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Technical Paper

An intercomparison between primary high-pressure gas flow standards with sub-permille uncertainties

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1 INTRODUCTION

Currently, state-of-the-art commercial calibrations of high-pressure gas flowmeters are performed with uncertainties that range between 0.13% and 0.25%, depending on pressure and flowrate. These measurement capabilities are traceable to primary standards using several steps in which the flowrate range and pressures are increased. For the primary high-pressure calibration facilities in Western Europe these traceability chains are described in [1]. In France a pVTt tank is used, in The Netherlands, Germany and Denmark piston provers are used. The National Metrology Institutes and Designated Institutes of these countries cooperate with the high-pressure calibration laboratories in the EuReGa consortium (European References for Gas).

Every three years, after recalibration of the participants' high-pressure gas flow laboratories, EuReGa organises an intercomparison at the level where commercial calibrations are performed. These results are used to average the traceability chains of the laboratories, which also results in lower uncertainties. This process is called harmonisation and the procedure and data processing is described in [2]. The results of the harmonisation exercises are reported by EuReGa [3]. In the past 20 years of harmonisation the differences between the laboratories have diminished and the uncertainties have improved [2].

After the success of 20 years of intercomparisons, EuReGa extends the intercomparisons to the level of the primary standards. These are operated with sub-permille uncertainties, i.e. with expanded uncertainties ($k = 2$) better than 0,1%. Unfortunately, the French colleagues cannot participate. Their primary pVTt tank operates at variable pressure. For the pVTt tank critical flow Venturi nozzles (sonic nozzles) are suitable as intercomparison devices as their mass flowrate does not depend on the downstream pressure. An intercomparison between LNE-LADG, PTB, NIM and NIST using sonic nozzles [4], demonstrated the equivalence of the French and the German primary standards.

The two DN100 turbine gasmeters used in this comparison have been used in previous EuReGa intercomparisons. The last time in 2017 – 2018 [3]. In this paper these results will be compared with the present results utilising piston provers.

2 PISTON PROVERS

The characteristics of the piston provers are listed in Table 1. VSL uses a 24" gas-oil Piston Prover (GOPP). The prover is filled with oil on one side and gas on the other side of the free moving piston. The maximum flowrate is 230 m^3/h. PTB uses a 10″ gas-gas Piston Prover (HPPP), it consists of a honed 250 mm diameter in which a piston can travel at a maximum speed of 3 m/s (approx. 480 m^3/h) over a length of 6 m with an effective measurement length of 3 m. Finally, FORCE Technology uses a 26″ Twin gas-gas Piston Prover with two parallel cylinders with bidirectional pistons inside them. The actuated pistons can displace up to 400 m^3/h. The bottom row of Table 1 shows the CMC uncertainties, which range between 0.065% and 0.086%.

Table 1 – Characteristics of the piston provers of the participants.

Institute Country	**VSL** The Netherlands	**PTB** Germany	**FORCE** Denmark
Primary device	24″ Gas Oil Piston Prover (GOPP)	10″ Piston Prover (HPPP)	26″ Twin Piston Prover
Piston	Passive	Passive	Active
Nominal diameter	600 mm	250 mm	660 mm
Absolute operating pressure	1 – 62 bar	8 – 51 bar	1 – 66 bar
Piston stroke	12 m	6 m	2.8m
Effective piston stroke	6.5 m	3 m	0.6 – 2.7 m
Flowrate range	3 – 230 m^3/h	3 – 480 m^3/h	2 – 400 m^3/h
Maximum piston speed	0.25 m/s	3 m/s	0.17 m/s
CMC ($\boldsymbol{k} = \mathbf{2}$)	0.070 – 0.086%	0.065 %	0.080 %

3 METER PACKAGES AND TEST PROTOCOL

The turbine gasmeters used in this intercomparison, are part of a so-called meter package. Each meter package consists of a flow conditioner, an inlet spool, a G250 turbine gasmeter and an outlet spool with thermowell. The package is shipped and stored in its entirety. The meter packages are labelled EuReGa DN100 M1 and EuReGa DN100 M2, which will be denoted in the rest of this paper by M1 and M2, respectively.

