Evaluation of two new volumetric primary standards for gas volume established by PTB

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Abstract: The PTB has been operating a bell prover as the main primary standard for gas volume with a proofed uncertainty [1] of 0.06 % for more than 25 years. In the last two years there were two new primary volumetric standards established which operates in flow rate ranges comparable with the existing bell prover. One of them is a conventional bell prover of similar construction as the old one and has therefore the identical main operating range between 1 to 65 m^3/h. The second one is a new actively driven piston prover based on a so-called comparator principle [2][3] operating mainly between 0,04 and 4 m^3/h.

The paper will describe the main principles and steps for providing the traceability for these new devices as well as the experimental evaluation of the uncertainties using sonic nozzles as transfer standards. The results will be evaluated also in relation to the actual defined reference value for gas flow determined in the CCM.FF-KC6 [1] and to the results of nine other inter-comparisons.

1. Introduction

The development, maintenance and continuously improvement of primary standards for gas volume has been one of the core tasks of PTB's gas flow group for many years. One of the best established primary standard is the so called bell prover used with atmospheric air for flow rates about 1 to 65 m^3/h. Its was build up 30 years ago and has been mechanically unchanged since that time. Only the sensor equipment for pressure and temperature as well as data acquisition has been refurbished continuously to implement modern concepts. The reliability of the claimed uncertainty of 0.06 % was proven in many inter-comparisons as well as checked by regular recalibrations of our own control standards and of customer devices. Hence, we have here our best maintained standard with remarkable documented history.

In the year 2004 the Shanghai Institute of Metrology and Testing Technology (SIMT) started with their activities to establish a complete new equipment for air flow measurements based on their own primary standard. It was an honour to us that they were interested to get a bell prover of PTB design.

Parallel to this, we have had made special efforts since 2002 to establish new volumetric standards for flow rates below 1 m^3/h based on actively driven piston provers. The two main aims were the improvement of uncertainty down to a level comparable to the bell prover as well as establishing of new behaviour like the possibility to test critical nozzles with active driven provers or to apply different gases at different pressure levels. The patent pending construction was applied successfully first for small flow rates in the range of 6 ml/h to 6 l/h [2][3].

2. The new bell prover

As the PTB is not a manufacturer, it was decided that the bell was to be manufactured by a competent German company[1] which got a license from PTB to produce a copy of the PTB

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[1] Ehrler Prüftechnik GmbH, which is also manufacturer of the flow comparator devices in different sizes.

bell. The traceability (measurement of dimension) and the final product acceptance tests were done then by PTB. The opportunity to check in detail a real copy of our own best primary at two different locations with complete disassembling and reassembling in between was a quite unique occasion for us to verify and proof all of our basic statements about the reliability of volumetric flow standards.

That the new bell prover is a real copy of the PTB bell prover can be easily recognized in Fig. 1 when comparing the photos of both bells. The manufacturer made only some small adoptions of some components to implement the actual level of mechanical technology into the construction. The details of the special characteristics are published in [4].

at manufacturer site at SIMT existing bell prover of PTB

Fig. 1: *Photos of the new constructed the bell prover*
left at manufacturer site
middle at Shanghai Institute of Metrology and Testing Technology (SIMT)
as well as the PTB bell prover (right)

Compared to the establishment of the PTB bell 30 years ago, the main difference can be found in the procedure and the equipment to determine the volume (diameter) inside of the bell in dependency of the height. As the uncertainty of the diameter measurement is the most important value inside the uncertainty budget, we like to describe here some essentials about this.

The equipment which is used nowadays was already successfully applied for the determination of the inner diameter of the reference volume of PTB's high pressure piston prover [5]. In Fig. 2 the outline of the equipment is shown as well as a photo of its application to measure the bell dimensions. It consists of a basis which is bearing a construction of spindle, stepper motor and gliding shafts. At one end of the spindle there is a arm mounted which bears pneumatic driven length testers.

For one fixed position of the basis inside the cylinder the arm with the length testers is move through the cylinder by means of the spindle and the stepping motor. At user-defined positions the length testers measure their relative position to the wall by pressing them on to the wall by pneumatics. Therefore we get information about the relative positions inside the cylinder of both length testers in form of a spiral.

One stroke of the spindle is about 80 cm, therefore we had to move the bell relatively to cover the total length of the bell of 1.2 m.

