



PIGSAR - The extended test facility and new German national primary standard for high pressure natural gas

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Introduction

PIGSAR™ is the National Primary Standard of Germany for high pressure natural gas and is operated by Ruhrgas AG, Germany. Under supervision of the Physikalisch Technische Bundesanstalt PTB1, PIGSAR™ is responsible for maintaining and disseminating the unit of volume for natural gas under high pressure conditions since 12th May 1999. With respect to the contract of PTB and NMI VSL2 (The Netherlands) signed 2nd June 1999 [1], the new Dutch-German "harmonised reference gas cubic meter" were established and has been disseminated since November 1999.

The paper describes the extended test facility PIGSAR™ and its measuring capabilities. The operation range of the test facility allows to calibrate gas meters in a pressure range of 16 to 50 bar and at flow rates under actual working conditions of 8 to 6500 m³/h in the whole pressure range. With this capabilities PIGSAR™ is quite unique in Europe. If compared with other high pressure gas facilities world-wide, PIGSAR™ offers most appropriate calibration capabilities for industrial use. This will be documented here by a comparison with operation ranges of other test facilities.

The calibration of the facility will be explained in detail. The high pressure calibration chain of PIGSAR™ refers to the basic SI-unit meter in only a few steps. It starts with a piston prover which has been geometrically calibrated, therefore the piston prover is representing the unit cubic meter. Because the unit cubic meter in high pressure natural gas is based on a volumetric method using a piston prover, the description of the prover and its use for calibration is one main part of this paper. The detailed explanation of uncertainty analysis of PIGSAR™ is given in the accompanying paper by Bremser et al. [2] of this 5th ISFFM (2002) "Traceability and Uncertainty of the National German Flow Rate Measurement Standard PIGSAR" and in [3].

Furthermore the procedures for establishing and maintaining the new Dutch-German harmonised reference gas cubic meter will be explained. Finally, results of the harmonisation process will document the level of uncertainty of the test facility PIGSAR™ and the cubic meter disseminated.

1.0 Description of PIGSAR and its Measuring Capabilities

In figure 1 an outline of PIGSAR™ is given which illustrates the gas flow through the facility. Downstream of the station inlet the gas flow is stabilised by a temperature and pressure regulator unit, passes a bench of working standards and the working section for meters under test or the high pressure piston prover (HPPP) for calibration of PIGSAR™ and leaves then the facility. The bench of working standards consists of turbine meters with maximum flow rates of 1600 m³/h (four meters), 400 m³/h (four meters) and 160 m³/h (one meter). Figure 2 gives an impression how the facility looks like. For further information see also PIGSAR's web site [4]

1 The PTB is the National Metrology institute and the national institute for science and technology and highest technical authority of Federal Republic of Germany for the field of metrology.

2 National Meetinstitute Van-Swinden-Laboratory, responsible for standards and its dissemination in Netherlands

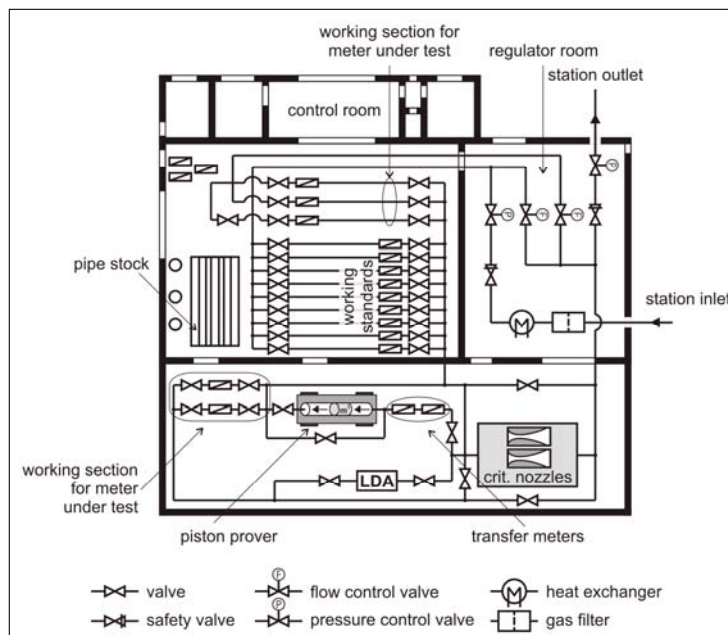


Figure 1. Outline of PIGSAR and its flow scheme.

The flow goes through pressure and temperature regulators after station inlet, passes first the working standards and then the meters under test.

In the regulator room between pressure regulator and station outlet there is a bypass system for flow rate regulation and emergency bypass. The third working section for meter under test is removed for calibration with piston prover.

As one can see in figure 2, PIGSAR™ has three working sections for meters under test with comfortable size. It is possible to calibrate meters of diameters from DN80 to DN4003.

The maximal length of a test run is 13,5 m which corresponds up to 33 Diameter of DN400.

Another advantage of PIGSAR's piping system is the location of working standards upstream

to the test runs (see figure 1). Therefore it is possible to check and calibrate highly contaminated meters.

Type of meters calibrated by PIGSAR™ are usually turbine meters, ultrasonic meters, vortex meters and Coriolis meters. Rotary piston provers could be used inside PIGSAR™ only in special cases due to problems with pulsation caused by such meter type.

Table 1 gives a summary of technical data and capabilities of PIGSAR™.



Figure 2. Photo of PIGSAR™. On left side you can see the working section for meters under test and on right side the working standard section.

Table 1. Technical Data of calibration facility PIGSAR™

pressure range	15 ... 50 bar
pressure stability	< 20 mbar
temperature range	8 ... 20 °C
temperature stability	< 0,1 K
flow range (working condition)	8 ... 6500 m³/h
uncertainty for meters calibration (k = 2)	0,15 % (harmonised value)
uncertainty of density determination	0,1 % (measured with single - sinker desitometer [5]) 0,15 % (from gas composition according SGERG88 [6])
number of working standards	9
number of test runs	DN80 ... DN400 (3,5" ... 16"), ANSI600
Size of meters under test	3
length of test runs	max. 13,5 m
meters usually calibrated	Turbine meters, ultrasonic meters, vortex meters, Coriolis meters

The high acceptance of PIGSAR™ is documented by more than 900 calibrations per year with 70 % international customers, due to its measuring capability and its availability over the year. Figure 3 and figure 4 compare the capabilities of several European and non European facilities with PIGSAR™.

