0.04	0.00	0.25	0.08	0.30	0.31	0.07	0.02	0.31	0.05	0.02	0.30	0.00	0.35	7.81	ok
9.00	0.32	0.04	0.00	0.31	0.09	0.02	0.29	0.08	0.14	0.34	0.06	0.15	0.32	0.00	0.31	7.81	ok
14.00	0.36	0.04	0.38	0.34	0.08	0.01	0.31	0.10	0.04	0.29	0.06	0.61	0.33	0.00	1.04	7.81	ok
16.00	0.37	0.04	0.29	0.35	0.09	0.00	0.33	0.08	0.04	0.32	0.06	0.36	0.35	0.00	0.68	7.81	ok
18.00	-	-	-	0.37	0.09	0.32	0.28	0.11	0.18	0.31	0.05	0.02	0.32	0.00	0.52	5.99	ok
20.00	-	-	-	0.33	0.09	0.01	0.29	0.11	0.09	0.33	0.05	0.01	0.32	0.00	0.11	5.99	ok
25.00	-	-	-	0.34	0.09	0.00	0.29	0.11	0.21	0.36	0.06	0.06	0.34	0.00	0.27	5.99	ok

Tab. 6.3: Analysis overview of the corrected chi-squared test. By canceling the provers with the largest influence onto the chi-squared value, the test is satisfied over the all flow range.

7. Final considerations

The aim of the project was to ensure that there is a good agreement between the gas provers of the Swiss and Italian NMIs. The comparison involved four primary standards, two Bell- and two Piston-Provers.

The different analyses of the obtained results have shown a few discrepancies that in principle might be attributed to a large palette of sources, like real systematic differences among the provers, non-ideal behavior of the transfer standard, resonance phenomena [1], leakages or even handling errors.
However, INRIM having performed several supplementary tests of direct gas transfer between their two provers (without using the TS), the main source for the inconsistencies that were found in the comparison is believed to lie in the well known and always influential installation effects [1]. In our case these may consist in both mechanical and fluid-dynamic factors, such as positioning and horizontal leveling of the TS, different length and size of upstream piping and adoption (or not) of an upstream flow control valve (that happens to be necessary with bell provers only). Indeed the four installations were different in all those aspects.
The major result of the comparison, as stressed in ref. [1], is the experimental proof that the large gas piston provers of the type adopted at both INRIM and METAS exhibit uncertainties that are approximately one half of those of bell provers constructed and operated in the same laboratories with similar conditions.

Globally, the obtained results are quite satisfactory, and are reasonably consistent with the estimated reference values.

Literature

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