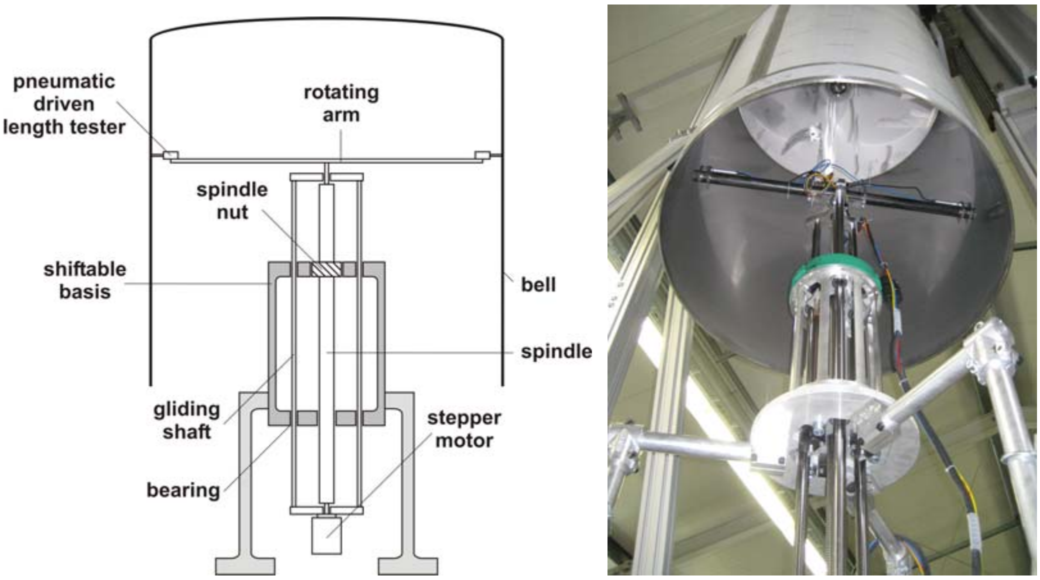

Fig. 2: *Outline of the measurement equipment for diameter (left) and photo of its application at manufacturer site (right)*

The zero point for both lengths testers were calibrated after initialisation of the electronics against a reference calliper and this calibration was checked twice during the measurement campaign and finally at the end of the measurements again to determine the stability of the zero setting.

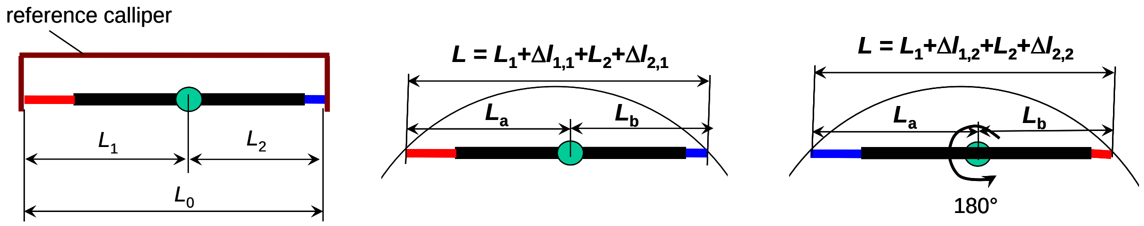

Fig. 3: *Principle relations in calibration measurements to determine the arm lengths with respect to the rotation centre.*

As shown in Fig. 3 (left), the reference calliper provides only the total length L_0 but not a information of the partial length L_1 and L_2 with respect to the rotation arm. To get this, one has to perform additional measurements against a fixed (but not necessarily known) length L as shown in Fig 3. (middle and right). Hereby the length to be measured shall be fixed against the rotation centre and is measured twice with the equipment by rotating the arm by 180°. As in this case the length L_a and L_b are constant and one gets for indications from the two length tester $\Delta l_{1,1}$ to $\Delta l_{2,2}$, one can calculate the values of L_1 and L_2 out of these information.

The translation of the arm with length testers per one rotation of the spindle is 5 mm. We defined measurements at every 30° of rotation what was enough for our measurements. Each measurement gives the lengths of two half chords with respect to the rotating centre of the rotating arm.

The information of two chords (four half chords) would define a circle from which we want to know the diameter. To get some information about repeatability we gathered six measurements to a set assuming that the diameter of the bell is constant per 2.5mm-slice as shown in Fig. 4. Out of each of these sets we calculate the diameters for the different positions inside of the cylinder. Additionally we got also information about the deviations from the circularity.

The Fig. 5 shows all the results for the diameter versus the position inside the cylinder. The agreements of the different strokes of measurements (indicated by different colours) demonstrates an impressive reproducibility of these measurement. Last but not least in Table1 we give some information about the different impacts to uncertainty.

