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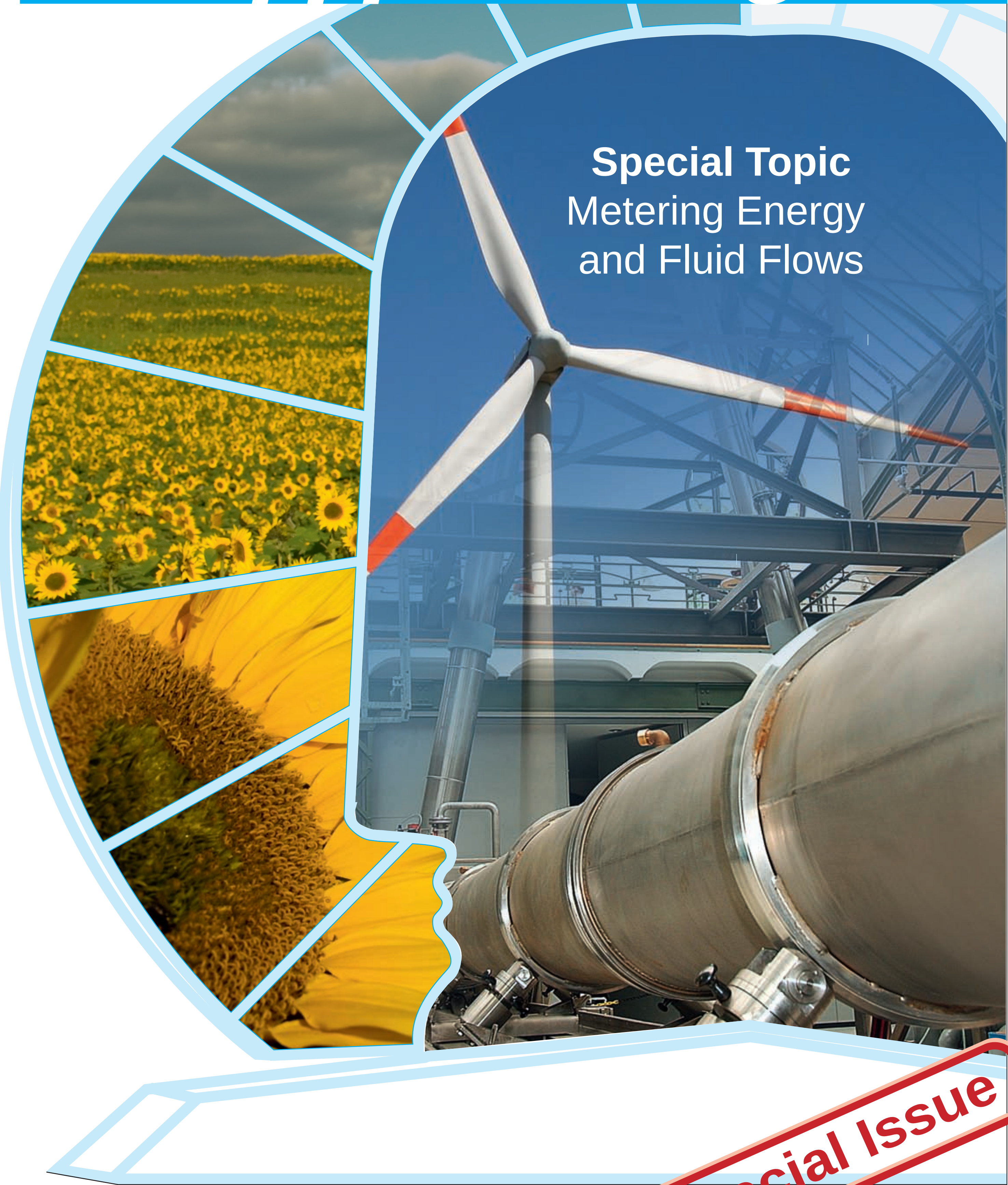
Fachorgan für Wirtschaft und Wissenschaft



Special Topic

Metering Energy
and Fluid Flows

Special Issue

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Metering Energy and Fluid Flows

Roman Schwartz[1], Helmut Többen[2]

In Germany, Europe and worldwide, huge amounts of gaseous and liquid media are moved, measured, traded and – finally – sold to the end consumer. In view of the outstanding economic significance of the supply with gas, water, mineral oil, heat and, lately, also cooling, and of the discussions held in politics on energy efficiency, the future of energy supply, alternative energy sources and climate protection, an accurate and reliable measuring technique for fluid flows and energy is of vital importance.

Climate protection and energy efficiency have increasingly come to the fore in politics and the economy in recent times. By means of EU Directives and their transposition into national law, Europe – and especially Germany – have set themselves ambitious goals for the next few years. One of the most important directives is the "EU Directive 2006/32/EC on energy end-use efficiency and energy services" which was implemented in Germany via the "National Energy Efficiency Action Plan (EEAP) of the Federal Republic of Germany" of 27 September 2007. But also the requirements of "Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for the transport sector", which are also to be found in the Federal Law on Immission Protection and Biofuel Share, are worth mentioning, as well as, for instance, the Law on Combined Heat and Power Generation (CHP).

In detail, these legislative guidelines specify, amongst others, the following goals to be reached by 2020:

- Doubling energy efficiency compared to 1990;
- Replacing fossil fuels by 20 %;
- Increasing the efficiency of power plants by 40 %;
- Ensuring the heat supply of new buildings without using fossil fuels.

As already mentioned at the beginning, a reliable and accurate measurement of the liquid and gaseous energy carriers used, not only with regard to their quantity but also with regard to their energy content, is of considerable importance for this purpose.

But also technical progress and the rapid development of novel technologies such as, e. g., in the field of micro and nano technologies, place new requirements on the measurement of fluid flows. Basically, it is no longer the task to just determine the quantity of a product, but rather to ensure, for example, the quality of an overall production process by means of real-time measurements, the operational safety of a large-scale plant or power plant or, in medical care, the correct dosing of an infusion or of an artificial respiration.

Last but not least, consumer protection must be mentioned as an important legal task of PTB which, due to the new European Measuring Instruments Directive 2004/22/EC ("MID") and its transposition into the German Verification Act, places growing demands on the measurement of fluid flows.

All these aspects and developments of the flowrate, volume and heat measurement of gaseous and liquid media are the subject of this issue of "PTB-Mitteilungen". Starting with an overview of "PTB's Metrological Infrastructure for Gas Measurement" – including "European Harmonisation for High-Pressure Gas" – the following contributions deal with "LDA Utilisation in Flowrate Measurement", "Gas Measurement and Gas Meter Testing in Practice", "Ensuring the Traceability of Volume and Flow Measurements of Liquids", aspects of "Legal Metrology in the Field of Fluid Measurement Technology", „Applied Calorimetry in Flowing Fluids: Heat Meters and Cooling Meters", "Flowrate Measurement in Power Plants", "Renewable Energy Sources – Metrological Challenges in Production and Trade" and finally the topic of "Microflowrate – Flowrates in the Range Microlitre per Minute", i. e. the measurement of small and smallest flowrates of gas and liquids.

We hope that the interested reader will profit greatly from reading theses contributions on the subject of "Metering Energy and Fluid Flows"

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PTB's Metrological Infrastructure for Gas Measurement

Bodo Mickan[1], Rainer Kramer[2]

1 Introduction

PTB operates quite a large number of technical facilities with which gas measurements can be performed in Germany and elsewhere with the same measure. If such a technical basis for calibrating gas meters with uniform reference values did not exist, the principles described in this issue in the article "Gas Measurement and Gas Meter Testing in Practice" could not be implemented to the full extent. In the following, we will give an overview of PTB's technical facilities, whereby the field of gas measurement for high-pressure natural gas will be described in more detail, due to its special importance for the economy and due to the particularities in international trade.

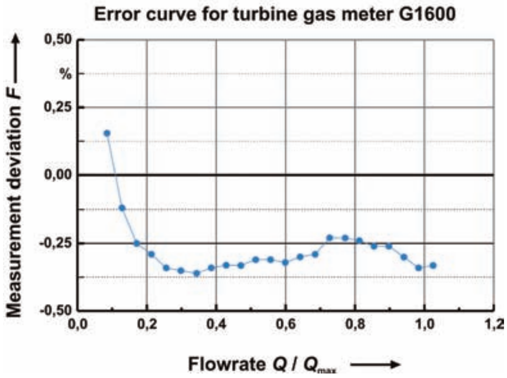

Figure 1:
Typical error curve of a gas meter

2 Fundamentals of calibrations and tests

Test or calibration facilities serve to determine the measurement deviations of a measuring instrument as a function of the utilisation factor – that means, in the case of volumetric meters, of the flowrate. It is usual to indicate the relative measurement deviation F of the object under test according to:

$$F = \frac{V_P - V}{V} = f(Q) \quad (1)$$

Hereby, V_P is the volume indicated by the test object and V is the volume indicated by the reference standard. If several single measurements are performed for each measurement point (flowrate value), the results are scattered around a mean value which can be interpreted as the systematic measurement deviation. The curve of the systematic measurement deviation as a function of the flowrate is called "error curve". It can be used to correct the measurement value indicated by the measuring instrument. Figure 1 shows, as an example, the error curve of a turbine meter measured with atmospheric air.

In general, all types of meters have characteristic error curves. However, it can happen that meters of the same type display strongly shifted error curves. The reason for this lies in production tolerances, storing conditions, distortions, etc.

After a test, a measuring instrument can be adjusted, calibrated or verified:

- *Adjustment:* alteration of the settings of the test object in order to keep the measurement deviation as low as possible over the whole flowrate range;
- *Calibration*: Determination of the measurement deviation over the whole measuring range of interest, in order to be able to correct the measurement result once in use;
- *Verification/certification:* Checking and confirmation of compliance with the maximum permissible errors on verification of an approved measuring instrument by a verification authority or an officially recognised test centre. The validity of verification is generally limited in time.

Test facilities are operated by the most diverse private organisations and public institutions, for example measuring instrument manufacturers, operators of supply networks, local verification offices, calibration laboratories and research institutes.

In order to ensure that measuring instruments work accurately and reliably once in operation at the user's, a closed calibration chain

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must exist which extends from the physical realisation of the SI units (core task of PTB) to the calibration/verification of devices for the end user. In order to fulfil their tasks, testing or calibration facilities make use of appropriate standard measuring instruments which are traced back to the national standards. With such standard measuring instruments, metrologically validated comparisons with the display of the object under test are carried out, e. g. for the volume having flowed through, or for the set flowrate.

Standard measuring instruments are subdivided into primary, transfer and working standards. Primary standards are normally operated at the national metrology institutes in order to realise the units in the range of interest and for the direct traceability to the SI units. Transfer standards are used for the dissemination of the units from the primary standards to the test centres, for the realisation of comparison measurements and for the calibration of working standards. Working standards are used in the different test centres, e. g. at the local verification offices and at the laboratories of the DKD (Deutscher Kalibrierdienst) in order to determine the true (correct) measurement value.

3 Overview of the calibration and testing capabilities of PTB

For the volume measurement of flowing gases, PTB operates various technical facilities which cover a wide range of flowrates or gas quantities. Figure 2 shows the calibration hierarchy for the realisation and dissemination of the units in the field of gas quantity measurement. For the volume, the most important link in the hierarchy of the measuring chain is, of course, the link-up with the unit "meter" (top left in Fig. 2). Since, for the correct determination of a gas volume, it is also necessary to measure the pressure and the temperature in order to take into account the thermodynamic behaviour, corresponding links with the reference standards of these measurands must exist. Furthermore, the metrological properties of gas meters depend nearly always on the flowrate, i. e. on the amount per time unit, and therefore, traceability to the standards of time is necessary as well.

PTB's primary standards for the traceability of volume measurements for gases are, from the point of view of their basic principle, so-called "volumetric standards", i. e. the core of the techni-

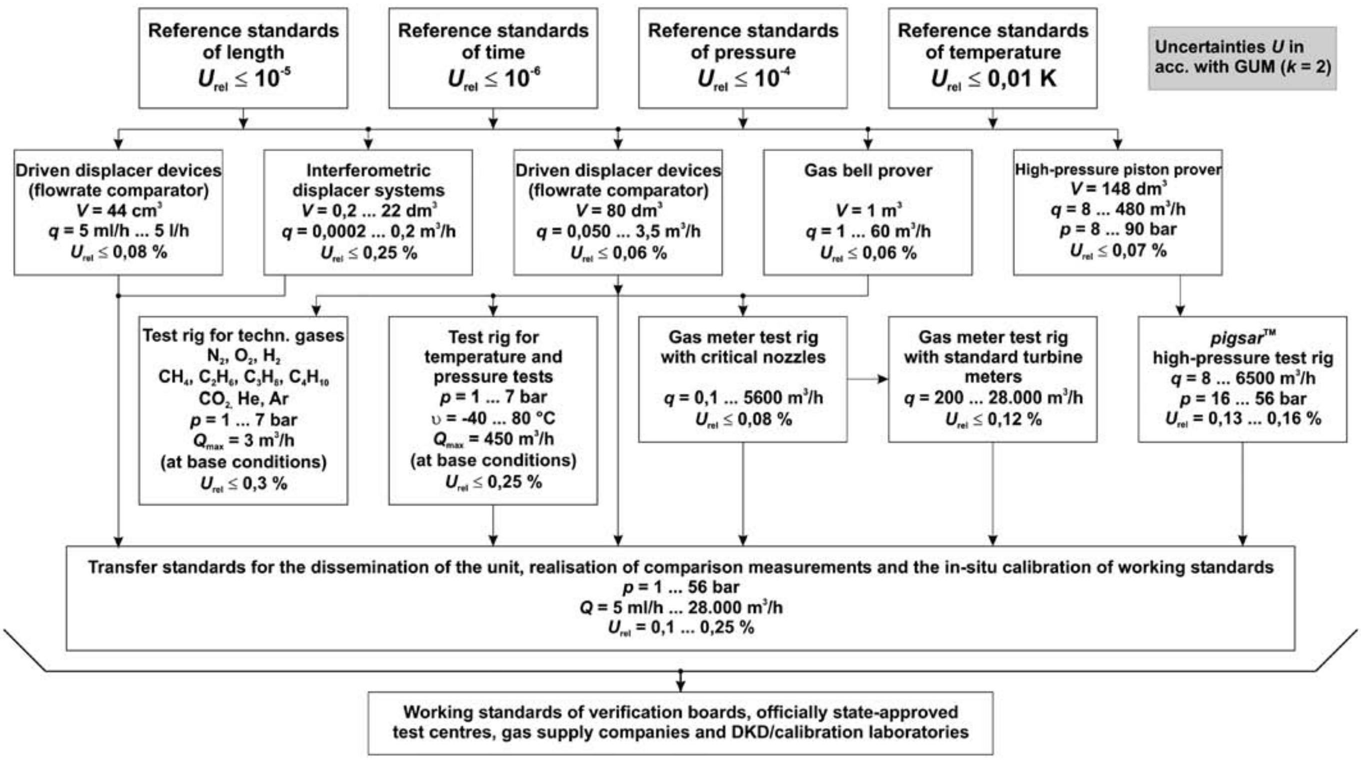

Figure 2:
Overview of PTB's calibration facilities for the determination of flowrates and quantities of flowing gases

cal realisation for the traceability to the meter is a geometrically measured reference volume which serves for the comparison with the display of a test object. PTB's equipment thereby covers a flowrate range from 5 ml/h to 28 000 m^3/h – which represents more than 9 orders of magnitude (factor $5.6 \cdot 10^9$). Together with the – in large parts – achievable measurement uncertainties of approx. 0.06 %, this represents a worldwide unique bandwidth and is, thus, the basis for PTB's internationally recognised position. This has also led to a strong demand for services in the field of gas measurement for third parties.

Apart from the primary standards, PTB also operates test rigs with which the dissemination of the unit can be performed effectively, or with which measuring instruments can be inspected as to their metrological properties in a large application range for pressures and temperatures (from -40 °C to +80 °C). The latter is, in particular for the assessment of the quality of a measuring instrument for commercial transactions, extremely important – amongst others for the end consumer of natural gas.

Due to the great trade volume and cross-border trade with high-pressure natural gas, the sector represented in the far-right corner of Fig. 2 is of extreme significance for the economy. Therefore, we will, in the following, highlight this sector in more detail.

4 National calibration chain and European harmonisation for high-pressure natural gas

Gas meters such as, e. g., turbine gas meters, generally show a dependency of their calibration values on the conditions of application, especially with regard to the operating pressure of the gas to be measured. In order to achieve the lowest possible measurement uncertainty in the operation of these measuring instruments, it is therefore necessary to calibrate them, as far as possible, according to the expected conditions of use. For this purpose, the measuring instruments are subjected to a high-pressure test.

In order to guarantee the high-pressure test, a corresponding metrological basis is necessary. In Germany, six test rigs are currently in use for this purpose; in total, they cover a pressure range of up to 50 bar and flowrates of up to 6500 m^3/h. They are designed for the calibration of commercially available gas meters.

