

Primary Piston Prover Intercomparison Between PTB, VSL and FORCE Technology

Arnthor Gunnarsson¹, Jos van der Grinten²,
Mijndert van der Beek³, Bodo Mickan⁴

¹FORCE Technology, Navervej 1, 6600 Vejen, Denmark

²Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany

³VSL, Thijsseweg 11, 2628 JA, Delft, The Netherlands

⁴Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany

E-mail (Arnthor Gunnarsson): agu@force.dk

Abstract

The EuReGa members that use a Piston Prover as a primary calibration device (PTB, VSL and FORCE Technology) performed an intercomparison in 2018-2019. This paper will describe the Piston Provers used in the intercomparison after which the intercomparison results and their implication will be presented.

Degree of equivalence has been determined on multiple occasions in the past between the participants. What distinguishes this intercomparison from others is that it is performed with Piston Provers, which is the starting point in the respective participants traceability systems. This means that the CMC reported in the intercomparison is lower compared to previous intercomparisons between the participants, with reported CMC uncertainty between 0.07% and 0.086%. The traceability of the participants is independent from each other, since the results are directly traceable to the participants respective Piston Provers, the Piston Provers being primary calibration systems traceable to length.

EuReGa consists of four members with established traceability chains, LNE-LADG, PTB, FORCE Technology and VSL. LNE-LADG did not participate in the intercomparison because they use a PVTt system to establish their traceability.

The results support the CMC claims of the participants, showing that also at the starting point in the traceability, and therefore at the low end of the uncertainty spectre of the participants, there are acceptable differences between the members of EuReGa. The intercomparison report for this project has been submitted under EURAMET project no. 1301 which forms a basis for this report [1].

1. Introduction

Every three years the members of EuReGa perform a harmonization exercise for high-pressure flows of natural gas [2], [3], [4]. In the harmonization, equivalence has been demonstrated between the four EuReGa members and the differences between the laboratories are minimized through harmonizing. This project describes the results of an intercomparison using the primary standards, which are the first step in the respective participants' traceability chains. Consequently, this intercomparison has been performed at the lowest uncertainty levels achievable by the participants. Unfortunately, the French colleagues cannot participate in this intercomparison as their primary is a PVTt system. However, LNE-LADG, PTB, NIM and NIST did perform a primary intercomparison in 2015 [5]. So, using the intercomparison from 2015 and this Piston Prover intercomparison, the circle can be closed with PTB as the connecting institute in both intercomparisons.

Thus equivalence can be determined between all EuReGa members at a low uncertainty.

The meters used in this intercomparison are two of the meters used in the harmonization exercise and have been used in many intercomparisons in the past. Data from this intercomparison can be used with results from previous harmonization exercises to be analysed. Dependent on there being noticeable differences between those results, that can be used to identify where differences occur in the participants respective traceability systems.

2. Participants' Piston Provers

All participants in the intercomparison use a Piston Prover as a primary reference. 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 m³/h) over a length of 6 m with an effective measurement length of 3 m. 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 m³/h. 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 m³/h. The characteristics of the provers can be seen in Table 1. [1]

Table 1: Characteristics of the participants piston provers.

Institute	VSL	PTB	FORCE
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 / effective stroke	12 m / 6.5 m	6 m / 3 m	2.8 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	0.070 0.086%	– 0.065 %	0.080 %

3. Transfer Meters and Test Protocol

Both meter packages used in this intercomparison consist of a G250 turbine meter with a fixed upstream flow conditioner, upstream spool and downstream spool with thermowell. The meter packages are designated EuReGa DN100 M1 and EuReGa DN100 M2. They are normally used in the EuReGa intercomparison every three years, the last time in 2017 and 2018 [2]. In this intercomparison, the packages were calibrated individually, not in series. The meters were calibrated at flowrates 25, 40, 65, 100, 160, 250 and 400 m³/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 m³/h. In addition, VSL calibrated one meter package: EuReGa DN100 M2. [1]

In 2013, the EUREGA group published a review about the long-term performance of the transfer standards used in the harmonisation **Error! Reference source not found..** The outcome for the G250 meters was a random drift of approximately 0.1 % within 6 years or 5 applications in intercomparison rounds respectively. Assuming a pure random process (what is justified by the data base), we can

conclude an additional uncertainty contributed by the transfer meters at a level of 0.05% per intercomparison round.

