The harmonized European gas cubic meter for natural gas as realized by PTB, NMi-VSL and LNE-LADG and its benefit for user and metrology

L'harmonisation d'un « mètre cube européen » de gaz naturel entre la PTB, le NMi-VSL et le LADG et les bénéfices retirés par les utilisateurs et les métrologues

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Abstract

The paper describes the backgrounds of the harmonized reference values for the cubic meter of natural gas, which are in use in Germany and The Netherlands since November 1st 1999. The harmonization process has been finalized on May 4, 2004 due to the incorporation of the French LNE-LADG to the harmonized reference value. The outcome was named: "Harmonized European Natural Gas Cubic Meter" as realized by three independent national metrology institutes.

The prerequisites of the harmonization process, underlying procedures, results obtained so far and the mutual benefits will be pointed out as well as the economic consequences for the European market.

KEYWORDS: HARMONIZED REFERENCE VALUE, NATURAL GAS, COMPARISON, EUROPEAN HARMONIZED NATURAL GAS CUBIC METER.

Résumé

L'article décrit le contexte des valeurs de référence harmonisées pour le mètre cube de gaz naturel qui sont utilisées en Allemagne et aux Pays-Bas depuis le 1er novembre 1999. Le processus d'harmonisation a été mené à bonne fin le 4 mai 2004 suite à l'intégration du LNE-LADG (France) dans la valeur de référence harmonisée. Le résultat a été appelé : « Mètre cube harmonisé de gaz naturel » réalisé par trois laboratoires nationaux de métrologie indépendants.

Les conditions préalables au processus d'harmonisation, les procédures sous-jacentes, les résultats obtenus et les intérêts mutuels tels que les conséquences économiques pour le marché européen seront présentés.

MOTS CLÉS : VALEUR DE RÉFÉRENCE HARMONISÉE, GAZ NATUREL, COMPARAISON, MÈTRE CUBE EUROPÉEN HARMONISÉ DE GAZ NATUREL.

1. Introduction

Since the seventies an increasing use of natural gas as energy source and in Europe a vast network (gas-grid) has been realized. In this expanding gas grid more and more points of transfer of ownership are installed, leading ultimately to an increasing demand for reliable and stable reference values for high-pressure gas-flow measurements. The principle of third party access, supported in the future by direct invoicing of energy-shipment, makes it of vital importance that gas-transport organizations have at all times a clear knowledge about the contents of their transport-grid.

Hence, long-term stability of reference values is gaining importance. Although small (insignificant) changes in (national) reference values are accepted by metrologists, the impact of variations on *e.g.* invoicing will probably never be understood nor accepted. The drive for one equivalent reference value in this working field of natural gas resulted in an extensive cooperation between three national metrology institutes (NMIs) holding test facilities for high-pressure natural gas in Europe.

2. Prerequisites for harmonization procedure

In previous papers and mainly during the last FLOMEKO 2003 in Groningen the authors have already described the harmonization procedure between PTB-Pigsar and NMi-VSL in detail, see *e.g.* [1] and [2]. The participating facilities at NMi-VSL are presented in [3], the German national standard Pigsar has been described in [4] in detail and uncertainty budgets are open for the public in all details, see *e.g.* [5], [6] and [7].

As the metrological activities of PTB, NMi-VSL and LNE-LADG affect the national and international trade of natural gas, the approach of the harmonization process shall be summarized here and we present the latest results to define the "European harmonized reference level" or the "Harmonized European natural gas cubic meter" respectively.

The underlying procedure follows strictly BIPM recommendation for so-called key comparison reference values. These recommended procedures for key comparisons among national metrology institutes (NMIs) have been prepared by the BIPM director's advisory group on uncertainties with members from all major NMIs. This expert group has summarized its recommendations in [8] in a very comprehensive way.

The same procedures have been applied in the European harmonization process since 1999 very successfully and the main prerequisites for such a weighted average of reference levels, which we call harmonization shall be summarized here, because these are the key points for understanding the whole procedure.

It must be pointed out here, that the harmonization process of PTB, NMi-VSL and LNE-LADG follows strictly this recommendation as described in chapter 2 (Conditions of use) and chapter 5 (Procedure A) of [8].