In Germany, the calibration chain for high-pressure natural gas is based on a primary standard of PTB, the so-called "high pressure piston prover" (HPPP), whose way of operation is described in Section 4.1. Since PTB does not have a suitable infrastructure of its own for the operation of a high-pressure standard, it has signed a cooperation contract with E.ON Ruhrgas AG which operates the technically high-grade test rig *pigsar* ™ which has large capacities. Within the scope of this cooperation agreement,

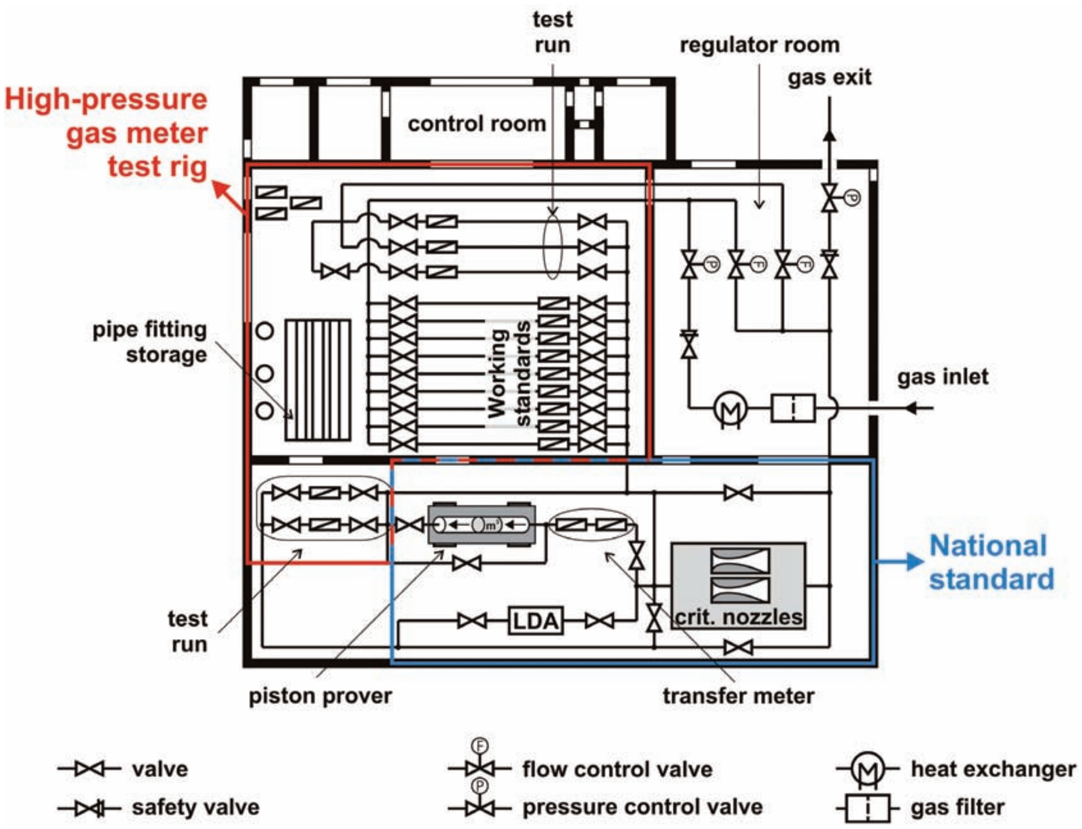

Figure:
Schematic overview of the pigsarTM high-pressure test rig and PTB's national standard for high-pressure natural gas (High Pressure Piston Prover - HPPP)

PTB can operate its facilities for the realisation of the unit there. Figure 3 shows the schematic set-up of the *pigsar*™ test rig and the spatial arrangement of PTB's national standard for the high-pressure natural gas calibration chain. Besides the already mentioned HPPP, further facilities of PTB are located there for research purposes in the field of realisation and dissemination of the unit at high-pressure conditions.

The *pigsar*™ test rig's working standards are calibrated by means of the HPPP for their total range of application. Since the HPPP is not designed for continuous use, the unit "cubic metre" for high-pressure natural gas is disseminated on behalf of PTB by the *pigsar*™ test rig after the working standards have been calibrated. The *pigsar*™ test rig therefore acts as a subcontractor for PTB for the dissemination of the unit to third parties or for comparison measurements with third parties.

A particularity of the high-pressure calibration chain in Germany is the "European Harmonisation". The Federal Republic of Germany has, together with the Netherlands and France, signed an agreement on the harmonisation of the German, Dutch and French calibration chain. On the basis of this agreement, thorough comparison measurements between Germany, the Netherlands and France take place every three years. The comparison measurements serve to determine any differences in the realisations of the units which may lie within the corresponding measurement uncertainty but can yet be observed as being systematic in the sense of reproducible. A correction determined on the basis of the comparison measurements eliminates such differences. Another advantage of this harmonisation lies in the reduction of the measurement uncertainty. A more exhaustive description of the fundamentals and of the method can be found in Section 4.2. Figure 4 shows a schematic overview of the traceability chain for the range of high-pressure natural gas in Germany and the corresponding test rigs with their working ranges for pressure and flowrate, as well as the corresponding measurement uncertainties.

By means of appropriate transfer meters which have been calibrated on the *pigsar*™ high-pressure test rig, five subordinate test rigs are calibrated. For the pressure range between 16 bar and 50 bar for natural gas, this can also be performed – in the classic sense – by comparison of the displayed measured values of the transfer standard with those of the working standard of one specific test rig point by point at the same pressure and same flowrate. For the calibration of test rigs with pressure ranges between 1 and 16 bar or in the case of a change of medium from natural gas to air, additional information must be taken into account in the calibration process. For this purpose, an additional calibration of the transfer meters by means of the PTB standards for air is performed at 1 bar.

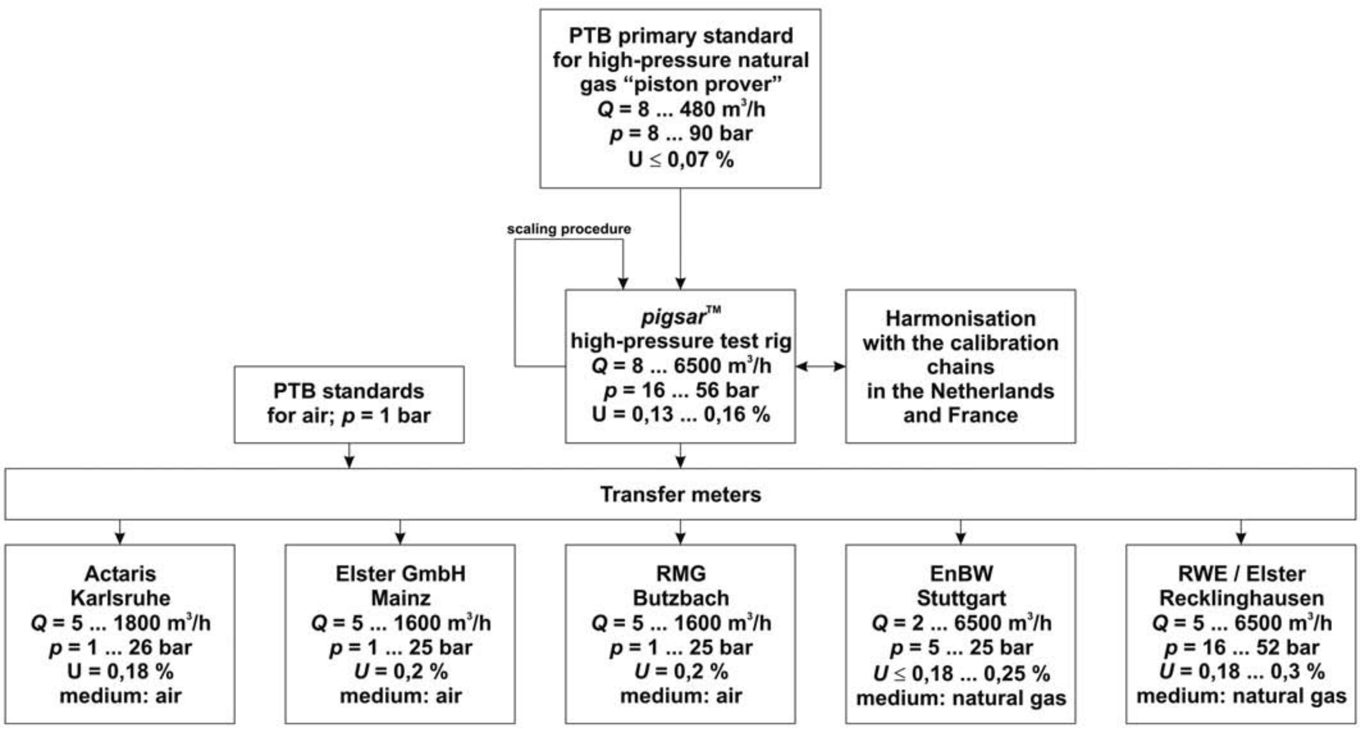

Figure 4:
High-pressure calibration chain in Germany

4.1 High-pressure calibration chain in Germany

PTB's volumetric primary standard for high-pressure natural gas is a passive piston prover system, i. e. it is driven by the gas flow. Over the years, specialists have been calling this specific high-pressure primary standard of PTB the "high pressure piston prover (HPPP)". Figure 5 shows a schematic representation as well as a photo of the piston prover. The core of the piston prover is a geometrically exactly measured cylinder which establishes the reference volume and through which a displacer runs which is driven by the flowing gas. This clearly defined gas volume then flows through the test object – here usually transfer meters such as the permanently integrated turbine gas meter G250. Of course, the local pressures and temperatures in the reference volume and in the test object must be carefully taken into account for the comparison of the gas volumes according to the thermodynamic behaviour of gas.

With the piston prover it is possible to calibrate a test object having a maximum flowrate of 480 m³/h as a transfer meter by comparison with the geometrically measured reference volume with low uncertainty (approx. 0.06%) which, in turn, will be used for further calibrations of the working standards of the *pigsar*™ test rig (and also turbine gas meters, see Fig. 3 and Fig. 4). By means of suitable step-by-step methods, the calibration can be extended beyond the working range of the piston prover to the flowrate range from 8 to 6500 m³/h. The technique and procedures are described in detail in [1].

4.2 European harmonisation between Germany, the Netherlands and France

Especially in international, cross-border trade with goods having a considerable merchandise value – as in the case of trade with natural gas – it is particularly important that the measurements are performed by means of the same measures. Against this background, in 1999, the International Committee for Weights and Measures (CIPM), on behalf of the Metre Convention, launched an agreement on the mutual recognition of calibration results (Mutual Recognition Agreement, MRA) which is an internationally concerted and surveyed method of ensuring the equivalence of calibration and test results, and is thus aimed at ensuring fair methods of trade worldwide.

"Equivalence of calibration results" means primarily that two measurement results for the same test object that have been performed on two different test rigs differ by no more than a certain proportion which is defined by the rules of statistics and the calculus of probabilities. In the case of two measurements (i. e., for example, the determination of the measurement deviation f of a gas meter) which are traced back to two different primary standards, this proportion is determined by the squared sum of the measurement uncertainties corresponding to the measurements:

$$d_{1-2} = f_1 - f_2 \leq 2 \cdot \sqrt{\left(u_1^2 + u_2^2\right)}$$

with u_1 and u_2 standing for the standard uncertainties of the respective measurement result for the measurement deviations f_1 and f_2.

PTB with its calibration facilities is, of course, also embedded in the MRA system and regularly takes part in corresponding international comparison measurements. In the field of intra-European trade with natural gas, this process culminated in an agreement between PTB, the Dutch "Van Swinden Laboratories (VSL)" and the French "Laboratoire National de Métrologie et d'Essai (LNE)" on the realisation and dissemination of a joint reference value to determine the volume of high-pressure natural gas (the so-called "Harmonised European Cubic Metre") [2].

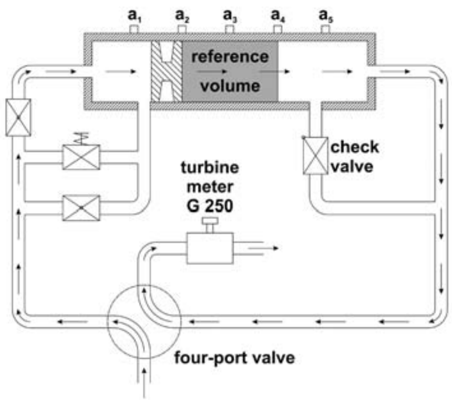

Figure 5:
PTB's primary standard for high-pressure natural gas (High Pressure Piston Prover)
a_1, a_5: plunger position switch
a_2: volume switch (start)
a_3, : volume switch (halfway)
a_4: volume switch (stop)

This joint reference value has been determined at regular intervals and via thorough comparison measurements between the partners since 1999.

From a certain point of view, the harmonisation agreement leads even further and goes beyond the simple proof of equivalence of all measurements performed by the signatory partners. What is decisive is that the total measurement uncertainty of a measurement result obtained on one of the test rigs of the signatory partners does, to a large extent, not depend on random measurement errors only. This is shown schematically in Figure 6. Each of the partners determines the calibration quantity of the comparison measuring instrument on his test rig – this is shown by the arrows in different colours. The centre of the target is the true (for us unknown) value of the calibration quantity. Since all measurements, as they are described above, are equivalent to each other, all measurements hit the target. Multiple shots, however, do not considerably modify the overall picture, i. e. the arrows of each partner (e. g. the green arrow representing PTB) always hit the same area (symbolised by small yellow spots around the arrow tips) with a small scattering. Metrologically speaking, this means that the reproducibility of the measurements (yellow spots) is significantly smaller than the measurement uncertainty. Obviously, in cross-border trading, this circumstance easily leads to the situation that the users of the measuring instruments select the test rigs according to their needs: depending on whether they are buying or selling gas, they could choose that test rig that is most favourable for the calibration of their measuring instrument.

Mathematically, the joint harmonised reference value $f_{\text{reference value}}$ is determined according to the rules of the measurement uncertainty determination of independent measurements [3] and is based on a weighted mean value of the measurement results:

$$f_{\text{reference value}} = w_1 \cdot f_1 + w_2 \cdot f_2 + \ldots + w_n \cdot$$

with

$$w_i = \frac{1}{u_i \cdot \sum_k \frac{1}{u_k}}$$

where u stands for the standard uncertainties of the measurement results f of the individual harmonisation partners. In the schematic diagram in Figure 6, it is represented as the green dot in the target which now comes closest to the true value.

As a result of this, each i^{th} harmonisation partner has a value

$$d_i = f_i - f_{\text{reference value}}$$

at his disposal which, as a correction factor of the respective calibration chain, eliminates the systematic differences between the harmonised partners.

Figure 7 shows typical results for the calibration of a turbine gas meter of PTB (*pigsar*™) in Germany and of NMi (now VSL) in the Netherlands before 1999 and after the coming into force of the harmonisation, i. e. after 1999. They show that the difference prevailing before 1999 could be considerably reduced and that the only differences still occurring are random fluctuations which can no longer be systematically exploited to the disadvantage of a partner in trade. Of course, it is particularly important for the overall process to ensure a continuous check of the stability of the participating calibration facilities – which is guaranteed in the agreement between Germany, the Netherlands and France by bi-annual comparison measurements.

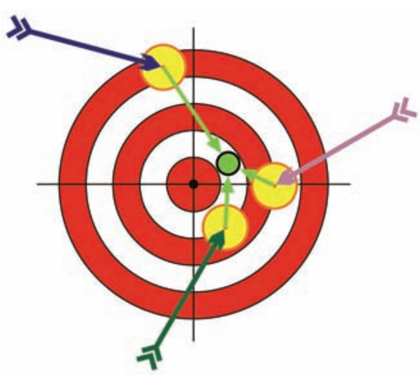

Figure 6:
Representation of the visualisation of the relations between the measurement results of the different test rigs as a function of the true value.

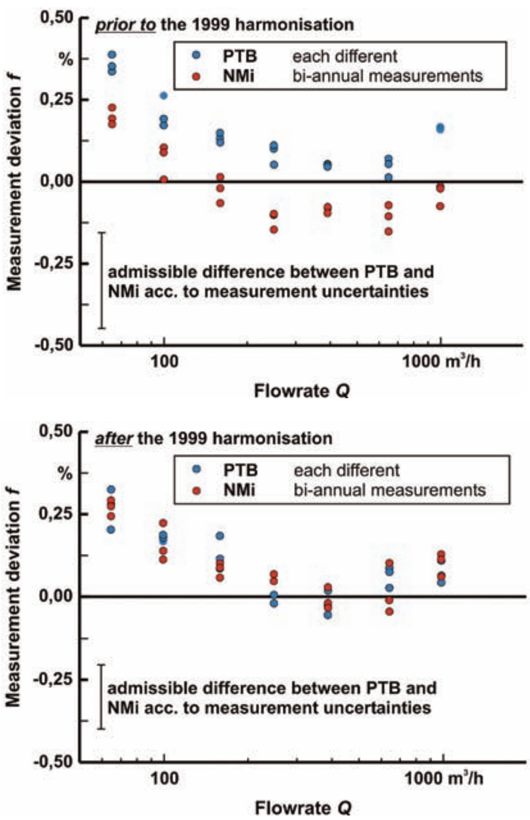

Figure 7:
Typical measurement results for the calibration curve of a turbine gas meter at 35 bar with natural gas on the test rigs of PTB (pigsarTM) and of the NMi Netherlands, (now VSL) before and after the harmonisation in 1999.

6 Summary

Trade with gas has a great economic significance, especially because natural gas has become one of the most important fuels in Germany. Accordingly, the availability of a uniform measure for the volume determination of gas is of paramount importance. PTB therefore operates an exhaustive infrastructure to enable the traceability of all gas measurements to the SI units. Furthermore, there is an agreement with the Netherlands and France to ensure a uniform measure (European Harmonisation) for cross-border trade with high-pressure natural gas within Europe.

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LDA Utilisation in Flow Measurement

Harald Müller[1], Volker Strunck[2], Norbert Pape[3], Jessica Kampe[4]

1 Introduction

As a matter of principle, all measurement results in the field of flow measurement are not only defined by the quantity of the measurands to be determined, but also by the retroaction of the measuring instruments on the flow, which depends on the specific properties of the device. In particular the use of non-interacting optical measurement procedures therefore offers a high potential to reduce the measurement uncertainties for the realisation and dissemination of the units of flow measurement quantities.

For flowing media, especially the volume flowrate is a decisive measurand which can be traced back directly via the measurement of flow velocities or via the analysis of flow velocity profiles and fields of cross-sectional areas in measuring chambers, pipes or ventilation shafts. The accurate, non-interactive and thus laser-optical flow velocity measurement in flowing media is therefore of paramount importance.

In this context, laser Doppler anemometers play a particular role: as high-accuracy measuring instruments, they make it possible to measure flow velocities in optically transparent media with typical measurement uncertainties in the range of 0.1 % with high spatial and temporal resolution. Therefore, laser Doppler anemometers, which were traced back (calibrated) by PTB, are becoming increasingly used in calibration laboratories, test facilities for the flowrate measurement of air and natural gas, and at large-scale test rigs for fluid and heat measurement as transfer standards for the recording of the measurand „flow velocity“

2 Laser Doppler Anemometers (LDAs)

2.1 Basic principle of LDAs

The conventional laser Doppler anemometers (LDAs) which are normally used work according to the cross-beam method – which is also called “Doppler difference method”.

For this method, a collimated laser beam is divided via a beam splitter into two partial beams of the same intensity. These two partial beams are superimposed by the imaging optics of the LDA probe in the measuring volume where an interference field is formed having a fringe spacing Δx (Fig. 1).