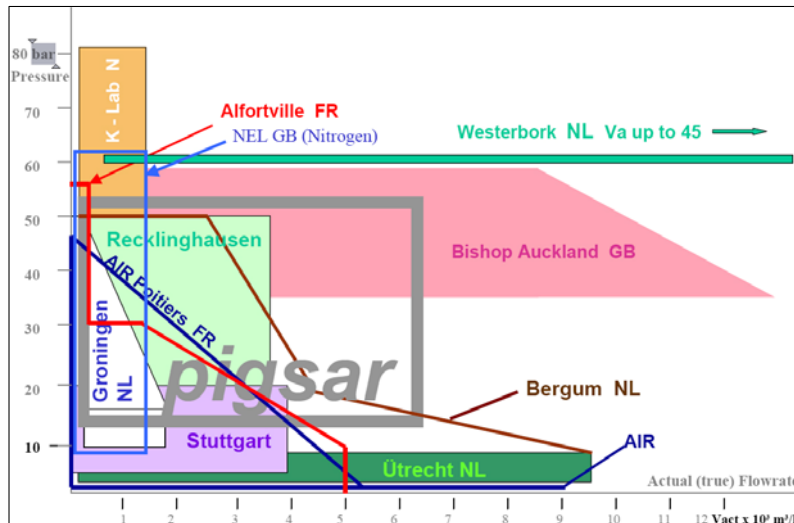


Figure 3. High pressure calibration capabilities of facilities of European test rigs⁴ as compared with PIGSARTM. PIGSAR's capabilities overlap with most of all other European facilities, except the facilities Utrecht (NL) and Westerborg (NL) due to their pressure ranges.

The range covered by PIGSARTM is quite comfortable and quite unique in the world. Especially in the area of higher flow rates above 3000 m³/h and pressure higher than 20 bar only a few test facilities are able to calibrate, for instance Bishop Auckland (Bishop Auckland is accredited by UKAS⁵ and has traceability to PIGSARTM). Some of them with extremely high flow capacities e.g. Westerborg NL (figure 3) or CEESI and TCC (figure 4) offer a limited pressure range at higher pressures. Outside Europe PIGSARTM has the best overlapping range with GTI High Pressure Loop" and the facility in Chengdu (China), which has traceability to NIM (Beijing). PIGSARTM also overlaps with the National Standard Didsbury of NRC in Canada.

All values shown in Figure 3 and 4 were results of a Calibration and Measuring Capability Evaluation (CMC) carried out by the chairman of EUROMET Technical Committee Flow, Prof. Dr.D. Dopheide.

⁴ Recklinghausen and Stuttgart are the locations of calibration facilities for verifications in Germany accredited by local authorities with traceability to PIGSARTM.

⁵ UKAS is the United Kingdom Accreditation Service.

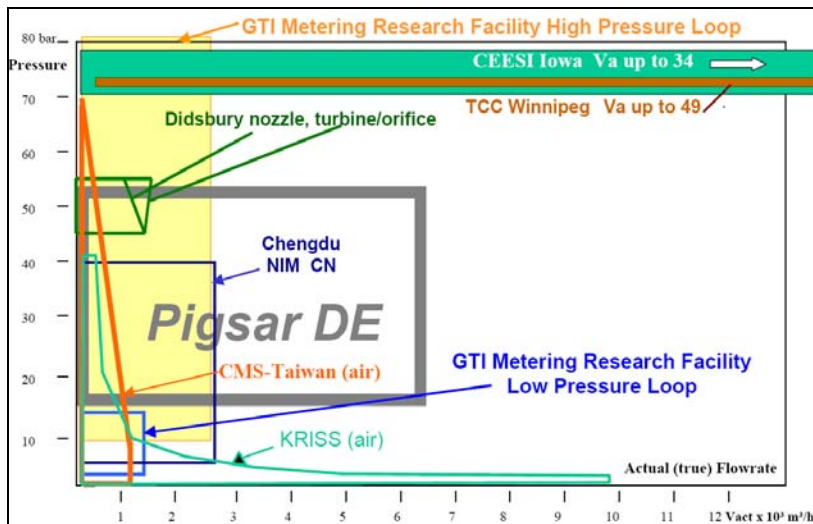


Figure 4. High pressure calibration capabilities of facilities outside Europe compared with PIGSAR™.

2.0 Calibration Chain of PIGSAR™

The high pressure calibration chain of PIGSAR™ (see figure 5) refers to the basic SI-unit meter in only a few steps. A piston prover was designed, built up and geometrically measured [7], therefore the piston prover is representing the unit cubic meter. In the next step the prover's reference meter (a turbine meter G 250) has been calibrated. This prover's reference meter can be used up to a flow rate of 480 m³/h. Up to this range the working standards of PIGSAR™ (turbine meters) of all sizes were calibrated directly. In order to reach higher flow rates, a transfer standard meter G 1000 was calibrated using four working standards G 250. In the last step the working standards of PIGSAR™ with size G 1000 were calibrated in the higher flow rate using the transfer standard.

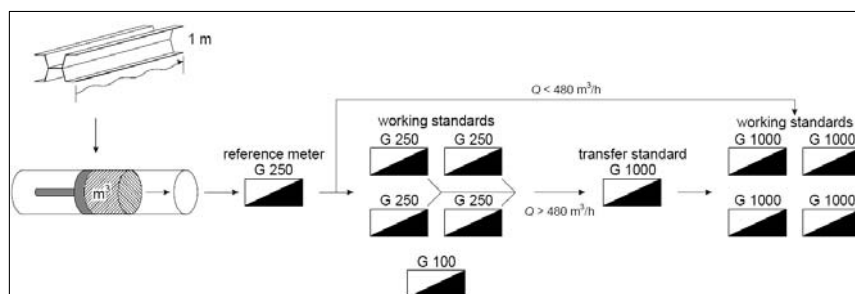


Figure 5. Principal calibration chain in high pressure gas for PIGSAR™

The calibrating of the reference meter G250 with the piston prover is the main and most important work inside PIGSAR's calibration, hence the use of piston prover will be described here more extensively.

3.0 Description of the High Pressure Piston Prover (HPPP) and its Use for Calibration

The piston prover [7] with its piping system inclusive the reference meter is mounted on a trailer (see also figure 6). The piston prover was made of stainless steel. The cylinder itself is made of ASTM 315 stainless steel because pipes of this material are available at lengths of a maximum 6 m. In order to keep the differential pressure at the piston and hence the piston travel speed constant, the piston run must have a constant diameter over its full length. This can only be ensured if it is made from a single pipe section so as to exclude the effects of welding and flange connections on piston travel speed. Therefore, the length of the pipe is 6 m. The internal diameter is 250.8 mm.

In table 2 are summary of main technical features is given.

Table 2. Technical Data of High Pressure Piston Prover (HPPP)

Length of cylinder	6 m
Length of measuring section	3 m
Material of cylinder	Stainless steel
Material of piston	aluminium
Piston support and sealing ring material	PTFE (Teflon®)
Diameter of cylinder	0,2508 m
Displaced volume for calibration	0,1482 m ³
maximum allowable pressure	90 bar
differential pressure at piston	0,07 to 0,11 bar
flow rate range	25 ... 480 m ³ /h
Uncertainty (K = 2) of geometical calibrated volume [7]	0,02 %



Figure 6. Photo of high pressure piston prover (HPPP) mounted on trailer with reference meter

Figure 7 and 8 are schematics showing the piston prover's operating principle.

