Uncertainty Analysis and Long-Term Stability Investigation of the German Primary High-Pressure Natural Gas Test Facility *pigsar*

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Abstract
The high-pressure gas flow meter test facility pigsar operated by Ruhrgas AG serves for testing and calibration of turbine-wheel and ultrasonic meters for natural gas in the pressure range between 14 and 50 bar and flow rates ranging from 8 to 6500 m^3/h. Pigsar is the national standard of high-pressure natural gas flow under supervision of the German national metrological institute PTB. It represents and disseminates the unified German-Dutch reference value for the unit of volume for high-pressure natural gas. The uncertainty analysis of the test facility presented here was one of the main pre-requisites for the creation of the harmonised reference value.

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Introduction

The Ruhrgas-AG-operated high-pressure gas meter test facility *pigsar* is used to test and calibrate gas meters used for fiscal metering in national and international gas trading. Calibration of the test facility itself is accomplished by a closed chain of reference measurements and is derived from the basic units for length and time. The credibility of the gas flows measured and invoiced does not only depend on the quality of the gas meters themselves and their installation and operating conditions, but is above all determined by the quality and trustworthiness of meter calibration, which is defined by the transparency of testing/calibration procedures and calibration chains used, the uncertainty of meter calibration, and the deviations that occur when a gas meter is calibrated at different test facilities. Recently, the last aspect has become a focus of special attention [1]. For this reason, a sound quantitative assessment of the maximum permissible measurement errors is of crucial importance. So, the described below complete investigation of the uncertainty of the test facility *pigsar* has been undertaken. It meets all requirements of the ISO Guide to the Expression of Uncertainty in Measurement [2].

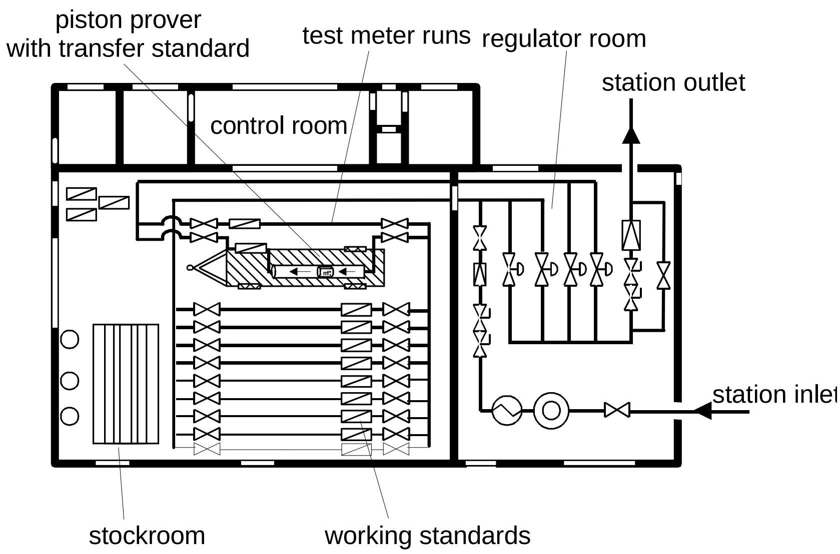

Fig. 1 Scheme of pigsar flow rate measurement standard

Test Facility Description

Fig. 1 schematically illustrates the configuration of the test facility [comp. 3]. The room on the right houses the controller and preheater facilities to adjust gas flow, pressure and temperature. In the left room featuring the test equipment, the gas first passes through a set of parallel working standards (turbine flow meters) sized G250 (4 x), G1000 (4 x), and G100 (1 x) and then through one of the two meter runs fitted with the test specimen.

The number of working standards used depends on the total gas flow rate. In the first stage of the calibration process, a mobile piston prover with a down-stream piston prover transfer standard is installed instead of the test specimen. The piston prover RPS is the reference standard for *pigsar*.

Traceability Chain

The calibration chain starts from realisations of the basic units for length and time and extends over the piston prover dimensions and exact piston movement description to the various stages of gas meter calibrations by comparison. The investigation described here starts with the piston prover already calibrated as described in [4]. The piston prover defines a reference flow rate fully traceable to the basic units "meter" and "second", with an uncertainty as stated in the calibration certificate.

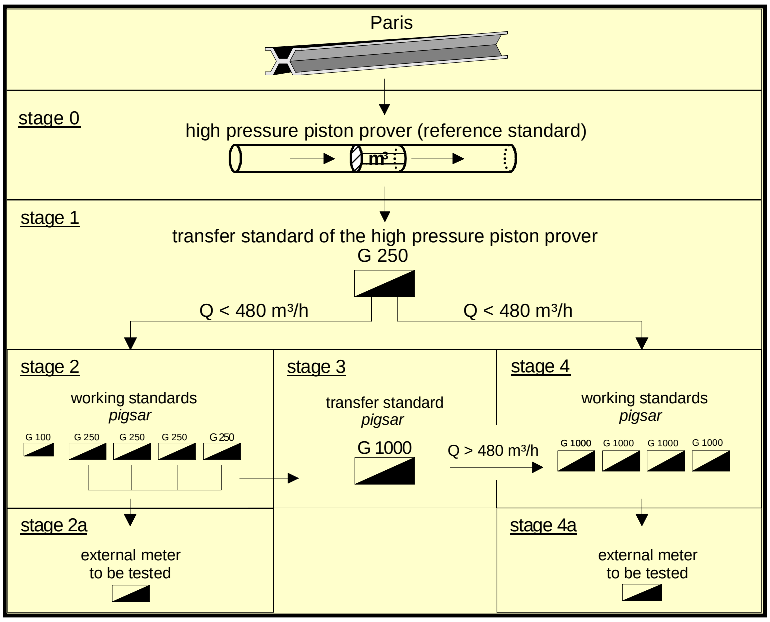

Fig. 2 pigsar traceability chain

The full traceability chain for the facility's working standards (see Fig. 2) comprises 2 (for the G250 working standards) or 4 stages (for the G1000 working standards).

The external (client) gas meter is calibrated in the subsequent stage (2a or 4a).