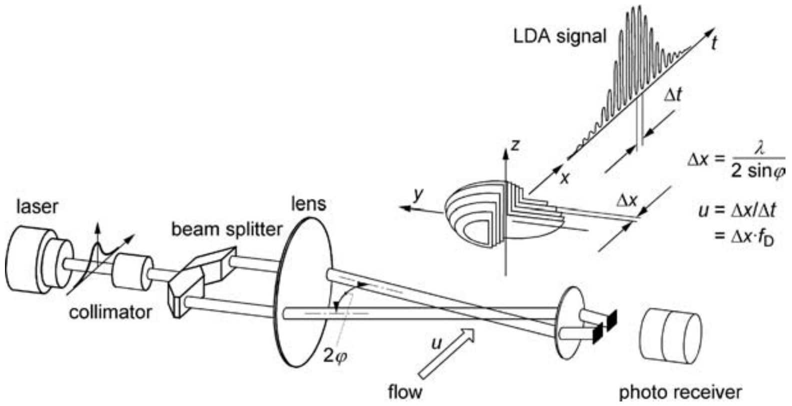

Figure 1:
Schematic representation of an LDA system according to the crossbeam method

If a particle moving with the flow crosses the interference fringe field with a velocity u, the light scattered by the particle from the crossing area generates on a photoreceiver a periodically modulated signal whose modulation frequency f_D is directly proportional to the velocity component u to be measured. Via the Doppler frequency f_D analysed from the photoreceiver signal and the fringe spacing Δx known from the laser Doppler anemometer calibration, it is possible to directly determine the velocity component u with a spatial resolution which is pre-defined by the size of the measuring volume.

For conventional LDA systems with common working spacings in the range of only few decimetres, one obtains measuring volume sizes with measuring volume lengths of approx. 1 mm to 2 mm and measuring volume diameters of some 100 μm.

2.2 LDA calibration

For precise velocity measurements, the LDA system must be calibrated. Thereby, the fringe spacing Δx is determined in the LDA measur-

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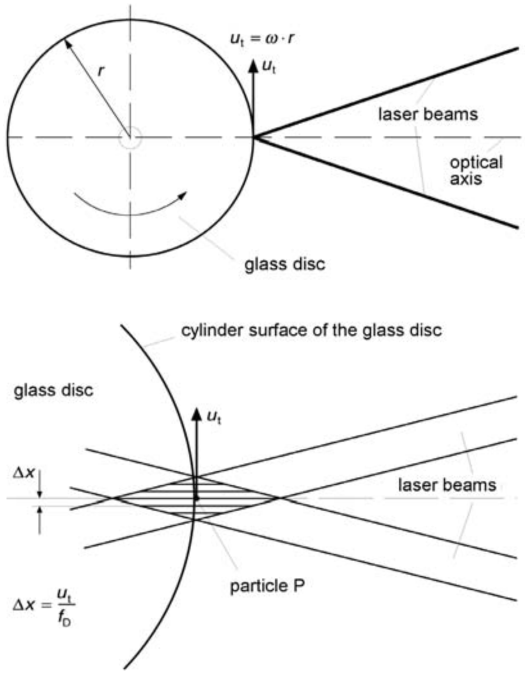
ing volume which depends on the LDA optics (collimators, lenses, apertures) used and on their adjustment, as well as on the radiation characteristics of the laser. LDAs are calibrated by a velocity primary standard realized by a rotating disc (see Fig. 2).

In the case of a disc radius r, which has been determined in a geometrically exact manner, the "standard" velocity u_t of single scattered particles selected at the lateral surface of the polished cylinder results from the angular speed ω which has been predefined with high accuracy.



Figur 2:
Principle of the LDA calibration for the determination of the interference fringe spacing Δx via a defined particle velocity u_t which is generated by a rotating glass disc.

The spatial dependence of the fringe spacing, which serves as a material measure of length in the measuring volume, is checked before an LDA system is used as a transfer standard for calibration purposes, and is minimised as far as possible by adjusting the LDA transmitting optics. The lower limit of the measurement uncertainty for the LDA calibration is mainly caused by the uncertainty of the realisation of the velocity by means of a rotating glass disc as a velocity standard – which is currently estimated to be of approx. 0.05 %. In the case of semiconductor LDA systems, one obtains, with the usually achieved homogeneity of the LDA fringe system, typical measurement uncertainties in the range of 0.2 % ($k = 2$) for velocity measurement.

3 Laser Doppler Anemometers – selected fields of application

3.1 Calibration of anemometers

Correspondingly to the variety of different designs and physical principles, anemometers are used for various applications in flow measurement. They cover applications ranging from ventilation and air-conditioning techniques to wind energy and meteorology, and also to the determination of volume flowrates in ventilation channels and pipe systems.

In order to assess the comparability of measurement results and calibrations, it must be taken into account that retroactions between the anemometer and the flow field may have a different influence on the measurement result, depending on the measurement and calibration facilities used. In the case of comparison measurements, this can lead to deviations of up to several per cents and points out the need for uniform and, if necessary, anemometer- and application-specific calibration procedures.

For the non-interacting realisation of the flow velocity in measuring facilities for the calibration of anemometers, laser Doppler anemometers are therefore increasingly used as transfer or reference standards [1]. The measurement uncertainties of these calibrated LDA systems which are traced back to the national velocity standard (principle: see Section 2.2) usually lie below 0.3 %.

At PTB for example, for the calibration of anemometers, the flow velocity curve along the wind tunnel axis of the wind tunnel used is measured with and without a test object (Fig. 3). Thereby, the flow velocity is measured downstream from the wind tunnel nozzle by means of LDAs and related to the flow velocity measured by a further LDA at the output of the nozzle.

The measuring point for the reference velocity determination in the wind tunnel is always to be chosen at a sufficient distance from the test object, i. e. where the flow field with and without a test object only differs within the limits of the measurement uncertainty for velocity determination.

Due to the minimum distance to be kept between the reference point and the test object position, a wind-tunnel-specific correction factor must be taken into account for the selected position of the test object which, in turn, depends on the velocity and can lie in the order of 1 % (see Fig. 4).

Thus, due to the fact that retroaction influences are dealt differently, one must expect for the calibration of commercially available anemometers measurement deviations in the range of 1 %, although the laser-optical, non-interacting velocity measurement is more accurate by one order of magnitude.

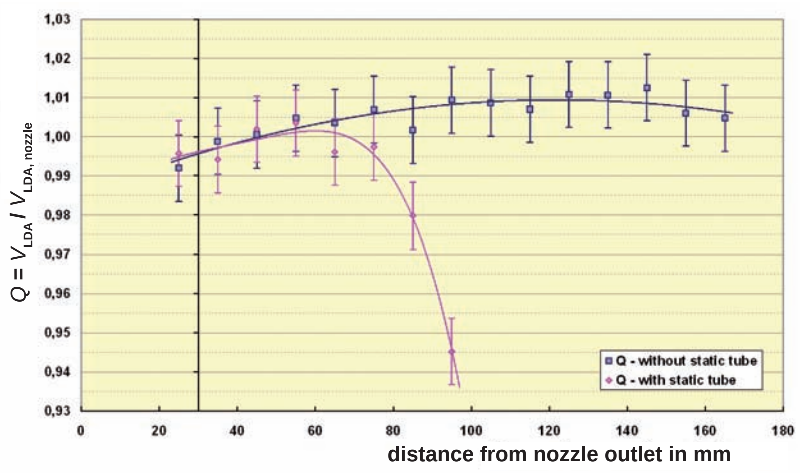


Figure 3:
Flow velocity curve along the wind tunnel axis measured by means of LDA, related to the nozzle output velocity at 17 m/s with and without Prandtl tube

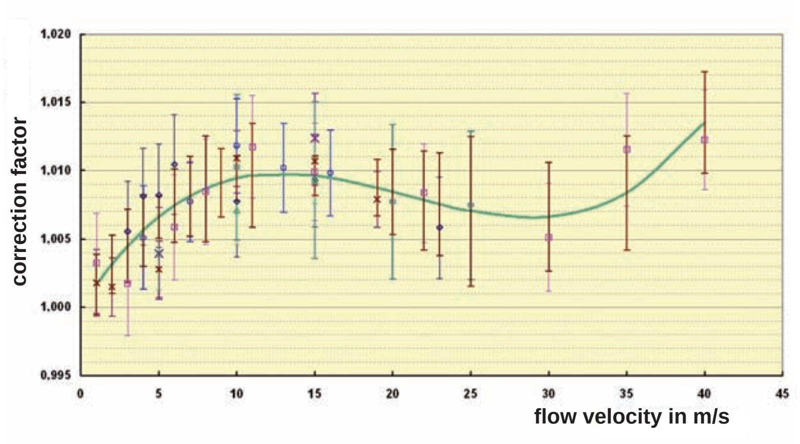


Figure 4:
Correction factor as a function of the flow velocity for a test object positioned 85 mm after the nozzle output

3.2 Flowrate measurement of natural gas under high-pressure conditions

The volume flow of natural gas under high-pressure is linked up via a volumetrically working primary standard – piston prover – which is operated by PTB on E.ON-Ruhrgas' *pigsar*™ test rig. In order to improve the measurement uncertainty on *pigsar*™ not only for the flowrate ranges covered directly by the piston prover, but also for the flowrate range which is possible beyond that, a second, independent primary standard is being developed on the basis of laser Doppler anemometry with an aspired measurement uncertainty of 0.1 % for the volume flowrate. The flowrate measurement of the gas is thereby traced back to a non-interactive measurement of the velocity in the gas stream [2].

To determine the mass flow Q_m of the gas through a cross-sectional area A using the measured flow velocities u and the known gas density ρ, the velocities and density have to be integrated over the area A:

$$Q_m = \int_A u\rho \mathrm{d}A$$

Via flow conditioning in the nozzle inlet section, the design of the nozzle outline and the high contraction ratio of the nozzles, a rotationally symmetric, almost box-shaped flow profile is generated at the nozzle exit plane with deviations of only 0.1 % and a very low turbulence in the core flow (see Fig. 5).

Provided the nozzle flow is rotationally symmetric, the measurement of the velocity profile can then be limited to measuring over a nozzle radius r from the centre of the nozzle with $r = 0$ to the nozzle edge with $r = r_{max}$. In this case, the integration of the mass flow is simplified to:

$$Q_m = 2\pi \int_{r=0}^{r_{max}} u(r)\rho(r) r \mathrm{d}r$$

Figure 6 shows the optical flowrate measurement facility in the measuring room, with the seeding fixture for the generation of small scattering particles whose velocity is measured in the gas flow, with the inlet pipe, and with the LDA nozzle module with measuring window arrangement. The downstream nozzle assembly with critical nozzles arranged in parallel represents the transfer standard between the optical flowrate standard and the prover loop; at the same time, it is used as a flowrate stabiliser during the LDA measurements.

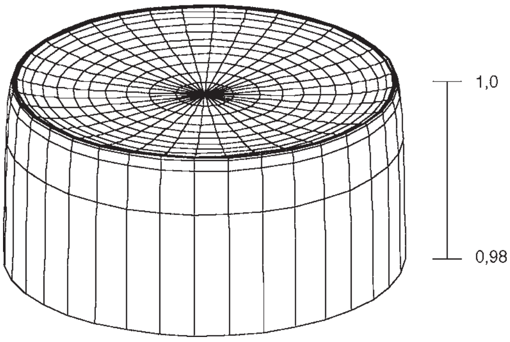
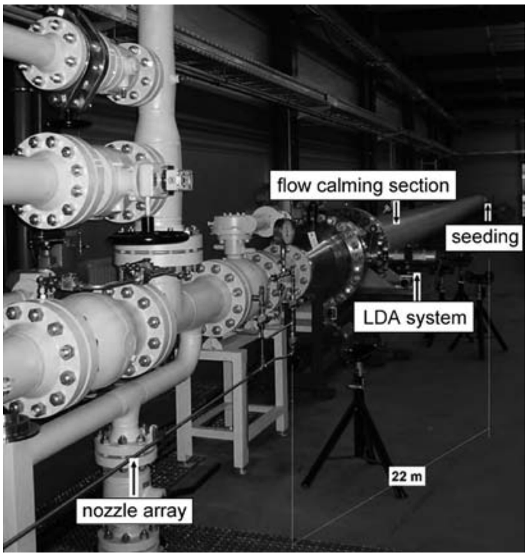


Figure 5:
Standardised velocity distribution above the nozzle exit surface



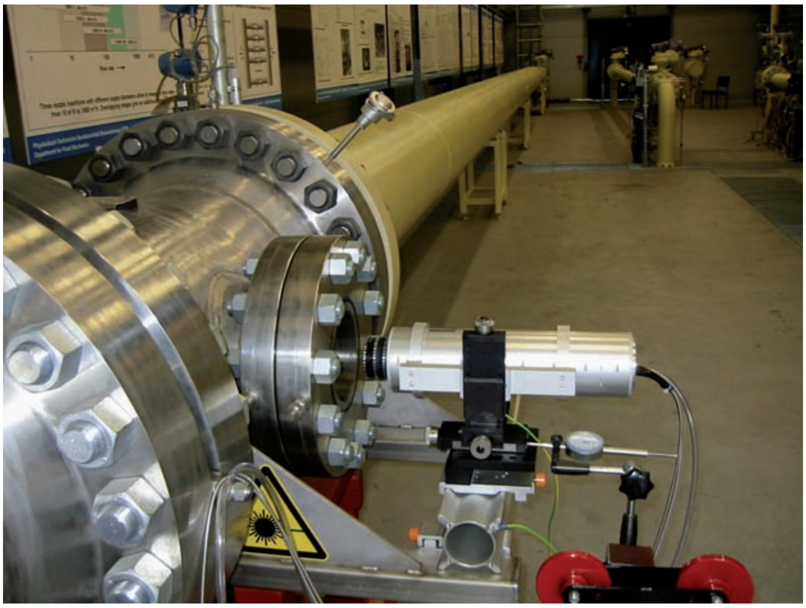


Figure 6:
View of the optical flowrate measurement facility in the measuring room

In order to be able to determine also the fraction of the mass flow at the nozzle edge with $r = r_{max}$ sufficiently accurately, a special flow profile sensor was developed. For example, the thickness of the boundary layer occurring in the case of a measuring nozzle having an exit diameter of 64 mm is of approx. 1 mm. This corresponds to a mass flow share of approx. 5 %. With the achievable spatial resolution of conventional LDA systems, it would not be possible to measure the boundary layer with sufficient accuracy. The newly developed flow profile sensor enables a spatial resolution of a few µm within the size of the conventional LDA measuring volume. The method used (see Fig. 7) consists in analysing the phase relationship of the LDA signals of two photo receivers whose signal phase difference supplies direct spatial information on the passage of scattered particles within the measuring volume [3].

By using the profile sensor, flow profiles with increased spatial resolution can be recorded immediately at the nozzle exit. Figure 8 shows the schematic representation of the measuring arrangement as well as a promising flow velocity profile measured directly at the nozzle exit.

4 Summary

Laser Doppler anemometry is used as a non-interacting high-precision measuring method for the calibration, realisation and dissemination of flow measurands in the field of flow velocity and flowrate measurement. The scopes of utilisation encompass the use of LDA systems for the realisation of standards for volume flow and flow velocity, as well as for the non-interacting flow field analysis for the reduction of the measurement uncertainties in testing and calibration facilities.

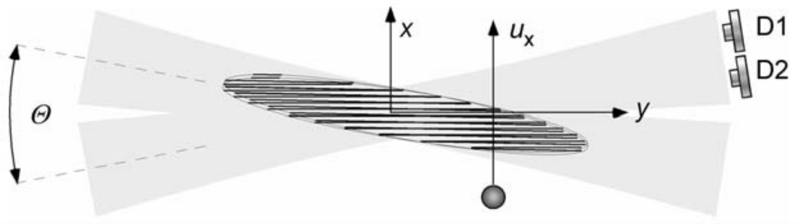
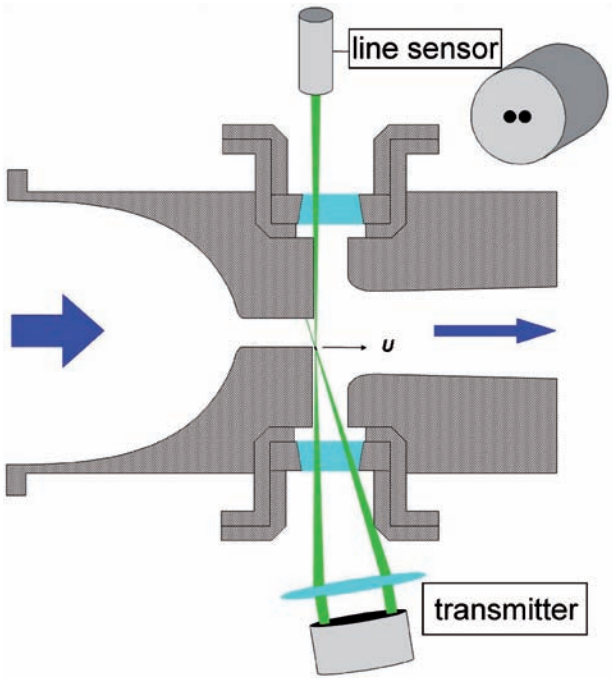


Figure 7:
Principle of the profile sensor according to the reference flow method in forward scattering direction



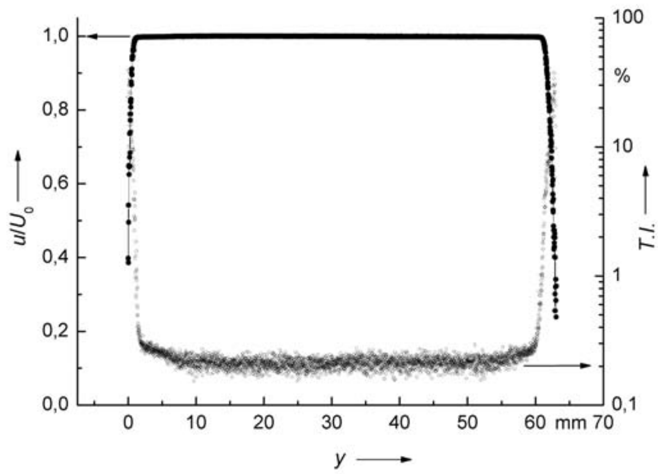


Figure 8:
Measuring arrangement of the flow profile sensor and measured velocity profile standardised against the flow velocity in the core flow, as well as measured turbulence degree in the high-pressure natural gas stream

5 Literature

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Gas Measurement and Gas Meter Testing in Practice

Rainer Kramer[1], Bodo Mickan[2]

1 Introduction

At present, approx. 100 billion m^3 of natural gas are consumed in Germany every year. Besides electric power and petroleum, natural gas thus represents one of the most important energy sources in the Federal Republic of Germany. The largest proportion of this gas is imported from countries such as Russia, Norway and the Netherlands.

