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# Reducing measurement uncertainties of high-pressure gas flow calibrations by using reference values based on multiple independent traceability chains

Reduzierung der Messunsicherheit bei Kalibrierungen im Bereich von Gasdurchfluss unter hohem Druck durch Referenzwerte basierend auf mehreren unabhängigen Kalibrierketten

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**Abstract:** This paper describes the recently updated realization of the harmonized cubic metre for natural gas. It is a procedure based on an intercomparison, that combines the mutually independent traceability chains of four primary laboratories in the field of high-pressure gas flow measurement. The reference value, also called harmonized cubic metre, is the weighted average of at least two laboratories with weighing factors that are inversely proportional to the squared uncertainties of the calibration results. This results in lower uncertainties for the laboratories as long as the stochastic contributions (Type A) to the overall measurement uncertainties are significantly smaller than the uncertainties arising from the traceability chain (Type B). This condition is fulfilled in practice as traceability uncertainties are at least a factor ten greater than the other uncertainty sources. When evaluating the data of intercomparisons, curve fitting is used for the representation of the calibration data. A polynomial equation of maximum four degrees, expressed in the logarithm of the flow Reynolds number, proves to be the optimum choice for fitting the calibration curve of the turbine gas-meters.

**Keywords:** Harmonized cubic metre, reference value, uncertainty, traceability, high-pressure natural gas.

**Zusammenfassung:** Der Artikel beschreibt die kürzlich aktualisierte Realisierung des Harmonisierten Kubikmeters für Erdgas. Es ist eine Verfahrensweise im Gebiet der Volumen- und Durchflussmessung von Gas, die auf der Basis von Ringvergleichen mehrerer unabhängiger Kalibrier-

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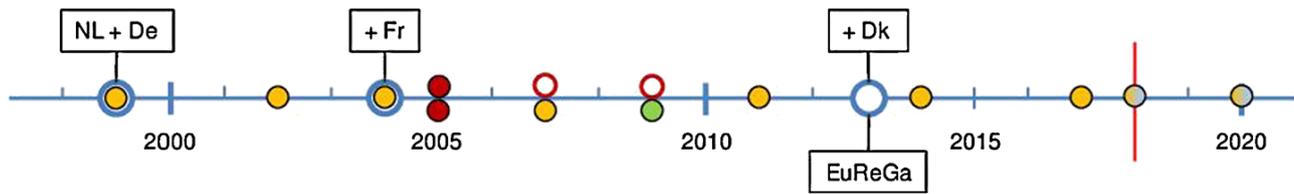
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ketten kombiniert. Der Referenzwert, auch harmonisierter Kubikmeter genannt, ist der gewichtete Mittelwert von mindestens zwei Laboratorien, wobei die Gewichtungsfaktoren umgekehrt proportional zum Quadrat der Messunsicherheiten sind. Dieses Verfahren ist unter der Voraussetzung erfolgreich, dass die stochastischen Beiträge (Typ A) zu den Gesamtmessunsicherheiten signifikant kleiner sind als die anderen Unsicherheiten (Typ B), die aus der Kalibrierkette stammen. Diese Bedingung ist in der Praxis erfüllt, da die Unsicherheiten der Rückführung in der Regel mindestens um den Faktor zehn größer sind als die anderen Unsicherheitsquellen. Für die Auswertung der Daten aus den Ringvergleichen werden approximierende Funktionen als Repräsentanten der Messwerte benutzt. Polynome maximal vierten Grades und basierend auf dem Logarithmus der Reynolds-Zahl, erwiesen sich als beste Wahl für die Anpassung von Kalibrierkurven von Turbinenradgaszählern.

**Schlagwörter:** Harmonisierter Kubikmeter, Referenzwert, Unsicherheit, Kalibrierkette, Hochdruck-Erdgas.

## 1 Introduction

Despite competition from other energy sources natural gas remains a popular commodity in the energy mix. Investments are made in new pipelines, new metering stations, and also new high-pressure calibration facilities. The gas market has a keen interest in both small differences between the high-pressure calibration facilities, and a high accuracy, i. e. a low uncertainty of the calibration result. These calibration facilities operating in the range between 0.4 and 6.6 MPa absolute pressure, achieve measurement uncertainties in the range of 0.13 % and 0.3 %, while the repeatability of the gasmeter contributes only one tenth of this value. As will be shown in section 2 the most important uncertainty source to the Calibration and Measurement Capability (CMC) is the traceability chain. The Holy Grail for high-pressure gas flow calibrations is to achieve a CMC of 0.10 %. In the past decades, several steps