Uncertainty Analysis

Part I: Developing the Model

As the measurement and evaluation processes are basically the same for each calibration stage, the model only has to be developed for one stage and can then be applied repeatedly to all other stages using the results of the previous stage. The measurand of the facility is the deviation of the reading (in m³/s) of the meter tested Fe_{pr} (or De_{pr} if referred to the nominal temperature of 20 °C) from a given reference value at a given flow rate (expressed as Reynolds number), pressure p and temperature T which is traced back via the calibration chain to the primary standards for length and time. Given these meter deviations at several flow rates, a meter deviation function may be calculated by regression.

Fig. 3 shows the model for the measurement process: In each stage, the readings of the reference meters $Q_{ref,\,raw}$ are corrected using the deviation function Fe_{ref} determined in the previous stage to give the aggregate reference value. This aggregate reference value (for T_{ref} and $p_{ref} = p + \Delta p$) is converted to the actual flow conditions (T_{pr} and p) of the gas at the test specimen's place of installation (with due account for the compressibility K of the gas) and then compared with the specimen´s reading. This comparison is made in each step for three test pressures (18, 35 and 50 bar). In each of the subsequent calibration stages (2, 3 or 4), a 4th order polynomial is fitted to these deviations yielding the deviation function

$$De_{pr} = \Sigma\, a_i^{(k)} * [\, \lg(Re_{pr}/10^6)\,]^i.$$

This is done separately for each pressure level. Testing of external meters (stages 2a and 4a), however, is based on a deviation function fitted jointly across all pressure stages.

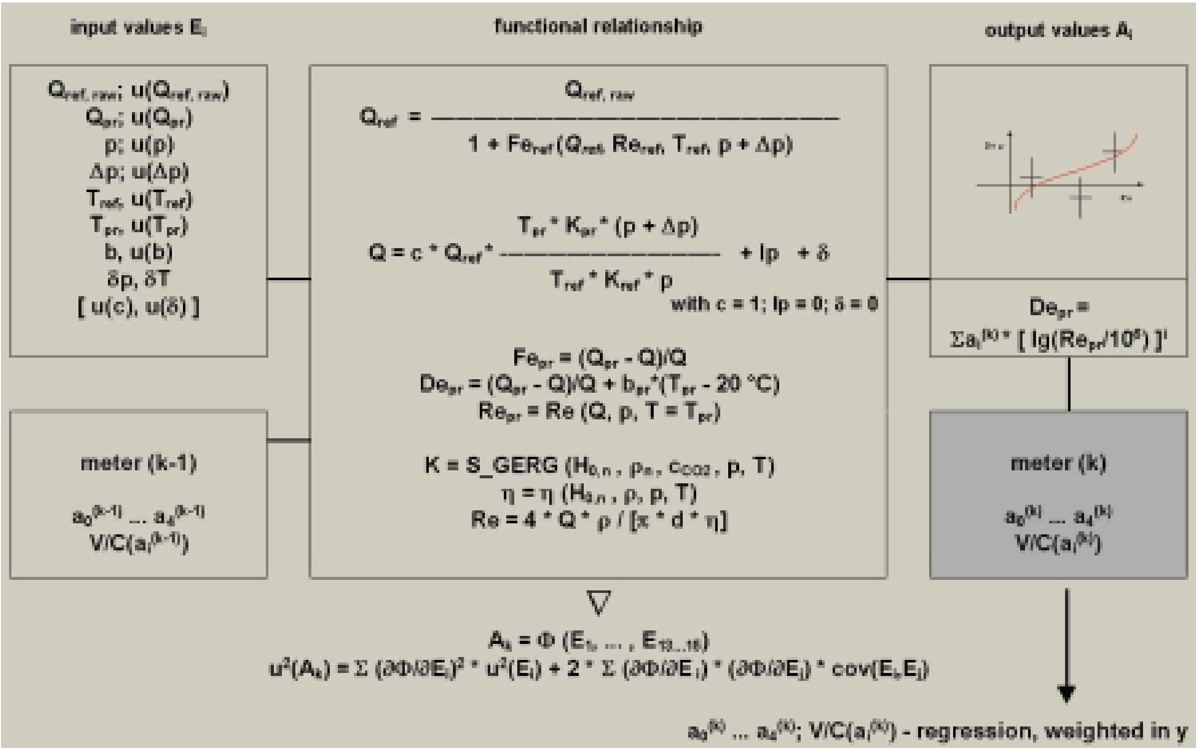

Fig. 3 Model for a gas flow meter calibration on pigsar, stage (k)

Pressures and temperatures can fluctuate and may not be the same at the beginning and the end of recording (drift), causing a certain amount of gas to be trapped in, or released from the pipe volume located between the reference meters and the test specimen. This so-called line-pack effect is mostly random and tends to be small (provided maximum drift is under control), so that there is no need (but huge difficulties) to correct for. Therefore, the corresponding additive term lp in the model is zero, but introduces an uncertainty estimated from the maximum admissible drift values δT and δp. Further reduction of the line-pack effect is achieved by steadily increasing measuring time from 120 sec to 480 sec towards small flow rates (built-in time programme).

Part II: Identifying and quantifying influential uncertainties

The input variables and their uncertainties are listed in the two left-hand side boxes of fig. 3, where the upper box refers to values measured during the actual calibration procedure, and the lower one to the five parameters of the reference-meter deviation function and their variance-covariance matrix, both determined during a preceding calibration step.

All uncertainties are based on the details given in calibration certificates or the manufacturer's documentation or are values determined from experience. Except for the deviation functions (see below), all input variables are independent from each other, because they either refer to different physical variables or are generated at different locations. The uncertainty contributed by the gas property variables (gross calorific value, normal density and CO_2 content) via the real gas factor (or compressibility) is small due to the small differential pressures between the reference meter and the test specimen (approx. 100 mbar). The same applies to the uncertainty introduced by the SGERG real-gas-factor calculation method itself. Owing to the special calibration method (e.g. stage 3), there are no flow disturbances caused by changing installation conditions, which might have an additional impact on the uncertainty. The values of the relative uncertainties for all influential variables are listed in Table 1.