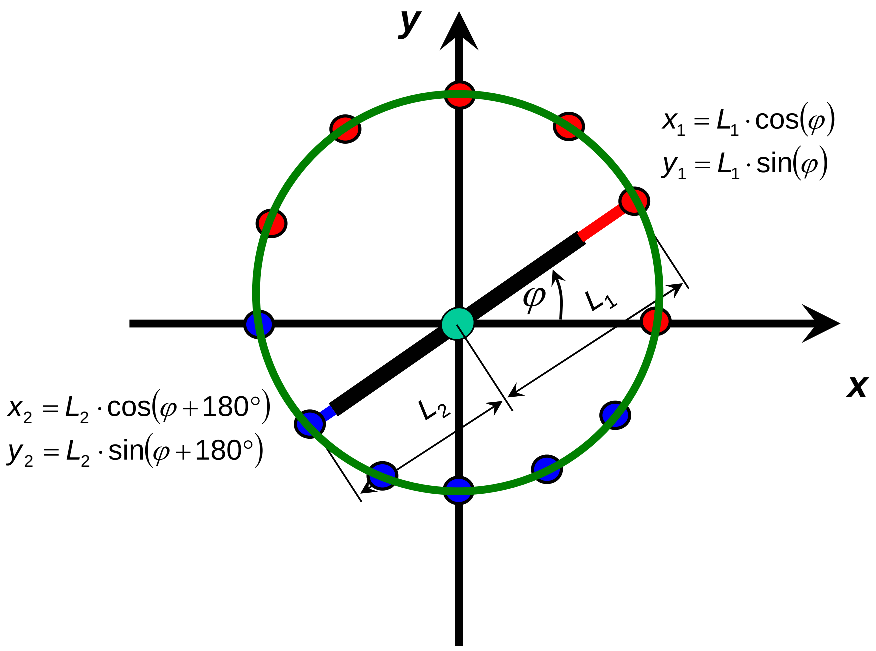

Fig. 4: *Determination of circle out of measurements.*

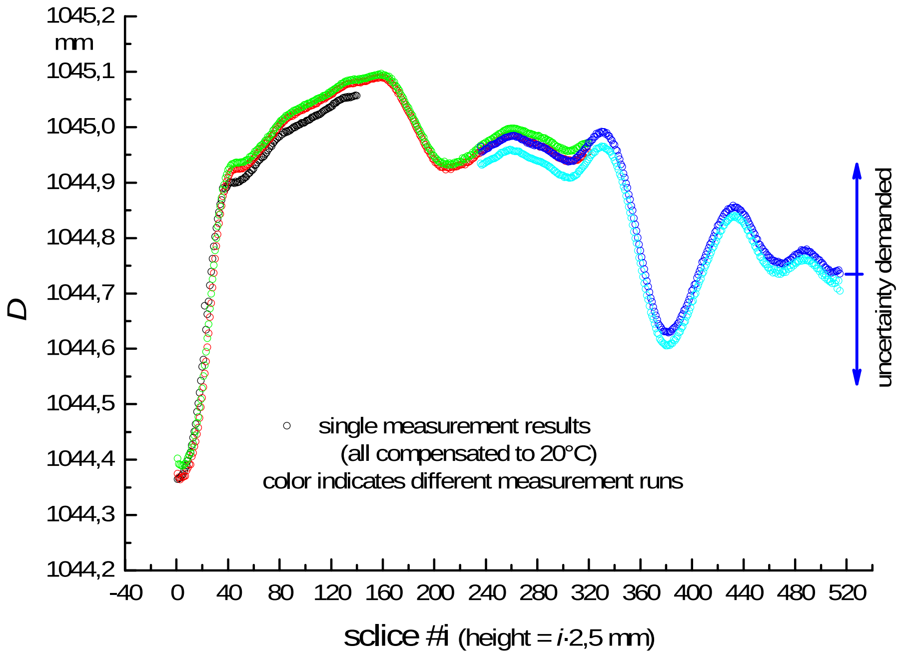

Fig. 5: *Results of diameter determination*

Table 1: *List of influence factors to the diameter determination*

Influence factor	Standard uncertainty contribution to the value of diameter *D* (in µm, *k* = 1)
Temperature	14
Reference Length Standard L_0	5
Stability of Zero-Point of the length tester	6
Determination of L_1 an L_2 at rotating arm	12
Definition of height Zero at the bell	12
Sampling the shape	81
Parallaxes	10
Reproducibility	25
Total uncertainty	88.6

The demand for standard uncertainty in diameter *D* in the uncertainty budget was determined as 100 µm (i.e. 50 µm for the radius *R*) to reach the level of 0.06 % in total uncertainty. With 88.6 < 100 µm, the demand of the uncertainty budget was fulfilled.

The uncertainty of the volume determination is an non stochastic, systematic impact into all measurements because the values is practically constant all over time. A second important value inside of the uncertainty budget directly related to the volume is the oil film thickness on the wall. Due to stick to oils with a fixed viscosity and fixed procedures for measurements, this value is also systematic. The third which has to be considered in a similar way is the uncertainty of the mechanical length scale. All these parts together give a value of type B uncertainty of 0.04 % (*k* = 2) for measurement results. Even under the circumstances of disassembling and reassembling, these calibration values do not have to change and define a critical level for the maximal acceptable difference when we compare the test results of the new bell done first at manufacturer site and secondly at customer site.

3. The new flow comparator

For the calibration of gas meters, PTB is developing fundamental devices, which are on top of the calibration chains. To be able to accurately present medium volume flows, a novel bell-piston prover device with a spindle stepper motor drive has been developed and has already been successfully tested. The piston device allows flow rates with a very good repeatability to be generated and also permits the calibration of test objects, which generate a continuous flow rate themselves, like critically operated nozzles, which are often also used as transfer standards.

The bell-piston prover, which is moved via a stepper motor and a ball screw spindle including a ball screw nut at the top end (see Figure 1), is located in a pressure-proof container. At its outside and inside at the guide bars, the bell body is sealed by a double seal. A potential leakage can be detected by means of a pressure measurement between the seals. The system consists of an upper and a lower chamber which are interconnected by a pipeline with an integrated valve V1 and a flow indicator.

In comparison to a conventional piston device, this construction has the advantage that the traceability to the unit of length is provided via outside diameter values. The latter can be measured with considerably lower uncertainties than inside diameter values. With a coordinate measuring device of PTB, the diameter values relevant to the realisation have been determined with a relative uncertainty of less than $U_{rel} = 8 \cdot 10^{-5} \left(k = 2\right)$.