4. Data Processing

The processing of the measurement data was done according to [6]. For each pressure and flowrate the average error of all successive measurements performed by laboratory i is $e_{lab\ i,flow\ j}$. The associated uncertainty $U_{lab\ i,flow\ j}$ is calculated as the reported lab uncertainty $U_{(lab\ i,flow\ j)}$ with the added meter stability (drift), U_{meter} uncertainty of 0.05% based on section 3.

$$U(e_{lab\ i,flow\ j}) = \sqrt{U_{(lab\ i,flow\ j)}^2 + U_{meter}^2} \quad (1)$$

For each laboratory a weighing factor $w_{lab\ i,flow\ j}$ is calculated according to equation (2).

$$w_{lab\ i,flow\ j} = \frac{1}{U_{lab\ i,flow\ j}^2} \quad (2)$$

The sum of the weighing factor for each flowrate is

$$W_{flow\ j} = \sum_i w_{lab\ i,flow\ j} \quad (3)$$

They are used along with each laboratory's average error $e_{lab\ i,flow\ j}$ to calculate a weighted mean error \bar{e} also called comparison reference value (CRV).

$$\bar{e}_{flow\ j} = \frac{1}{W_{flow\ j}} \sum_i w_{lab\ i,flow\ j} e_{lab\ i,flow\ j} \quad (4)$$

The uncertainty of each $\bar{e}_{flow\ j}$ is then calculated by

$$U(\bar{e}_{flow\ j}) = \sqrt{\frac{1}{W_{flow\ j}}} \quad (5)$$

Based on each laboratory's average error $e_{lab\ i,flow\ j}$ and the weighted mean error \bar{e} , the difference $d_{lab\ i,flow\ j}$ is calculated for each laboratory's pressure and flow:

$$d_{lab\ i,flow\ j} = e_{lab\ i,flow\ j} - \bar{e}_{flow\ j} \quad (6)$$

Based on the values for each flow, a chi-squared test for consistency can be performed. The chi-squared test is a statistical method that in this case is performed to investigate if the observed differences correspond to what can be expected with regards to the uncertainty and it being reported with 95% confidence. This has been performed in established key comparisons in the past, see [7]. Equation (7) shows how the χ_{obs}^2 is calculated:

$$\chi_{obs,flow\ j}^2 = \sum_i \frac{d_{lab\ i,flow\ j}^2}{\left(\frac{U(e_{lab\ i,flow\ j})}{2}\right)^2} \quad (7)$$

The chi-squared consistency check fails if, $Pr\{\chi_v^2 > \chi_{obs}^2\} < 0.05$ which corresponds to $CHIINV(0.05; v) < \chi_{obs}^2$. If the consistency check passes, then the CRV is accepted, but if it fails, then the laboratory with the highest value of $\frac{d_{lab\ i,flow\ j}^2}{\left(\frac{U(e_{lab\ i,flow\ j})}{2}\right)^2}$ is excluded in the calculation of the CRV for that specific flowpoint. This means that a new calculation of the CRV is performed in that flowpoint according to equation (4), with one laboratory excluded.