The European harmonized reference level or gas cubic level comprises of a weighted average of three different individual national realizations of the gas cubic meter (reference levels). This weighted average is based upon the following metrological prerequisites:

- a. PTB, NMi-VSL and LNE-LADG operate independently realized traceability-chains. At NMi-VSL a system based on mass-comparison of gas-flow is in use (basis verification system), whereas the German national facility for high-pressure gas-flow standards, PTB-Pigsar has its traceability-chain in operation based mainly on a piston-prover (volume comparison plus density determination) and LNE-LADG applies the PVTt-method (mass comparison);
- b. The uncertainty-budget of each of the systems is fully known, understood and mutually accepted;
- c. A permissible difference between the two systems smaller than the root square sum of the corresponding uncertainties (2σ) is established;
- d. The stability of each chain (sets of reference values) is demonstrated. Stability refers to the reproducibility of the reference values over the years;
- e. The degree of equivalence is established (based on historic performance and on accepted uncertainties).

The procedure has been applied in all overlapping flow rate and pressure ranges of Pigsar-PTB, NMi-VSL and LNE-LADG. This next ancillary condition can be considered as prerequisite:

- f. LNE-LADG, PTB and NMi-VSL have applied three to four sets of different turbine meters (two in series) to allow a maximum of overlap. In addition, we have applied a choked nozzle too.

Figure 1 presents the calibration and measuring capabilities of the participating NMIs in the harmonization procedure. The degree of overlap in flow rate and pressure range is quite large.

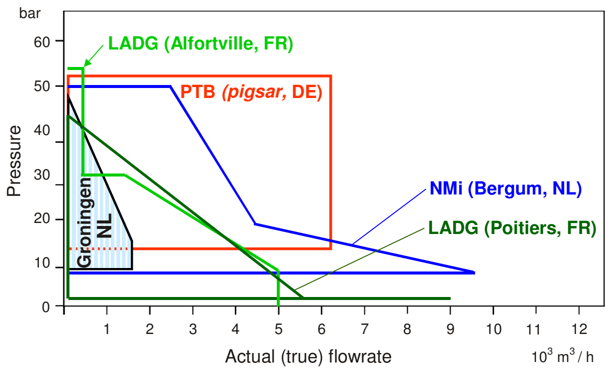


Fig. 1. - Calibration and measuring capabilities of PTB-Pigsar, NMi-VSL and LADG. Harmonization has been mainly applied in the overlapping ranges.

All partners have agreed to search continuously for improvements of the independently realized traceability chains to meet future demands for more stable reference values with smaller uncertainties. The main benefit for customers is the same and equivalent calibration of meters at any calibration test rig in Germany, The Netherlands and France. The harmonization as accomplished by PTB, NMi-VSL and LNE-LADG is principally open to third parties if all five prerequisites can be met and if it is practically feasible. So far however, there is no other national facility available in the world that meet all prerequisites.

3. Situation previous to harmonization

Figure 2 gives typical results of a meter calibration done at PTB (Pigsar) and NMi-VSL (Bergum) at pressure stages 20 bar and 50 bar before harmonization. The meter readings of Pigsar and NMi-VSL are a little bit different, however, the uncertainties due overlap in the entire Reynolds range, far better than the specified uncertainties. This demonstrates the high reproducibility of commercial available meters. Due to this high reproducibility that is much better than the uncertainty, a difference $\Delta_{\text{PTB-NMi}}$ between the calibration in Netherlands and Germany can be observed. It has to be emphasised that such difference is not significant (because it is less than the uncertainty range) but there is a chance to divide the market into a seller and buyer market.

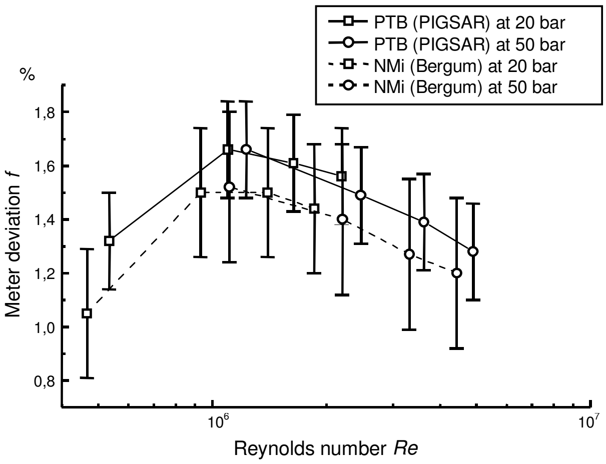


Fig. 2. - Typical results of meter calibration done at Pigsar and NMi-VSL (Bergum) before harmonisation (before 1999). All results of meter deviation f are inside the overlapping range of the uncertainty levels. Only due to high reproducibility of both calibration facilities as well as gas meters (which is much better than the uncertainties) a difference $\Delta_{\text{PTB-NMi}} = f_{\text{PTB}} - f_{\text{NMi}}$ can be observed. The uncertainty levels (2σ) shown in the graph are the particular uncertainties of Pigsar and NMi-VSL.