On its way from the place of exploitation to the place of final consumption, the gas is measured approximately three times. In the supra-regional supply networks, gas is, most of the time, transported at a pressure of 60 bar, in some cases up to 80 bar. It is then expanded several times and, depending on the application for which it is needed, it is finally brought to combustion at a relatively low pressure (in domestic networks 22 mbar differential pressure to the atmospheric pressure).

Due to the fact that natural gas comes from different sources, its composition – and thus its properties, such as calorific value and compressibility – can vary considerably. This makes a whole series of metrological measures necessary which make it possible to bill gas according to its actual energy content.

In the following, we will first deal with the quantities used in commercial and official transfer. Some of the most important measuring instruments used to determine those quantities will be briefly presented with regard to their operating principle before a final overview of the legal fundamentals for the utilisation of these measuring instruments in official and commercial transfer is given.

2 Gas types

Fuel gases from the public gas supply networks are gaseous fuels (see DIN 1340) which are provided to households, businesses, public facilities and industry for general purposes – mainly for heat generation. One distinguishes between diverse gas families with properties or compositions which are, to a large extent, analogue:

- hydrogenous gases (town gas and grid gas);
- high-methane-content gases (most of the time natural gases from natural deposits or substitute natural gases);
- liquefied gases according to DIN 51622, and
- hydrocarbon/air mixtures.

Currently, mostly high-methane-content gases (referred to as "natural gas" in the following) are used. Natural gases are classified according to their composition and thus to their calorific value as L (low) or H (high), whereby the calorific value may lie between approx. 9.5 and 12 kWh/m^3.

3 Quantities

The aim of gas measurement is to determine the energy E conveyed, in the form of gas, to a contracting party via a distribution line within a billing period. This energy is the result of the product of the volume of the gas at standard conditions V_n and the calorific value of the gas $H_{s,n}$:

$$E = V_n \, H_{s,n} \qquad (1)$$

The calorific value is, according to [1], defined as the energy which is generated by the combustion of 1 m^3 of dry gas (at standard conditions). This also includes the heat quantity which is released by the condensation of the vapour formed by combustion. The inferior calorific value of a gas does not take into account condensation heat and is therefore, depending on the gas composition, lower by up to 9 % than the calorific value.

Practically all gas meters measure the gas volume under the conditions prevailing in the measuring instrument, also called "volume under operating conditions" V_b. The operating conditions are determined by the quantities "temperature" T and "pressure" p. For the different types of meters, these quantities must be measured at different places which are defined in the general instructions or in the approval certificate.

To be able to use Equation (1) for the calculation of energy, the gas volume measured at operating conditions must be converted to the volume of dry gas at standard condi-

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tions. "Standard conditions" are, according to DIN 1343, the pressure or the temperature $p_n = 1.01325$ bar and $T_n = 273.15$ K or $\vartheta_n = 0$ °C. Standard conditions are necessary especially for billing purposes since the operating conditions prevailing for gas measurement deviate considerably from those.

By definition, the volume at standard conditions V_n is the product from the conversion factor Z and the volume at operating conditions V_b:

$$V_n = Z V_b \tag{2}$$

For a real gas, the equation of state below is valid:

$$p V = z\, n\, R\, T \tag{3}$$

Hereby, n is the number of moles, R is the gas constant, and z is the so-called "gas law deviation factor" which, in the case of real gases, depends on the gas qualities (gas composition) and on its pressure and temperature.

The ratio between the gas law deviation factors at standard conditions z_n and at operating conditions z is called "compressibility factor" K.

$$K = \frac{z}{z_n} \tag{4}$$

By definition, the compressibility factor of a gas is, at standard conditions, 1. It can be calculated on the basis of the gas composition according to the algorithms indicated in the Technical Directive Gas 9, whereby for the determination of the gas composition, gas chromatographs are usually used. Thus, for the volume at standard conditions, the following applies:

$$V_n = V_b \frac{T_n\, p}{p_n\, T} K \tag{5}$$

The conversion of a gas volume V_b – having been determined at operating conditions – into the volume at standard conditions V_n is performed by means of electronic volume conversion devices which use the digitalised information on the measured volume V_b and the corresponding pressures and temperatures, taking into account the gas qualities (compressibility).

4 Equipment technology

In the following, we will provide an overview of the gas meter designs which are currently in use. For further information on the way they function and their properties, please refer to the listed literature [4].

4.1 Gas volume meters

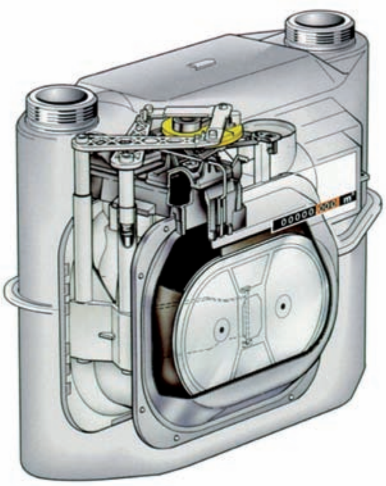
Gas volume meters are divided into displacement gas meters and flow gas meters. In the case of displacement gas meters, which are also referred to as "volumetric gas meters", the volume is determined directly by means of the periodical filling and emptying of one or several measuring chambers. Diaphragm gas meters and rotary displacement gas meters, which are used in large numbers, belong to this group of gas meters.

In the case of flow gas meters, the volume is determined indirectly, i.e. flow-physical effects are used which are detected by means of specifically adapted measuring elements or sensor systems. Some of the most widespread flow gas meters are turbine gas meters and ultrasonic meters.

Diaphragm gas meters

For domestic purposes, numerous diaphragm gas meters are in use which are produced and commercialised by several German and foreign companies. Due to their large numbers and the sophisticated production technologies, these meters can be placed on the market at relatively low prices, which has, up to now, always impeded the prevalence of modern electronic meters.

Diaphragm gas meters are volumetric meters with four measuring chambers. Two chambers each, which are separated from each other by a deformable wall (the diaphragm), form a unit. The diaphragms of both units are linked with each other by means of levers and rods; via a crank assembly, they drive the gate valves and the counter (see Fig. 1).



Figur 1:
Sectional view of a diaphragm gas meter

During the measuring operation, after having flowed through the inlet nozzle and gone through an open valve, the gas reaches a measuring chamber and fills it. Simultaneously, the gas flows from the opposite measuring chamber towards the outlet. After the diaphragm has reached its final position during the filling process, the rods switch the valves – which are designed in the form of a gate valve – in such a way that the measuring chamber that has just been emptied is filled and, respectively, that the gas flows out of the full measuring chamber towards the outlet which is thus emptied. The other unit works in the same way, but with a "phase shift". Thereby, achieving that the forces necessary for switching the gate valve are supplied by the other unit is possible.

Today, diaphragm gas meters are designed in such a way that it is possible to generate, at the index, pulses which are proportional to the volume. They can thus, like other gas meters, be equipped with sometimes very different systems for transmitting the index read-outs to the volume conversion devices or ancillary devices. The most widespread devices are encoders and magnetic pulse generators.

Diaphragm gas meters are manufactured in the physical sizes G1.6 to G250, whereby the physical sizes G4 (Q_{max} 6 m^3/h, Q_{min} 0.04 m^3/h) and G6 (Q_{max} 10 m^3/h, Q_{min} 0.06 m^3/h) are the most widespread ones.

For billing purposes, a base temperature of 15 °C is selected. Since the gas volumes depend – as described above – on thermodynamic influences, in order to reduce measurement deviations, also a temperature correction can be taken into account, or a temperature-correcting diaphragm gas meter can be used. These diaphragm gas meters are equipped with temperature-sensitive elements, e. g. bi-metal levers, which effect a temperature-dependent adjustment of the measuring chamber volume.

The period of validity of verification of diaphragm gas meters is 8 years, whereby it can be prolonged by 4 years each time as long as a certain number of meters of the same type are gathered into a batch and a sample test provides positive results. The sampling procedure makes it possible to considerably reduce the amount of work arising to public utilities for subsequent verification – without consumer protection being endangered.

Rotary piston gas meters

Rotary piston gas meters are volumetric meters in which two pistons rotate synchronised by a gear against each other in a housing. The cross section of the pistons vertically to the rotation axis is designed in such a way that the gaps between the displacers themselves and the housing – independent of the position – are small. The pistons are synchronised by means of a gear with little clearance so that they do not touch when rotating. The measured volume is conveyed between each displacer and the wall of the housing.

The main counter and the pulse generator are connected to the synchronisation gear. The gap dimensions can be kept low due to modern production techniques, which makes it possible to achieve very large flowrate ranges from Q_{max}/Q_{min} up to 250. On the other hand, the low gap dimensions lead to an increased sensitivity to impurities. In order to prevent damage to the displacers, which are made of light alloy, suitable precautions must be taken if need be, e. g. by means of filters.

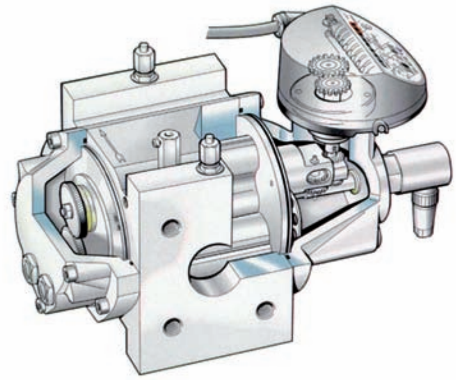


Figure 2:
Set-up of a rotary piston gas meter

Rotary piston gas meters are mainly manufactured in the physical sizes G16 to G1000. The maximum flowrate Q_{max} is the G value of the next larger physical size in m^3/h (e. g.: a G16 has a Q_{max} of 25 m^3/h). The minimum flowrate Q_{min} can, depending on the approved measuring range, lie between 1/5 Q_{max} and 1/250 Q_{max}.

Turbine gas meters

To measure large quantities of gas in the medium and high pressure range, mostly turbine gas meters are used. Turbine gas meters consist of a pressure-tight housing, a displacement body, the turbine wheel and a drive which runs the main counter.

The meters are equipped with one or several pulse outputs which supply high- and low-frequency pulses. High-frequency pulse generators often use the blade ends of the turbine wheels or lock washers to generate pulses. Magnetic couplings are used to ensure the leak tightness of the housing. By using a second pulse generator, it is possible to generate a phase-shifted pulse signal. If the signals are analysed appropriately, it is possible to suppress disturbances and to check whether the meter is working correctly.

Whereas the high-frequency pulses usually deliver a non-integral pulse value (pulse/volume unit) which is determined when the meters are tested, it is possible to achieve integral pulse values with low-frequency pulses by adjusting the counter drive. Furthermore, low-frequency pulses are generated outside the pressure-tight housing in the main counter, which is easier.

For high-pressure applications, the meters are usually tested over the total pressure range. Thanks to constructional improvements within the last few years, achieving that the error curves for the different pressures deviate only slightly now from the low-pressure curve (which is measured with air) was possible.

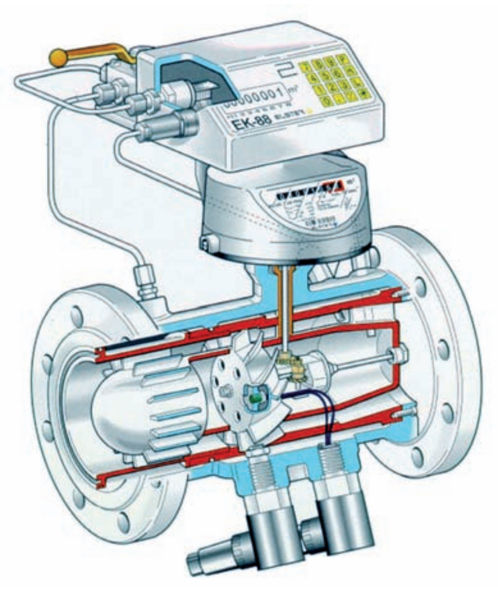


Figure 3:
Schematic representation of a turbine gas meter (with volume conversion device)

Ultrasonic meters
Within the past decade, the use of ultrasonic meters has increased, especially in larger gas measuring stations. The advantage of this type of meter is that it contains no mobile parts which would be subject to mechanical wear. The measurement principle is based on the fact that, from the influence of the flow velocity on the propagation of sound, it is possible to draw conclusions on the flow rate. If an acoustic pulse is, for instance, sent by transducer A and received by transducer B (see Fig. 4), then the propagation time t_{ab} of the pulse as a function of the flow velocity u_m is smaller than without flow. If, on the contrary, the acoustic pulses are sent in the opposite direction, i.e. from B to A, the propagation time t_{ab} is larger than without flow. After measuring both propagation times t_{ab} and t_{ba}, the sound velocity c is eliminated from the conditional equation for the average path velocity u_m, so that in the result, the average flow velocity along a path can be calculated from geometrical quantities and the propagation time difference of the acoustic pulses by means of Equation (8).

$$t_{ab} = \frac{L}{c + u_m \cos(\varphi)} \tag{6}$$

$$t_{ab} = \frac{L}{c - u_m \cos(\varphi)} \tag{7}$$

$$u_m = \frac{L}{2\cos(\varphi)}\left(\frac{1}{t_{ab}} - \frac{1}{t_{ba}}\right) \tag{8}$$

If it is ensured – as in the case of ultrasound domestic gas meters – that the flow profile, independent of the upstream flow conditions, always builds up in the same way, then it is sufficient to use a single ultrasound path. In the case of large-scale gas meters with nominal diameters DN 80 and larger, even at 10 DN inlet length, one cannot expect a fully formed flow profile. In order to reach a sufficient "scanning" of the flow, approved ultrasonic meters (large-scale gas meters) are equipped with at least 3 paths. The volume rate Q is then built from the path velocities u_m and by a weighted summation. Since the propagation times measured also allow a calculation of the sound velocity, in order to monitor the meter, it is possible to use a comparison with the sound velocity values which were calculated from the gas qualities (if measured).

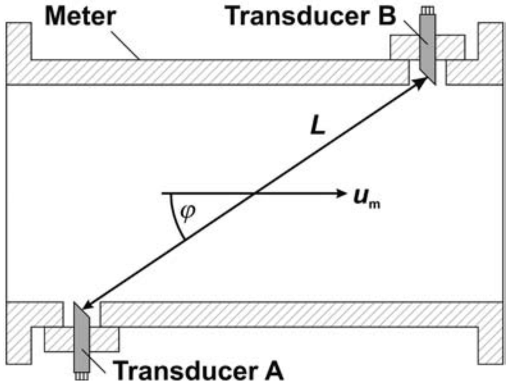


Figure 4:
Functioning principle of an ultrasonic meter

4.2 Gas qualities measurement

To determine the calorific value $H_{s,n}$ of natural gas at standard conditions, various techniques are suitable, of which gas chromatographs and gas calorimeters are the most significant ones. Calorific value reconstruction systems represent a particularity to calculate the calorific value of the gas in a net.

Gas calorimeters
Figure 5 shows the set-up of a gas calorimeter. A combustion chamber builds the core piece and is surrounded by a heat exchanger. The heat-conveying fluid (e.g. water) is heated up by the energy released by the combustion of the gas to be measured, whereby the heat exchanger is designed in such a way that also the condensation heat of the water vapour arising from combustion is detected. The calorific value follows from the relation:

$$H_{s,b} = \frac{V_W \cdot c_W \cdot \Delta t}{V_G} \tag{9}$$

where:
$H_{s,b}$ is the calorific value of the gas at operating conditions;
V_G is the volume of the gas at operating conditions;

V_W is the volume of the heat-conveying fluid (e. g. water);
c_W is the thermal capacity of the heat-conveying fluid;
Δt is the temperature increase of the heat-conveying fluid.

In order to calculate the calorific value of the gas at standard conditions, the calorific value at operating conditions $H_{s,b}$ has to be divided by the conversion factor Z.

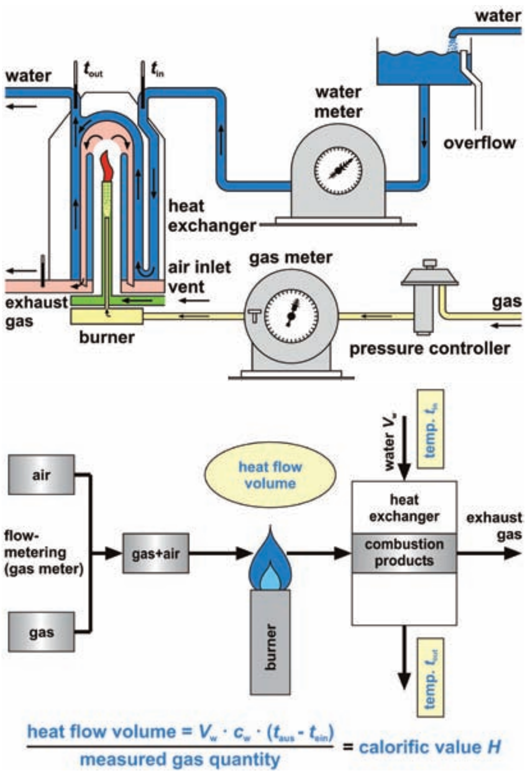


Figure 5:
Set-up of a gas calorimeter

Determination of the calorific value by means of a gas chromatograph

A relatively widespread procedure for the measurement of the calorific value consists in determining the gas qualities by means of process gas chromatographs. The latter are modified laboratory gas chromatographs which carry out the sampling, analysis and indication of the measured values fully automatically. Contrary to calorimeters, gas chromatographs work in measurement cycles which are, at the time being, of 3 minutes at a minimum for approved devices. As shown in Fig. 6, the gas analysis is performed by means of separating columns through which an inert carrier gas is led. At the beginning of a measurement, a certain quantity of the gas mixture to be measured is injected into the carrier gas by means of a selector valve at the sample loop. The components of a gas mixture need different times (retention times) to reach the outlet of the separating column, and they generate peaks of different widths and heights in the detector (thermal conductivity detector) which is equipped with a reference cell filled with pure carrier gas to compensate environmental influences. The analysis of the signal curve (chromatogram) provides a statement on the concentration of the individual components. A sufficiently low uncertainty of the analysis can only be ensured if the devices are regularly calibrated and adjusted with a calibration gas which, with regard to its composition, should come close to the gas to be determined.