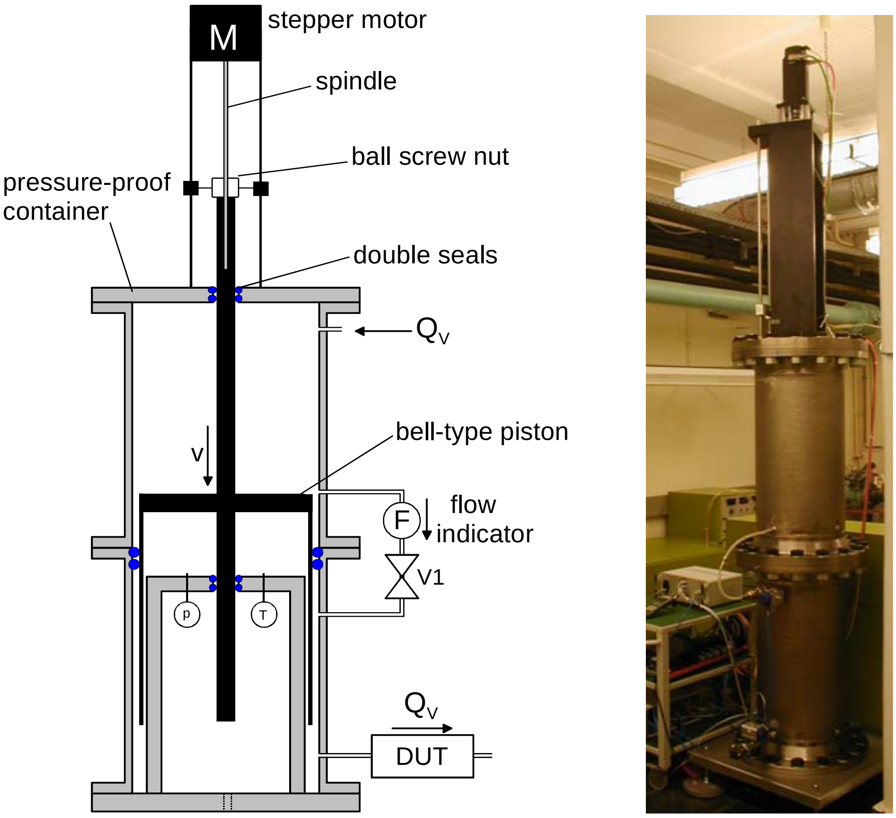

***Fig. 6:** Outline and photo of the new flow comparator*

With an outside bell diameter of approx. 380 mm and a lift of 720 mm the maximum displaced volume amounts to approx. 80 litres. The range of realisation is between $Q_V = 40$ l/h and 4000 l/h, the measuring time is at least 1 min.

To achieve a temperature adjustment, the test air flows through the whole system for a certain period of time prior to the measurement, i.e. through the upper chamber to the lower chamber via the connecting pipeline, past the standing piston and finally through the test object. Depending on its principle, the test object can also generate the flow rate, like, for example, for a critical nozzle.

During the actual measurement of a critical nozzle, the bell-piston prover is slowly moved downwards with increasing velocity starting from the pole position. The flow rate led through the chambers is increasingly carried out by the bell-piston prover, i.e. the flow rate value indicated by the flow indicator in the connecting pipeline decreases. As soon as the flow indicator has reached the value 0, the bell-piston prover has generated the flow rate $Q_{V,nozzle}$ specified by the nozzle, which can be traced back via the diameter values d_{piston} and $d_{guiding}$, the stepper motor frequency f and the spindle pitch s according to the following equation:

$$Q_{V,nozzle} = \frac{\pi \cdot (d_{piston}^{2} - d_{guiding}^{2})}{4} \cdot f \cdot s \qquad (1)$$

The more complex details of the flow comparator and the calibration procedure for sonic nozzles are detailed described in [2] [3].

The presented measuring principle for the first time realises a piston device, which can be operated as flow comparator. Due to its design, the device allows for the first time direct nozzle calibrations for inlet pressures of up to 10 bar with an actively driven piston. Moreover, the operation with different test gases is possible in principle. With the new apparatus, the measurement uncertainty can be reduced as to the traceability of volume flows to $U_{rel} = 0.04\ \%$ ($k = 2$).

4. Test results for evaluation of uncertainties

The test for final evaluation for both new devices were done similar to a comparison between independent test facilities using critical nozzles as transfer standards. The measurand is always the volumetric flow rate of the critical nozzle $Q_{V,20,1000,dry}$ which is a value out of the measurements with atmospheric air slightly corrected for dry air at $\vartheta = 20$ °C and $p = 1000$ mbar and which is determined according to the methods and procedures documented in [6] and [7].

4.1 Measurements with the new bell prover

For the test of the new bell a set of five sonic nozzles were chosen which covers reasonably the flow rate range of the bell. Fig 7 shows the relative differences of the flow rates $Q_{V,20,1000,dry}$ determined with the new SIMT-bell with respect to the values at the PTB-bell. The error bars indicate the expanded uncertainty of this relative differences which is the quadratic sum of the uncertainty of two independent measurements. As for both test facilities an uncertainty of 0.06% is claimed, the value is 0.086 %.