4. Harmonization process for reference values

To understand the technique of the weighted average, which has been applied in the harmonization process, let us discuss the method for two partners at first and then it shall be expanded towards all 3 partners using latest results from 2004.

This method has already been explained in previous papers, *e.g.* [4], [5] and shall therefore just be summarized.

Based on the facts equivalence and independence of calibration chains, the "true value" f_{Ref} of meter deviation shall be assumed as the weighted average of any pair of results. In figure 3 an example of one pair of meter calibration is given. The meters used in the transfer packages are Reynolds balanced; therefore the determination of difference $\Delta_{\text{PTB-Ref}}$ ($\Delta_{\text{NMi-Ref}}$ resp.) to the common reference level is done with respect to Reynolds number. In practise each pair of measuring points is close together but is not exactly at the same Reynolds number. Thus polynomial approximation of calibration curve f is used as to be seen in figure 3. The weighted average f_{Ref} is calculated now using the polynomials. The differences $\Delta_{\text{PTB-Ref}}$ and $\Delta_{\text{NMi-Ref}}$ are determined for each measured point relative to average polynomial,

$$f_{\text{Ref}} = w_{\text{NMi}} \times f_{\text{NMi}} + w_{\text{PTB}} \times f_{\text{PTB}} ,$$

where

$$w_{\text{NMi}} = \frac{1}{\dfrac{U_{\text{NMi}}^2}{U_{\text{PTB}}^2} + 1} ,$$

$$w_{\text{PTB}} = \frac{1}{\dfrac{U_{\text{PTB}}^2}{U_{\text{NMi}}^2} + 1} ,$$

$$\Delta_{\text{PTB-Ref}} = f_{\text{PTB}} - f_{\text{Ref}} ,$$

$$\Delta_{\text{NMi-Ref}} = f_{\text{NMi}} - f_{\text{Ref}} .$$

The following notations are used:

f : meter deviation;

w : weighing factor;

Δ : difference;

U: uncertainty ($k = 2$).

Here f_{Ref} is the meter deviation of the meter under test based on the harmonised high-pressure cubic meter of NMi-VSL and PTB.

This weighted average has been defined in exactly the same way as recommended by Cox, see [8], chapter 5.

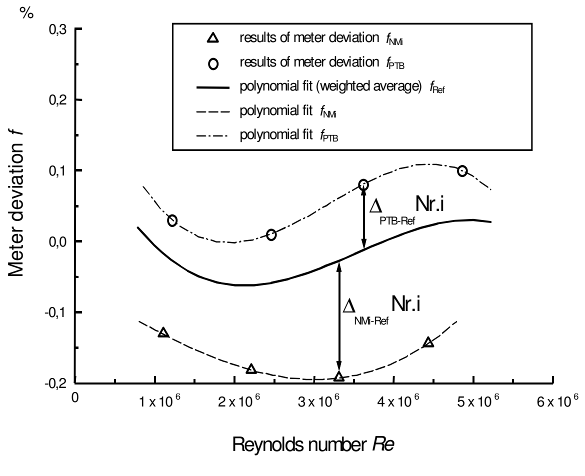


Fig. 3. - Results of comparison for one meter at one pressure stage and determination of differences $\Delta_{\text{PTB-Ref}}$ and $\Delta_{\text{NMi-Ref}}$.

The outcome is, that the participant who offers the smallest uncertainty will pull the reference value towards him heavily.

Finally, all determined differences $\Delta_{PTB\text{-}Ref}$ and $\Delta_{NMi\text{-}Ref}$ for all meters at all pressure stages were put into one graph depending on Reynolds number (fig. 4) presenting the original data from 1999. The reproducibility (2σ) of calibrations is less than the half of the uncertainty budget of each participant. Nearly every result of one participant lies in the uncertainty interval of the other. Although three different meter sizes and two different pressure stages for each size were used, there is no significant discontinuity to be seen. This is an evident demonstration of high quality and reliability of calibration work of partners, NMi-VSL and Pigsar.