**Figure 1:** Time-line of intercomparisons using turbine gasmeters intended for high-pressure natural gas. The yellow dots indicate harmonization intercomparisons, the yellow-gray dots planned intercomparisons, the red dots key comparisons, the red rings subsequent bilateral comparisons and the green dot a Euramet bilateral comparison. The white flags mark the dates at which the labs participated in the harmonization consortium. In 2013 the cooperation was renewed under the EuReGa label. (Graphic courtesy of EuReGa).

have been undertaken to reduce measurement uncertainties. The first step is to shorten the traceability chain. This approach was used in the Netherlands where the traditional long traceability chain [1] was replaced by a much shorter one [2, 3]. Also in Germany, a more solid foundation for high-pressure gasmeter calibrations was developed [4] and improved [5]. In France the traceability chain was re-designed [6]. The actual traceability chains of the laboratories that participate in the intercomparison, are documented on the EURAMET website [7].

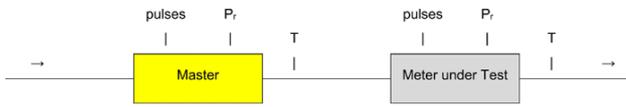
The second step to reduce the measurement uncertainties has a historic origin. In the early nineties substantial differences were observed in cross-border gas metering between the Netherlands and Germany. The commercial choice for a specific calibration facility was mainly determined by the fact whether the client was buying or selling natural gas. Although the differences were not significant from a metrological perspective, this practice was unacceptable to both the gas market and the National Metrology Institutes. The latter started several intercomparisons and agreed on a new reference value based on an averaging procedure where the results were weighed with weighing factors that were inversely proportional to the squared uncertainties [8]. The uncertainty of this average value is smaller than each of the uncertainties obtained by the respective laboratories, which will be shown in section 4 (f). This new harmonized  $m^3$  was established by bilateral agreement between the national standards institutes of the Netherlands (VSL) and Germany (PTB) in 1999. The French national institute (LNE) joined in 2004. In 2013 the international cooperation was extended with the Danish designated institute (FORCE Technology), which participated in 2014 for the first time in a new intercomparison. Together the four National Metrology Institutes form the EuReGa consortium (European Reference for Gas metering). Not all EuReGa partners have their own calibration facilities for high-pressure natural gas. VSL co-operates with EuroLoop, PTB with pigsar, LNE with Cesame Ex-adébit, and only FORCE Technology has its own facilities.

Figure 1 gives a time-line of high-pressure gas flow intercomparison events performed in the past two decades. The harmonization intercomparisons (yellow dots) are performed approximately every three years, the last was conducted in 2017 [9]. In 2005 two key comparisons (red dots) were performed: CCM.FF-K5a [10] and CCM.FF-K5b [11], followed by bilateral comparisons CCM.FF-K5a.1 [12] in 2005, CCM.FF-K5a.2 [13] in 2007 and EURAMET.FF-K5.a [14]. During the different intercomparisons a new model for the meter curve of turbine gasmeters was introduced. As this is not a common choice in the gas market a comparison of different mathematical descriptions is discussed in section 3.

One of the observations made over the past two decades is the improvement of the respective traceability chains of the participating countries: measurement differences between high-pressure calibration laboratories have decreased and the uncertainties of the measurement results have been reduced. The change of a national reference value into an international harmonized reference value is a key point to be addressed in the laboratories' quality systems. They need to explain to their respective accreditation bodies that part of their operating range is traceable to more than one traceability chain. Despite the fact that the principle of obtaining harmonized reference values has not changed over the years, the increased number of participants requires the data processing procedure to be formalized. For that reason modifications in the data processing have been introduced in the past years. Section 4 gives a cumulative update. The objective of this paper is to show the present state.

## 2 Characteristics of gasmeter calibrations

For the comparison of high-pressure gas flow laboratories turbine gasmeters are used. All gas flow laboratories uti-



**Figure 2:** Schematic drawing of the calibration process with a turbine meter reference. Pr is the pressure reference point at which the pressure is measured. T is the temperature measurement point. Pulses are directly collected from the turbine wheel of the gasmeter.

lize a calibration method where a meter under test (MuT) is compared with a reference under stationary flow conditions. Three laboratories use turbine gasmeters as references, one laboratory (Cesame-Exadébit) utilizes critical flow Venturi nozzles (also called sonic nozzles) with a cylindrical throat [15]. The calibration process is a practical application of the mass conservation principle: per unit time the same mass of gas flows through both the reference and the MuT. As conditions are never completely stationary, a small correction is applied for line-pack effects, i. e. the change of the mass in the volume between the reference and the MuT during the calibration lap. For turbine meter references the process is schematically depicted in Fig. 2. Both meters are volume flow meters which produce pulses proportional to a certain volume increment. The pressure is measured at the Pr point on the meter and behind the meter there is a thermowell in which the temperature is measured. The conversion between volume flow and mass flow is obtained by using a real gas law for which pressure, temperature and the gas composition are inputs. The real gas factor is depending on pressure, temperature and the gas composition. This can be a relatively simple algorithm like S-GERG [16], or much more complex algorithms like AGA-8 [17] or GERG2008 [18].