The packages are calibrated individually, not in series like in the previous intercomparisons. The meters are calibrated at flowrates 25, 40, 65, 100, 160, 250 and 400 m^3/h at absolute pressures of 8, 20 and 50 bar. At each flowrate the laboratories report the meter deviation e, which is the average of four or five successive measurements, and its expanded measurement uncertainty. PTB and Force cover the entire range while VSL covers the range up to 200 m^3/h. In addition, VSL calibrated only the M2 package [5].

The long-term performance of the intercomparison packages was reviewed in 2013 [6]. In a period of 6 years in which 5 intercomparison rounds were performed, the DN100 meters showed a random drift of approximately 0.1%.

The calibration results obtained by the piston provers is compared with the results of the previous intercomparison [3], performed in 2017-2018 using the same pressures and flowrates as above. Force and LNE-LADG performed the calibrations at all pressures and flowrates. LNE used air instead of natural gas. PTB cannot perform routinely calibrations at 8 bar and the M1 and M2 meter packages are too small for calibration by VSL. The data of the previous intercomparison were reprocessed in the same way as the calibration results obtained with the piston provers. In addition, PTB calibrated both meters in the Braunschweig flow facility with atmospheric air. Table 2 presents a schematic overview of the calibration data included in the present study.

Table 2 – Overview of the current and previous intercomparisons. The figures in the cell indicate the calibration pressure in bar.

		Piston prover intercomparison		2017-2018 intercomparison	
Institute	**Fluid**	**M1**	**M2**	**M1**	**M2**
VSL	Natural gas		8, 20, 50		
PTB	Natural gas	8, 20, 50	8, 20, 50	20, 50	20, 50
FORCE	Natural gas	8, 20, 50	8, 20, 50	8, 20, 50	8, 20, 50
LNE-LADG	Air			8, 20, 50	8, 20, 50
PTB	Air			atmospheric	atmospheric

4 DATA PROCESSING AND THE PTB TURBINE GASMETER MODEL

The data processing is done identically to [8], [7]. For each combination of pressure and flowrate, the weighted average of the laboratories' results is calculated with the associated uncertainty. These are fitted in the Reynolds domain by a least-squares approximation.
Up till the present intercomparison, the calibration data were fitted using the formula

$$e_{Re} = \sum_{j=0}^{n} a_j \, [\log(Re/10^6)]^j \qquad (1)$$

where e_{Re} is the meter deviation that is dependent of the Reynolds number. The coefficients a_j ($j = 0..n$) are obtained by curve fitting. The value of n is chosen from 1 to 4, depending of the best curve fit result. The factor 10^6 is introduced to obtain arguments of the logarithm that are around 1, which supports the numerical stability of the least-square approximation. The Re number is defined as

$$Re = \frac{\rho v D}{\eta} = \frac{4\rho Q}{\pi D \eta} \qquad (2)$$

where ρ is the density, D the nominal internal diameter of the meter, η the dynamic viscosity and Q the volume flowrate.

Equation (1) works well as long as the meter behaviour is dominated by flow forces. At low flowrates the bearing friction causes the turbine gasmeter to deviate from the Reynolds behaviour. An interaction between the turbine wheel and the pressure measurement point will become significant at high flow speeds at the turbine wheel (Mach number effect) and is small for modern, balanced turbines (in order of 0.1 to 0.2%). Now the deviation of the meter under test (MuT) e_{MuT} can be composed of a contribution of the flow force e_{Re} in equation (1), a contribution due to the bearing friction e_b and a contribution due to the Mach effect at high flowrates e_p.

$$e_{MuT} = e_b + e_{Re} + e_p \qquad (3)$$

where $e_b = \frac{b_0}{\rho Q^2} + \frac{b_1}{\rho Q}$ (4) and $e_p = c_p Q^2 \frac{\rho}{p}$ (5)

Equations (1, 3, 4, 5) form the PTB turbine gasmeter model [9]. In the period 2007– 2019 the experiments to have an independent measurement of the coefficients for bearing friction and the Mach effect dependencies were determined [10]. The coefficients b_1, b_2 and c_p are to be established for each individual meter. In addition, c_p is depending on the type of gas, air or natural gas. The coefficients were determined when both meter packages were for calibration at PTB in Braunschweig using atmospheric air. After the normal calibration, a so-called spin-down test was performed under low-density, no-flow conditions. In addition, so-called jump tests were performed, in which during steady conditions the flow is suddenly increased or decreased with 10% $Q_{\max}$. The characteristic times obtained from both experiments result in the coefficients [10].