The determined difference $\Delta_{PTB\text{-}NMi}$ between NMi-VSL and Pigsar increases slightly with Reynolds number. The slope of the results of NMi-VSL is only a mathematical effect of the weighing process because the uncertainty U_{NMi} of NMi´s chain increases with pressure stage. The trends for $\Delta_{PTB\text{-}Ref}$ and $\Delta_{NMi\text{-}Ref}$ in figure 4 can finally be approximated by a linear function depending on the logarithm of Reynolds number. These linear functions are used as correction functions in order to disseminate a harmonised value of cubic meter high-pressure natural gas in both countries.

In figure 4 the harmonized reference level has been put on the zero line to demonstrate the effects of weighted means. The uncertainty levels (2σ) shown in the graph are the particular uncertainties of Pigsar and NMi-VSL.

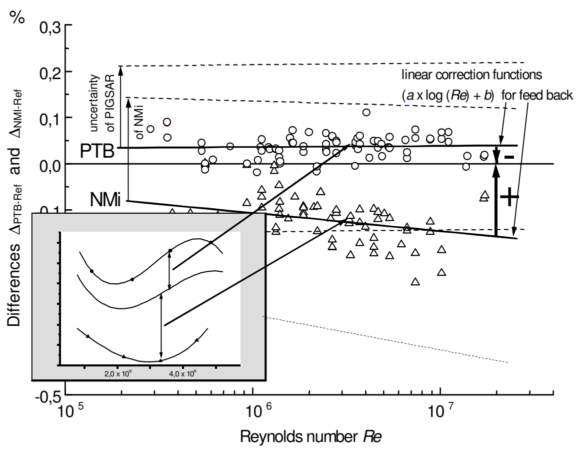


Fig. 4. - Summary of all determined differences $\Delta_{PTB\text{-}Ref}$ and $\Delta_{NMi\text{-}Ref}$ for all meters in all pressure stages plotted as function of the *Re*-number.
The difference between both traceability chains is clearly to be seen but much smaller than the uncertainties. Within the reproducibility of the results there is no significant discontinuity although three different meter sizes and two different pressure stages for each size were used. To implement the feed back of comparison results linear approximations of differences $\Delta_{PTB\text{-}Ref}$ and $\Delta_{NMi\text{-}Ref}$ were determined.

The following conclusion from figure 4 can be drawn.

The partner with the smaller uncertainty pulls the reference value towards him. In figure 4 PTB is a little bit closer towards the harmonized reference value.

The cubic meter obtained at Pigsar is (was in 1999) a little bit too large and the cubic meter obtained at Bergum is a little bit too small and therefore both sides have to correct their results with a correction factor (which is actually a function of *Re* number, pressure and flow rate).

Due to the comparison measurements we have two independent sources of information of the "true value" given by both calibration chains, hence we obtain a lower uncertainty level U_{Ref} of meter deviation f_{Ref} based on harmonisation:

$$U_{\text{Ref}} = \sqrt{w_{\text{NMi}}^2 \times U_{\text{NMi}}^2 + w_{\text{NMi}}^2 \times U_{\text{PTB}}^2} \quad ,$$

with

$$w_{\text{NMi}} = \frac{1}{\dfrac{U_{\text{NMi}}^2}{U_{\text{PTB}}^2} + 1} \quad ,$$

and

$$w_{\text{PTB}} = \frac{1}{\dfrac{U_{\text{PTB}}^2}{U_{\text{NMi}}^2} + 1} \quad .$$

The following notations are used:

U : uncertainty ($k = 2$);

w : weighing factor.

Here U_{Ref} is the uncertainty of the deviation of meter under test based on the harmonised high-pressure cubic meter of NMi-VSL and PTB.

E.g. if both parties would have equal uncertainties of $U_{NMi} = U_{PTB} = 0{,}1$ % the resulting uncertainty would be:

$$U_{\text{Ref}} = \frac{1}{\sqrt{2}} \times 0{,}1\ \% = 0{,}07\ \% \quad .$$

In the harmonisation process an over-all uncertainty level $U_{Ref} = 0{,}15$ % was determined. However, it shall be mentioned, that the uncertainty will never reach zero of course. The reproducibility and long-term stability of transfer meters and facilities are limiting the lower bound of uncertainty.

The positive outcome for the customer is, that he gets always the same calibration in Germany and the Netherlands at any test facility and he can enjoy the benefit of a very stable and small uncertainty of the harmonized reference value.