For the non-excluded results, the uncertainty of the difference is obtained by

$$U(d_{lab\ i,flow\ j}) = \sqrt{U(e_{lab\ i,flow\ j})^2 - U(\bar{e}_{flow\ j})^2} \quad (8)$$

The uncertainty of a laboratory with excluded results in a flowpoint is

$$U(d_{lab\ i,flow\ j}) = \sqrt{U(e_{lab\ i,flow\ j})^2 + U(\bar{e}_{flow\ j})^2} \quad (9)$$

The only difference between equation (8) and (9) is the sign in the right-hand-side of the equation, which leads to higher uncertainties for the excluded data points. Finally, based on equations (6, 8 and 9), the degree of equivalence $E_{N,lab\ i,flow\ j}$, also called normalized deviation, can be determined by

$$E_{N,lab\ i,flow\ j} = \frac{|d_{lab\ i,flow\ j}|}{U(d_{lab\ i,flow\ j})} \quad (10)$$

5. Results

In total there were 102 points and therefore 102 differences and normalized differences (E_N values). The calibration results with Reynolds number on the x-axis are shown in figures 1 and 2. The results can be seen as points and a Reynolds fit is included with 95% uncertainty contours.

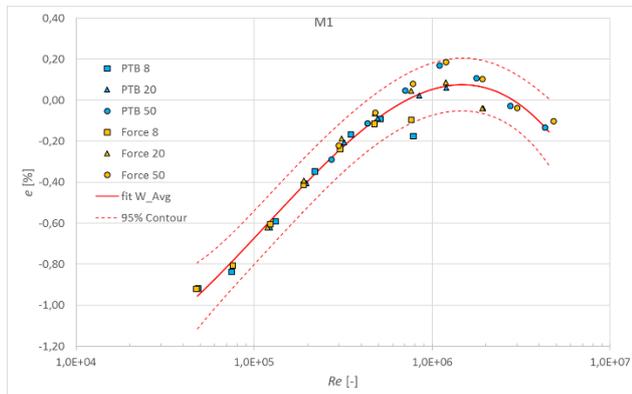


Figure 1: Calibration results of DN100 M1. The observed meter error e [%] is plotted versus the Reynolds number Re [-]. The

solid line is the least-squares fit and the dashed lines represent the 95% uncertainty contours.

The contour uncertainty is approximately 2.4 times higher for M1 than for M2, note that the range on the y-axis is considerably higher for M1. So, although there are more points outside of the uncertainty contours for M2, this is because the contour uncertainty is low. The uncertainty contours are an indication of how well the Reynolds fit actually represents the CRV for each flow point. Thus, M2's errors fit well to a Reynolds curve while M1 has some differences, especially in the boundary layer (high and low flowrates for each pressure) when comparing the CRV for each flow point with the Reynolds fit.

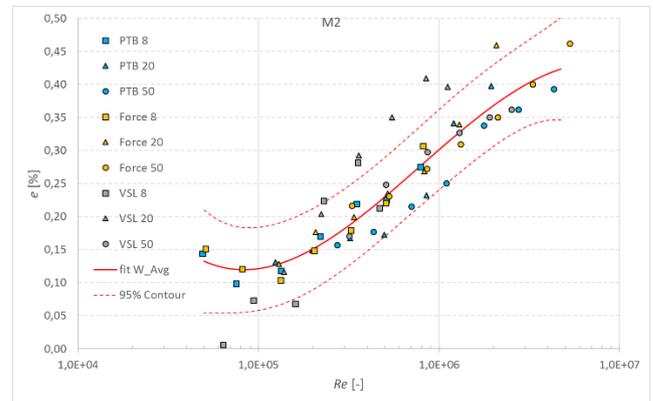


Figure 2: Calibration results of DN100 M2. The observed meter error e [%] is plotted versus the Reynolds number Re [-]. The solid line is the least-squares fit and the dashed lines represent the 95% uncertainty contours.

After calculating the differences, the chi-squared consistency check was performed where it was found that three points should be excluded. After excluding the three values in calculation of the CRV, the consistency check for the points was accepted. Note that the polynomials in figures 1 and 2 are based on the results after exclusion of the three points.

The differences d are shown in Figure 3 and the E_N values are shown in Figure 4. Both are plotted with Reynolds number Re on the x-axis.