Table 3 – Values of the coefficients of the turbine gasmeter model for meter packages M1 and M2

Meter	b_0 [kg m³/s²]	b_1 [kg/s]	$c_{p,air}$	$c_{p,NG}$
M1	-7.64·E-05	-2.45·E-02	-9.65·E+05	-2.34·E+05
M2	-8.17·E-05	-3.65·E-02	1.80·E+05	1.00E+06

5 CALIBRATION DATA AND LEAST-SQUARES APPROXIMATION

Figure 1 depicts all calibration data as the observed deviation e_{MuT} versus the Reynolds number Re, which is plotted on a logarithmic scale. In this way the results obtained at different pressures can be compared. For meter package M1 the results are shown in the upper part of Figure 1. The results of meter package M2 are shown in the bottom part of Figure 1. The scale divisions of both figures are equal, as is the legend. The first impression is that both meters have different characteristics, which is understandable as the meters are different brands.
The solid markers represent the calibration results obtained when using the piston provers. The red solid line is the least-squares fit of the weighted average of the laboratories' results and the dashed lines represent the 95% uncertainty contours. The open markers represent the calibration results from the previous intercomparison [3]. The black solid line is the least-square approximation of the weighted averages of the intercomparison data. For reference, the associated expanded uncertainties are indicated in the bottom-right corner of each figure. It clearly shows that the results obtained with the piston provers have a much lower uncertainty than the results of the previous intercomparison.
The shape of the black line has a similar shape as the red fit, running between its 95% contours and not deviating more than 0.05% from the red fit. Most data agree within their uncertainty with the fit. This clearly demonstrates the consistence of the previous intercomparison results with the present calibration results obtained by the piston provers.
As the data points of the calibrations with atmospheric air are in a much lower Reynolds range than the pistop prover intercomparison, they are excluded from the fits. For meter package M1 the air flow results are within the 95% contours. At lower flowrates the curve bends away from the fit. Here the influence of the bearing friction becomes visible. For M2 the upper air flow data points are parallel to the fit at approximately 0.25% distance which is greater than the uncertainty.

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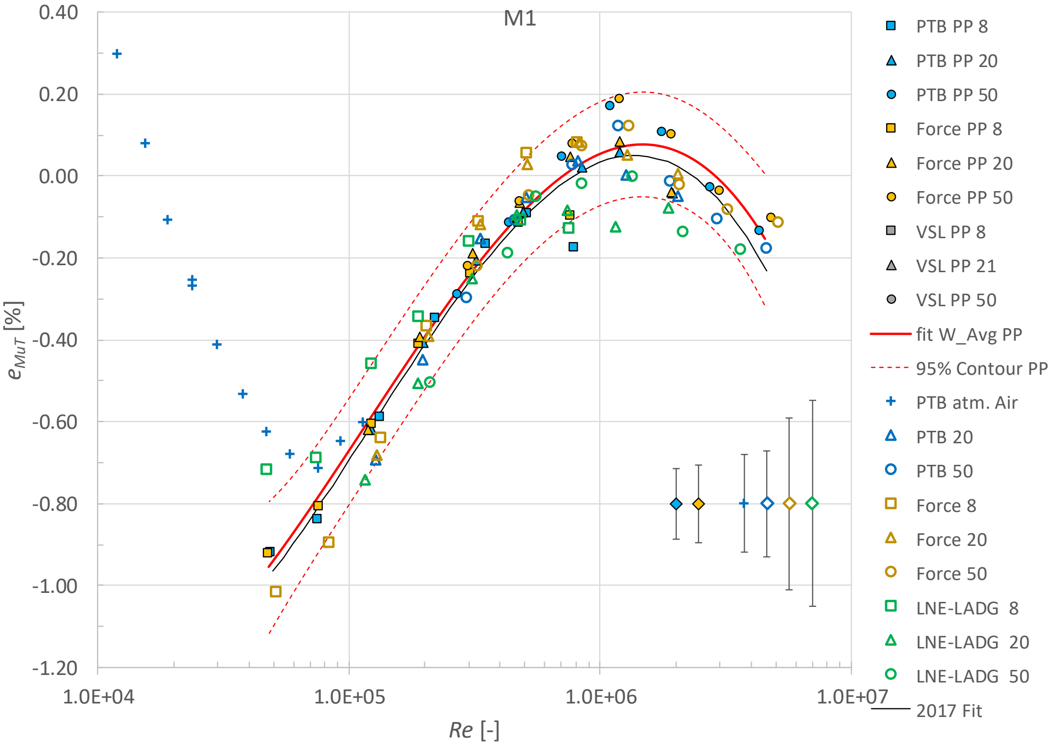