Table 1: Relative uncertainties of the input variables (1σ level)

Geometric volume of piston prover	0.01 %
Values indicated by gas meters (scatter for repeatability tests)	0.01 %
Pulse counting for each gas meter (= uncertainty of time measurement)	0.01 %
Temperature measurement	0.018 %
Absolute pressure measurement	0.05 %
Differential pressure measurement between test meter and reference meter	0.14 %
Gross calorific value measurement	0.15 %
Normal density measurement	0.15 %
CO_2 level measurement	4.7 %
Line-pack effect (derived from an assumed rectangular probability distribution of pressure and temperature drifts)	depends on measuring point
Meter deviation function (regression)	from previous stage

Part III: Calculating the uncertainty of the output variables

The meter deviation De_{pr} at the actual flow rate Re_{pr} depends on all input variables listed in fig. 3 in a complicated manner (e.g. via the Reynolds number itself). Furthermore, the correction of the reference meter raw data is an iterative process, and both the gas compressibility and viscosity at the actual state conditions are calculated by a numerical procedure. So, the resulting uncertainty of an output variable cannot be calculated by methods other than numerical. So, the output value is considered being a function of numerous input values $A_k = \Phi\ (E_1, \ldots, E_n)$, and its uncertainty calculated by numerically determining the sensitivity coefficients and combining them according to

$$u^2(A_k) = \Sigma\ (\partial\Phi/\partial E_i)^2 * u^2(E_i) + 2 * \Sigma\ (\partial\Phi/\partial E_i) * (\partial\Phi/\partial E_j) * \mathrm{cov}(E_i,E_j)$$

(uncertainty propagation). By this procedure, both the total uncertainty and the contribution of each source (uncertainty budget) are provided. From the values determined experimentally, the meter deviation function is calculated which transfers the calibration results to the next stage in the form of the five function parameters $a_1, \ldots, a_5$. In order to transfer the uncertainty, weighted (in y) regression has to be used for determining the function parameters. Only this type of regression actually transfers the cumulated so far uncertainty (in the form of the parameter V/C matrix) to the next stage (instead of the residual scatter attained in only the current calibration procedure).

Part IV: Moving through the traceability chain

As long as one-to-one meter comparisons at the different stages are carried out, the developed model may repeatedly be applied to all stages using the resulting meter deviation function parameters and their V/C matrix of the preceding stage as input values for the subsequent stage. In cases where several reference meters are operated in parallel, reference meter correlations have to be taken into account (part V).

Part V: Accounting for reference meter correlations

To increase the flow rate, several working standards calibrated against the same reference meter in the previous calibration stage are installed in parallel. Therefore, the working standards' readings corrected with the deviation functions are not independent of each other, but partly correlated. The uncertainty of a flow meter *i* calibrated at a reference meter splits into $u^2_{in}(i)$, the part independent of the reference meter, and $u^2_{dep}(i)$, the uncertainty contribution of the reference meter. With **p**(i) being a vector consisting of the partial derivatives of the *i*-th meter deviation function with respect to the 5 function parameters a_k, and V the V/C matrix of the reference meter, it holds

$u^2(i) = u^2_{in}(i) + u^2_{dep}(i) = u^2_{in}(i) + \mathbf{p}^T(i) * V * \mathbf{p}(i)$ and $u^2(j) = u^2_{in}(j) + u^2_{dep}(j) = u^2_{in}(j) + \mathbf{p}^T(j) * V * \mathbf{p}(j)$

$cov(Fe(i), Fe(j)) = \mathbf{p}^T(j) * V * \mathbf{p}(i) = \mathbf{p}^T(i) * V * \mathbf{p}(j)$

Using the relationship $[\mathbf{p}^T(j) * V * \mathbf{p}(i)] * [\mathbf{p}^T(i) * V * \mathbf{p}(j)] \leq [\mathbf{p}^T(i) * V * \mathbf{p}(i)] * [\mathbf{p}^T(j) * V * \mathbf{p}(j)]$, it can easily be shown that cov(Fe(i), Fe(j)) can be estimated as

$$cov^2(Fe(i), Fe(j)) = u^2_{dep}(i) * u^2_{dep}(j).$$

The value of $u^2_{dep}(i)$ forms part of the budget of the corresponding meter calibration. When operated in parallel with any other working standard, the correlation can easily be estimated with the above formula.

On the other hand, according to the measurement model, the deviations Fe(i) and Fe(j) are defined by (see fig. 3)

$Fe(i) = [Q_{pr}(i) - Q(p(i), T(i),..., \mathbf{Fe_{ref}})] / Q(p(i), T(i),..., \mathbf{Fe_{ref}})$

$Fe(j) = [Q_{pr}(j) - Q(p(j), T(j),..., \mathbf{Fe_{ref}})] / Q(p(j), T(j),..., \mathbf{Fe_{ref}})$

where Q is a function of the same form for both Fe(i) and Fe(j), and Fe_{ref} the common source of uncertainty (reference meter deviation). If taken at the same p, T, and Δp, it holds for $\partial Fe(i)/\partial Fe_{ref}$

$$\partial Fe(i)/\partial Fe_{ref} = - Q_{pr}(i)/Q^2 * \partial Q/\partial Fe_{ref} \quad \text{and} \quad \partial Fe(j)/\partial Fe_{ref} = - Q_{pr}(j)/Q^2 * \partial Q/\partial Fe_{ref}$$

With these partial derivatives, cov(Fe(i), Fe(j)) can be calculated according to

$$cov(Fe(i), Fe(j)) = \partial Fe(i)/\partial Fe_{ref} * \partial Fe(j)/\partial Fe_{ref} * u^2(Fe_{ref})$$
$$= Q_{pr}(i) * Q_{pr}(j) / Q^4 * [\partial Q/\partial Fe_{ref}]^2 * u^2(Fe_{ref})$$

From this expression where $Q_{pr}(i) > 0$, $Q_{pr}(j) > 0$ and all other terms are positive, it becomes obvious that cov(Fe(i), Fe(j)) > 0.

In order to cope with all computational requirements of the developed model, a tailored software has been written and compiled using PowerBasic 3.5 IDE and compiler.