Objective of the calibration is the evaluation of the deviation of the gasmeter, which is defined as the relative deviation  $e_i = Q_i/Q_{ref} - 1$  [%] of the indicated volume flowrate  $Q_i$  and the reference volume flowrate  $Q_{ref}$ . The calibration is performed in the operating range of the gasmeter, which is minimally 1:20 for a turbine gasmeter and which can be as much as 1:100 for an ultrasonic meter. The mathematical description of the calibration process using turbine meter references, based on the integral formulation of the mass conservation law, can be found in [19]. Although not the main subject of the paper, the authors present an extensive uncertainty evaluation utilizing Monte Carlo methods of a calibration of a gasmeter using two reference meters in parallel. In the paper 44 uncertainty contributions are listed: reference flowrate, pressures, temperatures, pulse counting, time interval measurement and gas composition. The input parameters have been categorized by the order of magnitude they contribute to the overall

**Table 1:** Order of magnitude uncertainty contributions of the calibration of a high-pressure volume flow gasmeter compiled from [19].

Input quantities	Order of magnitude uncertainty
Reference flow	$10^{-3}$
Pressure and temperature	$10^{-4}$
Repeatability of the MuT	$10^{-4} - 10^{-5}$
Pulse counting	$10^{-5}$
Time interval measurements	$10^{-6}$
Gas composition	$10^{-7} - 10^{-8}$

uncertainty. The result is displayed in Table 1. Note that the reference flowrate is the most important contribution. The repeatability of the meter is an order of magnitude better than the traceability. Please observe that this situation is different from other metrological fields where the repeatability of the calibrated instrument gives a much higher uncertainty contribution than the uncertainty of the reference.

### 3 Optimum curve fits for turbine gasmeters

Before discussing intercomparisons a few words need to be mentioned about curve fitting as this plays a vital role in the processing of intercomparison data. The curve fitting method is a multi-linear ordinary least squares curve fit, which is generally applied in the field of high-pressure gasmeter calibrations. Turbine gasmeters are the metrologist’s choice to use for reference purposes in intercomparisons. These meters offer good stability and demonstrate excellent repeatability during calibrations. The shape of the calibration curve is generally expressed as:

$$e = a_0 + a_1x^p + a_2x^q + a_3x^r + a_4x^s \quad (1)$$

In this equation  $e$  is the deviation of the meter,  $a_i$  the curve fit coefficients and  $p, q, r, s$  are the powers. The variable  $x$  can be the volume flowrate  $Q$ , the non-dimensional volume flowrate  $Q/Q_{max}$  or the Reynolds number  $Re$  defined as:

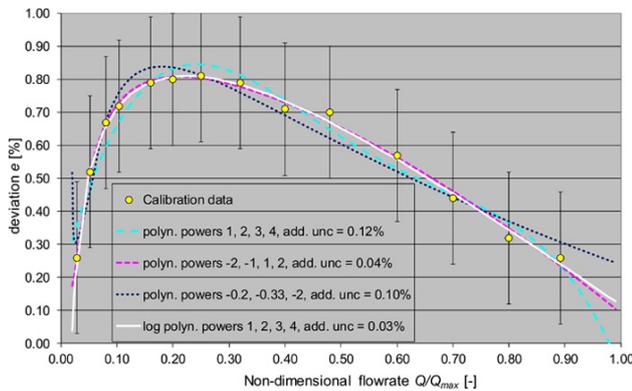
$$Re = \frac{\rho \bar{v} D}{\eta} = \frac{4\rho Q}{\pi D \eta} = \frac{4q_m}{\pi D \eta} \quad (2)$$

in which  $\bar{v}$  is the average gas velocity in a cylindrical pipe with internal diameter  $D$ ,  $\rho$  is actual gas density,  $\eta$  the dynamic viscosity and  $q_m$  is the mass flowrate of the gas.

An overview of parameters used in practice is given in Table 2. The effect of the different parameters is demon-

**Table 2:** Overview of commonly used parameters in Equation (1) for fitting the calibration curves of turbine gasmeters and ultrasonic gasmeters. Not all parameters are required.  $\nu$  is the number of degrees of freedom.