Before measurements start (figure 7a), the gas flows through the 4-way valve and starting valve S2 (starting valve S1 is closed) then passing the prover run, the 4-way valve and the meter to be tested from where it is returned into the high-pressure grid. The piston is not moved. If conditions are stable (constant temperatures, pressures and flow) measurements may be started by simultaneously closing starting valve S2 and opening starting valve S1, thereby allowing gas to flow behind the piston which then starts to move. Piston movement is indicated by switch a_1 . On passing a_2 , b_2 and c_2 (figure 7b), various impulse and time counters are started and the recording of analogue values (pressures and temperatures) begins. When the piston passes switches a_4 , b_4 and c_4 , the measurement is stopped. To ensure a constant travel speed Switch a_3 is used to control the travel time of piston at the half way. If the piston reaches the end of the piston run, the gas is released through the bypass and the check valve (non-return valve).

The 3 m measuring section itself has been located towards the rear end of the 6 m pipe to ensure a sufficiently long straight inlet section of 2 m, thus making sure that the acceleration process when the piston starts to move has finished when measurements start. Therefore, the outlet section is only 1 m. Switches $a_2 - a_4$, $b_2 - b_4$ and $c_2 - c_4$ give three separate measuring volumes. During piston movement from a_2 , b_2 , c_2 to a_4 , b_4 and c_4 , these three volumes are compared with the volumes measured at the meter tested. The three values obtained from the three volumes $a_2 - a_4$, $b_2 - b_4$ and $c_2 - c_4$ must agree within a very narrow tolerance range of less than 0,01 %. Deviations indicate outliers or spurious values and such measurements are discarded.

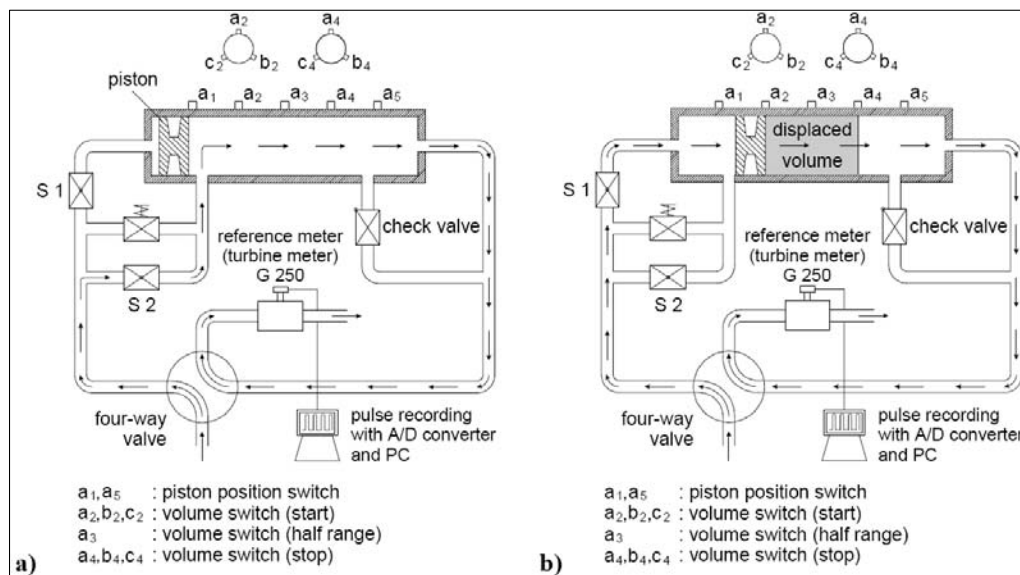


Figure 7. Outline of HPPP and flow scheme including the reference meter

(a) left side: flow bypasses the piston and reference meter stands by for calibration of working standards or for changing pressure or flow rate

(b) right side: flow drives the piston and reference meter are calibrated by comparison of meter indication with displaced volume

The three volumes must be corrected for the actual temperature of the cylinder (flow) and the pressure inside the pipe. Also, they have to be recalculated to take account of the conditions at the meter, which makes it necessary to determine the real gas coefficients. The instrument taps for determining the absolute pressure and the absolute temperature are located at the end of the prover run. Pulses of the meter under test, the pressure differences across the prover's piston as well as the pressure and temperature differences between the piston prover and the meter under test are recorded over full movement of piston. Moreover, the pressure differentials across the 4-way valve and the filter are measured to ensure valve tightness and determine the degree of leakage rate, respectively. The measuring signals from the pressure sensors and the 4-wire resistance thermometer are digitised by a data acquisition system and transmitted to a computer, which also processes the signals from the control electronics, the impulse counter and the timer. This allows all control operations for the piston prover to be performed through the computer which also processes the data received.

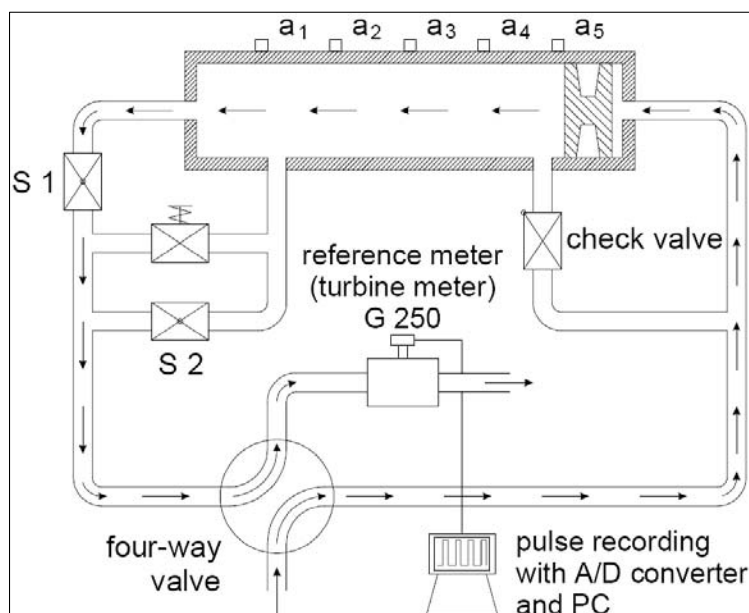


Figure 8. Outline of HDPP and flow scheme including reference meter to move back the piston

In order to prevent the piston from being subjected to excessive pressure during changeover of the 4-way valve, a pressure relief valve is installed at the inlet to the piston run. The valve is set to open when the pressure difference at the piston exceeds 2 bar. This situation can occur, for example, when the 4-way valve is switched to return flow, the piston is already in its starting position but starting valve 2 is still closed due to a defect. The non-return valve (check valve) is necessary to ensure that the piston can be moved from the end position back into the starting position even for low gas flows, because otherwise the low flow resistance would cause the gas to pass through the bypass without moving the piston back into its starting

position. Figure 8 shows the flow situation to move back the piston into its starting position by switching the 4-way valve which reverses the direction of flow inside the prover e.g. 1.33 s at flow rate $q = 400 \text{ m}^3/\text{h}$. During this time, about 2100 pulses are generated by the blades of the reference turbine meter. A rounding error of ± 1 pulse would produce a high measuring uncertainty. Therefore, the "double stopwatch method" is applied. This method involves the use of two separate stopwatches for the prover and the meter tested to time the period in-between two associated blade edge impulses. The time measured is the basis for flow calculation. The measuring time at the test meter starts and ends with the first blade edge pulse following the prover impulse. Figure 9 give an impression of pulses generated by reference meter during a prover run.