The calculation of the calorific value of the examined gas is performed by adding the concentrations x_i and calorific values H_i of the individual components according to DIN 51 857 or ISO 6976

$$H_{s,n} = \sum_{i=1}^{11} x_i H_i \qquad (10)$$

A particular advantage of using gas chromatographs resides in the fact that, besides the calculation of the calorific value, also the density as well as other parameters of the gas can be calculated on the basis of the gas composition. It is then possible to check other measurement systems (e. g. density sensors) by continuous comparison of the measured and the calculated values.

Calorific value reconstruction systems

Due to the fact that it is tedious to determine the calorific value at one measuring point, for gas networks, systems have been developed which allow a determination of calorific values for billing purposes by means of a reconstruction. Thereby, only the gas qualities of the gas flows which are fed into a certain network are measured and then gas qualities and its time-dependent evolution at any random points of the network are calculated by means of an appropriate model (see Fig. 7).

A pre-condition for this is to know the geometry and topology of the network (piping length, pipe inner diameter, pipe roughness, etc.), of the measurement data on the inlet and outlet volume rates, as well as of the pressure measurement data of hydraulically closed network branches. Since the volume rates are sometimes buffered at the measurement point and are only available with some delay, the reconstruction of the calorific value and its time-dependent evolution takes place subsequently. Reference measurement points are provided for the assessment of the system's function. Calorific value reconstruction systems must comply with exhaustive requirements; approval is granted by PTB.

If gases which differ only slightly with regard to their calorific value ($\Delta H < 2\,\%$) are fed into a supply network, the calorific value to be billed can be determined using the algorithms indicated in the DVGW (German Association for Gas and Water) Worksheet G 685.

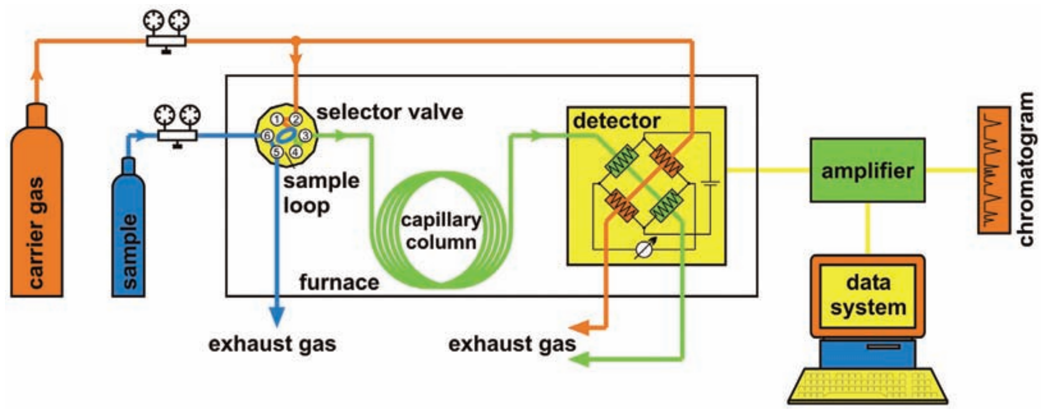


Figure 6:
Functioning principle of a gas chromatograph

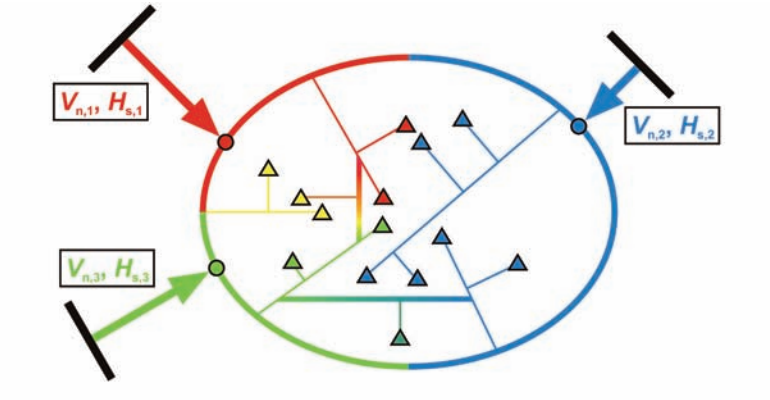


Figure 7:
Schematic representation of a network with calorific value reconstruction
○ Input points: measurement of the supplied quantity V_n and calorific values H_s
△ Consumption points: measurement of the quantity and calculation of the calorific values based on the input and on modellig of the flow through the network

5 Approval of gas meters

For the purposes of consumer protection, in order to ensure fair competition and to increase confidence in official measurements, it is necessary to approve and verify measuring instruments. In Germany, the Verification Act and the Verification Ordinance lay down which measuring instruments must be verified according to which requirements. Verification of a measuring instrument is possible if the instrument has been granted an approval certificate. In Germany, verification itself is performed by verification authorities or officially recognised test centres; verification is a sovereign act which is incumbent on the federal states.

In 2004, the "European Measuring Instruments Directive" (MID) was adopted to create a single European market for legally regulated measuring instruments. Contrary to the European directives following the "Old Approach", MID defines technology-independent requirements for measuring instruments. Within the scope of a conformity assessment procedure, which replaces approval and verification, the manufacturer must prove conformity of the measuring instruments with the MID requirements and finally, the instruments obtain a special CE marking. Measuring instruments which have been legally granted the CE marking are equivalent to instruments having passed initial verification and must be accepted in all EU countries for measurements subjected to verification.

In Germany, measuring instruments for the measurement of gases, water and liquids other than water, and heat must, as far as they fall under the MID, undergo conformity assessment according to the MID requirements. For measuring instruments which are mainly used for industrial applications and are not covered by the scope of the MID, such as, e. g., orifice plate meters and ancillary devices, national approval to verification can be achieved by an approval procedure.

The legal basis for the approval to verification or conformity assessment of gas meters is a series of laws, provisions, directives and standards whose index is regularly updated in the PTB-Mitteilungen [2]. A non-exhaustive list of the provisions relevant for gas measurement is given below.

As general provisions for measuring instruments, the following apply:

- European Measuring Instruments Directive 2004/22/EC (MID);
- Law on Units in Metrology;
- Law on the Metrology and Verification System (Verification Act);
- Verification Ordinance (EO);
- Legal Metrology – General Regulations (GM-AR);
- Law on Electromagnetic Compatibility (EMVG), and
- Administrative Expenses Act relating to the issuing of approvals.

The MID was published in the Official Journal of the EU on 31 March 2004 and came into force on 30 October 2006. This regulation applies to measuring instruments which are used or placed on the market in high numbers. With regard to public utility meters, the MID focuses on domestic, commercial and light industrial measuring instruments.

The Measuring Instrument Directive 2004/22/EC (MID) regulates:

- the requirements on gas meters until their putting into use and commissioning;
- the fundamental requirements on measuring instruments (independent of technology);
- provisions with regard to conformity assessment and CE M marking (replacing approval and verification);
- the description and definition of possible conformity assessment modules;
- the requirements placed on notified bodies (in charge of conformity assessment).

After its coming into force, the MID was transposed into national law by adjusting the Verification Act and the Verification Ordinance (EO).

In the EO‘s general provisions (EO-AV), the general requirements on measuring instruments, notified bodies, approval and verification or conformity assessment are defined by reference to other legal directives, especially the MID. In the Annexes to the Verification Ordinance, special requirements for the individual categories of measuring instruments are defined, if applicable by reference to the MID. Annex 7 (EO 7) is dedicated to measuring instruments for gas.

National law regulates:

- the duties of users of measuring instruments and the mandatory verification of measuring instrument categories;
- re-verification, metrological evaluation or examination;
- the requirements applying after the "putting into use"; the permitted errors in service;
- the period of validity of verification;
- responsibility for market surveillance;
- fees and administrative offences.

To ensure a uniform enforcement of the verification system, PTB testing instructions have been adopted. They serve to describe test facilities, testing procedures, etc. which are used for the verification of gas meters or ancillary devices. Concerning the execution of the sampling procedure for the prolonging of the period of validity of the verification of diaphragm gas meters, two methods were published in "PTB-Mitteilungen" [2]. For the regulation of special problems, Technical Directives Gas (TR G) are issued in addition to the PTB requirements and testing rules.

PTB requirements, PTB testing rules and Technical Directives are worked out by PTB in collaboration with the verification authorities and representatives of industry. They are submitted to the corresponding associations (e. g. the DVGW) for comment. Once they have been adopted by the "Full Assembly for Verification", they will become accepted rules of verification technology.

6 Summary

On its way from the source to the end-user, the quantity and energy content of the energy source "natural gas" is measured several times. Due to the extremely diverse measurement conditions with regard to gas pressure and flow rate at the different measurement locations, and due to the different gas qualities from different sources with regard to their energy content, a wide range of measuring instruments exists and a complex system to ensure that the measured values and the measuring instruments are used correctly is in force.

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Ensuring the Traceability of Volume and Flow Measurements of Liquids

Gudrun Wendt[1], Rainer Engel[2], Jörg Riedel[3]

1 Introduction

Volume and flowrate measurements of liquids occur in numerous fields of the economy, science and society. The liquids to be measured range from potable water, petroleum and liquefied gases to pharmaceutics, lacquers, paints and many other chemical intermediate and end products. Thereby, large ranges must be covered with regard to the measurands quantity and flowrate and to the material parameters of the liquids to be measured – such as density and viscosity – as well as with regard to the operating conditions „temperature" and „pressure".

2 Current state-of-the-art of the traceability in liquid flow metering, as well as future concepts

It is in general true that, for ensuring uniform and correct measuring, the measurement must be traced back to a national or international standard for the corresponding measurand. This means that the reading of the measuring instrument used can be compared with the primary standard which stands at the top of the corresponding calibration hierarchy in an uninterrupted chain of successive comparisons.

In the field of liquid flow measurements, PTB has a series of standard measuring facilities at its disposal whose core is the hydrodynamic test field (HTF). Before describing these standard measuring facilities any further, we would like to point out a few particularities in the field of the volume and flowrate measurements of liquids.

- In total, four measurands occur – volume, mass, volume flowrate and mass flowrate – whereby both volume-flow- and mass-flow-related measurands, within the traceability process, may be converted into one another by incorporating the measurand „density".
- Before the HTF was commissioned for liquid flow measurands in 2003, there was no uninterrupted chain of traceability to a national standard available. Each measuring facility used for testing and calibration was traced back to the required standards of mass, length, density, temperature and time, element by element, according to its active principle of measurement (volumetric or gravimetric). In such a case, the measured value which is defined to be the stimulating reference input to the meter under test is „statically" composed of the corresponding above-mentioned individual measurands. Since such a traceability is not based upon the measurand to be determined, influences on the measurement result which originate from the dynamics of the measuring process are not suitably taken into account. Among these are, for example, disturbed velocity profiles or high degrees of turbulence of the flow at the place of installation of the meter under test, fluctuating fluid flows during the measurements, instable operation of flow control devices, effects due to pump vibrations, to mention only some.
- All methods which have been known up to now and on which liquid flow measurements are based display, besides the fact that they can be dynamically influenced, also a – sometimes very strong – dependence on the material parameters of the liquid to be measured. It is therefore mandatory to test or calibrate each measuring instrument solely with the fluid it is dedicated to. This means that, for each metrologically relevant liquid, it would be necessary to establish a specific traceability chain, which, for economic as well as for metrological reasons, does not make sense.

PTB has therefore elaborated an alternative, long-term concept. The plan is that all liquid measurements can be traced back to one single national standard – the HTF – by means of medium-independent transfer standards and methods which still have to be developed. In this way, the measurands which can be realised with the HTF with the fluid „water" can be disseminated to all subordinate testing and calibration facilities by means of such transfer standards – independent of the liquid to be measured with which these facilities work. Figure 1 shows this concept.

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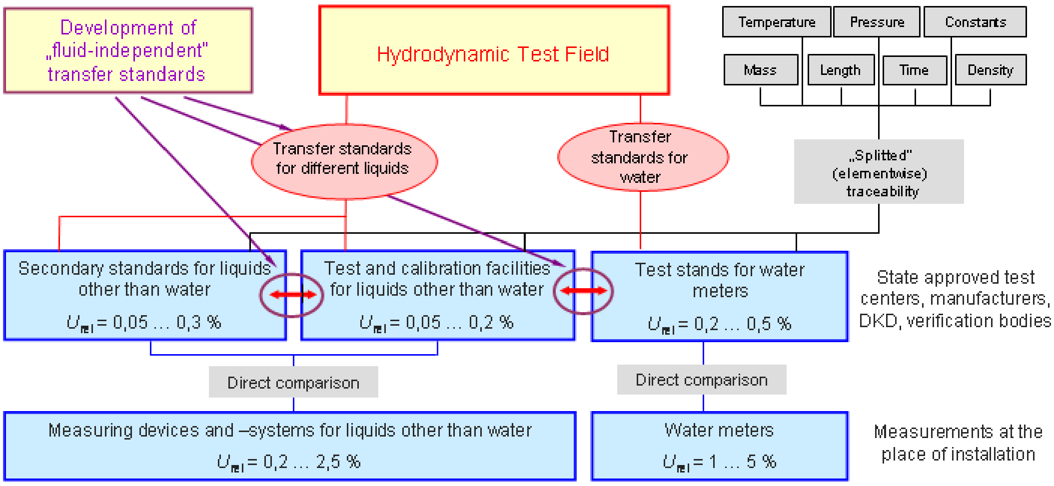

Figure 1:
Long-term concept for the creation of a uniform, closed system of traceability of all liquid measurements to the hydrodynamic test field

3 Standard measuring facilities in the field of liquid measurements

3.1 Hydrodynamic Test Field

The hydrodynamic test field (Fig. 2) realises all four measurands which are relevant for the total flow and flowrate measurement of liquids: mass, volume, mass flowrate and volume flowrate of a streaming liquid. It is operated with the fluid "water" in a flowrate range from 0.3 m^3/h to 2100 m^3/h and with an expanded relative measurement uncertainty of 0.02 %.

The core component of the HTF is a gravimetric reference standard which consists of three weighing systems with a 30-ton, a 3-ton and a 300-kilogram balance. The mass which is determined in this way – if necessary using the density of the fluid to be measured, as well as the measuring time – is compared with the readings of the meter under test. Figure 3 shows the part of the measuring room in which the HTF is located. In the foreground, the two measuring sections are to be seen, each of which can be operated alternatively and in which flowmeters can be mounted with nominal diameters between 20 mm and 400 mm. In the background, one can see two of the three weighing systems – the 30-ton balance and the 3-ton balance.

The HTF's three weighing systems basically work according to the same operating principle: they combine a "classic" lever scale with an electromagnetic force-compensating load cell and strain-gauge force transducers as sensor elements. In addition, each weighing system is equipped with an integrated calibration facility. In order to isolate them from dynamic disturbances, the weighing systems were set up on a vibration-isolated concrete foundation. A detailed description of the weighing system and of the vibrationisolation system can be found in [3] and [4].

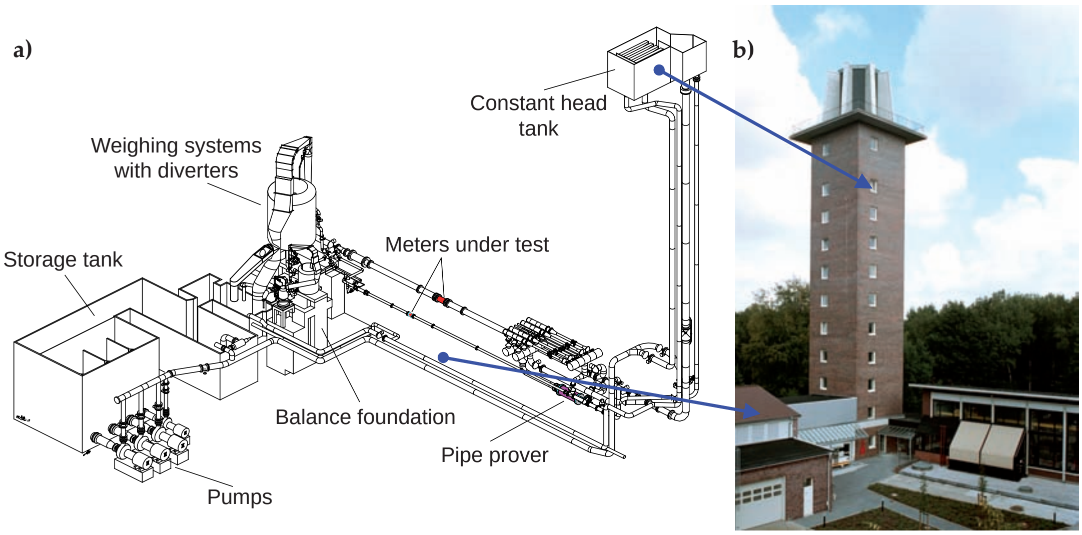

Figure 2:
a) Cutaway view of PTB's water flow calibration plant
b) PTB's Willy Wien Tower
(housing the constant-head tank of the standard flow facility on the 9th floor, at a hight of 35 m)

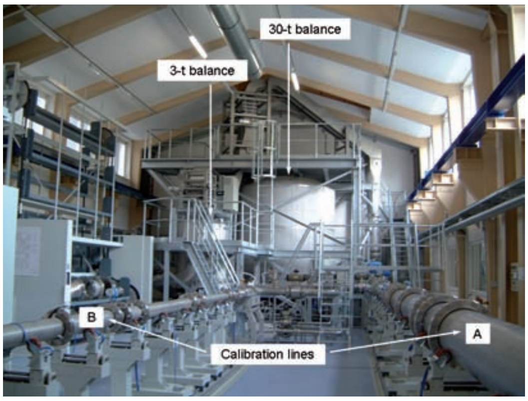

Figure 3:
View of the measuring room where PTB's hydrodynamic test field is located

Flow is generated and stabilised by a system of electronically regulated pumps and a constant-head tank with an overflow weir. The constant-head tank has a capacity of 56 m^3, is located 35 m above ground level and serves, in addition, as a high-precision flowrate stabiliser.