$x$	$p$	$q$	$r$	$s$	Remarks
$Q$	1	2	3	4	Unstable, especially for low $\nu$ [21]
$Q$	-2	-1	1	2	Smooth, used in ultrasonic meters
$Q/Q_{max}$	-0.2	-0.33	-2		Straatsma [20], may be unstable at low $Q$ [21]
$\log Re/10^6$	1	2	3	4	Smooth, Mickan et al. [22]
$\log Q/Q_{max}$	1	2	3	4	$Re$ is proportional to $Q$ , ceteris paribus



**Figure 3:** Calibration curves obtained for a turbine gasmeter using the parameters from Table 2. The meter deviation  $e$  is displayed versus the non-dimensional flowrate  $Q/Q_{max}$ . The vertical bars represent the overall uncertainties ( $k = 2$ ) of the individual calibration results.

strated for a turbine meter that was calibrated at 14 different flowrates. The result is depicted in Figure 3. For each curve fit the associated uncertainty is displayed in the legend. The simple power equation (biggest dashes) gives the highest uncertainty (0.12%) and the bending points that are characteristic for higher grade polynomials are visible. For a lower number of degrees of freedom, i. e. the difference between the number of data points and the number of coefficients that are fitted, this type of polynomials becomes unstable. The combination of both positive and negative integer powers results in a smooth curve fit with a much lower uncertainty (0.04%). The so-called Straatsma polynomial was based on modeling the characteristics of a turbine meter [20]. It may become unstable at low flowrates and has the second highest uncertainty contribution (0.10%). The work performed by PTB in the past two decades on modeling the physical behavior of turbine gasmeters was aggregated in [22]. This paper tells the up-

per range of flowrates is best described by an  $n^{th}$  degree polynomial using  $\log Re/10^6$ , where the degree  $n$  ranges between 1 and 4. When calibrating at constant conditions the polynomial can be expressed in  $\log Q/Q_{max}$ . The use of logarithms makes the curves both smooth and stable. It is not the most frequently used mathematical description. However, it results in the lowest uncertainty contribution (0.03%) from the fit and is therefore the metrologist's choice for curve fitting turbine gasmeters.

Like for any curve fit it is not necessary to use all powers listed in Table 2. Reduction of the number of coefficients will increase the number of degrees of freedom  $\nu$  and may lower the uncertainty of the fit. The extreme case is  $\nu = 0$ , which will result in an infinite uncertainty. In order to achieve the lowest uncertainty, it is possible to optimize between the complexity of the mathematical description and the number of degrees of freedom. In section 4, the grade of the polynomial is optimized by minimizing the surface of the 95% contour of the fit. In the literature on curve fitting this is called the Akaike Information Criterion (AIC), see e. g. [23]. Before the start of the intercomparison the grade of the polynomial is optimized for each combination of meter, pressure and laboratory.

## 4 Key comparison

From a quality perspective intercomparisons are necessary as additional check on the laboratory's accuracy and corresponding CMC claims. In this case the intercomparison is used to compare the high-pressure gas flow traceability chains of the different countries, for which the term key comparison is used. To this end several meter packages are used consisting of a flow conditioner, a five-diameter or ten-diameter upstream pipe spool (10D or 5D inlet), a turbine gasmeter and downstream a 3D or 4D outlet spool. For each calibration two of these packages are put in series. The meter in the upstream package is referred to as M1, the downstream meter as M2. The packages have a nominal interior diameter of 100 mm, 150 mm, 250 mm and 400 mm. With the increased flowrates of the high-pressure facilities there is now a discussion to build packages up to 600 mm. Specific calibration conditions differ from one laboratory to another, i. e. the actual pressure, temperature and gas composition, which determine the density and viscosity of the gas. As the performance of a turbine meter is depending on the actual gas density  $\rho$  and viscosity  $\eta$ , the Reynolds number  $Re$  (2) is used to convert the laboratories' calibration conditions into a domain where they can be compared.

The intercomparison is performed according to the following stepwise procedure, which is repeated for each meter and each pressure.