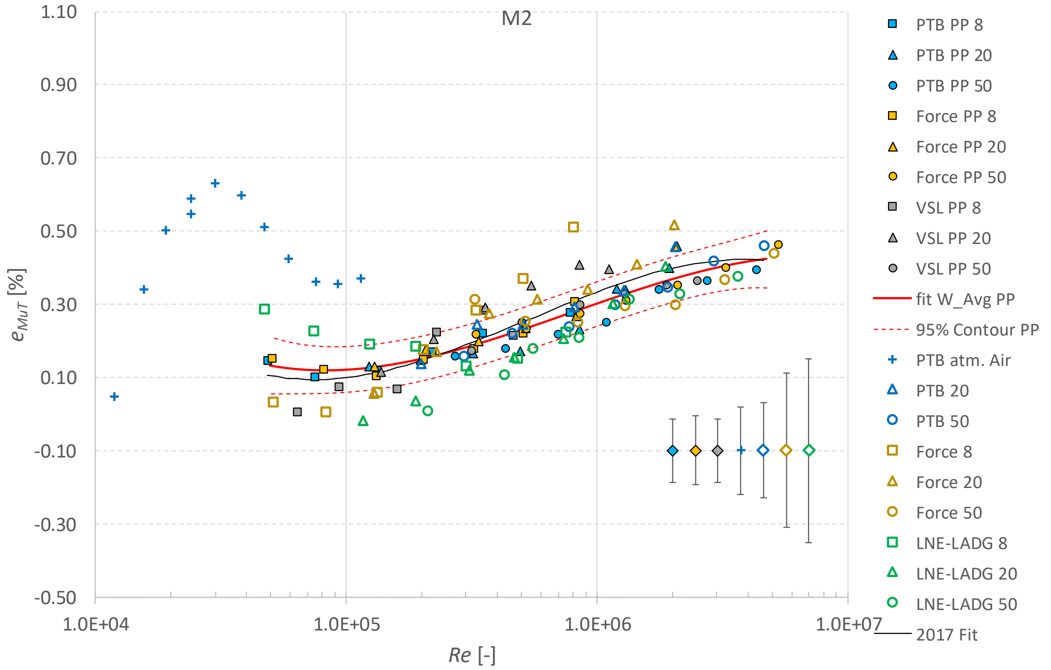

Figure 1: Calibration results of the DN100 turbine gasmeters M1 upper and M2 bottom. The meter deviation e_{MuT} [%] is plotted versus the Reynolds number Re [-] on a logarithmic scale. The solid markers represent the results obtained with the piston provers. The red solid line is the least-squares fit of these results and the dashed lines represent the 95% uncertainty contours. The open markers are the result from the previous intercomparison [3]. The black solid line is the fit of these intercomparison data. The crosses (+) are the calibrations with atmospheric air, which are excluded from the fits. For reference the associated expanded uncertainties are indicated in the bottom-right corner.