The benefit for metrology is the reduced uncertainty of the harmonized reference value.

Since November 1st, NMi-VSL and PTB have disseminated the same ("harmonised") high-pressure natural gas cubic meter for all calibrations, which have been performed at their test facilities.

5. Stability of the transfer packages and the facilities

In this chapter we discuss the experiences with the transfer meters within the harmonization procedure. To perform the harmonization procedure carefully, the transfer standards must have sufficient small reproducibilities.

To illustrate the stability and reproducibility of the applied transfer tandem meters, some typical results of reproducibility analysis of transfer meters shall be given here. Figure 5 shows a typical correlation plot for the residue (meter deviations d*f*) of both turbine meters on a transfer package using results from 1999 to 2003.

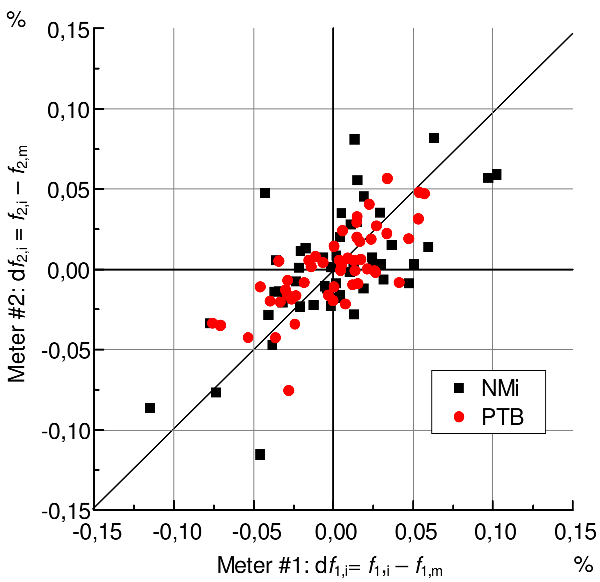
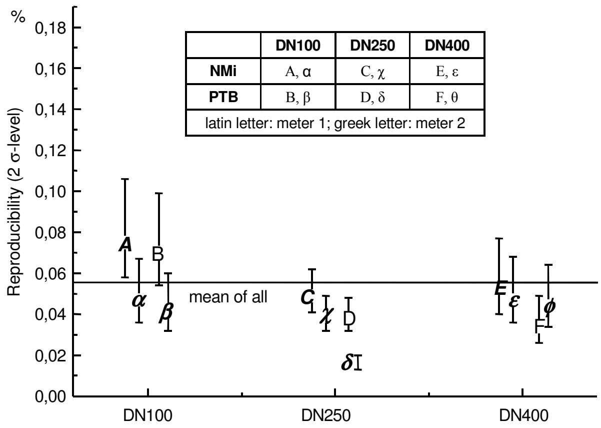


Fig. 5. - Correlation plot of d*f* for the transfer package DN250 used for harmonization between NMi (Netherlands) and PTB (Germany) during 1999 - 2003.

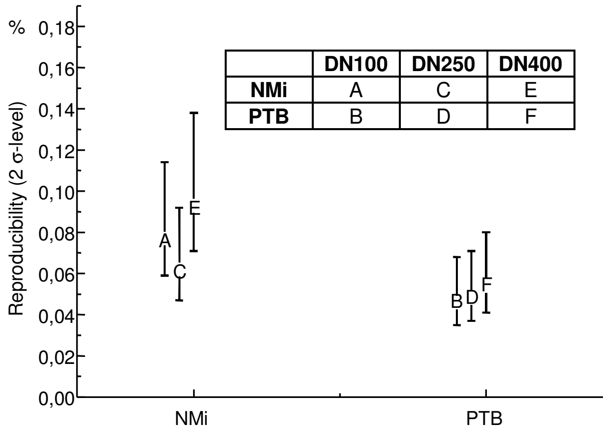
For every transfer package used in the harmonization and for every facility (NMi and PTB) we can establish a plot according to figure 5 and we can calculate the related standard deviations using the techniques described in [9] by Pöschel. The results for the standard deviations of the transfer meters (*i.e.* here the reproducibility) are given in figure 6 at the 2σ-level. Please note that here we lost the information of repeatability, because we only saved the mean of repetitions at one flow rate. The correlation plot contains therefore only the information about hysteresis and the overall reproducibility.