Uncertainty Analysis Results

Influence of Regression

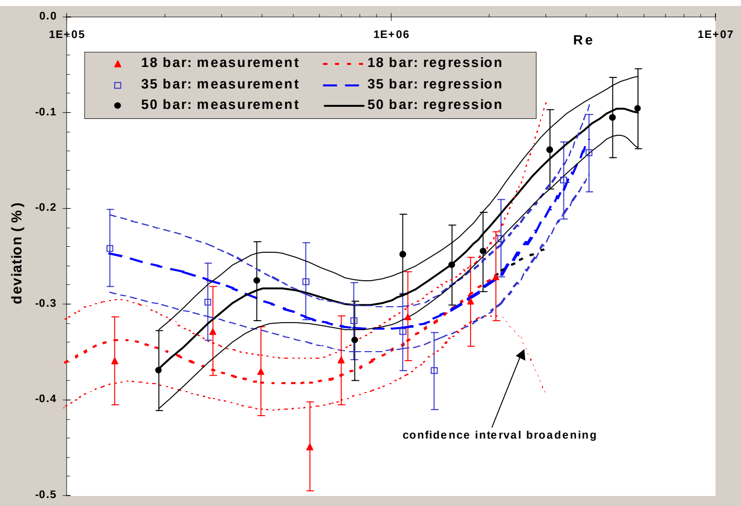

Fig. 4 Measured deviations and their uncertainties for the transfer standard

Fig. 4 shows the calibration results of the first stage as an example: measured points, their uncertainties, the meter deviation functions, and the corresponding confidence bands, all on the 1σ confidence level.

As common, within the range covered by data points, regression is a valuable tool for reducing the uncertainty involved in the calibration process as opposed to the use of individual values. It can also be seen that a joint regression across all pressures is admissible from a statistical point of view. The 2σ uncertainty bands would overlap sufficiently to consider the three functions statistically indistiguishable.

However, statistical consistency is supervised by testing the well-know statistic

crit = residual sum of weighted squared deviations / degrees of freedom

against the statistical expectation. Consistency may be confirmed if *crit* is less than 2 (at the 95% confidence level), what has been the case for all regressions carried out.

Uncertainty Budget Development

In each calibration stage, the individual uncertainty contributions (uncertainty budget) and the total uncertainty of the gas meter to be calibrated have been determined. For each stage, the Reynolds-number dependent total uncertainty and the budget contributions may be plotted. The development of the budget can best be illustrated by plotting the budgets at a constant flow rate or Reynolds number for all stages in one graph. This is shown in fig. 5 (for a constant flow rate of 256 m³/hr, since diameter changes for the large flow meters). The total uncertainty develops across the various calibration stages due to a superposition of several effects:

- At each stage, there are new (random) uncertainty contributions caused by the scatter of the meter readings, pressure, pressure difference, temperatures, and the linepack effect.
- The contribution of the deviation function of the previous stages does not directly reflect the total uncertainty of the reference meter at the same flow rate in the previous stage, but is reduced by the averaging effect of regression.
- Where standards are installed in parallel, correlations between the deviation functions of the working standards have been taken into account.

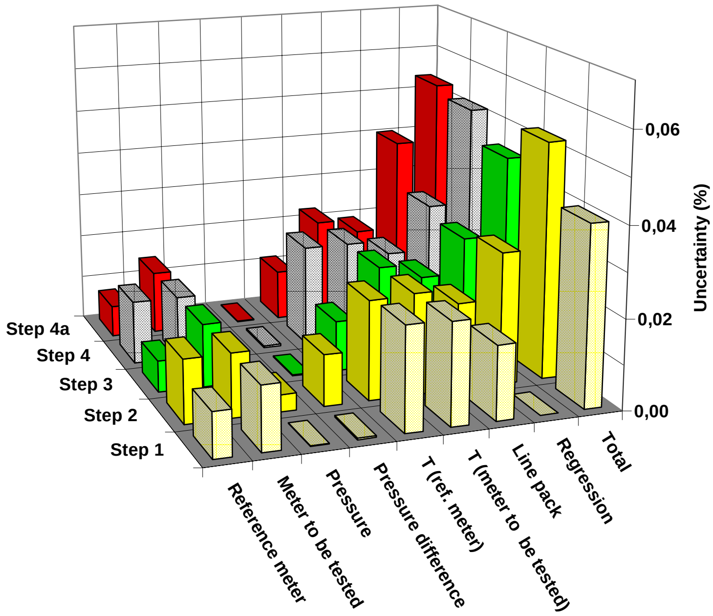

Fig. 5: Development of uncertainty budget and total uncertainty for stages 1 to 4a for p = 35 bar and Q = 256 m³/hr

- With standards installed in parallel, the random contributions from pressure and temperature measurements are reduced by (roughly) a factor of $1/\sqrt{n}$ with n being the number of standards installed in parallel (effect similar to taking the mean and the uncertainty of the mean).
- Since parallel installation of standards reduces the individual flow rates through these standards, the uncertainty contribution of the deviation curves may increase as the operating point shifts towards the edges with broader uncertainty bands (in the fig. stage 4a).

Over a large application range, the uncertainty of a gas meter calibrated on *pigsar* is not much higher than 0.1 % (2σ) and rises relatively sharply at the edges to as much as 0.2 %. However, owing to flow perturbations and installation-related effects, meters installed in the field can show higher uncertainties.

Experimental Verification

Short-term stability

Comprehensive short-term reproducibility investigations have been carried out on a set of 2 "real-life" external turbine-wheel meters (stage 2a and, resp., 4a in figure 2). All measurements were made using the regular test protocols and data acquisition/data processing routines. Therefore, the obtained results characterise the attainable reproducibility (as a significant constituent of the overall uncertainty) of the test facility *pigsar* at the place of installation of the meter to be tested and under practical application conditions. For the tests, two turbine-wheel gas meters with nominal width DN 400 and of considerably different construction have been installed at the test facility and tested under the following conditions:

Table 2: Experimental conditions for reproducibility investigation of 2 turbine-wheel gas meters

se-tup	volume flow	reference meter combinations		single measurements per cycle	pressure points (bar)
1	6 000 m^3/h	N6 to N9	4 x G 1 000 at 0,94 Q_{max}	12	20
2	3 000 m^3/h	N6 to N9	4 x G 1 000 at 0,47 Q_{max}	12	20, 50
3	1 600 m^3/h	N6 to N9	4 x G 1 000 at 0,25 Q_{max}	12	20, 50
4	1 600 m^3/h	N6	1 x G 1 000 at Q_{max}	12	20, 50
5	1 600 m^3/h	N2 to N5	4 x G 250 at Q_{max}	12	20, 50

Figures 6 and 7 display the determined meter deviations (expressed as the mean of single deviations measured in the corresponding cycle) for the two meters in dependence on the Reynolds number. The dashed lines represent the overall uncertainty (expanded with an expansion factor of k = 2) of the facility as currently used for the dissemination of the internationally harmonised reference value for the volume unit of high-pressure natural gas.