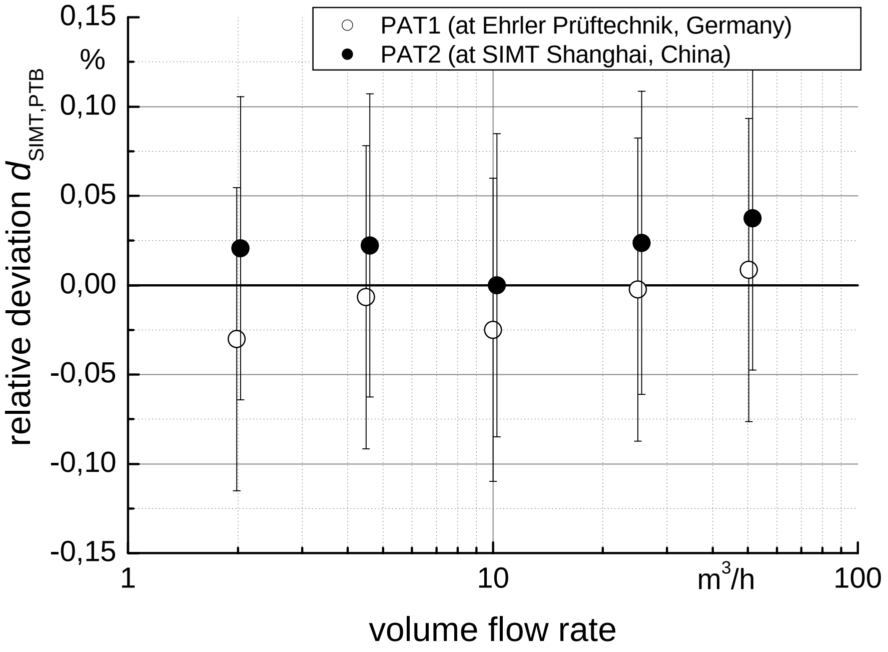

Fig. 7: *Results of inter comparison measurements between new bell prover for SIMT and bell prover of PTB.*

In both product acceptance tests at manufacturer site (PAT1) and at customer site (PAT2), the determined differences are significantly smaller than the maximal permitted value of 0.086% but the observed values were always below 0.04 %, mainly below 0.025%.

Furthermore, the differences between the to acceptance tests PAT1 and PAT2 are small too. The observed differences between PAT1 and PAT2 were mainly 0.028 %. For them we have to expect a smaller value of uncertainty for this differences because we have to consider the correlative impact of non stochastic parts in the uncertainty budget for the new bell as mentioned above (see Table 1 and end of chapter 2). Finally we get a maximal acceptable difference between the PAT1 and PAT2 of 0.058 % which is also fulfilled for all test results shown in Fig. 7.

4.2 Measurements with the new flow comparator

The new flow comparator has a sufficient overlap with the operating rate range of the our bell prover. The minimum flow rate of the bell prover is officially claimed with 1 m^3/h but this limit is set by the standard procedure to limit the testing time and to limit the effort considering environmental test conditions during daily calibrations. Hence, for special occasion like this evaluation test we spend time to exceed the minimum of the bell prover down to 0.45 m^3/h.

Furthermore we used the several sonic nozzles to compare the new flow comparator with two other air flow standards at PTB, the mercury sealed piston provers and the calibration via our secondary sonic nozzle test bench. All the results are given in Fig. 8.

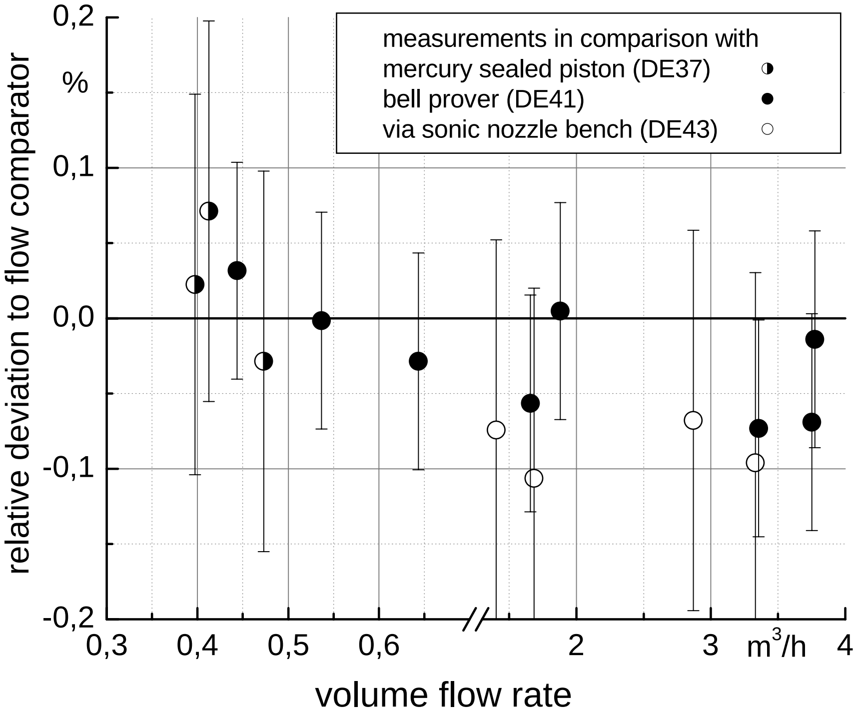

Fig. 8: *Results of inter comparison measurements between new flow comparator and different air flow standards of PTB.*

The maximal acceptable differences given by the square sum of uncertainties ranges from 0.071 % to 0.13 % depending on the standards to be compared. As to be seen in Fig 8, the obtained differences fulfil these limits sufficiently. Hence, the equivalence of the measurements with the new flow comparator was proven compared to our established standards within the claimed low uncertainty of 0.04 %.