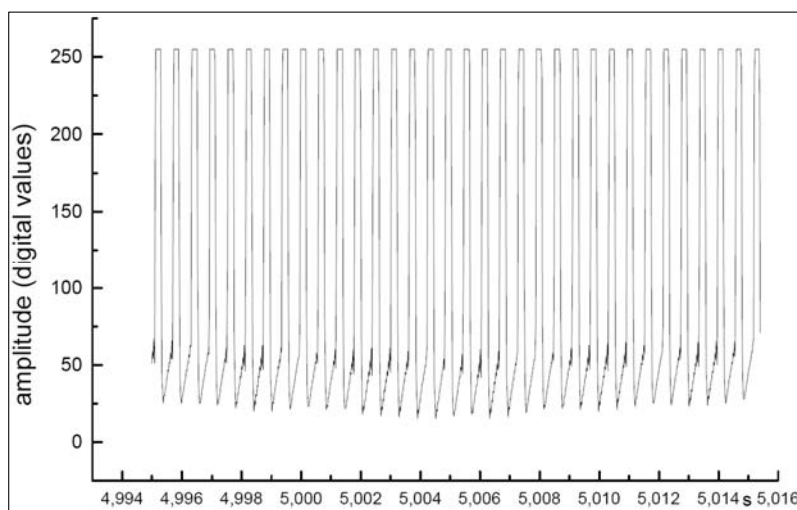


Figure 9. Pulses of reference meter recorded during calibration process.

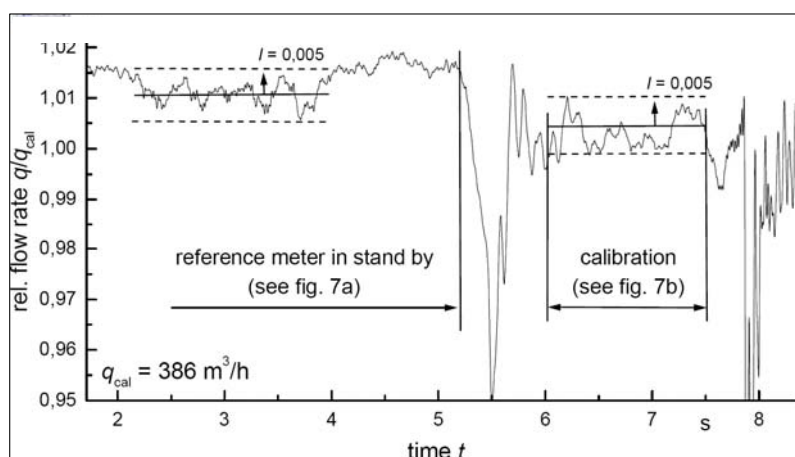


Figure 10. Flow rate indicated by reference meter. The flow rate is calculated from time between two pulses.

Pulse series as shown in figure 9 can be used for determination of an on-line flow indication of reference meter based on time between two pulses. Figure 10 gives example of flow rate plot measured. In the first part of the curve (up to time $t = 5.2$ s) the reference meter stands by as shown in figure 7a. In this range the normal short time stability of flow can be observed. A small variation with relative amplitude $I = \Delta q/q = 0,005$ normally occur. After switching starting valves S1 and S2 (see also figure 7b) the piston accelerates which can be seen in flow rate indication (drop down going and up going within time $t = 5,2 \dots 5,8$ s). At the end of acceleration of piston the flow rate is a little smaller than before starting the piston due to the slightly higher flow resistance. To avoid any additional oscillations caused by flow regulators, these regulators are frozen during prover run.

Reaching the volume switches a_2 , b_2 and c_2 (see figure 7) at time $t = 6,1$ s the measurement for calibration starts and stops at $t = 7,5$ s (piston at volume switches a_4 , b_4 and c_4). Within that time, the variation of flow rate observed in meter indication has the same level as it is normal for the piping system of PIGSAR™.

Short time after end of measurement the piston reaches the end of the cylinder and stops immediately. Hence, the flow is decreased rapidly for a short moment what can be observed at time $t = 7,75$ s. The flow rises again with pulsation caused by pressure wave. It is impressive to see, how fast the meter can follow these flow variations.

With the procedure described above, the result at each working point are determined from 10 single measurements. The reference meter is calibrated in three pressure stages (16, 35 and 50 bar) and 10 different flow rates at each pressure stage. Figure 11 shows the results of calibrations in the years 1993, 1995 and 1998. Polynomials are used to describe the calibration curve over the whole Reynolds range. The quality of measurements with piston prover and long time stability of PIGSAR's base standard is documented by the small drift of less than 0,04 % over the years and lies within the uncertainty range which is calculated (see also [2] or [3]).

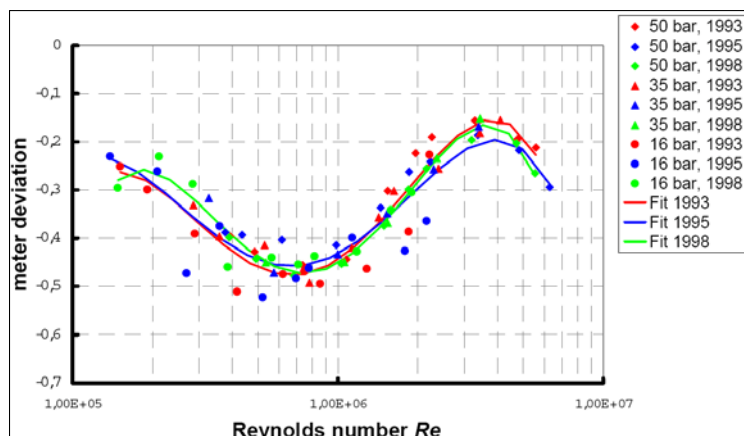


Figure 11. Reference meter calibration with High Pressure Piston Prover (HPPP): results of three calibration periods. Each single point was determinate by 10 single measurements. The resulting calibration curves are polynomials depending fitted with Least Square Method. The very small drift between calibrations curves of less than 0,04 % all over the Reynolds range has to be emphasised.

4.0 Procedure of Working Standard Calibration within PIGSAR™

In the following the stepping procedure of calibrating PIGSAR™ test rig will be described with outlines of flow given in figure 13 to 15. The first step given in figure 13 is the calibration of a reference meter as described above. In principle it would be of course possible to calibrate every working standard of PIGSAR™ with the piston prover in the same manner as the reference meter. The main reason for using a reference meter here is the impact of the so-called line-pack-effect on measurement uncertainty (see also [2]). The amount of line-pack-effect depends on the ratio of volume used for calibration V_{HPPP} and dead volume V_{D} between piston and meter under test as well as the relative difference of temperature and pressure (temperature drift $\Delta T_{\text{Drift}}/T$ and pressure drift $\Delta p_{\text{Drift}}/p$) between start and stop of measurement. In case of piston prover the volume used for calibration is only $0,15 \text{ m}^3$, therefore only a small dead volume is acceptable. The size of dead volume is for working standards in PIGSAR™ about 3 m^3 but for reference meter only $0,4 \text{ m}^3$.