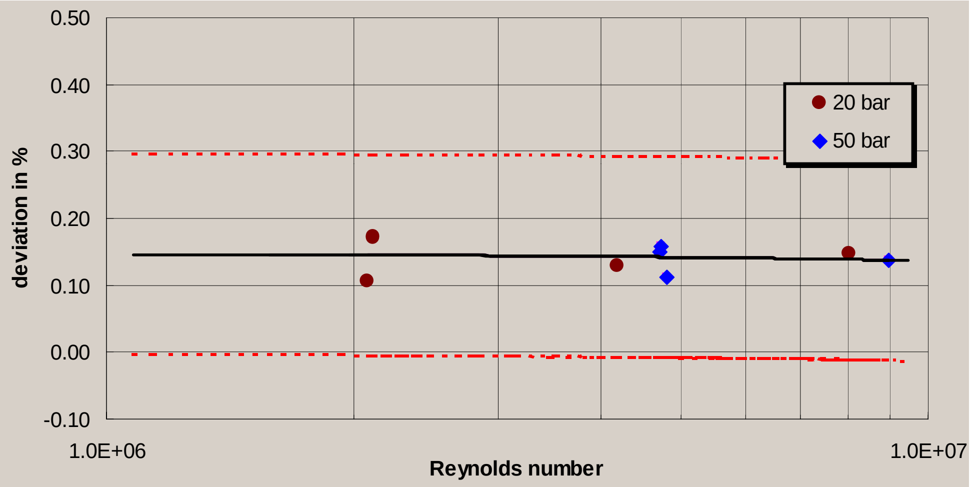

Fig. 6 Deviations of turbine-wheel meter No 1 in dependence on the Reynolds number for pressure points 20 bar and 50 bar, and the combinations of reference meters according to table 2

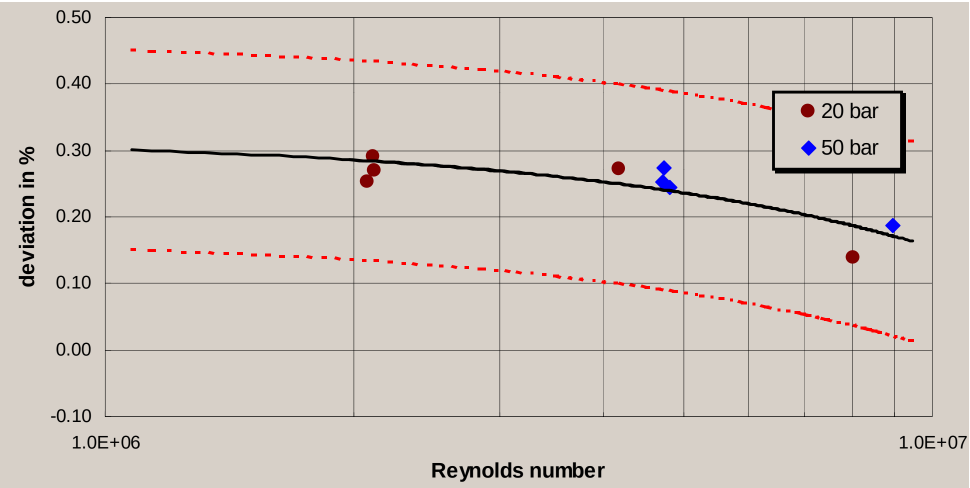

Fig. 7 Deviations of turbine-wheel meter No 2 in dependence on the Reynolds number for pressure points 20 bar and 50 bar, and the combinations of reference meters according to table 2

Since the standard deviations for all measurement cyles at all measuring points do not exceed 0.016 % ($1.6\cdot10^{-4}$), the assessment based on mean values of the results is fully justified. The figures reveal that the meter deviations determined under different experimental conditions may well be described by a deviation function which exclusively depends on the Reynolds number. Different test pressures do not affect this functional relationship.

It should particularly be emphasized that the indications of the test meters practically do not depend on the combination of reference meters used for the realisation of the corresponding volume flow rates. As can be seen from table 2, the volume flow rate of 1600 m^3/h was realised by three different combinations of reference meters (two of them being different sets of 4 meters operated in parallel, and one a single large meter operated at the maximum flow rate). A significant impact on the meter indications cannot be observed.

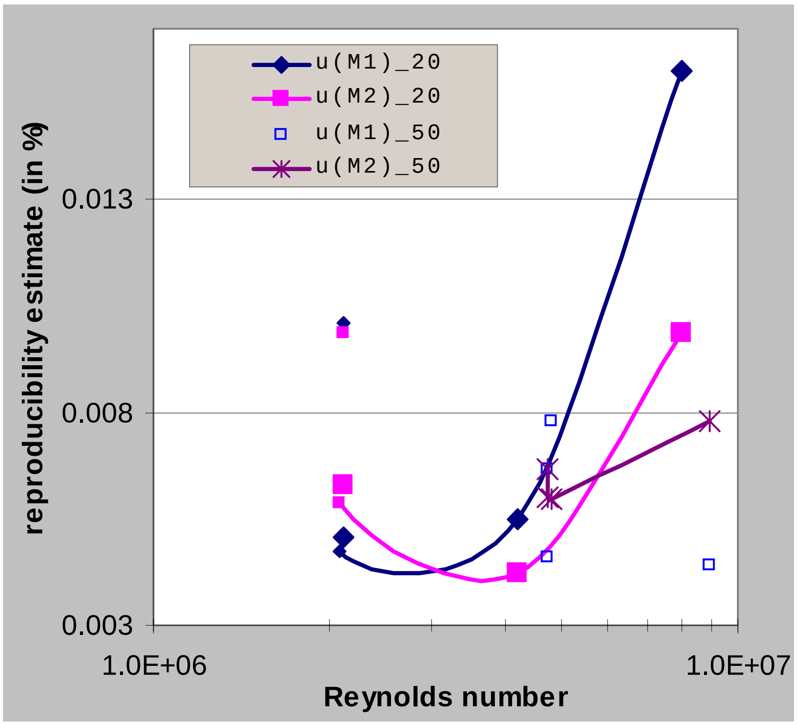

Fig. 8 Reproducibility of the measured value for both turbine-wheel meters in dependence on the Reynolds number and for pressure points 20 and 50 bar. Note that the "outlying" estimates at 1600 m^3/h and 20 bar correspond to setup No 4 (1 large reference meter at Q_{max}).