The measuring and operating mode in which the highest calibration accuracy is achieved – and which is utilised at PTB's measuring facility – is static weighing with flying-start-and-finish operation. In this operation mode, the test liquid is kept in a constant circulating motion through the system's pipework prior to and during a calibration run. The actual measuring operation is started by switching the diverter's diverting edge from the bypass position into the diverting position in which the liquid flow is directed towards the weighing tank. When passing the centre of the diverter's liquid jet, a gate signal is initiated that launches data acquisition from the test meter's signal output and starts an electronic counter which determines the diversion time. Upon reaching a pre-defined quantity of water in the weighing tank, the diverter is switched back into its initial position. And when passing the jet's centre again, the signal acquisition of the test meter and the time measurement are stopped.

From the very beginning, all components of the test field were designed and built in such a way that their individual uncertainty components realise pre-defined projected values which, in turn, ensure for the total expanded measurement uncertainty of the facility a value which is better than the above-mentioned value of 0.02 %. When a flowmeter with a pulse frequency signal output f (e. g. a turbine meter, an electromagnetic or Coriolis flowmeter) is calibrated, the equations for the determination of the standard measurement uncertainty of the meter K-factor K_{meter} have the following form:

$$K_{meter} = \frac{f}{\dot{V}_{REF}}$$

$$u^2_{K\_meter} = \left(\frac{\partial K_{meter}}{\partial f} u_f\right)^2 + \left(\frac{\partial K_{meter}}{\partial \dot{V}} \cdot \frac{\partial \dot{V}}{\partial m} u_m\right)^2 + \left(\frac{\partial K_{meter}}{\partial \dot{V}} \cdot \frac{\partial \dot{V}}{\partial \rho_{water}} u_\rho\right)^2 + \left(\frac{\partial K_{meter}}{\partial \dot{V}} \cdot \frac{\partial \dot{V}}{\partial (\Delta V_{IP})} u_{\Delta V}\right)^2 + \left(\frac{\partial K_{meter}}{\partial \dot{V}} \cdot \frac{\partial \dot{V}}{\partial (\Delta V_{T\_div})} u_{T\_div}\right)^2 + \left(\frac{\partial K_{meter}}{\partial \dot{V}} \cdot \frac{\partial \dot{V}}{\partial T_{MEAS}} u_T\right)$$

$$\left(\frac{u_{K\_meter}}{K_{meter}}\right)^2 = \left(\frac{u_f}{f}\right)^2 + \left(\frac{u_m}{m}\right)^2 + \left(\frac{u_\rho}{\rho_{water}}\right)^2 + \left(\frac{u_{\Delta V}}{V_0}\right)^2 + \left(\frac{u_{T\_div}}{V_0}\right)^2 + \left(\frac{u_T}{T_{MEAS}}\right)^2$$

where

u_{k_meter} is the standard measurement uncertainty of the measuring instrument's K-factor:

u_f is the standard measurement uncertainty of the measurement of the pulse signal frequency f

u_m is the standard measurement uncertainty of the determination of the mass m of the liquid to be measured

u_ρ is the standard measurement uncertainty of the determination of the density ρ of the test liquid

$u_{\Delta V}$ is the standard measurement uncertainty of the determination of the connecting pipe's volume ΔV (pipe section between the meter under test and the standard device)

u_{T_div} is the standard measurement uncertainty of the diverter's time error

u_T is the standard measurement uncertainty of the determination of the measuring time T_{MEAS}

On the basis of this decisive criterion for the design of this water flow facility, all constructive, functional and uncertainty-determining metrological requirements have been correspondingly derived [1].

Furthermore, for the function of the entire flow standard facility, the optimal functional integration of all individual components into the overall system of the measuring installation is an indispensable precondition. This was realised by correspondingly designing the process control system of the entire facility [5]. For the weighing system, e. g., this means that also the measurement values of ambient temperature, atmospheric pressure and relative humidity required for the correction of the air buoyancy are acquired and made available to the supervising process control system for further processing of the measurement analysing and processing of the measurement data. Furthermore, the balance calibrations, which are performed each time a high-precision flow calibration is carried out, also provide data for the purposes of a qualified quality management. Thus, it can be continuously checked whether the limit values stated as well as their long-term stability are complied with. On the basis of the regularly recorded data and their permanent surveillance, it is possible to detect deviations from the "normal" functionality in real-time and to take, if necessary, maintenance or repair measures. Only this can reliably and credibly guarantee the measurement uncertainty of the hydrodynamic test field for each of the measurements performed.

It should be especially pointed out that also internationally, the high metrological level of the HTF is highly acknowledged and was clearly proved by the BIPM key comparison which was completed in 2006 [6]

3.2 Test rig for petroleum

Scientific work for the development of transfer standards which are independent of the fluid used, requires experimental investigations and verifications with liquids other than water. For this purpose, it is envisaged to use PTB's petroleum test rig (MÖZ) in particular. The principle of measurement as well as the test fluid differ from those of the HTF. As shown in Fig. 4, in total, four geometrically measured standard proving tanks, having a capacity of 5000 l, 1000 l, 200 l and 100 l, are used as basic reference standards. The test fluid used is white spirit which has a dynamic viscosity of 0.8 mPa·s and a density of 770 kg/m^3. The flowrate range which can presently be realised lies between 0.6 m^3/h and 120 m^3/h. The expanded measurement uncertainty, which was confirmed by international comparison measurements, amounts to 0.05 %.

At present, structural alteration works are being carried out on the petroleum test rig which will in future enable pump direct operation so that the measuring range can be extended, especially to smaller flowrates. At the same time, this will lead to improved conditions for the use of reference meters and thus, one will be able to choose measuring times totally freely. Furthermore, an automatic level gauge based on the magnetostrictive principle is being installed in order to rule out the limitations of the pre-defined test volumes to the respective tank sizes. In the long run, the use of further test fluids, especially liquids with higher viscosities, is envisaged in the lower flowrate range.

3.3 Pipette testing facility

Regardless of the presented long-term concept for the creation of a uniform, closed system of traceability of all liquid measurements, the measurement of small static volumes will continue to be of great importance. The verification of fuel dispensers or the volumetric measurement of tank lorries is performed solely by means of

Figure 4:
Standard proving tanks of the petroleum test rig with capacities of 5000 litres, 1000 litres, 200 litres and 100 litres

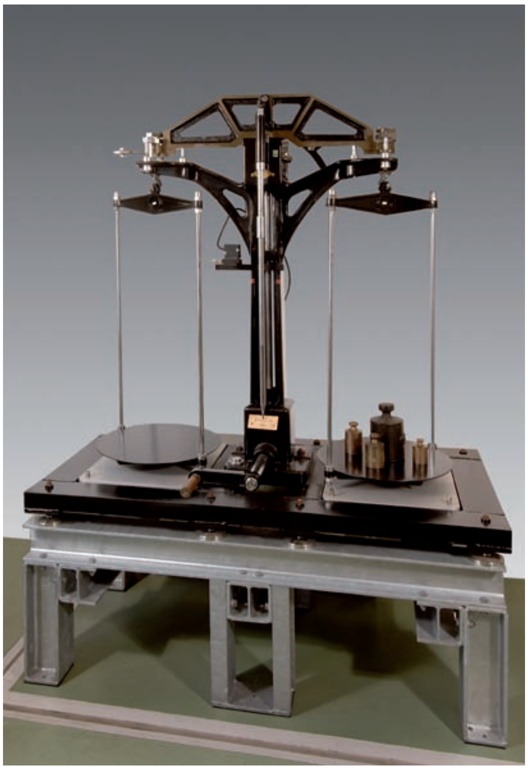

Figure 5:
Weighing system of the Pipette testing facility for the realisation of small static volumes of up to 100 litres

standard proving tanks. Also within the scope of the international harmonisation of fluid measurements, comparison measurements are carried out by means of static volume standards (standard graduated flasks and pipettes). The pipette testing facility shown in Figure 5 is operated with distilled water and is designed for volumes between 1 litre and 100 litres. It has given proof of its excellent metrological parameters on the occasion of numerous international comparisons, most recently within the scope of the key comparison which was completed in 2006 where the stated expanded measurement uncertainty of 0.004 % could impressively be confirmed.

4 Summary

PTB, with its standard measuring facilities for the realisation of the units of volume and flowrate of liquids, provides a closed system of measurement facilities which ensures the traceability of all fluid measurements in the economically relevant fields of application. The hydrodynamic test field thereby occupies the core position since it makes it possible, by combining several measures – such as the use of high-precision balances and diverters, the dedicated attenuation of disturbances and the operation via a constant-head tank – to achieve an exceptionally low measurement uncertainty of 0.02 % for liquid flowmeter calibration purposes.

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Legal Metrology in the Field of Fluid Measurement Technology

Michael Rinker[1], Gudrun Wendt[2]

1 Introduction

The economic importance of liquids whose measurement underlies legal control becomes evident when we look at the quantities traded and the costs arising thereby to manufacturers, public utilities and end consumers. In Germany, for example, approx.

- 56 million tonnes of petrol and diesel fuel
- 38 million tonnes of light fuel oil
- 6 million tonnes of aircraft fuels
- 5500 million cubic metres of potable water
- 32 million cubic metres of milk
- 2 million cubic metres of beer

are consumed yearly and measured by means of approved or verified measuring instruments and systems, e. g.

- 45 Mio million water meters
- 5400 measuring systems for milk
- 19050 road tankers and trailers
- 7600 petrol filling stations including all individual fuel dispensers.

2 Fluid measurements in the legally regulated area

The wide spectrum of flowrate ranges, maximum permissible errors and product properties leads to an abundance of different measurement techniques and methods: volumetric volume measurement by means of displacement meters, flowrate measurement by means of turbine meters, differential pressure transducers, magnetic-inductive volume integrators, mass measurement with Coriolis meters and their integration into the most diverse types of measuring systems.

The problems resulting from these different measuring methods call for an intensive coordination of the activities of the manufacturers of measuring instruments and their users, of the verification authorities, the notified bodies and the market surveillance bodies, with the aim of ensuring the continuous reliability of measuring instruments in commercial transactions under all conditions of their application. Depending on the individual case of application, maximum permissible errors from ± 0.2 % (pipeline meter) up to ± 2.5 % (measuring systems for cryogenic liquids) must be complied with.

PTB is therefore a service provider for a large number of German and European companies, as well as for verification and market surveillance authorities in the field of product certification, research and development – whereby this also includes extensive activities in the national and international standardisation and regulation bodies.

3 Product certification

For the type approval and product certification of fluid flow meters, three annexes to the *Verification Ordinance* [1] are relevant: Annex 4 "Measuring instruments for liquids at rest", Annex 5 "Measuring systems for flowing liquids" and Annex 6 "Water meters". Since the coming into force of the new European Measuring Instruments Directive 2004/22/EC (MID) in November 2006, PTB has become a notified body for water meters (MI-001) and for measuring systems for liquids other than water (MI-005), has issued more than 50 design examination certificates and type examination certificates and has participated in corresponding manufacturer audits.

This responsibility has decisively contributed to a consolidation of the position of the German measuring instrument industry, especially in the European market. Furthermore, 17 OIML certificates and test reports have lastingly facilitated the access of German manufacturers to global markets.

4 Research and development for the legally regulated area

As a national centre of competence for fluid flow measurement, PTB is increasingly using its capabilities in the field of research and development also for tasks which are closely related to ensuring reliable measurements at the place of utilisation. This is usually done in close collaboration with the verification authorities and is especially focused on the development and introduction

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of modern and effective procedures for the metrological testing of measuring instruments and systems under concrete operational conditions.

Thus, a measuring system composed of a laser scanner and specific software was developed together with the manufacturer and the *Eichdirektion Nord* (Verification Board for Northern Germany) which can optically measure the inner geometry of storage tanks [3, 4]. This system cannot only metrologically replace and improve the previous methods of calibration for storage tanks, but it also ensures drastic reductions in terms of time and physical strain for the testing staff. Figure 1 shows from left to right: a typical storage tank for petroleum products (here with a volumetric capacity of approx. 50 000 m^3), the laser probe installed within a storage tank, and the scatterplot composed of approx. 800 000 data points which is realised by means of a single scan in a measurement time of approx. 15 minutes. Depending on the size, shape and, if applicable, any existing internal fittings, it is thus possible to draw up an individual filling table for each tank by means of one or several scans. This filling table assigns, to each height, a corresponding tank volume so that, in use, the fluid volume which is currently present in the tank can be assigned to the filling stage measured with a measurement uncertainty of clearly smaller than 0.5 %.

Another example of a very successful cooperation with the verification authorities was the joint research project „Transfer Standards for Flowing Water" [5]. This project focused on the development of methods for the testing of water meters at the place of utilisation. Besides performing exhaustive measurements both on test rigs and in situ (in dwellings) and drawing up numerous statistics, the respective regulations relevant for verification [6] were modified and supplemented. In this way, an important contribution was made to consumer protection, especially within the scope of state examinations of water meters.

5 International standardisation

The increasing internationalisation of production and trade leads, of course, to an increasing importance of international standards and regulations. For legal metrology, the activities within the scope of OIML are, above all, decisive, whereby for the field of fluid measurement, especially the revision of OIML recommendation R117 "Dynamic measuring systems for liquids other than water" [7] is to be mentioned which was completed in 2007. This document already gained great international recognition when it was first published in 1995 and has since then been transposed into national law by many member states of OIML. Technical progress and growing requirements on the measurements, especially in the field of liquid fuels, as well as the fact that OIML R117 is used as a normative document in the MID made a thorough revision necessary. Besides the active representatives of 32 member states, also numerous observers from industry and manufacturers' associations were involved in the revision. The Secretariat coordinating the revision was formed by the USA (NIST) and Germany (PTB). More than 540 comments and modification proposals have been taken into account for the new version of R117 since 2002.

OIML R80 "Road and rail tankers" [8], too, was subjected to a complete revision; its new version was first coordinated by Slovakia (SLM) and Germany (PTB), since 2005 by PTB alone. The aim was particularly to take new technologies into account. This was especially the case for the liquid level gauge used on tank lorries, which was developed into market maturity in Germany and is usable in the legally regulated area and which is, in particular in terms of manipulation safety, much safer than the measuring systems so far applied [9]. The last draft of OIML R80-1 is presently in the final round of discussion, under the modified title "Road and rail tankers with level gauging".

Figure 1:
From left to right:
– storage tank in a tank farm;
– laser probe inside a storage tank;
– scatterplot resulting from a laser scan composed of 800,000 single data points

Of similar importance are the organs of WELMEC, which was founded in 1990 as "Western European Legal Metrology Cooperation" and whose task it is currently, on the one hand, to elaborate a harmonised, unambiguous approach to the problems of European legal metrology in general and, on the other hand, to implement the Measuring Instruments Directive (MID) for measuring systems for liquids other than water (WG 10) and water meters as public utility meters (WG 11).

Further important international standardisation bodies in the field of fluid measurements are in the Technical Committees of ISO and CEN whose main task is to create the preconditions for a worldwide recognition of test results, approvals and certificates by harmonising the requirements that are placed on liquid measuring instruments and metering systems.

6 Summary

Legal metrology is of paramount importance for liquid measurements whereby the focus lies, above all, on the measurement of petroleum and petroleum products as well as potable water and other liquid foodstuffs. Thereby, PTB assumes, in the first place, the role of a service provider. This applies to product certification, the anchoring of the results from research and development into new measuring instruments and test procedures, and the securing of consumer protection and health and occupational safety. PTB is, thus, a partner for numerous German and European companies as well as for the verification and market surveillance authorities. In this context, it is important to also mention its wide-ranging activities in the national and international regulation and standardisation bodies.

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Applied Calorimetry in Flowing Fluids: Heat Meters and Cooling Meters

Jürgen Rose[1], Thomas Lederer[2]

1 Introduction

Tempered water for heating or cooling purposes or warm tap water is the most expensive "packaging" of energy currently available on the market. The legislator therefore prescribes that, when the heating and warm water costs are billed according to the consumption, meters have to be used [1]. By this, he pursues two main goals: on the one hand, the costs shall be shared as justly as possible – and on the basis of precise measurements – between the producers and the consumers of energy. On the other hand, the consumer shall be able to use energy with greater awareness and in an economical way (which is the most important effect of precise measurements).

One of the great advantages of the measuring instrument "heat meter" is that the energy consumed is indicated by the meter in legal units (e. g. in kWh). This distinguishes heat meters from heat cost allocators, from whose indicated values the heat consumption is computed subsequently by means of a complicated – and for consumers often non-transparent – procedure. A further cost-saving advantage is that the place of installation of the heat meter can – again in contrast to the heat cost allocator – be chosen even outside the living space, and independent of the various geometric radiator designs.

The technical requirements placed on heat meters are, however – compared to other consumption meters – relatively high. For example, a heat meter intended for domestic use must be able to cope with tasks which are 12 times more demanding than for a power meter – and thereby still comply with all metrological regulations, such as measurement correctness and measurement consistency. Beyond this, a heat meter is, by far, the most complex consumption meter: each of the heat meter sub-assemblies supplied by the manufacturers, i. e. the flow sensor, the temperature sensor pair and the microprocessor-controlled calculator, can be based on different physical active principles.

2 Economic background

In the overall process, approximately 50 billion euro are spent on heating, cooling and warm water in Germany every year. 14 % of the heating are supplied via district heating networks, and approximately 30 % via local networks. The worldwide leading position of meters developed in Germany becomes evident when we look at the fact that every year, approximately 1 million meters are sold on the national market and on markets worldwide – which corresponds to a turnover of 80 million euros, with the tendency rising (as many meters have to be replaced after their validity period of verification of 5 years has expired).

The relative market share for water meters and heat meters made by German manufacturers amounts, in Europe, to 75 %, and to 45 % worldwide; in Germany, currently 95 % of the heat meters on the market have been developed and completed in Germany.

The heat meter manufacturers in Germany employ 3000 people, and it is estimated that 10 times as many persons are employed in the billing networks. Strong dynamics has been observed in China, where approximately 50 Chinese companies supply the local market. All the large German companies are active on that market, too (in the field of production; the field of development remains, however, in Germany).

In Germany, approximately 12 million heat meters are in use, whereby 45 nationally recognised test centres specialised in heat, numerous revision companies working as subcontractors, and the local verification offices employ approximately 2100 people in total. By means of this economic system, 2.4 million heat meters/heat meter sub-devices are prepared for initial or subsequent verification or are subjected to in-service testing every year. Every year, PTB issues and certifies approximately 130 EC type and design examination certificates as well as approval extensions. According to the manufacturers, these documents are of great importance for presenting the devices also on markets outside of Europe, especially in Russia, China, India and in the Far East.