Nevertheless, in Fig. 8 one can identify some tendency of the determined differences with respect to the flow rate. In the following chapter we summarize the outcome of in total 12 inter-comparisons and the result will demonstrate that the reason for this tendency is caused by the traceability through the bell prover but not due to the new flow comparator.

4.3 Embedding of the actual results into the history of inter-comparisons

In the past 20 years PTB has taken part in many bi- and multi-lateral inter-comparison with many different participants. Table 2 is listing all the comparisons which were performed together with recognised National Metrology Institutes, partly under the umbrella of Euramet (formerly Euromet) and the BIPM. Some others are documented in Lab reports which are also free available on request at PTB. One comparison report is part of a conference paper (see [8]). All these documentations provide information about the relative deviations among the participants or with respect to a comparison reference value as well as the relevant uncertainties.

Table 2: *List of comparison campaigns with participation of PTB*

		Year	Measurand	meter under test	Reference
1	NMIJ 92/98	1992+1998	$Q_{V,20,1000,\mathrm{dry}}$	Crit. nozzles	4th ISFFM [8]
2	VSL/OMH 97	1997	$Q_{V,20,1000,\mathrm{dry}}$	Crit. nozzles	Lab Report
3	E425	Sept.1998	Meter dev.	Rotary meter	EURAMET
4	E419	Jan. 1999	Meter dev.	Rotary meter	EURAMET
5	SMU 04	2004	$Q_{V,20,1000,\mathrm{dry}}$	Crit. nozzles	Lab Report
6	CCM.FF-K6	Mai 2005	c_D	Crit. nozzles	BIPM-KCDB
7	E862	April 2006	Meter dev.	Turbine meter	EURAMET
8	Co219	Mai 2006	Meter dev.	Turbine meter	COOMET
9	E806	Dec.2006	Meter dev.	LFE (Molblock)	BIPM-KCDB
10	E1006	April 2008	Meter dev.	Turbine meter	EURAMET
11	**SIMT 2008/09**	2008/2009	$Q_{V,20,1000,\mathrm{dry}}$	Crit. Nozzles	this paper
12	**Flow Comparator**	2009	$Q_{V,20,1000,\mathrm{dry}}$	Crit. Nozzles	this paper

To overview the relation of these inter-comparisons to the different air flow standards of PTB, Fig. 9 is showing that schematically. The listed comparisons are related to different air flow standards at PTB, partly to some secondary standards with traceability to the bell prover (DE37 piston/WGM; DE43 nozzle rig; DE47 turbine rig). Hence, the best pivot point to summarize all these data is the bell prover of PTB.

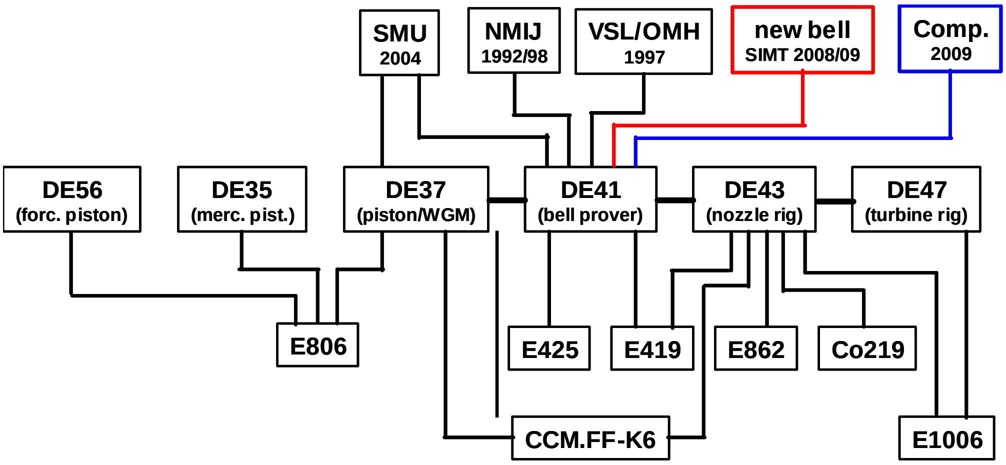

Fig. 9: *Overview of comparison campaigns and their relation to air flow standards at PTB (with number of CMC-entry at BIPM database), see also Table 2.*

Because the measurands and the artefacts were quite different, we have to note something which has to be considered carefully while putting these data all together.

The results of comparison document relative documents of the measurands. They are used synonymously for the relative deviation of the flow quantity which is originally the scope of interest. This is valid of course but may lead to confusions while the relative deviation of the measurand may have the opposite sign of the relative deviation of the flow quantity.

Exemplarily we look to the relative meter deviation f_i of the indicated quantity[2] Q_{MuT} to the reference quantity $Q_{Lab\#i}$ provided by the Lab #i for the measurement (meter deviation f_i)

$$f_i = \frac{Q_{MuT}}{Q_{Lab\#i}} - 1 \tag{2}$$

Based on all results for the meter deviation f at the different laboratories the key comparisons reference value f_{KCRV} was calculated as a weighted mean (w_i is the weight for Lab #i based on the reported uncertainties for the results).

$$f_{KCRV} = \Sigma w_i \cdot f_i = \frac{Q_{MuT}}{Q_{KCRV}} - 1 \tag{3}$$

To express the degree of equivalence, the difference d_i (and its accompanied uncertainty) between the measured value f_i at Lab #i and the key reference value f_{KCRV} is calculated:

$$d_i = f_i - f_{KCRV} \tag{4}$$

As mentioned above, the original interest was finally the relative deviation $\Delta Q_{\#i,rel}$ of the quantity $Q_{Lab\#i}$ to the key reference quantity Q_{KCRV}:

$$\Delta Q_{\#i,rel} = \frac{Q_{Lab\#i}}{Q_{KCRV}} - 1\,. \tag{5}$$

The relationship of this to the usually used difference d_i (equ. (4)) shall be shown here.