Assuming small drifts you can describe the real volume V_{Meter} going through the reference meter as:

$$V_{\text{Meter}} = V_{\text{HPPP}} \frac{T_{\text{Meter}} \cdot p_{\text{HPPP}} \cdot K_{\text{Meter}}}{T_{\text{HPPP}} \cdot p_{\text{Meter}} \cdot K_{\text{HPPP}}} + V_{\text{D}} \left(\frac{\Delta T_{\text{Drift}}}{T} - \frac{\Delta p_{\text{Drift}}}{p} \right)$$

V_{Meter} - real volume at reference meter

$T_{\text{Meter}}, T_{\text{HPPP}}$ - gas temperature at reference meter or HPPP resp.

V_{HPPP} - volume displaced by piston prover

$p_{\text{Meter}}, p_{\text{HPPP}}$ - pressure at reference meter or HPPP resp.

V_{D} - volume between piston and reference meter

$\Delta p_{\text{Drift}}/p$ - difference of pressure between start and end of measurement

$K_{\text{Meter}}, K_{\text{HPPP}}$ - compressibility at reference meter or HPPP resp.

$\Delta T_{\text{Drift}}/T$ - difference of temperature between start and end of measurement

The maximal expected uncertainty due to line-pack-effect can be estimated by reproducibility measurements because the line-pack-effect is mostly random if experimental conditions are under control. Figure 12 shows measurements of reference meter deviations with HPPP at different pressures and flow rates. The maximal determined double standard deviation (reproducibility) of meter calibration is 0,043 %.

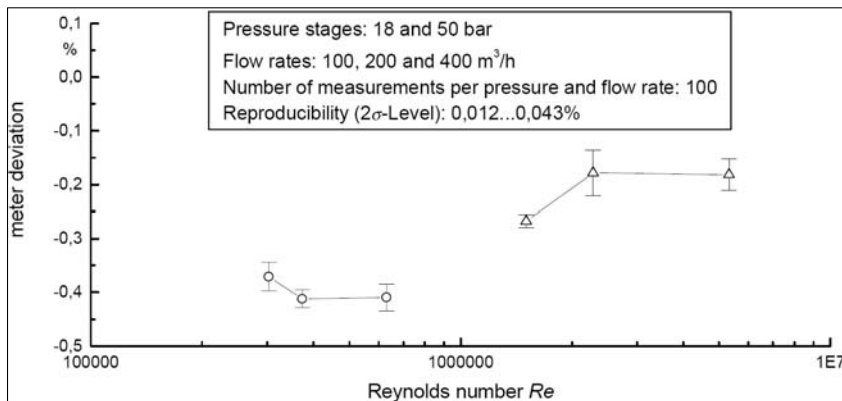


Figure 12. Reproducibility investigation of reference meter calibration using High Pressure Piston Prover (HPPP). In the graph the double standard deviation of 100 measurements at different pressures and different flow rates are given. The maximal value of double standard deviation indicates the maximal expected uncertainty due to line-pack-effect for a single measurement.

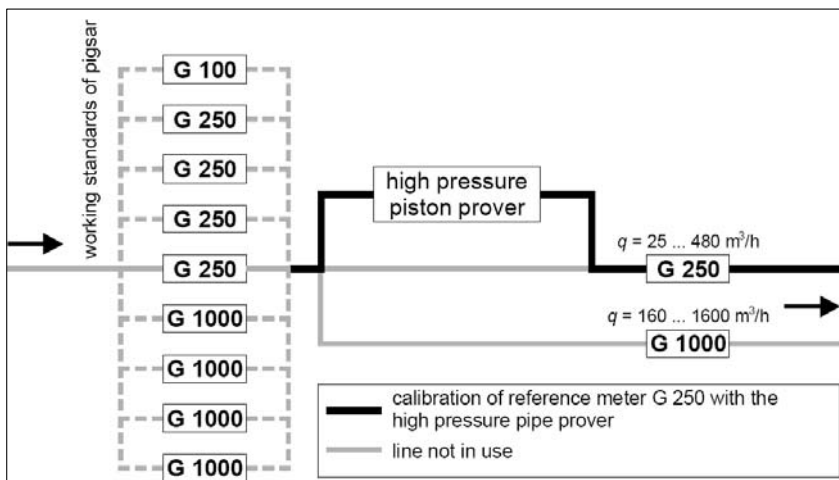


Figure 13. Outline of flow during reference meter calibration with High Pressure Piston Prover (HPPP)

In the next step (figure 14) the reference meter is used to calibrate every working standard up to the maximal flow rate of reference meter of $q_{\max} = 480 \text{ m}^3/\text{h}$. Here the ratio of dead volume to volume measured is much better because the volume measured is at least 4 m^3 . In this step the flow bypasses the piston as described in figure 7a. Hence, the reference meter has the same flow condition as in the step before, which avoids additional installation effect.

The minimal flow operated by piston prover is $25 \text{ m}^3/\text{h}$, therefore it is necessary to get other calibration sources to expand the range of PIGSAR™ to its full size down to $8 \text{ m}^3/\text{h}$. For that purpose a smaller working standard (G100, $q_{\max} = 160 \text{ m}^3/\text{h}$, $q_{\min} = 8 \text{ m}^3/\text{h}$) was chosen and an additional calibration with atmospheric air done at PTB was used to determine the calibration curve over the Reynolds range. The meter used here was extensively investigated to ensure that the calibration curve depends on Reynolds number smoothly.

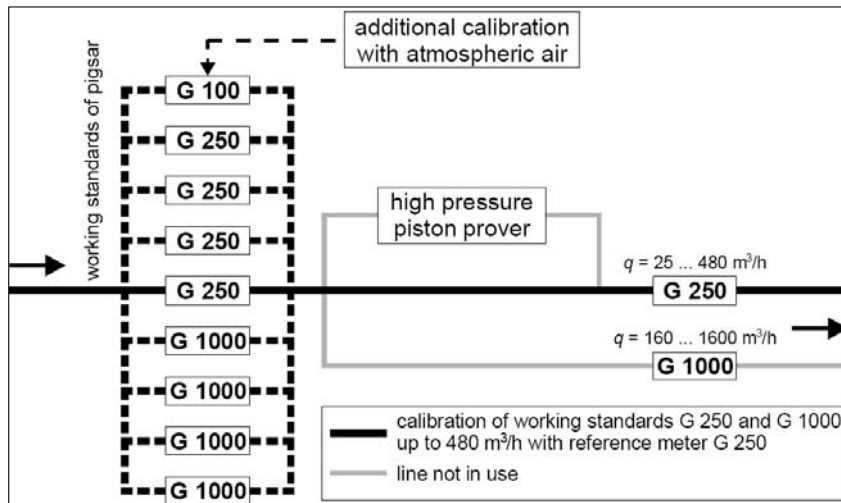


Figure 14. Outline of flow during working standard calibration with reference meter up to 480 m³/h.