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3 Physical fundamentals of thermal energy measurements

Measurements have shown that people feel most comfortable in a room when the temperature in this room is evenly distributed. Heat – in the physical sense – means an unsystematic movement of the molecules, and heat energy is their kinetic energy. The temperature is a measure for the mean value of the kinetic energy of the molecules.

Outside the physical laboratories, there is hardly any other physical quantity so difficult to measure economically as the thermal energy, which is composed of several measuring quantities. Also, the purchase and operation of a heat meter shall be as inexpensive as possible. Exemplarily for an overall heating system, we will consider in the following a radiator through which, in the stationary state, water flows as a heat transmitter (see Figure 1).

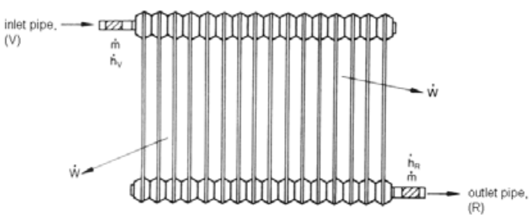

Figure 1:
Mass flow and enthalpy differences in the radiatorr

During the time Δt, a stationary mass flow $\dot{m}$ of the respective heat transmitter flows through the inlet pipe into the radiator. A mass flow of equal quantity leaves the radiator through the exit pipe. Heat is given up to the surrounding air by the radiator. The energy content of the heat transmitter is defined physically by the thermodynamic quantity of state "specific enthalpy" $h = h(p,\theta)$, which depends on the pressure p and the temperature θ. Through heat transmission, this energy content is reduced. Thereby, the water cools down.

For the heat quantity W delivered by the radiator to the surrounding air, over a time period from t_0 to t_1,

$$W = \int_{t_0}^{t_1} \dot{m} \cdot \Delta h \cdot dt \qquad (1)$$

follows.

In contrast to the quantities "mass flow" $\dot{m}$ and "time" Δt, which are easy to be measured, a direct measurement of the enthalpy difference Δh is not possible. What is measurable, however, is the temperature difference between the inlet and the exit. Thereby, use is made of the fact that the enthalpy difference for incompressible media such as water can be represented by means of the specific heat capacity at constant pressure $C_p(\theta)$:

$$\Delta h = C_p(\theta) \cdot (\theta_{inlet} - \theta_{exit}) \qquad (2)$$

In practice, it is often easier to measure the volume flows $\dot{V}$ than to measure the mass flows $\dot{m}$. The mass and the volume of the heat transfer medium "water" are interrelated via the (strongly temperature-dependent) density $\rho(\theta)$. Generally, the specific heat capacity at constant pressure $C_p(\theta)$ and the density $\rho(\theta)$ are pooled into the so-called "heat coefficient" or *k factor* $k(p,\theta_V,\theta_R)$ which takes into account specific properties of the respective heat transfer medium with regard to volume determination.

For the heat transfer medium "water", it is possible to compute, amongst others, from the equations of state for $\rho(\theta)$, $h(\theta)$, numerical values for the heat coefficient. The heat coefficients of other heat conveying fluids (e. g. mixtures of water and glycol) are determined by means of calorimetric investigations of the heat transfer fluids. Heat meters for heat conveying media other than water are not subject to legal verification in Germany.

For the technical work equation of the heat meter for the determination of the thermal energy W delivered by a heating system, it follows from the equations (1) and (2) for the steady case:

$$W = k(p,\theta_V,\theta_R) \cdot V \cdot (\theta_V - \theta_R). \qquad (3)$$

4 Set-up of heat meters

According to the technical work equation for the heat meter (equation 3) derived from the physical fundamentals for the measurement of thermal energy, measurements of the inlet and exit temperature and of the volume of the heat conveying medium are carried out in the heat exchanger system. As to their design, heat meters are composed of three sub-assemblies which can be distinguished from each other as follows:

the volume or flowrate sensor (hydraulic transducer), the temperature sensor pair, and the electronic calculator.

Depending on the design, the sub-assemblies can be either firmly and inseparately connected ("Complete heat meter", for an example of domestic use, see Figure 2) or be conceived such that they are interchangeable – taking, however, the electrical compatibility into account.

Each of the sub-assemblies offered by the manufacturers can be based on various physical active principles whose present industrial product range is presented below as a survey, using common designations [2]:

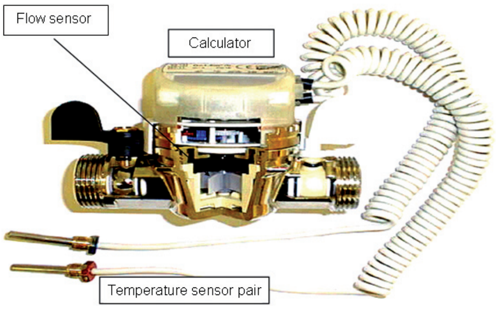

Figure 2:
Complete, compact-design heat meter with the possibility of integrating the exit temperature sensor directly (model cut)

Flow sensor according to mechanical active principles (turbine meters, meters with one or several impellers, Woltman meters, static or differential pressure procedures with diaphragm stops, sonic Venturi nozzles), and according to static active principles (magneto-inductive and ultrasonic procedures, vortex meters, oscillator flowmeters). For domestic use, a strong trend towards ultrasonic flowrate sensors can be observed.

Temperature sensor pair composed of industrial platinum resistance thermometers and measuring resistors in accordance with DIN EN 60751 (Pt 100, Pt 500, Pt 1000, Pt 10,000), semiconducting sensors and thermocouples.

Electronic calculator with microprocessor-controlled electronics, memory-programmed and interrupt process flow control.

5 Legal requirements placed on heat and cooling meters

For heat meters, the requirements are uniform and apply all over Europe. Within the scope of the implementation of the European Measuring Instruments Directive (MID), in Germany, the Fourth Ordinance amending the Verification Ordinance (EO) has been in effect since 8 February 2007 [3]. Cooling meters are regulated nationally. In Annex 22 to the Verification Ordinance, heat and cooling meters are therefore dealt with in separate sections with their maximum permissible errors. For older heat meters, which have already undergone subsequent verification, transitional regulations apply, whereby the maximum permissible errors on verification (MPEs) which apply today have to be complied with, in order to increase the billing accuracy.

In practice, heat and cooling meters must comply with the so-called "operational error limits" (OELs), which are twice as high as the MPEs. The measurement of small temperature differences – as are encountered, e.g., in underfloor heating and air conditioning circuits – and of low flowrates is an extremely demanding task for a heat meter. Due to uncertainty contributions of the physical influence quantities, thermal energy can, at best, be measured with a relative uncertainty of 0.4 %.

The legally permitted OELs for heat meters presently amount to up to 20 % – for low flowrates and small temperature differences – and decrease strongly down to 8 % for medium to large temperature differences and flowrates. These maximum limits are, however, not fully exploited by responsible operators. A field study has shown that the annual mean of the typical error of measurement of high-grade and correctly mounted heat meters amounts to approximately 2 % [4]. The obvious reason for this low measurement uncertainty is that the low flowrates and the small temperature differences contribute only little to the total energy consumption.

Nevertheless, numerous problems remain to be solved in the field of heat measurements; the goal must be to make heat meters more insensitive to erroneous specifications which, unfortunately, are often found in installations in practice and deviate from the approval. For example, insufficient heat coupling to the temperature sensor pair, volume measurement errors due to the flow, chemical water compositions which do not comply with the technical directives, and unequal pressures in the inlet and exit pipe lead to large measurement deviations. In individual cases, they can lie much higher than the operational error limits. Field studies have shown that maximal approximately 5 % of all heat meters lie outside the operational error limits after the validity of their verification period has expired.

An important instrument for PTB to continuously improve the measurement technique – and to contribute thus to environmental and consumer protection – is the execution of numerous research projects and investigations which are carried out in collaboration with partners from industry and with the technical support of supervising verification authorities and of international subject-related institutions. Thereby, the association "EMATEM" (European Metrology Association for Thermal Energy Measurement), which was founded by PTB together with other leading European national institutes, is an important forum serving as an organisational platform for international workshops, conferences and seminars. The "EMATEM Summer School" enjoys special popularity; it is held every year to deal with current problems of heat quantity and flowrate measurement.

A part of the research results is reflected in the publication of technical directives. A current example of this is the Technical Directive K 7.1 on the subsequent verification for heat meters and devices which have been tested for conformity according to the MID and in accordance with the transitional regulation, as well as the Technical Directive K 7.2 which deals with metrological investigations with regard to the type approval and verification of cooling meters. One of PTB's special focuses lies on the continuous development of subject-related fundamental standards providing a basis for the conformity assessment of the MID requirements. A special example is the harmonised EN 1434 issued by the European Committee for Standardization (CEN) which was strongly influenced by PTB developments and into which the "Neue Beschleunigte Alternative Abnutzungsprüfung" ("New accelerated alternative durability test") has recently been implemented, which was developed by PTB and the association of the German water and heat industry ("Deutsche Wasser- und Wärmeindustrie e. V."). Other investigations were dedicated to the hydraulic measuring component of measuring capsule meters according to EN 14154 and to the normative document R 75 of the International Organization of Legal Metrology (OIML).

6 Current challenges

6.1 Influences of deposits in flowrate sensors on the measuring stability

To be able to substantiate basic claims in consumer protection, the legislator stipulates that thorough investigations be carried out under real operating conditions which should also be considered in internationally standardised investigations on measuring accuracy and stability. For this purpose, PTB has, in close collaboration with industry, carried out investigations on the influence of deposits on the measurement uncertainty of flow sensors. Thereby, a procedure was developed in particular which generates typical deposits within one day which have similar physico-chemical properties as „real" deposits and thus exhibit comparable effects on the measuring properties of flowrate sensors [5].

6.2 Flow-related influences on the correctness of flowrate measurement sensors and development of optical flowrate measuring techniques

The measurement correctness of flow sensors in heat meters often depends on the quality of the upward flow before the measuring instrument. Especially swirl and asymmetric velocity profiles of the pipe flow can have disastrous effects, thereby leading to measurement deviations of up to 20 %. For the investigation of these influences, an international working group ("Laser-optical Flow Diagnostics") was founded, headed by PTB, together with the Swiss and Austrian national institutes METAS and BEV. Following exhaustive measurements at the national institutes, at test centres and manufacturers, an internationally recognised test directive was drawn up which was recommended for standardisation for the validation of flowrate test rigs permitting the comparability of different test centres and which, at the same time, represents a basis for the evaluation of testing facilities for liquids other than water. Furthermore, a request from industry was complied with (to take practical cases – by means of re-definitions of undisturbed inlet lengths after, for example, bent piping sections – more into account) [6].

6.3 Development of meters for cooling circuits and solar energy applications

The European Technical Committee in charge, TC 176 of CEN, demands the revision of the product standard EN 1434 which contains the requirements and testing specifications usually placed on heat meters in water/glycol solutions.

Also in cooling circuits under the sole use of water, new requirements arise for the measurement and testing techniques: due to the – compared to the heating – strongly reduced temperature level and the small temperature differences (in the circuit system, for example, 6 °C / 12 °C), higher requirements arise for the linearity and the deviation of the correctness, especially in the case of the A/D converters of the computing units.

The use of heat meters in collector circuits of thermal solar energy plants requires fast reactions to the high dynamics of the measurement quantities. Correspondingly, the integration and calculation times for the temperature difference and the flow rate must be harmonised. The necessary short thermal response time has to be verified by means of a corresponding testing facility. Therefore, a facility has been developed at PTB for the testing of the thermal transient behaviour of flow sensors which allows a cyclic switching between the upper and the lower medium temperature.

6.4 Smart meters

To contain the consequences of climate change, the stipulations of politics aim at a drastic reduction of the CO_2 emissions and an economical handling of fossil fuels. The measures taken in this regard include the creation of saving incentives to encourage responsible heat consumption; for this purpose, for example, the consumption has to be reported to the end consumer (e. g. flat tenant) immediately, i. e. every month. The heat meters which are presently being developed will therefore have to be able to transmit the heat quantities accumulated in separate energy registers to the collection centres of the billing services via remote read-out interfaces; the measurements in this process must be precisely timed and traceable to the individual end consumer. Thereby, it must be possible to take advantage of competitive prices when changing from one district heating provider or billing society to another. Furthermore, the new generation of measuring instruments shall also allow ratings in the results of measured process quantities such as, e. g., the exit temperature and the temperature difference which entice the end consumer to save energy – and thus costs, in order to exploit the energy potentials of optimal energy feeding processes of the district heating provider into the secondary consumer networks. Presently, for the so-called "smart metering" – i. e. the communicative meter generation – the preconditions to fulfil the demanding goals having been set by politics have been created as regards logistics, development, approval processes and verification of such meters.

7 Summary

If the installation has been carried out correctly and the measuring instrument is used in the proper way, heat and cooling meters make it possible at the present state-of-the-art to ensure that the legal requirements are complied with which ensure correct billing and create – at the same time – saving incentives for consumers to adopt a more responsible behaviour towards the use of fuels of all kinds and of thermal energy. The high physico-technical quality of modern measuring instruments is constantly being developed further, thanks to PTB's activities in the field of approvals, as well as due to concerted research and development work with partners in Germany and abroad and due to contributions to international standardisation in the field of thermal energy measurement. The manufacturers of measuring instruments, the operators of heating and cooling plants, the users of measuring instruments and the individual flat tenant are thus enabled to fulfil their respective duties as responsible members of society whilst relying on the accuracy and stability of the measuring instruments used.

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Flowrate Measurement in Power Plants

Thomas Lederer[1], Jürgen Rose[2]

1 Introduction

At present, the lack of precision in the measurement of volume rates or mass rates considerably restricts the efficiency of the operation of power plants. The uncertainty of fluid mechanics has, for example, to be taken into account concerning the thermal performance of nuclear power plants, which has to be lowered in the percentage range. For all types of power plants it must be assumed that the measurement uncertainties in flowrate measurement lead to exponentially sub-optimal command and control processes. In addition, increased measurement uncertainties have an impact on the safety margins, which limits the efficiency of the facilities. Flowrate measuring techniques also play an important role in the determination of the thermal energy in processes of combined heat and power generation. They have an influence on the overall energy management inside the power plant and, furthermore, they are of considerable importance as regards the supply of district heating in public networks. Flowrate measuring technology is thus a point to be focused on if the efficiency of power plants is to be increased.

2 Status quo with regard to measurement uncertainty improvement in power plants

Presently, a considerable part of flowrate measurements in power plants is based on differential pressure measurements, mainly by means of diaphragms or Venturi nozzles. The uncertainties of these measurements lie in the range of approx. 1 to 2 %. A problem of this measuring technique is that the relation between flowrate and measurement signal is, as a matter of principle, not linear; another problem is the considerable sensitivity of the displayed values to irregularities of the shape, the symmetry or the swirl of the inlet flow, as well as the increased measurement uncertainty at very low flowrates. Furthermore, these measurement procedures display significant problems with long-term drifts ("fouling" of the orifice plates), so that measuring stability becomes a problematic factor in the course of the very long operating times [1].

In the past few years, methods have been developed which deal with the symptoms of the high measurement uncertainty in flowrate measurement in power plants, however, not with its cause. Flowmeters have been metrologically investigated – in piping geometries which correspond, to a large extent, to the hydraulic set-ups as can be found in power plants – with the intention of finding comparable flow profile influences. This is certainly the case – at least in theory. However, these measurements have not been carried out at operating conditions (e.g. water at a pressure of 200 bar and temperatures of up to 280 °C). By means of extrapolation methods – which take into account thermally and pressure-induced geometry changes and also changes in the viscosity and density via the Reynolds number (similarity law) – it is possible to make corrections for the transfer to different operating conditions. One must, however, reckon with and put up with an increased measurement uncertainty.

Another metrological approach was, for example, the installation of additional ultrasound clamp-on sensors, in order to generate additional monitoring signals to obtain information on the drift behaviour of the process measuring instruments used. However, due to the excessively high uncertainty contribution of the tapping parameters to the total measurement uncertainty, this approach does not necessarily have to be pursued any further, from today's point of view.

In summary, one can say that the metrological approaches used for the determination of the volume flow or the mass flow in power plants have neither contributed to a significant reduction of the measurement uncertainty nor to a decisively increased measurement stability.

Due to the fact that in power plant measuring techniques, only little progress has been made in the field of metrological procedures, mathematical methods have been preferred lately. These correlate all the measurements with each other which have been carried out in the power plant (on the basis of mass balances, among other things). These methods were created in accordance with VDI Guideline 2048 "Uncertainties of measurements at acceptance tests for energy conversion and power plants" [2].

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Whereas the VDI Guideline clearly points out that this method may only be used to detect coarse faults (e. g. leaks or drifts), the advocates of this method have turned it into a procedure which they use conventionally to optimise their power plant processes and to reduce measurement uncertainties. The reason for this is that they start from a presupposition which, although it seems obvious, is – unfortunately – wrong: they assume that the correlation of measurement data will lead to a reduction in the measurement uncertainty, true to the motto “the quantity is measured repeatedly, therefore the measurement uncertainty decreases”. In reality, however, the correlation of measurement data when determining the measurement uncertainty enters with a positive or negative sign and thus the uncertainties may – depending on the measurement system considered – be increased or reduced. Moreover, this method is based on the further presupposition that the measurement equations used can be linearised. In the case of the measuring technique used in power plants, however, this might be totally wrong (e. g. in the case of orifice plates) and can lead to unrealistic solutions.

To summarise, one can say that the mathematical methods of optimising (“up-rating”) the efficiency for power plants cannot yet be regarded as being sufficiently validated. Proof of this is the fact that in the U.S., up-rating authorisations which were based on this method were recalled. The widespread use of these methods is probably due to the fact that the community of power plant operators is, for the greater part, not familiar with the modern concept and with mathematical methods to determine the measurement uncertainty.

3 Approaches to optimise the efficiency

From a metrological point of view, direct, traceable flowrate measurements are necessary at those points of the power plant that are important for the total energy balance and for the control concept. Such points are, for example, the determination of the volume rate in the inlet water pipe, in the various heat exchange pipes, at the uncoupling point for combined heat and power, etc. Basically, there are three different ways to cope with this.

At present, multi-way ultrasound measurement systems are the focus of attention. With these measuring instruments, promising and long-term experience has been gained in the field of measuring gas and petroleum products. To these measuring instruments, a – metrologically validated – uncertainty of less than 0.2 % is attributed. These measuring instruments seem to work linearly over a wide temperature and viscosity range of the media to be measured (see Fig. 1). For their utilisation in power plants, however, there is still a gap of approximately one order of magnitude between the validated measurement values and the operation point in the power plant (with regard to the Reynolds numbers prevailing there). For a typical power plant application, the Reynolds number lies in the range of approx. $5 \cdot 10^7$, i. e. approx. a decade above the presently available measuring ranges.