The relation is easily shown if we expand the expression (equ. (5)) by a unity Q_{MuT}/Q_{MuT}. Furthermore we make use of equations (2) and (3) as well as some small approximation due to the fact that f_i as well as f_{KCRV} are much smaller than 1.[3] The final outcome is that the usual used value d_i is the negative value of the original interest $\Delta Q_{\#i,rel}$.

$$\begin{aligned} \Delta Q_{\#i,rel} &= \frac{Q_{Lab\#i}}{Q_{MuT}} \cdot \frac{Q_{MuT}}{Q_{KCRV}} - 1 = \frac{1+f_{KCRV}}{1+f_i} - 1 \\ &\approx (1+f_{KCRV}) \cdot (1-f_i) \approx f_{KCRV} - f_i = -d_i \end{aligned} \tag{6}$$

The expansion by Q_{MuT}/Q_{MuT} in (equ. (6)) is made on the background that the dependency of the meter deviation f on the fluid quantity Q is normally negligible small, at least, for small changes of quantity. It has to be emphasized here that the expansion is independent to a special value of Q_{MuT} and therefore also independent to the meter under test. This means the independence of the $\Delta Q_{\#i,rel}$ to the meter under test used for comparison which was utilized in the past by silent agreement of the flow experts.

Finally, while collecting the data out of the comparisons we had to check carefully if the relative deviation d was determined base on measurands utilizing Q_{MuT}/Q_{Lab} or vice versa to consider the right sign.

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[2] Please note that here the quantity can be total volume, total mass, volume flow rate or mass flow rate according to the indication of the meter under test.

[3] E.g. if the deviations f are in the order of 0.5%, the final error of the approximations used in equ. (6) can reach ±0.005% in maximum. This is of course an additional uncertainty which has to be considered but in the field of these measurements definitely insignificant compared to the uncertainties.

The following, table 3 and Fig. 10 and 11 give the total summarize out of the extended data base. The different symbols shall indicate results out of the different comparisons and their different filling pattern the air flow standard used at PTB. The most interesting for us is of course here the PTB bell prover which is indicated with solid symbols.

Table 3: *Legend for Fig. 10 and Fig. 11, see also Fig. 9 and Table 2*

CMC-entry	DE37	**DE41**	DE43	DE47
NMIJ 92/98		⬢		
VSL/OMH 97		■		
E425		◕		
E419		●	○	
SMU 04	☆	★		
CCM.FF-K6	⧨	▼	▽	
E862			△	
Co219			◇	
E806	◀			
E1006			○	◑
SIMT 08/09		⬟		
Comp. 09	⧩	▶	▷	

Median using groups of 14 values: —●—

Fig. 10 shows the determined differences to the respective comparison reference values which have all the common source of traceability (bell prover). Each of them are accompanied with a related uncertainty which is not shown here to avoid an overload of the diagram. It can be obtained here that we have not a fully random scatter but tendencies versus the flow rate. Fig. 11 is showing the identical issue but using the normalised differences $En = d/U(d)$, the so-called degree of equivalence.

The En-value is useable to calculate an average out of the sample in Fig.11. To get a robust issue as well as an indication versus flow rate, we applied the median to groups of fourteen values with increasing order to flow rate. It is shown in Fig. 11 as yellow line which support clearly the visible tendency in Fig. 10 and 11. With this, the long term reliability as well as some smaller systematic effects below the uncertainty level of the measurements with the established bell prover at PTB are evident.

When we want to conclude out of Fig. 10 and Fig. 11 back to our initiating point (the evaluation of the new bell prover and flow comparator), we have to consider some helpful relation inside bi-lateral comparisons.

When the weights in bilateral comparison are based on the standard uncertainties of the contributed measurements, then following yields for the normalised differences:

$$\frac{d_{\text{Facility \#1}}}{U\left(d_{\text{Facility \#1}}\right)} = -\frac{d_{\text{Facility \#2}}}{U\left(d_{\text{Facility \#2}}\right)} \quad ; \quad En_{\text{Facility \#1}} = -En_{\text{Facility \#2}} \tag{7}$$

Together with the median line in Fig. 11 we get the issue that especially the flow comparator but also the new bell are in a very good agreement with the actual defined international key reference value out of the CCM.FF-K6 (down triangles).