	DN100	DN250	DN400
NMi	A, α	C, χ	E, ε
PTB	B, β	D, δ	F, θ

Fig. 6. - Results of reproducibility calculation for all transfer meters used in harmonization between NMi-VSL (Netherlands) and PTB (Germany). The calculation is based on all measurement within 1999 to 2003.

It can be concluded in figure 6 that the typical value of reproducibility of a turbine meter is less than 0,06 %. Also it is very important that the results do not significantly differ for the facilities. This is an indicator for the reliability of such a determination process. It has to be emphasized that the turbine meters are commercial available turbine meters, which are also typically used in metering stations.



	DN100	DN250	DN400
NMi	A	C	E
PTB	B	D	F

Fig. 7. - Results of reproducibility calculation for the facilities of NMi (Netherlands) and PTB (Germany) within the harmonization. The calculation is based on all measurement from 1999 to 2003.

The results of reproducibility for the different test facilities are given in figure 7. These data can be estimated from the data in figure 5 using the technique described by Pöschel [9].

The reproducibility of the facilities is extremely good; much smaller than the claimed uncertainties.

6. European gas cubic meter

6.1. Harmonization procedure between PTB, NMi-VSL and LNE-LADG

As the users have applauded the initiators for their work, they completed the harmonization procedure by inviting the French LNE-LADG and their "piscine" facility to participate. Again, all 5 or 6 prerequisites have been checked carefully in very long discussions and evaluation procedures. Since May 4th 2004 the French facilities represented by LNE-LADG are partner and full member of the European harmonization club.

Some of the harmonization results among all three NMIs shall be discussed here to in detail.

Figure 8 presents measured calibration results for a single turbine meter calibrated by the three different national high-press standards in Europe, named here Inst 1, Inst 2 and Inst 3. The claimed uncertainties of all measuring points are indicated. The transfer standard was a Dual turbine meter set.

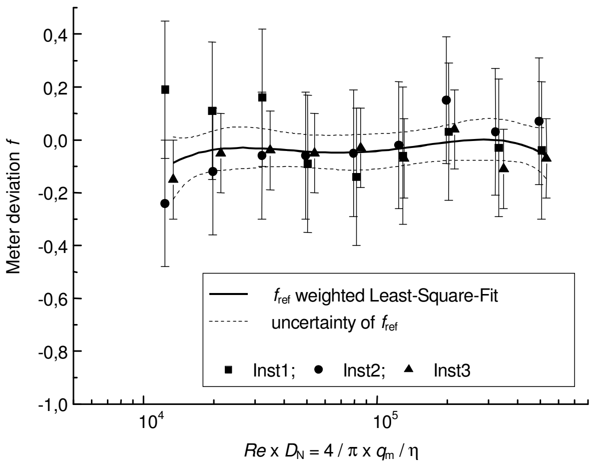


Fig. 8. - Practical measured meter deviations of one transfer meter within a package for one pressure. f_{Ref} is the weighted least-square-fit of all results (measured at 20 bar, package with two turbine meters, meter 1). This is the value that we use as the Harmonized European reference level.

The line in figure 8 denoted as f_{Ref} is the weighted least square fit of all measured data points at PTB-Pigsar, NMi-VSL and LNE-LADG for a particular meter. f_{Ref} is the harmonized European reference value as realized by this comparison presented in figure 8.

The f_{Ref} function has been calculated using the weighted average of all three participants PTB-Pigsar, NMi-VSL and LNE-LADG. The dashed line is the uncertainty function of the Harmonized reference value (Harmonized European gas cubic meter) f_{Ref} and is of course much smaller than the individual uncertainties of the participating institutes PTB, NMi-VSL and LNE-LADG.

One recognizes a quite good overlap of all institutes with the reference value f_{Ref}.

In order to quantify the degree of equivalence between the f_{Ref} function and the participants as well as the degree of equivalence among the participants, we have used here in addition the *En*-criterion as it is commonly in use in the accreditation area, see *e.g.* [10] and [11] and [6].