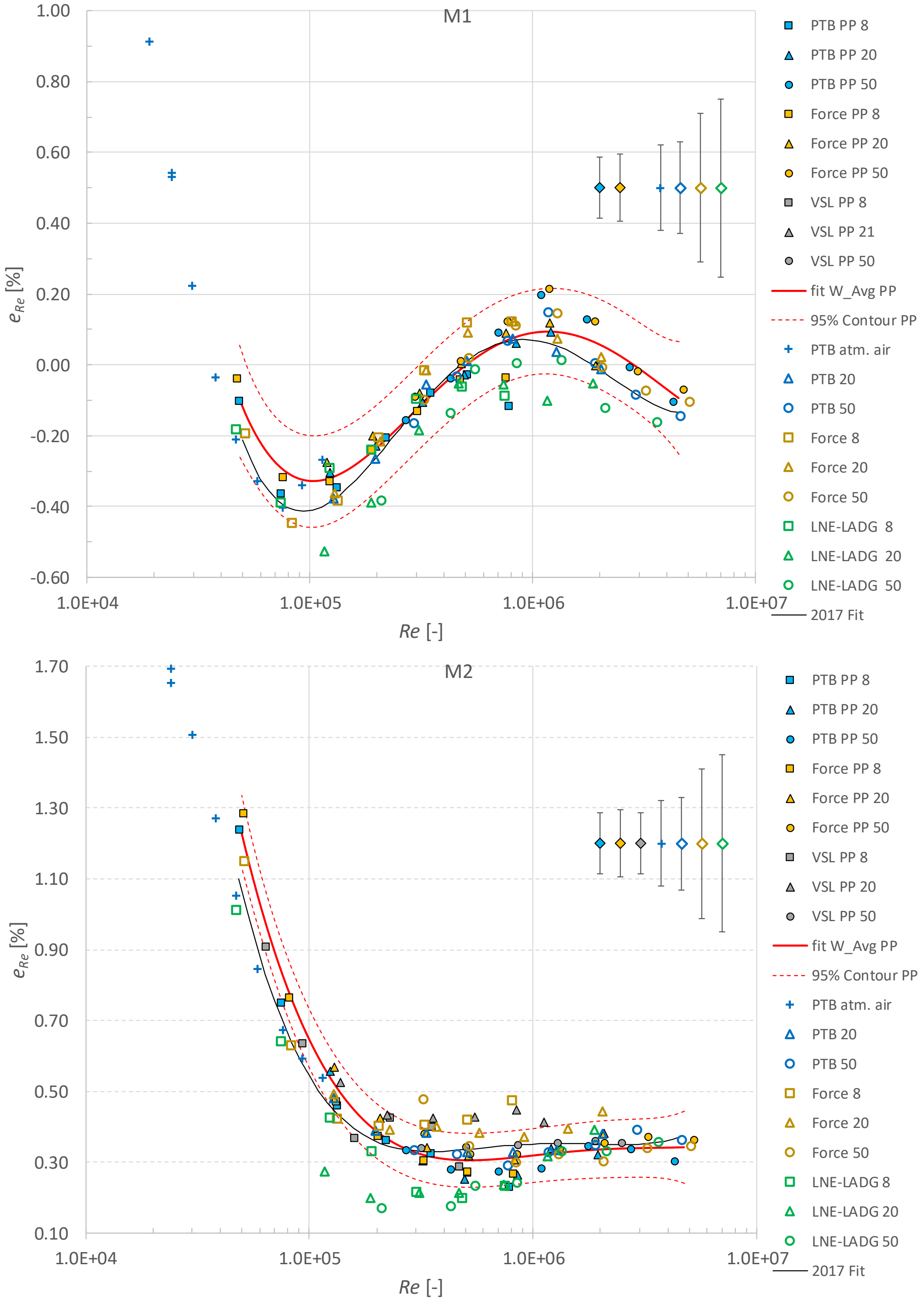

Figure 2: Calibration results of the DN100 turbine gasmeters M1 upper and M2 bottom. The meter deviation e_{Re} [%] is plotted versus the Reynolds number Re [-] on a logarithmic scale. The solid markers represent the results obtained with the piston provers. The red solid line is the least-squares fit of these results and the dashed lines represent the 95% uncertainty contours. The open markers are the result from the previous intercomparison [3]. The black solid line is the fit of these intercomparison data. The crosses (+) are the calibrations with atmospheric air, which are excluded from the fits. For reference the associated expanded uncertainties are indicated in the bottom-right corner.

The next step is the application of the turbine meter model. Each individual data point is corrected for the influence of the bearing friction and the high-speed Mach effect, using equations (4) and (5) and the constants of Table 3. For each data point e_b and e_p are calculated and subtracted from e_{MuT}, which results in e_{Re}. This is done for both the calibrations with the piston provers, the earlier obtained intercomparison results and the calibration results obtained with atmospheric air. Like Figure 1, Figure 2 depicts the results of e_{Re}. Again, the characteristics of both meter packages are different.