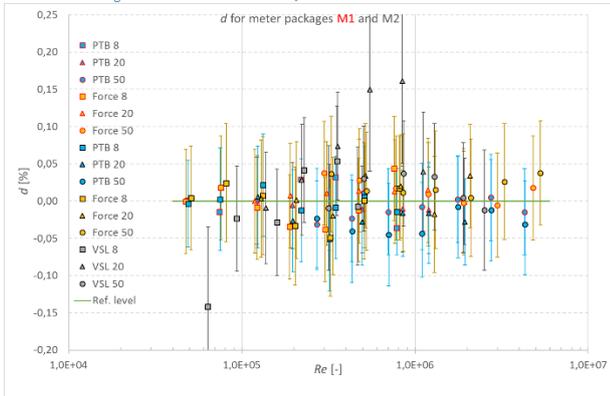


Figure 3: Differences d [%] with their respective expanded uncertainties shown as vertical bars versus the Re number [-].

Disregarding the three excluded points, the differences d are in the range -0.052% to 0.074% . Additionally, PTB has an average difference d of -0.011% , FORCE's average d is 0.007% and finally VSL has an average difference d of 0.023% . With different traceability systems, there can be systematic differences between the participants. It is evident that with these average differences that the systematic difference between the participants is low but the spread means that some of the differences are higher than what can be expected with these low reported uncertainties.

Figure 4 shows the normalized deviations (E_N values) for the intercomparison.

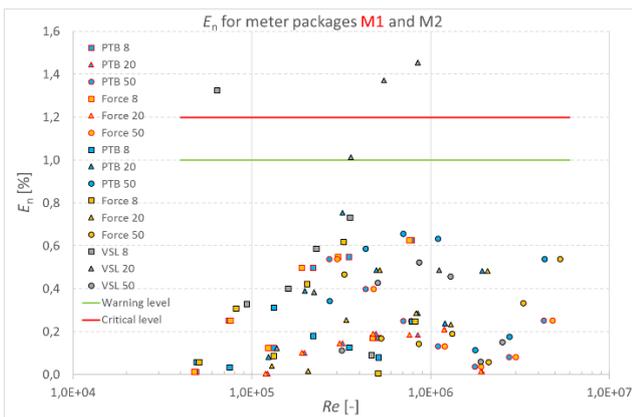


Figure 4: E_N values versus Re number. The green horizontal line is the warning level corresponding to $E_N = 1$. The horizontal red line is the critical level corresponding to $E_N = 1.2$.

Table 2: Frequency distribution of observed E_N values.

Histogram bin	Number	Percentage
$0 \leq E_N \leq 0.5$	82	80%
$0.5 < E_N \leq 1$	16	16%
$1 < E_N \leq 1.2$	1	1%
$1.2 < E_N$	3	3%

Table 2 shows the frequency distribution of the observed E_N values. The table shows that 96% of the results matches $E_N \leq 1$, 80% even matching $E_N \leq 0.5$. 3% of the E_N values lies above the critical level with the highest one being 1.45. The observed frequency distribution is consistent with the 95% confidence level of the applied statistics.

6. Discussion and Comparison with Historic Results

The present intercomparison demonstrates the equivalence of the primary standards. However, some test points of VSL had to be treated as outliers. Possible causes for the deviating behaviour of the calibration include:

- 1) The GOPP of VSL is designed and optimised to operate with rotary meters. Turbine meters might not be able to follow small irregularities in the applied flow rate as well as rotary meters would. This might cause over spinning of the turbine wheel.
- 2) The GOPP was operated at different temperatures than the primary standards of FORCE and PTB. A correction for the influence of the temperature on the meter dimensions and meter behaviour have been applied. These corrections could possibly be further improved.

An additional comparison between Force and VSL is currently being planned. This comparison will use rotary meters instead of turbine meters and will include an additional pressure of 61 bar.

The present intercomparison was performed with primary standards at an uncertainty level of $0.070\% - 0.086\%$. The observed variability of the results is consistent with the present CMCs. How much do the calibration results diverge as we go further down the traceability chains of the participants? Since the primary intercomparison can be used in conjunction with intercomparisons later in the traceability systems to measure this diversion of results, how can this be minimized? These are questions that could be of great value to investigate to better understand the respective participants traceability systems.