From the measured comparison results in figure 8 one can calculate the following quantities:

$$d_i = f_i - f_{fref}; \quad d_{i,j} = f_i - f_j$$

$$En_i = \frac{|d_i|}{U(d_i)}; \quad U(d_i) = \sqrt{U^2_{MuT} - U^2_{fref}}$$

with:

$$U^2_{MuT} = U^2_{CMC,i} + U^2_{TM} \; ;$$

d_i means the bias between f_{Ref} and measured value and $U(d_i)$ is the corresponding uncertainty of this bias between f_{Ref} and the measured value, which will be calculated according to Cox, see [6], chapter 5, section 4 (c) equations (3) and (5);

$U(d_i)$ is the uncertainty associated with the difference d_i;

U_{fref} is the uncertainty associated with the f_{Ref} function, the dashed line in figure 8;

U_{MuT} is the uncertainty of the meter under test;

U_{TM} is the uncertainty of the transfer meter.

Here we suggest using:

$$En_i = \frac{|d_i|}{U(d_i)} \; ,$$

to characterize the degree of equivalence of the national facilities.

In this way it will be possible to describe the degree of equivalence of a lab to the f_{Ref} function using a dimensionless number. *En* should be between 0 and 1 and may go up to 1,2. *En* should be as close as possible to "0" (*En* = 0 means no deviation between the f_{Ref} function and the lab; *En* = 1 means, that the error bars do just overlap).

Figure 9 presents the degree of equivalence *En* as determined from all measurement results between the European national standards as presented in figure 8.

From figure 9 one can conclude that in the overlapping range of PTB, NMi-VSL and LNE-LADG all institutes are equivalent (*En* < 1) with respect to the measured data in figure 8 (single meter, single pressure stage). In figure 10 we present the degree of equivalence making use of all measurements at all pressures between the European national facilities to give an impression on the very acceptable agreement between

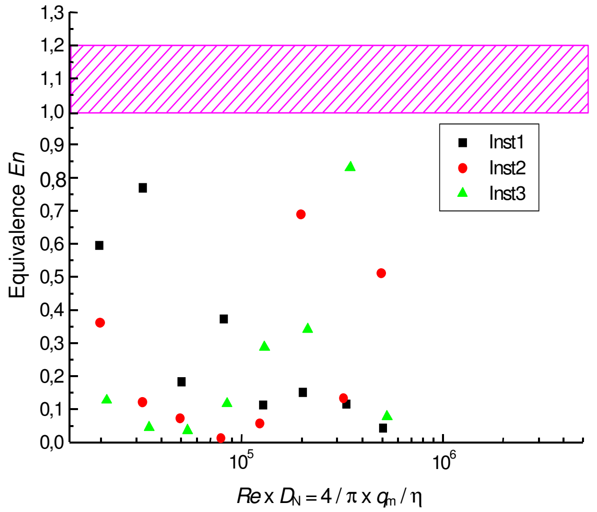


Fig. 9. - Degrees of equivalence *En* determined for all measured results in figure 8.

these gas facilities. The outcome is, that the institutes are equivalent to each other all *Re* numbers.

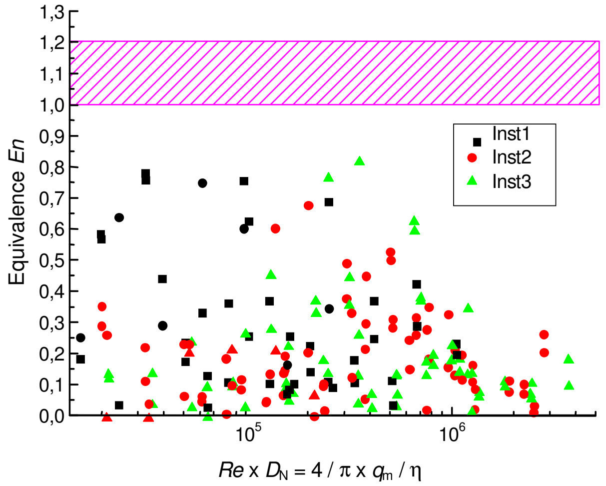


Fig. 10. - Degrees of equivalence *En* determined for all results determined at all high press national facilities in Europe, namely PTB-Pigsar, NMI-VSL and LADG [Measured at 20 bar; 40 bar and 50 bar; packages (DN150, DN250, DN400) with two turbines each; additionally single sonic nozzle (TF200)].

6.2. The degree of equivalence between all European national gas facilities

As we get a lot of single values of *En* for each measured result, it is helpful to define an overall value as a characteristic criterion for each laboratory taking part in the harmonization procedure in order to have a single number per institute.