- (a) Calibration of the meters at the agreed matrix of 3 pressures, 7 flowrates and 5 repetitions. The uncertainty of the calibration results is based on the laboratory's CMCs which have been confirmed by prior intercomparisons. The meter deviations  $e$  are plotted versus the Reynolds number  $Re$ .
- (b) For every pressure the calibration curve is fitted using polynomial equation (1) with  $x = \log Re/10^6$ . The grade is optimized according to the Akaike Information Criterion (AIC) explained at the end of section 3. For the details of the actual curve fitting the reader is referred to [22]. The curve and the residuals are plotted in order to enable a visual inspection of the results.
- (c) After data collection a consistency check is performed, in which the results of the present calibration are compared with the calibration results of the previous intercomparison. In a Youden plot the deviation change between two subsequent intercomparisons for meter 2, is depicted as a function of the same parameter for meter 1. The plot is made for all data points obtained for all meter sizes and all pressures. Instead of showing all individual data points the average shift of the participating laboratories is shown together with 2s ellipses that cover 95.4 % of the data. The straight line in the Youden plot represents the full correlation of the changes in M1 and M2. An elongated ellipse indicates correlated deviated changes. A circle would indicate no correlation.
- (d) For each separate meter and each pressure, the lowest maximum and highest minimum Reynolds numbers from the data set are taken. The five Reynolds numbers between these two values are computed assuming a logarithmic series. The previously obtained fits are used to compute for each laboratory the deviation of the curve at each of the seven Reynolds numbers.
- (e) For each Reynolds number  $Re_j$  the weighted average  $e(Re_j)$  of the interpolated deviations  $e_i(Re_j)$  of laboratory  $i$  ( $i = 1..M$ ) is computed as follows:

$$e(Re_j) = \frac{1}{W} \sum_{i=1}^M w_i e_i(Re_j) \quad (3)$$

with  $w_i = \frac{1}{u_i^2}$  and  $W = \sum_{i=1}^M w_i$ . For each laboratory  $i$  the uncertainty  $u_i$  is the root-sum-square of the uncertainty of the calibration result and the uncertainty due to the long-term stability of the meter (which is typically of the order of 0.05 %).

- (f) The uncertainty  $u(Re_j)$  of  $e(Re_j)$  is computed:

$$\frac{1}{u^2(Re_j)} = \sum_{i=1}^M \frac{1}{u_i^2} \quad (4)$$

which is equivalent to  $u(Re_j) = 1/\sqrt{W}$ . Please observe that  $u(Re_j)$  is always smaller than  $u_i$ .<sup>1</sup>

- (g) The chi-squared test for consistency check is performed at each test point  $Re_j$  using the deviations of the transfer standard  $e_i(Re_j)$ . The chi-squared value  $\chi_{obs}^2$  is the sum of a series of independent, standard normal variables:

$$\chi_{obs}^2 = \sum_{i=1}^M w_i [e_i(Re_j) - e(Re_j)]^2 = \sum_{i=1}^M w_i [e_{ij} - \bar{e}_j]^2 \quad (5)$$

The assigned number of degrees of freedom is  $\nu = M - 1$ , where  $M$  is the number of laboratories. The consistency check is failing when  $P(\chi_\nu^2 > \chi_{obs}^2) < 0.05$ . If the consistency check passes, then  $e(Re_j)$  is accepted as the Harmonized Reference Value  $e_{HRV}(Re_j)$  for the test point. If the consistency check fails then the laboratory with the highest value of  $w_i [e_i(Re_j) - e(Re_j)]^2$  is excluded for the next round of evaluation and the new reference value  $e_{HRV}(Re_j)$  (WME), the new standard uncertainty of the reference value  $u_{HRV}(Re_j)$  and the chi-squared value  $\chi_{obs}^2$  are calculated again without the results of the excluded laboratory. The consistency check is performed again. This procedure will be repeated till the consistency check passes.

- (h) The next step is to compute a curve fit of  $e_{HRV}(Re_j)$ , for which a polynomial equation (1) with  $x = \log Re/10^6$  is chosen.
- (i) Now, the normalized differences  $E_n$  (degree of equivalence) of the calibration curves and the weighted average curve are determined:  $E_n = \frac{1}{2} |d_{ij}| / u(d_{ij})$ , where  $d_{ij} = e_{ij} - e_{HRV,j}$  and  $u^2(d_{ij}) = u_{ij}^2 - u_{HRV,j}^2$ . In order to keep notation compact,  $e_i(Re_j) = e_{ij}$  and  $u_i(Re_j) = u_{ij}$ . If  $E_n \leq 1$  the results are consistent. After the chi-square test it is not expected to have  $E_n$  values over 1. However, as  $E_n$  is a criterion of a test with 95 % confidence, it is allowable that 5 % of the  $E_n$  values are greater than 1.
- (j) The last step is that the uncertainties of the laboratories are evaluated when they use harmonized reference values. Here the reproducibility of the turbine gasmeter plays an important role. The uncertainty

<sup>1</sup> Sometimes the question arises whether a zero uncertainty would be achievable. If  $M$  laboratories with identical uncertainties  $u$  participate, the resulting uncertainty equals  $u/\sqrt{M}$ . With 16 participating laboratories the resulting uncertainty is one fourth of the original uncertainty, which is still far from zero.