To reach higher flow rates than 480 m³/h a transfer meter of size G1000 ($q_{\max} = 1600 \text{ m}^3/\text{h}$) is used. Figure 15 shows the calibration of it with the four working standards used in parallel.

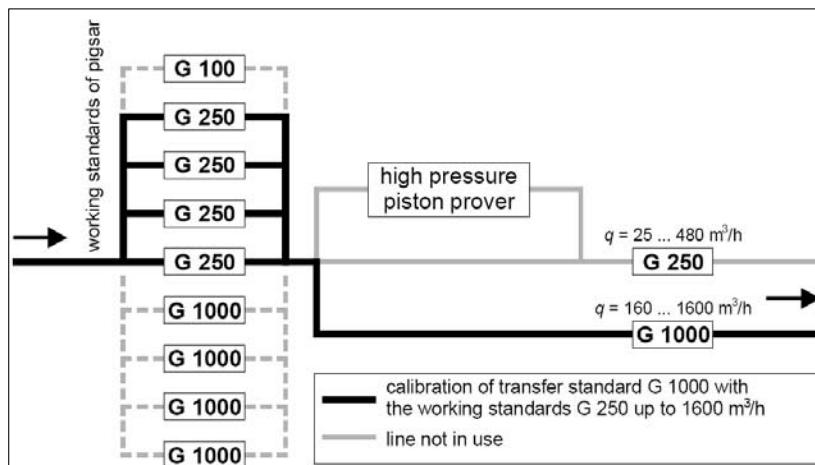


Figure 15. Outline of flow during transfer standard calibration with working standard higher than 480 m³/h

Finally (figure 16), the working standards G1000 are calibrated with the transfer standard up to their maximal flow rate. Again, the position and flow conditions of transfer standard are not changed, therefore no additional installation effects could occur. To control the quality of calibration the flow ranges of calibration of working standards G1000 with reference meter and with transfer standard are overlapping.

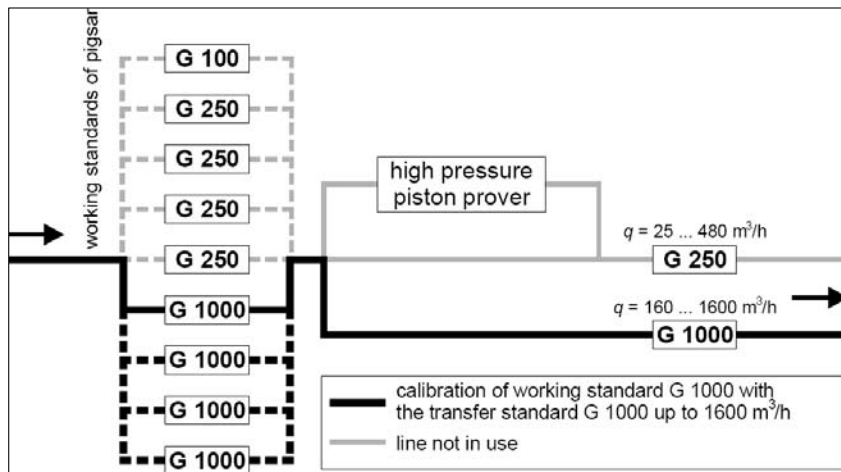


Figure 16. Outline of flow during calibration of working standard G1000 with transfer standard G1000 at flow rates higher than 480 m³/h

5.0 Summary of Uncertainties

For an analysis of uncertainty for meter deviation f_N in each stage N of stepping up a functional model is necessary. Following principal model is used:

$$f_N = \frac{V_N \cdot \rho_N}{T_N K_N \cdot \sum_{i=1}^n \frac{V_i \cdot \rho_i}{T_i K_i \cdot (1 + f_i)}} - 1$$

i - index of meters calibrated in the previous step

N - meter calibrated in actual step

n - number of meters parallel used for calibration

f - meter deviation

V - volume indicated by meter (or displaced geometric volume by HPPP in the first step)

ρ - pressure

T - temperature

K - compressibility

If the meter under test (last step, calibration for customers) is a mass meter (e.g. coriolis meter) then the meter deviation f_N is determined as:

$$f_N = \frac{m_N}{\sum_i^n \frac{V_i \cdot \rho_i}{(1 + f_i)}} - 1$$

ρ - density

The detailed analysis based on given model is documented in [2]. There are also correlation included which have to be taken into consideration if several meters are used for calibration.

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(for compressibility determination according SGERG88 [6])	0,15 %
CO2 level measurement(for compressibility determination according SGERG88 [6])	4,7 %
Normal density - measured with single-sinker densitometer [5] - calculated from gas composition according SGERG88 [6]	0,15 % 0,1 %
Line-pack effect	Depends on measuring point
Meter deviation function (regression)	From previous stage

Table 3 give a summary of the relative uncertainties of input variables.

6.0 Harmonisation and Common Reference Level for High Pressure Natural Gas between Germany (PTB) and Netherlands (NMI)

In international trade a low uncertainty and high stability of meter calibration is the metrological base for fair transactions. Due to the huge amount of gas traded between two countries e.g. Netherlands and Germany any small difference in calibration chains of both would lead to a monetary disadvantage of one of the trade partners.

Figure 17 gives typical results of a meter calibration done at PTB (PIGSAR™) and NMI (Bergum) in pressure stages 20 and 50 bar. The meter deviation curves with their uncertainties overlapping quite well in the Reynolds range, far better than the tolerances for measuring uncertainties specified. This demonstrates the high reproducibility of meters commercially available. Due to this high reproducibility which is much better than the uncertainty, a difference $\Delta_{PTB-NMI}$ between the calibration in the Netherlands and Germany can be observed. It has to be emphasised that such a difference is not significant (because it is less than the uncertainty range) but commercial customers might utilise it for unfair advantage in trade.

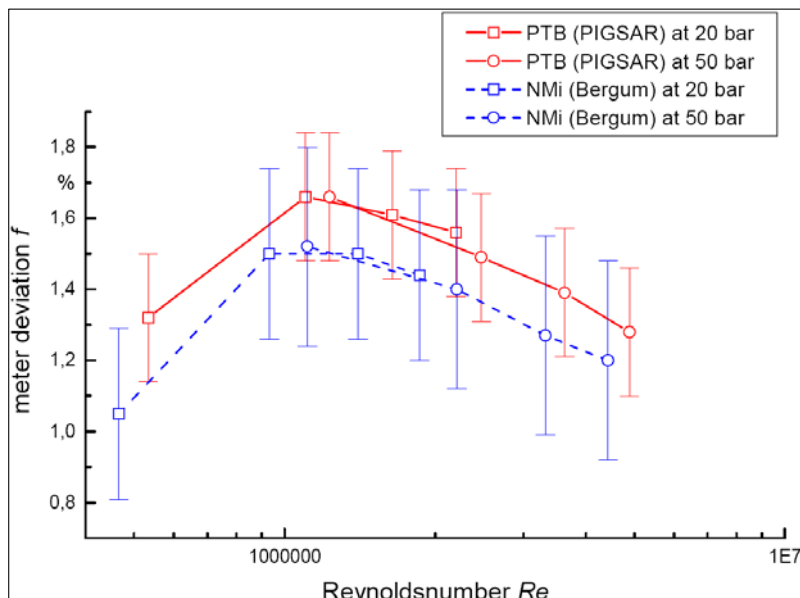


Figure 17. Typical results of meter calibration done at PIGSAR™ and NMI (Bergum) before harmonisation. All results of meter deviation f are inside the overlapping range of the uncertainty levels. Only due to high reproducibility of both calibration facilities as well as gas meters (which is much better than the uncertainties) a difference $\Delta_{PTB-NMI} = f_{PTB} - f_{NMI}$ can be observed.