Since the same meter packages were also used in the 2017 EuReGa harmonization process, the results from 2017 can be compared with the results of this piston prover intercomparison. Figure 5 shows the difference between the weighted average of the meters from this Piston Prover intercomparison finalized in 2019 and the EuReGa intercomparison from 2017.

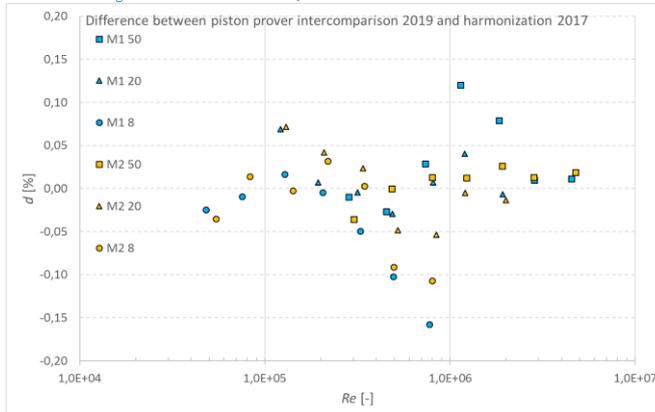


Figure 5: Differences between the weighted average of the Piston Prover intercomparison and the weighted average of the EuReGa intercomparison from 2017 using the same meters.

The results show that the average difference between the 2019 and 2017 comparison reference values results is -0.004%, which is small compared to the CMC values. Additionally, 50% of the absolute differences are lower than 0.024% and 95% of the absolute differences below 0.11% the maximum difference being 0.16%.

7. Conclusion

The results between the participants have been reported with a 95% confidence. With 96% of the E_N values lower than 1, the results are compliant. Taking into account the reasoning behind some of the high E_N values, the results support the CMC claims of the participants. Additionally, the results in this intercomparison match historic results with the same meters. This intercomparison can thus be regarded a successful demonstration of the CMC's of the participants. And as was mentioned in section 1, LNE-LADG, PTB and NIST performed a successful intercomparison in 2015 [5]. With these two intercomparison all four members of EuReGa are included and PTB is the connecting institute in both intercomparisons, This means that also at the low end of the uncertainty spectrum, there are acceptable differences between the members of EuReGa.

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References

[1] Jos van der Grinten, Arnthor Gunnarsson, Mijndert van der Beek and Bodo Mickan, "Intercomparison of primary high pressure flow

standards", EuReGa Communiqué No 3, EURAMET F1301, 2019,

<https://tinyurl.com/y39lx5ud>.

[2] Jos van der Grinten, Henri Foulon, Arnthor Gunnarsson, Bodo Mickan (2018): Reducing measurement uncertainties of high-pressure gas flow calibrations by using reference values based on multiple independent traceability chains, *Technisches Messen*, **85**(12), pp 754-763.

<https://doi.org/10.1515/teme-2018-0019>

[3] EuReGa, "EuReGa Communiqué No. 2 (2018): Harmonized Reference Value 2018", Euramet F1301, <https://tinyurl.com/yyzhh58l>

[4] EuReGa. "Traceability chains of EuReGa Participants for high-pressure natural gas", EuReGa White Paper, Euramet F1301, 2018

<https://tinyurl.com/y98xzpad>

[5] B. Mickan, M. van der Beek, J-P. Vallet, "Review of the European Harmonised Cubic Meter 1999 – 2012", 16th International Flow Measurement Conference, FLOMEKO, Paris, 24-26 September 2013, France.

[6] Cox, M. G. [The evaluation of key comparison data](#), *Metrologia*, **39**(6), pp 589-595, 2002.

[7] Miroslava Benková et al., "[CIPM key comparison CCM.FF-K6.2011, Comparison of Primary \(National\) Standards of Low-Pressure Gas Flow](#)", *Metrologia*, **51**(1A), pp 07004-07004 doi:10.1088/0026-1394/51/1a/07004