$U_{tot,HRV,i}$  of the harmonized calibration result of Lab  $i$  is:

$$U_{tot,HRV,i}^2 = 2(1 - r_i)U_{tot,i}^2 + (2r_i - 1)U_{HRV}^2 \quad (6)$$

in which  $r_i$  is the correlation coefficient for Lab  $i$  between the common mode uncertainties and the total uncertainty, i. e.  $r_i = (U_{CMC,i}^2)/(U_{tot,i}^2)$ , see Annex A of the final Key Comparison report [10]. For  $r_i > 1/2$  the laboratory benefits from the harmonization exercise, which means that repeatability and reproducibility are much smaller than the CMC.

## 5 Harmonized reference values

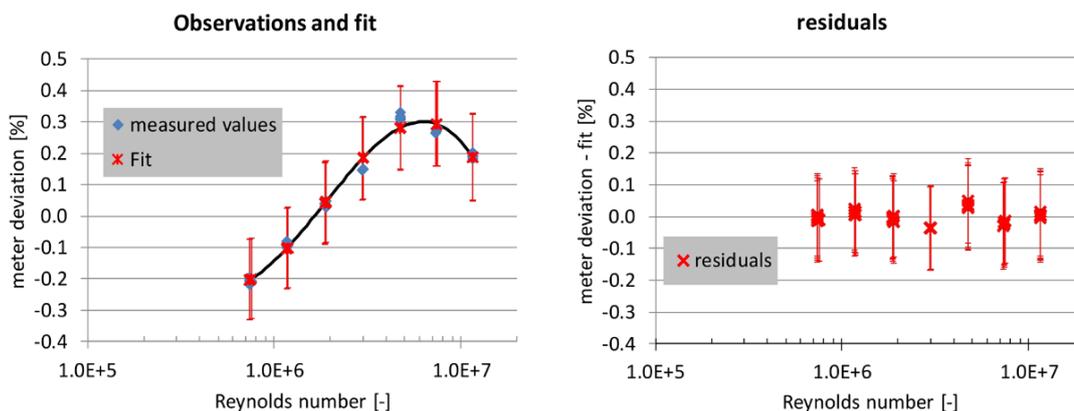
When the previous procedure is followed between national metrology laboratories the result is that the traceability chains are averaged and the uncertainty of the average is lower than each of the laboratories would achieve by its own efforts. In the world of high-pressure gas measurements this average of the traceability chains has been announced as harmonized reference values or – unofficially – harmonized  $m^3$  (cubic metre). An example of such a procedure is shown in Figures 4, 5 and 6. Figure 4 corresponds to the process steps (a) and (b). The left-hand-side shows the 5.0 MPa calibration results for a G1600 turbine gasmeter with a nominal diameter of 250 mm (DN250) together with the fit. The meter is the first from a package of two meters. The right-hand-side of Figure 4 shows the residuals.

Figure 5 shows the difference between the change of the deviation between 2017 and 2014 for meter 2,  $e_{\Delta}M2$  as a function of the same parameter for meter 1,  $e_{\Delta}M1$ .

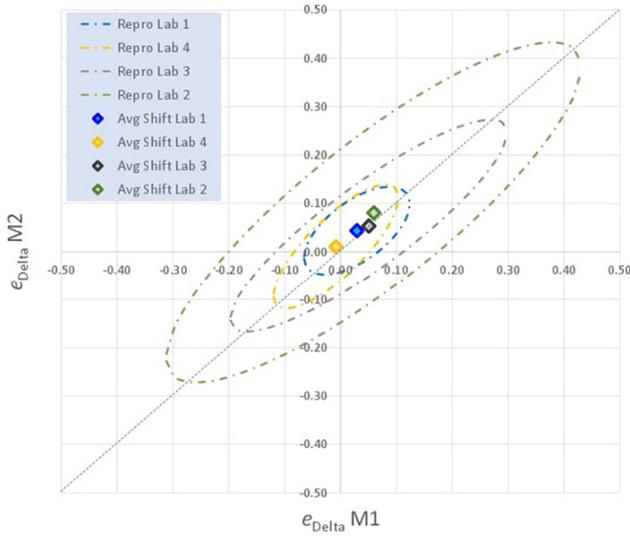
The plot is made for all data points obtained for all meter sizes and all pressures. Instead of showing all individual data point the average shift of the participating laboratories is shown together with 2s ellipses that cover 95.4 % of the data. The straight line in Figure 5 represents the full correlation of the changes in M1 and M2. An elongated ellipse indicates correlated deviated changes. A circle would indicate no correlation. In this example the average changes of the meter deviation are practically fully correlated. Their size is limited to 0.1 %. However, the scatter of the laboratories differs substantially.