Starting from the fact that the degree of equivalence is a random variable with a log-normal probability density, it is the simplest approach to use the geometric mean as the characteristic value En_{total}:

$$En_{\text{total}} = \left(\prod_{i=1}^{n} En_i \right)^{\frac{1}{n}} = \exp \left\{ \frac{1}{n} \sum_{i=1}^{n} \ln \left(En_i \right) \right\}$$

Institute n° 1: $En_{\text{total}} = 0{,}24$;

Institute n° 2: $En_{\text{total}} = 0{,}14$;

Institute n° 3: $En_{\text{total}} = 0{,}13$.

We get finally the following visual presentation for the degree of equivalence between PTB-Pigsar, NMi-VSL and LNE-LADG using the single *En*-numbers for each institute.

In spite of the fact that the degree of equivalence is excellent, we have not identified the institutes in figure 11, because these data are preliminary. We will use these numbers to characterize the degree of equivalence of the institutes.

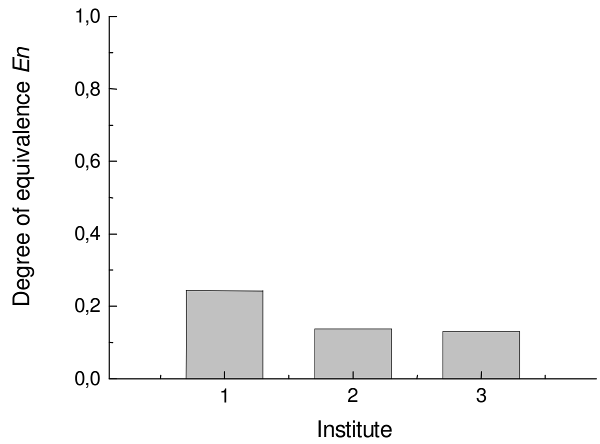


Fig. 11. - Characteristic degree of equivalence *En* for all institutes based on the geometric mean using all results in figure 10.

7. Final conclusion

This detailed analysis of the harmonization procedure between PTB-Pigsar, NMi-VSL and LNE-LADG shall demonstrate that a very careful uncertainty analysis has been done in order to make sure that all latest BIPM recommendations have been followed truly. The nice outcome is, that the harmonized natural gas cubic meter can claim a smaller uncertainty than the individual contributing NMIs.

All three institutes maintain their individual independent facility and apply permanent improvements in order to provide for a more stable and reliable gas cubic meter. All three institutes apply certain correction factors, which are actually correction functions to their calibration and they make sure that their secondary facilities get the same reference value. The user will get at the end the same calibration at all test facilities and there will be no bias between the calibration facilities any more.

In order to test this statement, we have made watchdog test (fig. 12) between PTB and NMi after the harmonization process has been completed and we got the following presentation which has to be compared with figure 2 which shows the situation before harmonization.

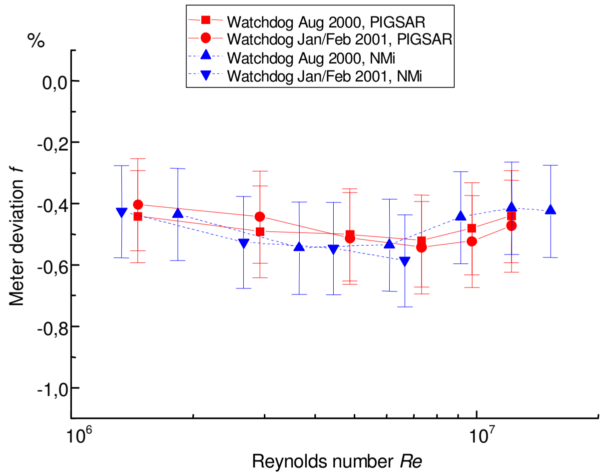


Fig. 12. - Calibration of a turbine meter DN250 (10") as watchdog checks. The uncertainty level (2σ) shown in the graph is the uncertainty U_{Ref} = 0,15 % of the harmonised reference value of PTB (Pigsar) and NMi-VSL as obtained in 1999. Compare with figure 2 to observe the effect of harmonisation: no bias is detectable for the end user any more.

The very positive outcome for the end user is the fact, that there is no bias between the European national standards from the view of the customer any more.

From an economic view the user can apply at any calibration facility. The participating NMIs are on their way to create a unique European natural gas cubic meter.

This harmonized European natural gas cubic meter will be disseminated towards all countries and all facilities in Europe (West and East). In the meantime the Canadian metrology institute, the NRC and MC, has already accepted it.

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