While this is valid for the meter indication itself, it does not hold for the scatter of indication in dependence on the different reference meter combinations. In figure 8, reproducibility estimates (expressed as the standard deviation of the 12 measurements in each cylce) as obtained during the study for both meters in dependence on the Reynolds number are shown.

Reproducibility estimates range from 0.005 to 0.016 % while typical calculated measurement uncertainties for stage 4a, and under the conditions realised during the study, are in the range between 0.04 and 0.05 % (comp. fig. 5). This is no contradiction since the reproducibility as determined within this study constitutes a significant, but not the only source contributing to the overall uncertainty of the test facility. One major point is that reproducibility does not include the trueness of measurement (in other words, traceability), which would be expressed by the uncertainties brought in by reference meters, and which are normally not taken into consideration for "pure" reproducibility studies. Moreover, reproducibility as determined here is at short term, long-term considerations (presented below) reveal a satisfactory agreement between experimental observations and calculated uncertainty budgets.

So, reproducibility estimates smaller than the overall uncertainty are normal and would be expected. The opposite case (i.e. reproducibility estimates exceeding the calculated overall uncertainties) would indicate the neglection of major uncertainty sources in the budget. However, it should be noted that the reproducibility estimates as given in figure 8 resemble the typical "bathtub"-like behaviour with smaller values near the centre of the measuring range, and an increasing scatter at the extremes.

Remarkable in the data as given in figure 8 are the "outlying" estimates (for meter No 1 and 2) at 1600 m^3/h and 20 bar which correspond to setup No 4. The scatter for this setup (one large reference meter at Q_{max}) is significantly higher than the scatter obtained for the same meters at the same pressure point and flow rates for combinations of 4 reference meters. Even in a statistical sense, the scatter is outlying as can be shown by a simple F test. Based on the results of the uncertainty budget calculations, this effect has been expected.

Long-term stability and intercomparisons for bilateral harmonisation

The results of the uncertainty analysis can be verified experimentally by comparing the scatter of several calibrations (i.e. all calibration stages from start to finish) with the calculated uncertainties. Because of the effort involved in obtaining the necessary data, the scope of data available for such a comparison is limited. Figure 9 shows the deviation functions of the G250 working standards (stage 2) and the G1000 working standards (stage 4) for *pigsar* calibrations performed within a time frame of 5 years.

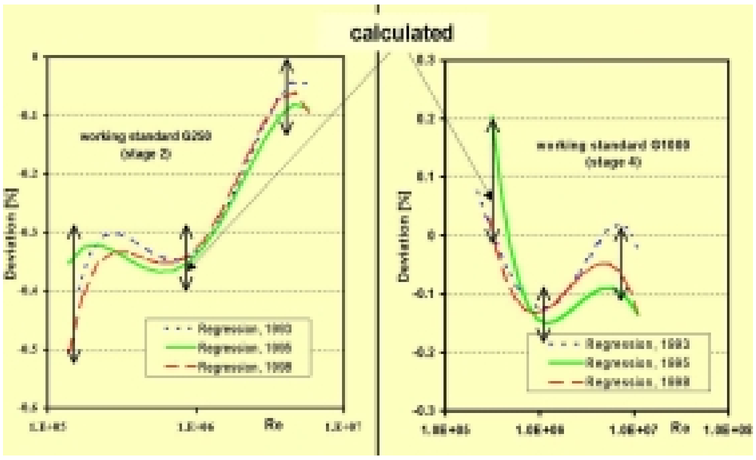

Fig. 9 Deviation functions of working standards for three calibration runs

In both qualitative and quantitative terms, the scatter observed exactly reveals the behaviour predicted by the uncertainty analysis:

- In the centre of the Reynolds number/flow range, the scatter is smaller than at the edges.
- The scatter largely remains within the double-standard deviation ($2\sigma = 0.1$ %) calculated. As expected, the scatter only increases at the edges ($2\sigma = 0.2$ %).
- The scatter increases with the length of the calibration chain.

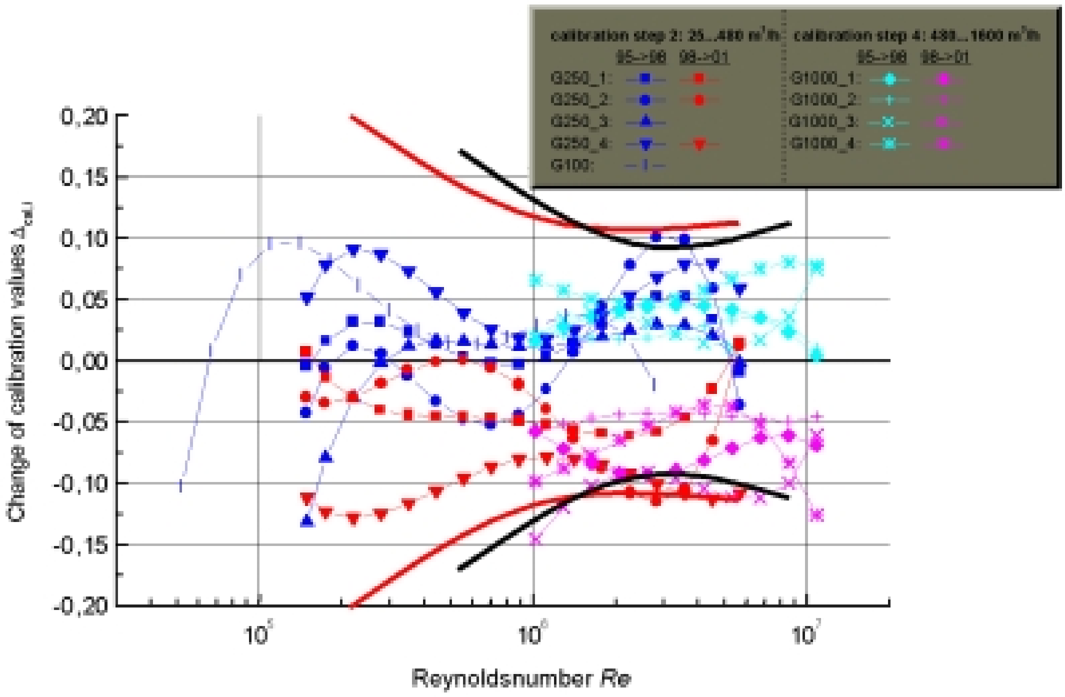

Fig. 10 Changes in the calibration value(s) $\Delta_{cal,\,i}$ for the nine working standards and two calibration campaigns, and calculated uncertainties (bold lines, red: G250 working standards, black: G1000).