Figure 6 shows the result of the procedure steps (d)–(h). Here the results of all laboratories obtained at all pressures are collected for one meter, in this case the first G1600 DN250 turbine gasmeter M1. The data points shown in the graph are interpolated values using the fits like the one shown in Figure 4. The 0.8 MPa pressure was not available at Lab 1. Please observe that the results obtained at 2.0 MPa and 5.0 MPa are practically coinciding. The harmonized reference values (HRV) are the red dashed lines. The uncertainty of the HRV is depending on the Reynolds number:  $u_{HRV}(Re_j) = u(Re_j)$ .

Step (f) of the procedure listed in section 4 promises a lower uncertainty for the participating laboratories. However, there are restrictions as already elucidated in procedure step (j). After applying the intercomparison procedure, the question is how much the uncertainties of the participating laboratories have been improved. To this end Table 3 gives an overview of the calibration results before and after the harmonization process. The Table shows for meter M1 (G1600, DN250) calibrated by Lab 1 at 5.0 MPa, the results at different Reynolds numbers. The leftmost column shows the Reynolds number. Then columns 2–4 show the original interpolated results shown in Figure 4

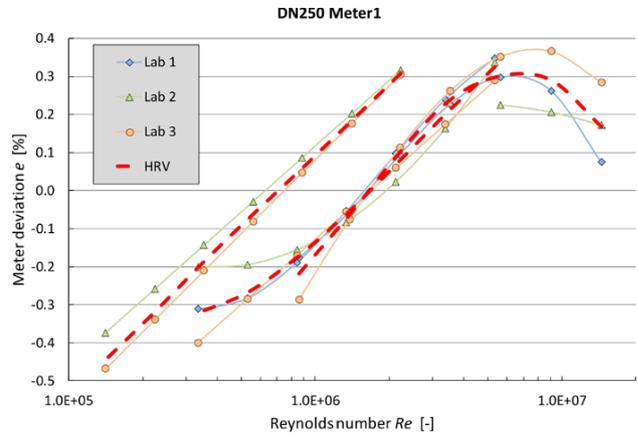


**Figure 4:** Interpolation curves obtained for a G1600 turbine gasmeter by Lab 1, 2 and 3. The meter deviation  $e$  is plotted as a function of the Reynolds number  $Re$  for three gas pressures: 0.8, 2.0 and 5.0 MPa, which correspond to the left, middle and right curves in the Reynolds range. The HRV curves are plotted separately for each pressure.



**Figure 5:** Youden plot showing the deviation change of M2 versus the deviation change of M1. For all participating laboratories the average shifts are shown together with the elliptical 2s scatter interval.

and Figure 6. The fifth column shows the correlation coefficient  $r$  from step (j). Columns 6–8 show the results after harmonization. The HRV is the harmonized reference value, which equals the deviation of the meter for all laboratories after the harmonization process.  $U_{HRV}$  is the corresponding uncertainty, which is basically a kind of CMC.  $U_{tot,HRV,1}$  is the total uncertainty of the meter under test obtained using Equation (6). This also means that the relationship between  $U_{tot,HRV,1}$  and  $U_{HRV}$  is not as simple as the root-sum-square relationship between  $U_{tot,1}$  and CMC. In practice  $U_{HRV}$  can be treated as a CMC with a margin of error in  $U_{tot,HRV,1}$  of approximately 0.01%. Looking at Table 3 it is clear that  $U_{tot,HRV,1}$  is not only smaller than  $U_{tot,1}$  but also smaller than  $CMC_1$ . The correlation coefficients are all 0.85, which is clearly above 1/2. Also, the other laboratories benefit from this harmonization procedure in a similar way.



**Figure 6:** Interpolation curves obtained for a G1600 turbine gasmeter by Lab 1, 2 and 3. The meter deviation  $e$  is plotted as a function of the  $Re$  number for three gas pressures: 0.8, 2.0 and 5.0 MPa, which correspond to the left, middle and right curves in the  $Re$  range. The HRV curves are plotted separately for each pressure.