Most data points agree within their uncertainty with the fit (red line) of the weighted averages of the piston prover calibrations. The black line, i.e. the fit of the previous intercomparisons, has the same shape as the red line fit and lies for meter package M1 within the 95% contours. For meter package M2 the black line is in the upper Reynolds range within the red 95% contours. For the lower Reynolds range it is running parallel to the red fit. The data of the atmospheric air calibrations connect to the visual extrapolation of both the red-line and black-line fits of e_{Re}. The atmospheric-air data are within the 95% contours of the M1 package. For the M2 package, the atmospheric-air data are in the lower range quite close to the contours of the fit.

In conclusion the turbine meter model is an adequate method to connect the calibration data obtained with natural gas at different pressures on one side and the calibration data with atmospheric air at the other. After applying the turbine meter model, the consistency of the piston prover results with results from previous intercomparisons remains.

6 Normalized deviations

The processing of the measurement data is done according to [8], [6]. Instead of using the laboratory observations e_{MuT}, the values corrected for bearing friction and Mach effect e_{Re} are used now. The data analysis is performed in the Reynolds domain. In this way the results obtained at different pressures can be compared. For each combination of pressure and flowrate $\bar{e}_{Re}$ is the weighted average of the deviations e_{Re} observed by the labs, which makes $\bar{e}_{Re}$ the reference level, also referred to as common reference value (CRV). The small differences between the corresponding Reynolds numbers of the laboratories' observations are ignored.

The next step is to calculate the deviations $d = e_{Re} - \bar{e}_{Re}$ with respect to the CRV ($e_{Re} = \bar{e}_{Re}$ or $d = 0$) and the corresponding uncertainties, calculated from $U^2(d) = U^2(e_{Re}) - U^2(\bar{e}_{Re})$.

The normalized deviations $E_n = d/U(d)$ are shown in Figure 3. Here E_n values are plotted versus the Reynolds number Re. The CRV ($E_n = 0$) is only based on the calibration results obtained with the piston provers. The results of the previous intercomparisons are also included. The data were processed for meter packages M1 and M2 separately. The results are combined in one graph. The markers for M1 obtained by piston prover have a red border, for M2 this is a black border. The open markers corresponding with the previous intercomparison, have a blank filling for M2 and a pink filling for M1. There are no E_n results for the atmospheric-air calibrations because there is no second lab in the Re range covered. Figure 3 shows that most of the normalised deviations are below $E_n = 1$. From the piston prover results two data points exceed the critical level and one exceeds the warning level. From the previous intercomparison four data points exceed the warning level and two data points exceed the critical level.

Table 4 shows the complete frequency distribution of the observed E_n values. This table confirms that 95% of the results matches $E_n \leq 1$. Approximately 74% of the results matches $E_n \leq 0.5$. Only 2% of the results exceeds the warning level $E_n = 1.2$.