The variability of meter deviations for the working standards G250 (stage 2) and G1000 (stage 4) from one calibration campaign to the next will now be considered more in detail. Figure 10 displays the change in the calibration value(s) $\Delta_{cal,\,i,\,X \to Y} = C_{i,\,year\,X} - C_{i,\,year\,Y}$ for the working standards used at *pigsar*.

The bold lines in figure 10 represent the expanded uncertainty (k = 2) as calculated. It can clearly be seen that the behaviour of the standards resembles the basic features of the Re-number dependence of the uncertainty. Furthermore, the limits of the expanded uncertainty are exceeded only by chance in a number of cases which corresponds excellently to the level of confidence (≈ 95%).

Obviously, the individual deviations of the working standards are grouped around a common bias for each of the calibration campaigns. Thus, a decomposition into a common deviation and residual scatter seems reasonable. The common deviation is $\Delta_{ref} = \frac{1}{n}\sum_{i=1}^{n} \Delta_{cal,i}$, and the residuals are $\Delta_{WS,i} = \Delta_{cal,i} - \Delta_{ref}$. The corresponding graphs are shown in figures 11 and 12.

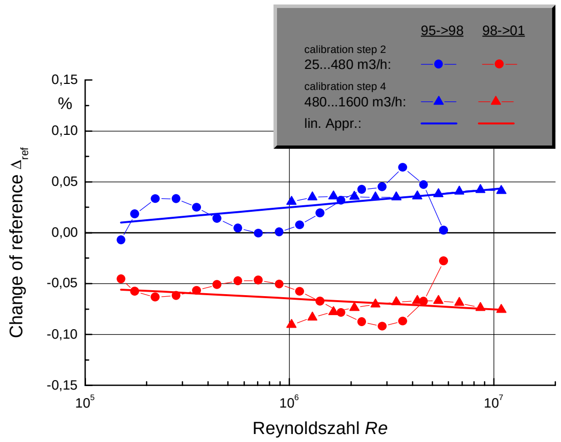

Fig. 11: Common deviation Δ_{ref} between the calibration campaigns.

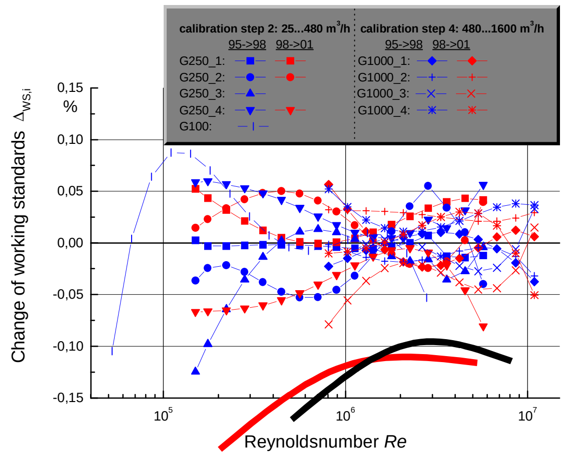

Fig. 12: Residual scatter (with reference to the common deviation) for the working standards.

The residual scatter reaches its minimum at around Re = 1,5 x 10^6. Once again, this is in good agreement with the uncertainty as calculated exhibiting a minimum in the Re-number range between 1 ... 2 x 10^6.

Since 1999 the unified German-Dutch reference value for the unit of volume for high-pressure natural gas is established. The results of comparison within the harmonisation process will be also used here to verify the stability.

For the purpose of harmonisation between the Dutch and the German national standards, three transfer packages consisting of 2 turbine-wheel meters operated in series (see figure 13) are in use. The harmonisation process will be described in a separate paper during FLOMEKO 2003.

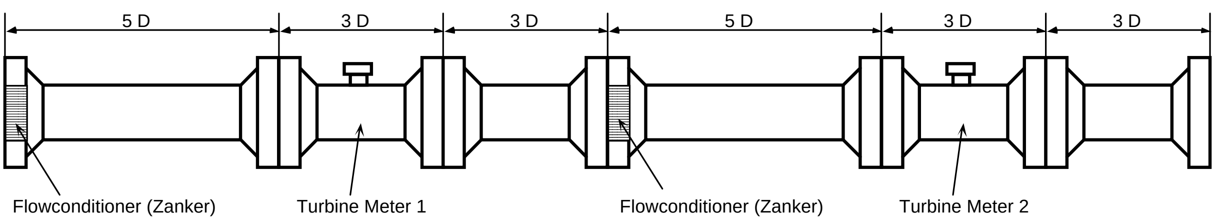

Fig. 13: Transfer package used for harmonisation purposes

The difference between the Dutch and the German standards is defined as the difference between the calibration values obtained for both transfer package meters at both test facilities, i.e.

$\Delta_{NMi\text{-}PTB,\ meter\ i} = C_{NMi,\ meter\ i} - C_{PTB,\ meter\ i}$

and is determined for a large series of pressure points and flow rates. Results for the 1999 and 2002 harmonisation campaigns are shown in figure 14.