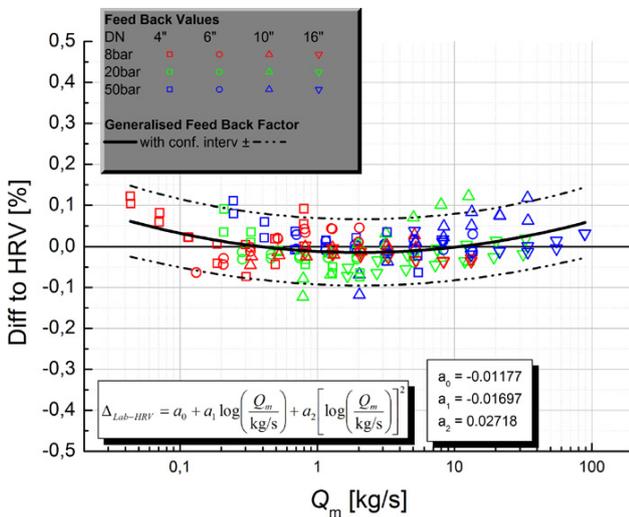
From procedure step (i) in section 4 the differences between the harmonized reference value and the interpolated laboratory result ( $-d_{ij}$ ) are available. This gives the correction to be added to the laboratory result when performing calibrations. So far, all analysis was performed for each combination of laboratory, pressure and individual meter. However, it is more practical to have one formula which provides the correction in the laboratory’s entire operating range covered by the harmonization process. This correction is called generalized feedback ( $GFB_i$ ), will be given to each Lab  $i$  as a function of the mass flowrate  $Q_m$ :

$$GFB_i = a_0 + a_1 \log Q_m + a_2 (\log Q_m)^2 + a_3 (\log Q_m)^3 \quad (7)$$

The  $GFB_i$  covers all pressures and all flowrates with which Lab  $i$  participated in the key comparison. A practical example of this feedback is shown in Figure 7. The individual corrections are marked with symbols, the solid line is the fitted curve according to Equation (7), the dashed lines represent the 95% contours.

**Table 3:** Overview of the calibration results of meter M1 (G1600, DN250) calibrated by Lab 1 at 5.0 MPa, before and after the harmonization process.

$Re$ [-]	Original, interpolated				harmonized		
	$e_1$ [%]	$CMC_1$ [%]	$U_{tot,1}$ [%]	$r_1$ [-]	HRV [%]	$U_{HRV}$ [%]	$U_{tot,HRV,1}$ [%]
1.5E+7	0.07	0.14	0.15	0.85	0.17	0.10	0.12
9.1E+6	0.26	0.13	0.15	0.85	0.29	0.10	0.12
5.7E+6	0.30	0.13	0.14	0.85	0.30	0.10	0.11
3.5E+6	0.23	0.13	0.14	0.86	0.24	0.10	0.11
2.2E+6	0.09	0.13	0.14	0.85	0.10	0.11	0.12
1.4E+6	-0.06	0.13	0.14	0.85	-0.06	0.11	0.12
8.6E+5	-0.18	0.13	0.14	0.86	-0.22	0.11	0.12



**Figure 7:** Generalized feedback for one of the participating laboratories. The correction (GFB) is shown as function of the mass flowrate  $Q_m$ . The solid line is the fitted curve according to Equation (7), the dashed lines represent the 95 % contours.

One point of discussion remains and that is the implementation of the HRV curves in the quality systems of the respective laboratories, which needs to be explained to the respective accreditation bodies. A further complication is that the HRVs may not cover the entire range of flowrates and pressures, which may introduce discontinuities in the curves of the meters under test when only part of the range is covered by the HRV. However, the most important point is that using the information available by different traceability chains results in smaller differences between the laboratories and a lower uncertainty.

## 6 Conclusions

A key comparison based procedure enables to combine the reference values of independent parallel traceability chains into a harmonized reference value, which is the laboratories' average weighted with the respective reciprocal squared uncertainties of the laboratories. The corresponding uncertainty is lower than each of the participating laboratories would be able to achieve by themselves. However, this procedure is only possible as long as the uncertainty resulting from repeatability and reproducibility of a gasmeter is much smaller than the uncertainty from the traceability chain. This condition is fulfilled in practice as traceability uncertainties are at least a factor ten greater than the other uncertainty sources, a situation that can be different in other fields of metrology. The harmonized ref-

erence values allow calibration laboratories to reduce their CMCs in the range covered by the harmonization, and subsequently reduce the uncertainties of the gasmeters that are calibrated in the range. For turbine gasmeters, a polynomial equation (1) expressed in  $\log Re/10^6$  has proven to be the optimum choice for fitting the calibration curve of a turbine gasmeter. It is therefore well suited to be used in intercomparisons of high-pressure gas flow facilities. The degree of the polynomial is maximally 4. In the current practice the degree is chosen such that the residual standard deviation or the surface of the 95 % confidence contours of the least squares fit (AIC) is minimized.

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