The uncertainty levels ($k = 2$) shown in the graph are the particular uncertainties of PIGSAR™ and NMI.

Concerning their responsibility for metrology the NMI Netherlands and the PTB Germany initiated 1998 a process of harmonisation to avoid differences $\Delta_{\text{PTB-NMI}}$ between the meter calibration performed in both countries [1], see figure 17. The preconditions for that process are the equivalence and independence of the traceabilities of the countries.

Equivalence was defined as:

- Stability of each of the chains has been demonstrated. Stability refers to the reproducibility of the reference value over the years.
- The uncertainty budget of each of the systems is fully known and mutually accepted
- A permissible difference between the two systems smaller than Root Square Sum of the corresponding uncertainties (2σ) is established.
- Degree of equivalency is established (based on historic performance and on uncertainties).

Independence:

The chains are independently traceable to the SI-units.

- At NMI VSL a system based on mass-comparison of gas-flow is in use (basic verification system).
- PIGSARTM (PTB) has a traceability chain in operation on a Piston Prover (volume comparison).
- Both calibration chains are completely independent of each other.

Type of meters	Reynolds balanced turbine meters
Number of meters per package	2 (two different construction in each meters)
Diameters	DN100 (4"); DN250 (10"); DN400 (16") all packages in ANSI600
Pressure stages used in harmonisation	20 and 50 bar
Flow rates (working conditions)	40 ... 400 m ³ /h (DN100); 400 ... 4000 m ³ /h (DN250); 650 ... 6500 m ³ /h (DN400)
Length of inlet pipe (each meter)	5 diameter
Length of outlet pipe (each meter)	3 diameter
Flow conditioner at inlet	Zanker - type
Over all length per package	22 diameter

Table 4. Technical Data of Transfer Packages

To reach the aim of harmonisation in a maximum range a huge number of comparison measurements had to be done. For that purpose three transfer packages were built up. The technical data are given in table 4 and an outline in figure 18. With every transfer package a comparison measurement at pressure stages 20 and 50 bar⁶ where done by both partners. So, in summary 12 pairs of comparable meter calibrations were collected.

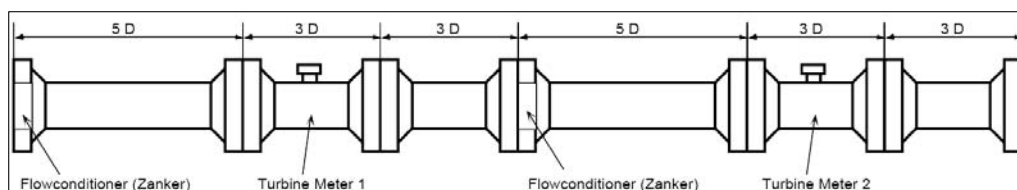


Figure 18. Outline of transfer packages used for harmonisation.

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 result. In figure 19 an example of one pair of meter calibration is given. The meters used in the packages are Reynolds balanced, therefore the determination of difference $\Delta_{PTB-Ref}$ ($\Delta_{NMI-Ref}$ resp.) to the common reference level is done with respect to Reynolds number. In practise each pair of measuring point 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 19. The weighted average f_{Ref} is calculated now using the polynomials.

The differences $\Delta_{PTB-Ref}$ and $\Delta_{NMI-Ref}$ are determined for each measured point relative to average polynomial.

⁶ In the case of DN400-package, NMI did also measurements at 60 bar (Westerborg).

$$f_{Ref} = w_{NMI} f_{NMI} + w_{PTB} f_{PTB} \quad \text{with } w_{NMI} = \frac{1}{\frac{U_{NMI}^2}{U_{PTB}^2} + 1} \quad \text{and } w_{PTB} = \frac{1}{\frac{U_{PTB}^2}{U_{NMI}^2} + 1}$$

$$\Delta_{PTB-Ref} = f_{PTB} - f_{Ref} \quad \text{and} \quad \Delta_{NMI-Ref} = f_{NMI} - f_{Ref}$$

f - meter deviation
 Δ - difference
 f_{Ref} is the meter deviation of the meter under test based on the harmonised high pressure cubic meter of NMI and PTB
 w - weighing factor
 U - uncertainty ($k = 2$)

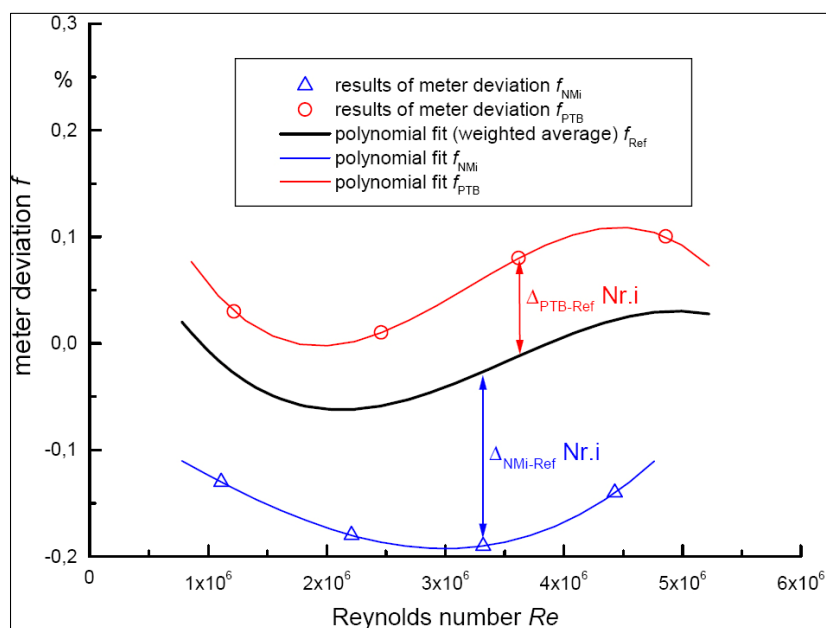


Figure 19. Results of comparison for one meter in one pressure stage and determination of differences $\Delta_{PTB-Ref}$ and $\Delta_{NMI-Ref}$

Finally, all determined differences $\Delta_{PTB-Ref}$ and $\Delta_{NMI-Ref}$ for all meters in all pressure stages were put in to one graph depending on Reynolds number (figure 20). The reproducibility (double standard deviation) of calibrations are less than the half of 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 both partners, NMI and PIGSARTM.