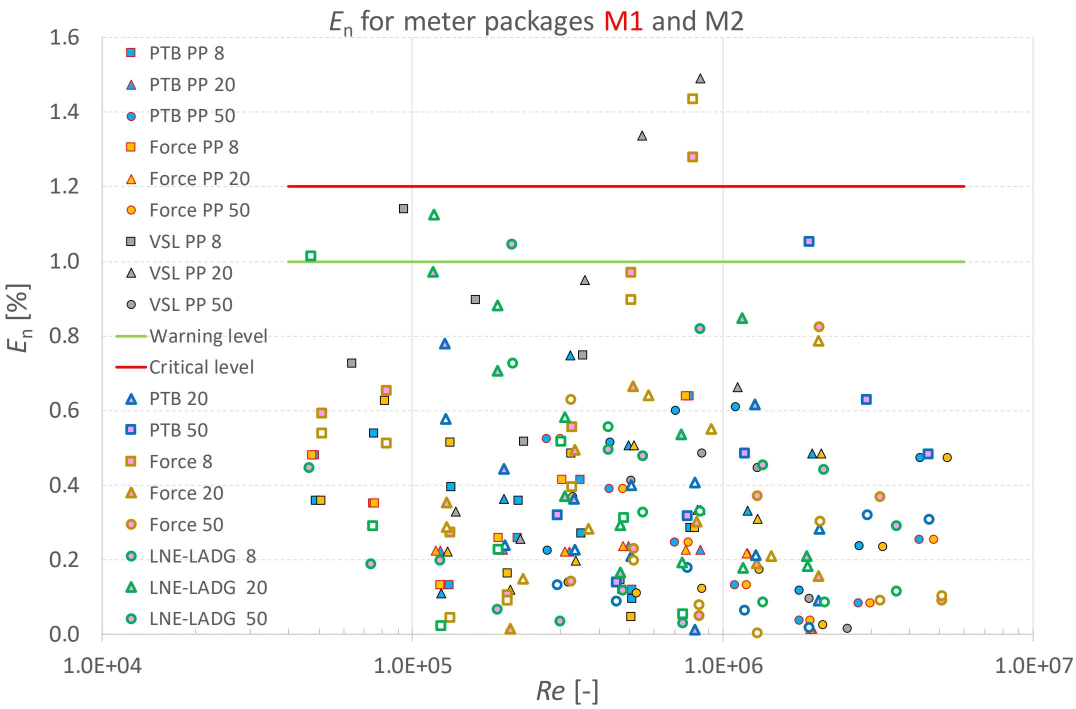

Figure 3: E_n [-] values versus Re number [-]. The green horizontal line is the warning level corresponding to $E_n = 1$. The horizontal red line is the critical level corresponding to $E_n = 1.2$.

Table 4: Frequency distribution of observed E_n values.

	2019 Piston Prover		2017-2018 Intercomparison	
Histogram bin	Number	Percentage	Number	Percentage
$0 \leq E_n \leq 0.5$	80	78.4%	79	70.5%
$0.5 < E_n \leq 1$	19	18.6%	27	24.1%
$1 < E_n \leq 1.2$	1	1.0%	4	3.6%
$E_n > 1.2$	2	2.0%	2	1.8%
Total	102	100.0%	112	100.0%

7 SUMMARY

A recently performed intercomparison between three laboratories using the piston provers as a primary reference, was re-evaluated using PTB's turbine meter model. The two DN100 transfer packages that were calibrated, were also utilised in a previous intercomparison and were calibrated at PTB using atmospheric air.
The unprocessed data show that most of the piston prover data lie within the 95% contours of the fit. Most of the data from the previous intercomparison also lie within the 95% contours of the fit of the piston prover results, which proves the consistency of the two intercomparisons. Only the air calibration results, which were measured at much lower Reynolds numbers show a different course.

In the PTB turbine meter model the meter deviation is split up into three contributions: the bearing friction, a high-speed Mach effect and the remaining flow forces. When the first two contributions are corrected for, a much better connection with the air calibration data is achieved. The consistency between the piston prover data and the data from the previous intercomparison remains. This makes the turbine meter model promising for future intercomparisons that are performed in a wider Reynolds number range.
For all calibration data except the atmospheric-air data, the normalized deviation E_n was calculated using the weighted average of the piston prover calibration as common reference value. At least 95% of the data matches the $E_n \leq 1$ criterion. Only 2% of the results exceeds the warning level $E_n = 1.2$.

8 NOTATION

Symbols

a	coefficient	
b	coefficient	
c_p	coefficient	
D	Nominal internal diameter of the turbine gasmeter	[mm]
d	deviation between measured deviation and CRV: $d = e - \bar{e}$	
E_n	Normalised deviation $= \lvert d \rvert / U(d)$	[-]
e	deviation or error	[-]
$\bar{e}$	average deviation, CRV	[-]
k	coverage factor	[-]
n	maximum grade of the interpolation of e_{Re}	[-]
Q	volume flowrate	[m³/h]
Re	Reynolds number	[-]
U	expanded uncertainty	
u	standard uncertainty	

Index

b	bearing friction
j	coefficient index
max	maximum condition
MuT	meter under test
p	pressure dependent
Re	flow force

Abbreviations

CMC	Calibration and Measurement Capability, i.e. the expanded uncertainty ($k = 2$) that can be achieved for a near ideal instrument under test
CRV	Common Reference Value
DoE	Degree of Equivalence, = normalised deviation
MuT	Meter under Test
TRM	Transfer Reference meter

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