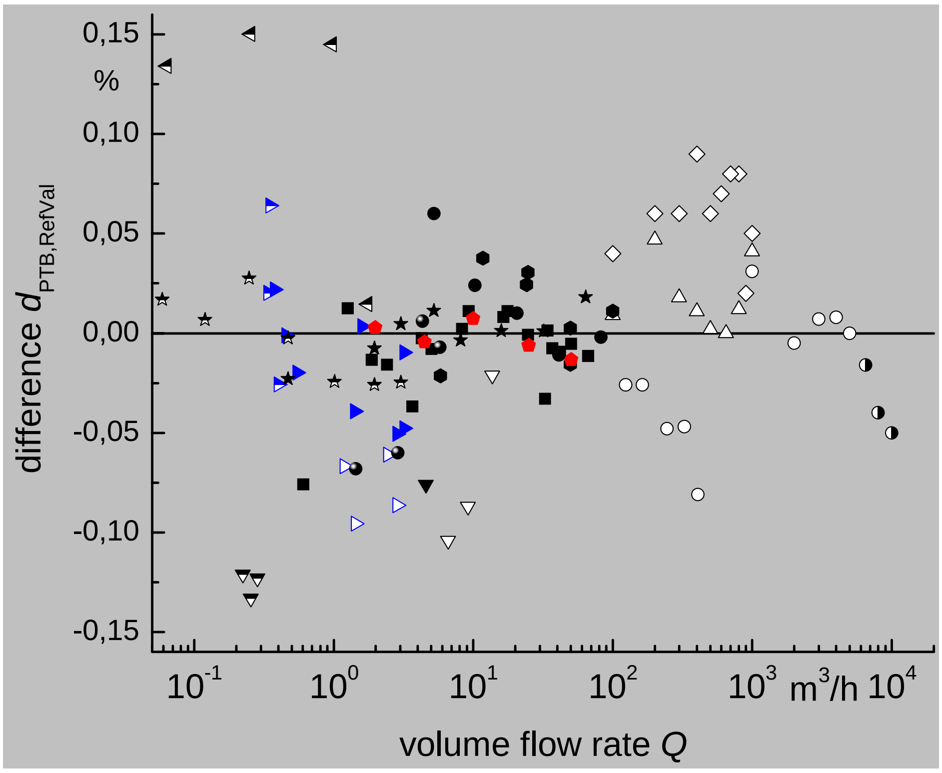

Fig. 10: *Difference $d_{PTB,RefVal}$ of PTB results to the reference values, see table 3 for legend as well as table 2 and Fig. 9 for overview of comparisons.*

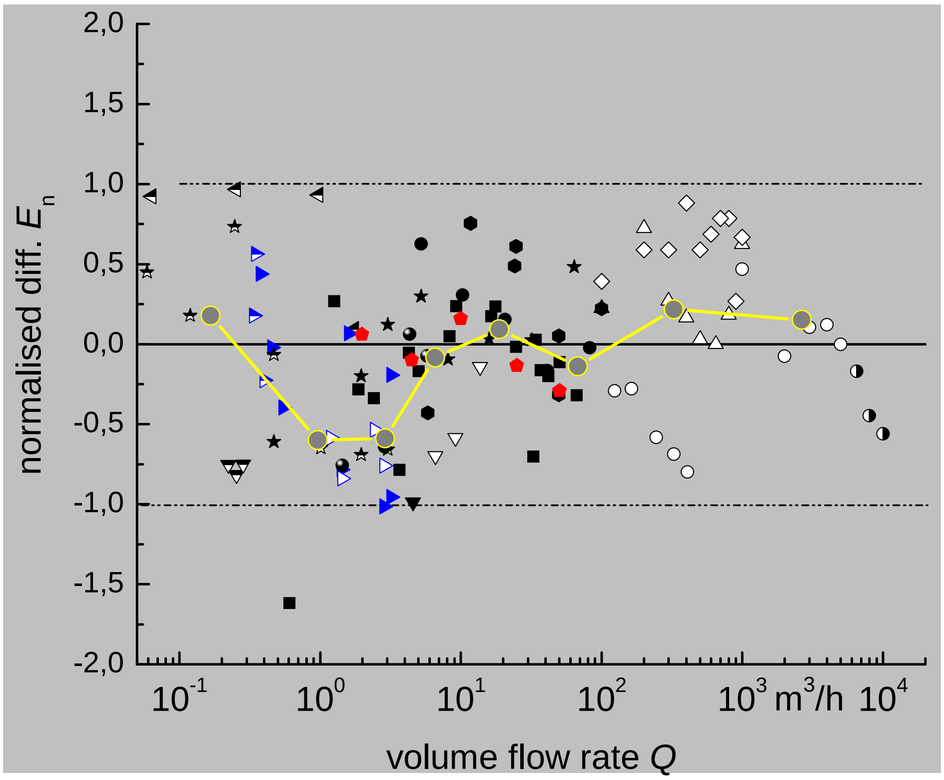

Fig. 10: *Normalised difference E_n (normalised with expanded uncertainty) of PTB results to the reference values, see table 3 for legend as well as table 2 and Fig. 9 for overview of comparisons.*

5. Conclusions

Two new volumetric primary standards were successfully proven by PTB. They stands both for well established technology of bell provers and for new technology called flow comparator. The comprehensive evaluation based on several comparisons made evident the reliability within the claimed uncertainties.

For the flow rate range between 0.04 and 4 m^3/h we will apply in future the new flow comparator which provides us a significant reduction of uncertainty from 0.12 % down to 0.04 % in this range.

Furthermore, the unique situation to test a bell prover twice with a complete disassembling and reassembling in between gave the chance for detailed proof of the uncertainty budget. It leads to an improved knowledge about bell prover technology, its basic calibration and measurement procedures.

The actual test results were reviewed also with respect to a data base of inter-comparisons. The outcome shows high consistency of the new equipment with the most actual key reference value defined by the CCM.FF-K6.

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