The determined difference $\Delta_{PTB-NMi}$ between NMi and PIGSARTM increases slightly with Reynolds number. The inclination of the results of NMi 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 $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$ in figure 20 finally approximated by a linear function depending on 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.

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:

$$U_{Ref} = \sqrt{w_{NMi}^2 U_{NMi}^2 + w_{PTB}^2 U_{PTB}^2} \quad \text{with} \quad w_{NMi} = \frac{1}{\frac{U_{NMi}^2}{U_{PTB}^2} + 1} \quad \text{and} \quad w_{PTB} = \frac{1}{\frac{U_{PTB}^2}{U_{NMi}^2} + 1}$$

U - uncertainty ($k = 2$) w - weighing factor
 U_{Ref} is uncertainty of the deviation of meter under test based on the harmonised high pressure cubic meter of NMi and PTB

E.g. if both parties would have equal uncertainties of $U_{NMi} = U_{PTB} = 0,1\%$ the resulting uncertainty would be $U_{Ref} = 1/\sqrt{2} \cdot 0,1\% = 0,07\%$. In the harmonisation process an over-all uncertainty level $U_{Ref} = 0,15\%$ was determined.

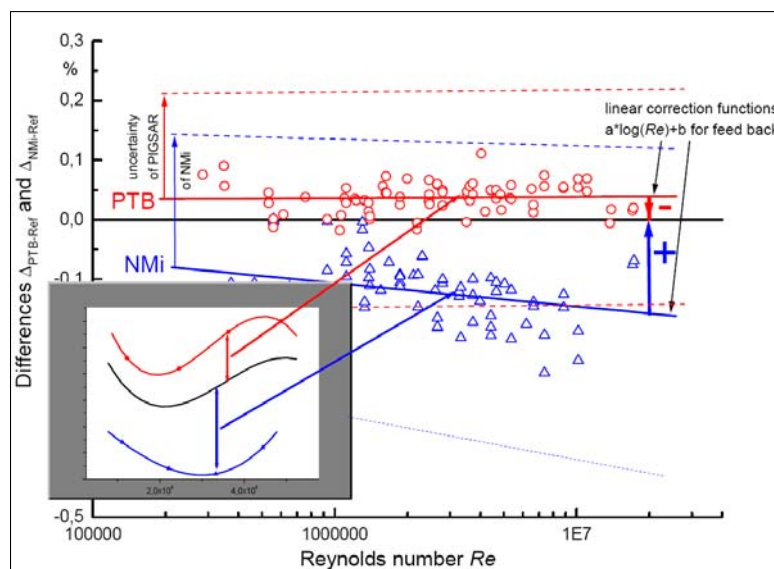


Figure 20. Summary of all determined differences $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$ for all meters in all pressure stages plotted as function of the Re-number. The difference between both traceability chains is clearly to be seen but much smaller than the uncertainties. Within the reproducibility 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 $\Delta_{PTB-Ref}$ and $\Delta_{NMi-Ref}$ were determined. The uncertainty levels ($k = 2$) shown in the graph are the particular uncertainties of PIGSARTM and NMi.

After establishing and disseminating the harmonised cubic meter since November 1999 regular checks have been necessary. These checks (so-called watchdog checks) have been done every half year with at least one of the transfer packages. With an example of these results this paper should close. In figure 21 the result of two watchdog checks for one meter of the DN250-package (10") are given. Comparing these results with the example in figure 17 the improvement is to be seen. First there is no difference between German and Dutch calibration which can be utilised. Secondly the uncertainty is reduced to the common level of 0,15 % and thirdly the reliability of long term stability of calibration chains is improved due to the regular checks.

Finally, it should be pointed out explicitly, that both NMIs, namely PTB (Germany) and NMI (The Netherlands) are disseminating since November 1999 the same ("harmonised") high pressure natural gas cubic meter for all calibrations, which are performed at their test facilities.

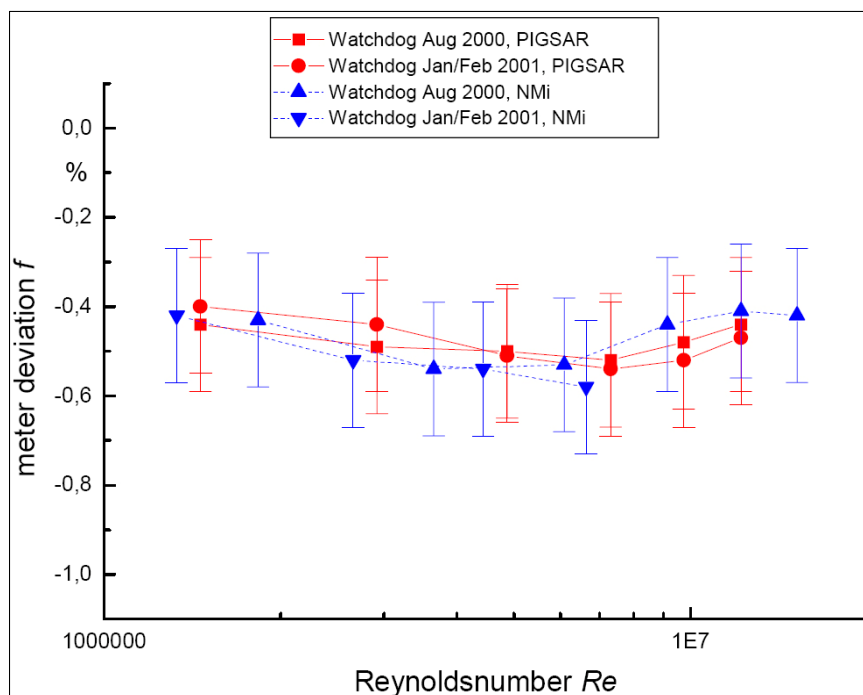


Figure 21. Calibration of a turbine meter DN250 (10") as watchdog checks . The uncertainty level ($k = 2$) shown in the graph is the uncertainty $U_{\text{ref}} = 0,15\%$ of the harmonised reference value of PTB (PIGSARTM) and NMI. See also figure 16 to observe the effect of harmonisation. The scale for meter deviation in figure 16 has the same division of 0,2 %.

7.0 Conclusions

In this paper the technical features and measuring capabilities of test rig PIGSARTM and the primary standard of the unit cubic meter in Germany were described. The description of the primary standard and its use for calibration explains the basic calibration process in details and the reliability and stability are documented with results of calibrations over several years. The quite unique capabilities and the high quality of work inside PIGSARTM over years lead to the approval of PIGSARTM by the German National Metrological Institute PTB as the National Standard of High Pressure Gas.

The high accuracy of measurements done at PIGSARTM are documented in this paper by the results of harmonisation process, which based on an agreement of June 1999 between the national metrological institutes of Germany and Netherlands. With harmonisation of both calibration chains and the continuously check of the harmonised reference value a really new metrological approach for mutual benefit in gas metrology has been achieved.

8.0 References

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