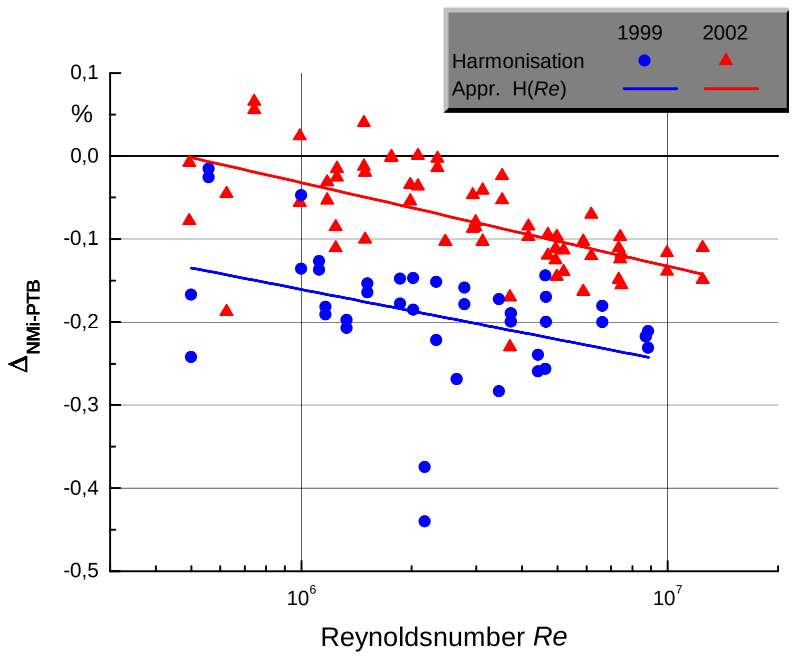

Fig. 14: Differences NMi-PTB for two harmonisation campaigns

As can be seen from the graph, the dependence of the difference on the Re number may be approximated by a linear dependence of the form

$H(Re) = a_0 + a_1 * \log(Re).$

The residual scatter of the data, i.e. a value $\Delta_{harm,\ meter\ i} = \Delta_{NMi\text{-}PTB,\ meter\ i} - H(Re)$, may now be plotted for meter 2 against meter 1 resulting in a Youden plot as shown in figure 15.

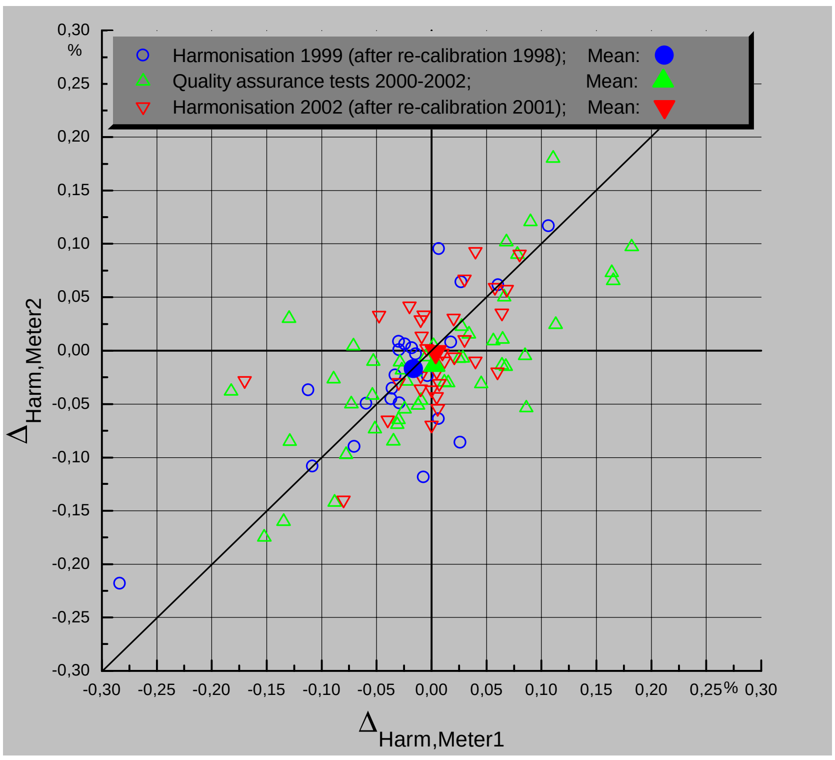

Fig. 15: Youden plot of differences with respect to the harmonised reference value for two harmonisation campaigns and the quality assurance test. Differences for meter 1 of the transfer package are plotted against the differences of meter 2.

Figure 15 contains the data for the 1999 and 2002 harmonisation campaigns and additional data obtained in a quality assurance test (watch dog test) carried out between 2000 and 2002. The latter included also the Dutch test facility at Westerbork. The mean values of each group of data shown in Fig. 15 demonstrate the long term stability of the harmonised reference value within 0.02 %.

Under certain assumptions (normality, independence and equal reproducibility of both test facilities), from the Youden plot as presented in figure 15 two estimates σ_{stab} and σ_{meter} can be derived using the statistical data processing algorithm described in [5 - 7]. The estimate σ_{stab} describes the reproducibility of the harmonised reference value which is equivalent to reproducibility of both test facilities, and σ_{meter} that of the meters used in the transfer package. Results are given in table 3.

Table 3: Estimates σ_{stab} and σ_{meter}

Campaign	σ_{stab}	σ_{meter}
Harmonisation 1999	0.031	0.025
Quality assurance tests (watch dog)	0.046	0.030
Harmonisation 2002	0.025	0.024

The values for σ_{stab} constitute an excellent proof of the short- and long-term stability of the facility as a whole, including all peripheral installations and data processing protocols and software.

Conclusions

In the study, the total uncertainties and the uncertainty budgets of each stage as well as of the whole *pisar* traceability chain have been calculated. All influential sources of uncertainty and the correlations between standards connected in parallel have been taken into account. This enables the calibration of any external (client) meter at any pressure and temperature point within the operating range of the facility being traceable to the basic SI units and accompanied by a sensible uncertainty statement.

Since 1999, *pigsar* represents and disseminates the unified German-Dutch reference values for the unit of volume for high-pressure natural gas. These common reference values are based on an agreement between the national metrological institutes of Germany and The Netherlands, PTB and NMi VSL, of June 1999, which harmonises the two national calibration chains and defines a resulting mean, weighted by the corresponding uncertainties. The uncertainty analysis presented was one of the main pre-requisites for the creation of harmonised reference values and the realisation of the German-Dutch agreement.

The results of the uncertainty analysis have been compared with the scatter found when re-calibrating the *pigsar* working standards and performing the extensive comparisons between NMi VSL and PTB. Data included in the comparison cover a time interval of more than 6 years and fully confirm the results of the uncertainty analysis.

The documented long term stability of better than 0,02 % and reproducibility of better than 0,05 % (1σ-level) of the harmonised reference value demonstrate also the stability of test facility *pigsar*.

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