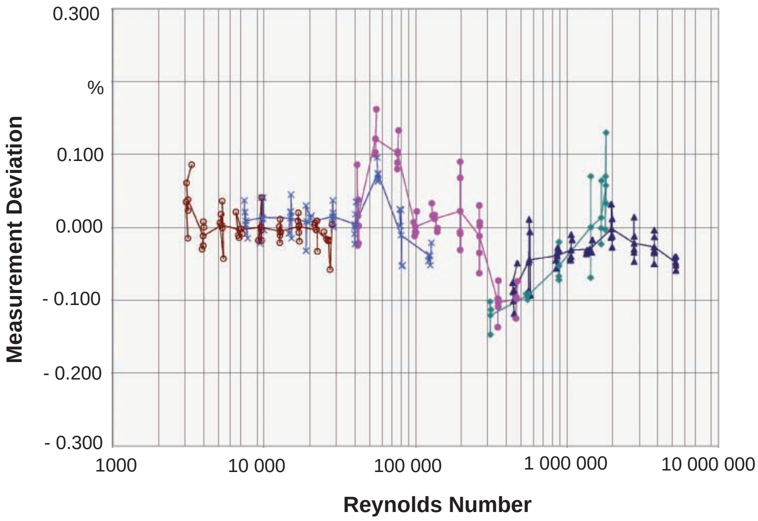

Figure 1:
Measurement deviation of a typical 5-way ultrasound sensor (here: Altosonic V by Krohne Messtechnik) for fluids of different viscosity (brown: 87.3 cSt; light blue: 28.8 cSt; red: 5.6 cSt; dark blue: 0.5 cSt; green: 1.1 cSt) as a function of the Reynolds number

Due to the importance of measurements in power plants, PTB is extending its measurement capabilities by investments amounting to several millions of euros. Upon completion, standard measuring facilities will be available which will enable traceable measurements over a temperature range from 3 °C to 230 °C, a volume rate range from 6 l/h to 1000 m^3/h and at pressures of up to 40 bar. These measurement systems will, for the first time, make it possible to make metrologically validated statements on the uncertainty of measurements in power plants. In order to clarify the fundamental scientific aspects involved, PTB is performing research in collaboration with the company Krohne Messtechnik.

An ideal method would be a calibration of the power plant measuring techniques at operating conditions – i. e. at volume rates up to 10 000 m^3/h, pressures of up to 200 bar and temperatures of up to 280 °C. There are some indications that installing such test rigs in a power plant would pay off. At PTB, several comparable cooperations with companies (e. g. with E.ON Ruhrgas) have already been launched, and within the scope of these, it has already been possible to realise a national standard on a privately run test rig.

Another possibility to be used for direct, traceable measurements of the flowrate in power plants would be the application of laser-optical methods, in particular laser Doppler velocimetry (LDV). Thereby, the volume rate is determined by the direct integration of the laser-optically measured velocity distribution at the place of measurement. The advantage of this method is that volume rate measurements can be performed without considerably increasing the measurement uncertainty, which is of approx. 0.2 %, even in strongly disturbed, swirling volume rates displaying a fast time-dependent flow variation and instable fluid temperatures.

Together with two innovative laser companies, Intelligent Laser Applications GmbH, Jülich, Germany, and Optolution GmbH, Reinach (Switzerland), PTB has developed and patented a corresponding measurement procedure [3], as well as set up and validated a measurement system. The measurement system is presently being put to the test in a district heating station in Vienna (see Fig. 2).

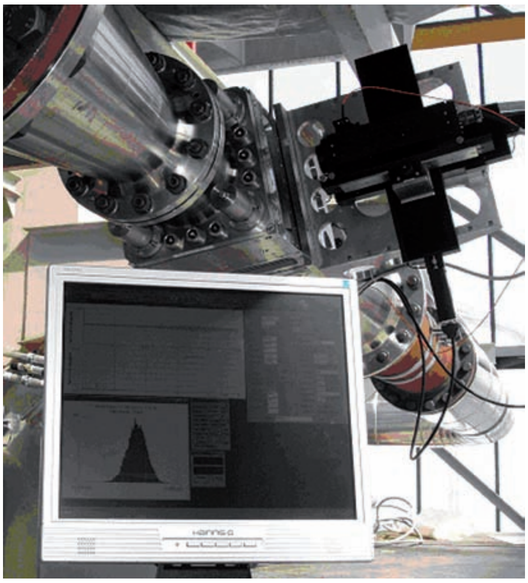

Figure 2:
Use of a laser Doppler velocimeter at the Kagran district heating station, Vienna

This patented measurement procedure unites non-contact LDV velocity measurement with placing the measurement point exactly on a predefined grid in the piping. The optical access to the flow is thereby performed via a refractive-index-adapting window chamber which is set up in a way optimised with regard to the flow. Presently, this system is limited to applications in water at up to 120 °C and 25 bar. From a technical point of view, designs adapted to higher pressures and temperatures are feasible. For this purpose, PTB collaborates closely with the German Technical Supervisory Board (TÜV). Developments are currently geared to procedures where optical components can be integrated into power plants while these are in operation. These "hot tapping" methods have been put to the test in power plant technology and in the chemical industry and have already been recognized.

4 Summary

With metrologically improved measuring methods, the efficiency of power plants could be increased by approx. 2 %, especially in the field of volume rate determination. PTB is currently working on two methods to mobilise resources for this purpose. On the one hand, a metrologically validated method is being developed to extrapolate the calibration of common process measuring instruments at low pressures and temperatures to the operating conditions in power plants. On the other hand, PTB is working on adapting laser-optical methods to the measurement conditions in power plants. A particular advantage of the laser-optical method is the direct determination of the volume rate, even at the most unfavourable flow conditions. The third – and most promising – method to reduce the measurement uncertainty of volume rates in power plants – the calibration of the process measuring instruments at operating conditions – would make it necessary to set up a standard measuring facility. This, however, would exceed PTB's financial capabilities. Together with partners from industry, such a measuring system could, however, be set up and operated profitably.

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Renewable Energy Sources – Metrological Challenges in Production and Trade

Stefan M. Sarge[1], Henning Wolf[2], Roland Schmidt[3], Harald Müller[4]

1 Introduction

Besides hydroelectric power (which has already been used intensively for a long time), energy sources from pre-industrialised times have increasingly come into use again lately. This applies especially to wind power – which is mainly used for power generation – and to the energy sources of chemical energy called regenerative fuels, from non-fossil, renewable sources, amongst which are solid biomass, vegetable oils, vegetable oil esters (biodiesel), bioethanol and biogas. Renewable energy sources are used increasingly, as they are expected to bring about a series of environmental and economic advantages. They are used to:

- reduce the emissions of greenhouse gases, especially carbon dioxide;
- reduce the dependence on energy imports;
- help develop new income sources in agriculture;
- support small and medium-sized enterprises;
- create sustainable jobs in innovative companies;
- open up new export possibilities to German industry,
- give an example of environmentally-friendly behaviour.

When it comes to using wind power, from a metrological point of view it is especially the measurement of the flow velocity which is particularly relevant; in the case of renewable energy sources and fuels, material parameters such as density, viscosity and energy content are the most important parameters to be measured.

Note: Energy can neither be generated nor can it be used up. It can only be transformed from one form of energy into another (1st law of thermodynamics). This is the reason why we – contrary to the relevant laws, literature, comments, etc. – call them "renewable energy sources", not "renewable energies".

2 Wind power

With over 30 billion kWh produced yearly, Germany is leading worldwide in the generation of wind power. Since 1991, wind farms having a capacity of more than 20 000 MW have been erected and thus, not only significant technological progress has been achieved but also the production costs for electricity (in €/kWh) have been reduced by approx. 60 %. With 30.5 billion kWh in 2006, wind power already provided 5 % of the total power supply in Germany and, thus, represents the largest share of power generation from renewable energy sources [21].

According to expected developments, renewable energy sources will achieve a share of 15.5 % by 2010 and of 27 % by 2020 from a current gross power consumption of 612 TWh which is expected to slightly decrease to 570 TWh [21]. According to this estimation, regenerative power generation will, thus, increase from 74 TWh (1 TWh = 1 billion kWh) in 2006 to more than 150 TWh in 2020, whereby wind power would account for more than half of the total amount.

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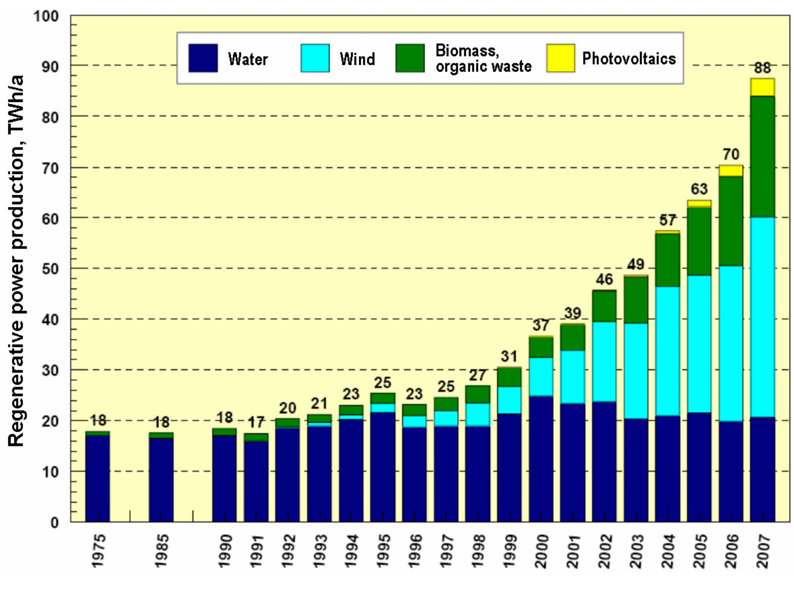

Figure 1:
Development of the power generation from "renewable energies" [22]

With regard to onshore wind power, an increase of approx. 50 % is expected within the next 10 years. This will be achieved by exploiting the remaining sites and, especially, by replacing older wind farms with new, more modern and thus more efficient ones (“repowering”). In the long run, however, the development of the use of offshore wind power is considered as being of significantly greater importance.

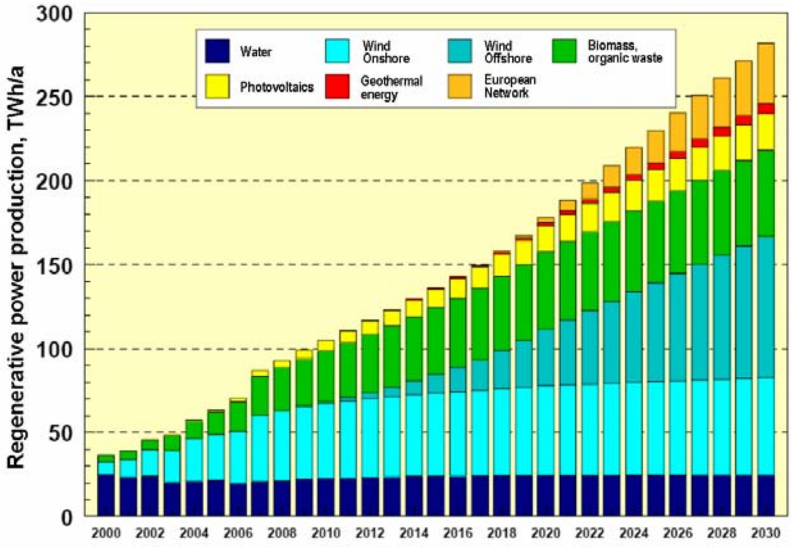

Figure 2:
Development of power generation from “renewable energies” [22]]

The accurate measurement of wind velocity is of central importance when it comes to wind potential analyses and efficiency considerations for wind farms. The power generated by the wind depends with the third exponent on wind velocity. If one presupposes a mean annual wind velocity of between 7 m/s and 10 m/s, then the measurement uncertainties of ≥ 0.1 m/s which are presently applicable to the generation of wind power for anemometer calibrations, lead to uncertainties of up to 8 % in the estimations on wind energy recovery.

With the prognosticated significance of wind power utilisation and the exploitation of development and cost-reduction potentials, there is, therefore, an increased interest in an improved traceability of the wind velocity measurement with reduced measurement uncertainty. The fact that in 2008, the number of anenometer calibrations performed by DKD for the sector of wind power alone exceeded 6000, accounts for the increased need for traceable wind velocity measurements, whereby the reduction of the measurement uncertainty has gained in importance with regard to the evaluation of the cost effectiveness of new wind farms.

In this respect, it is PTB’s task to, in future, be able to ensure the traceability of wind velocity measurements with measurement uncertainties clearly below 1 % in the range of 5 m/s to 10 m/s which is relevant for the performance characteristics of wind farms by applying suitable – especially optical – non-interacting measurement procedures.
In this context, PTB has extended its measurement capabilities by means of a new (“Goettingen-type”) wind tunnel with a nozzle diameter of 320 mm for air velocities from below 0.5 m/s up to more than 60 m/s.

3 Biofuels

Renewable fuels are used as pure substances or in mixtures with traditional fossil fuels. The properties of biofuels can be adapted to those of fossil fuels by chemical or physical procedures so that these processed substances can be used without having to modify the engines or facilities in which they are used. By modifying the engines and facilities, it is possible to use biofuels directly. When using mixtures with fossil fuels, the concentration is often chosen in such a way that the mixture can be used in engines and facilities which have not been modified. In both cases it is, however, necessary to ensure that the measuring instruments used to determine the material properties and quantities provide correct results according to the requirements including those, especially, of the Verification Act.

3.1 Political background

The German legislator supports the introduction of biofuels by prescribing a minimum share of these in fossil fuels. The Law on the Share of Biofuel, of 18 December 2006 [1], prescribes a share of 8 % biofuel in total to be achieved by 2015, of which at least 3.6 % has to be in petrol and at least 4.4 % in diesel – each as a function of the energy content. It is, however, up to the petroleum producers and retailers in which way they are going to fulfil this requirement – by selling fuels with biofuel mixtures or by selling both pure fossil and pure alternative fuels.

The Law on Renewable Energies, of 25 October 2008 [2], is aimed at, amongst other things, increasing the share of renewable energy sources for the supply of power to at least 30 % by 2020. For this purpose, the production of, amongst others, biogas and its utilisation for the generation of power in combined heat and power plants is promoted.

The Federal Government of Germany has committed itself to reducing the emission of climate-relevant gases by 40 % (270 Mt) by 2020. The use of biogas (see Fig. 3) as well as the use of biogenic liquid fuels in the sector of road traffic are considered as being particularly expandable.

3.2 Legal metrology

The Verification Act [3] regulates the trade with measurable goods by requiring the use of ap-

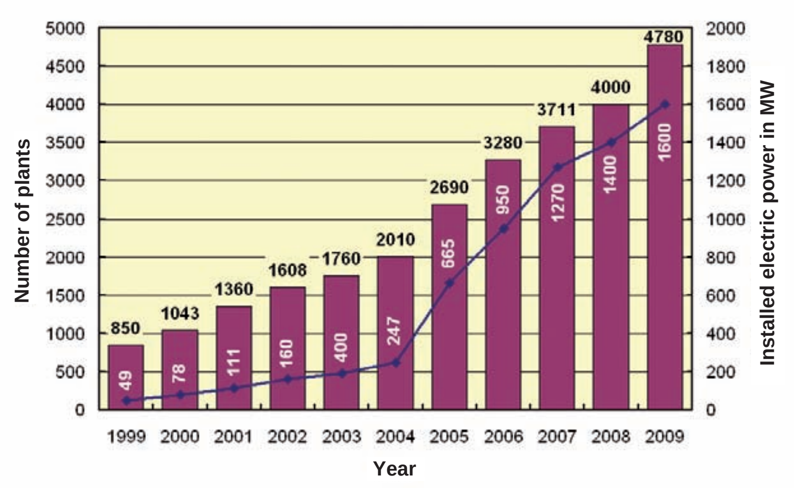

Figure 3:
Actual (1999-2007) and prognosticated (2008, 2009) growth in the number of biogas plants and in the capacity achievable by converting biogas to electricity.
Source: BMU

proved and verified measuring instruments in all areas where it is necessary for ensuring measurement reliability. The aim of this law is:

- to protect consumers when they buy measurable goods;
- to create the precondition for correct measurement in business transactions;
- to ensure measurement reliability in areas of public interest, and
- to increase the confidence of the public in official measurements.

As a matter of principle, the Verification Act requires the use of suitable measuring instruments. Thus, e. g. at petrol filling stations, the volume of the petrol filled in is measured by means of verified fuel dispensers and light fuel oil is delivered in tank lorries which are equipped with verified volumetric instruments. The calorific value of gases is determined at representative points of the gas grid by means of verified calorific value determination devices and the thermal energy of the delivered gas quantity is determined according to the accepted rules of technology.

3.2.1 Conventional gaseous fuels

The Verification Act has always been applied in the field of fossil fuels. This is true of both thermal energy measurement and gas volume measurement. The thermal energy of gas is the quantity of energy which is released in the form of heat by the combustion of a defined gas amount. The quantity of energy delivered to the end consumer is determined by converting the quantity of gas determined by volume measurement in situ to base conditions (standard temperature $T_n = 273.15$ K, standard pressure $p_n = 1013.25$ mbar) and multiplied by the billing calorific value which, in turn, results from the measurement of the calorific value of the gas at a representative point in the gas grid. It is necessary to measure the calorific value at a representative point of the network because natural gas, as a natural product, underlies fluctuations in its composition and thus in its energy content – which is quantitatively expressed by the calorific value.

The conversion of the measured volume at operating conditions to a volume at base conditions is performed by means of equations of state which describe the pressure/temperature/volume behaviour of a natural gas as a function of its composition. The conversion methods must be verified by PTB and approved for the envisaged application. At present, three methods are in accordance with the accepted state of the art of technology: direct density correction [4], state conversion with the SGERG-88 equation of state [5] and the state conversion with the AGA-8-DC92 equation of state [6]. The state conversion with the GERG-2004 equation of state [7] is not yet recognised as an accepted rule of technology according to the Verification Ordinance.

3.2.2 Renewable gaseous fuels

Also in trade with renewable fuels, verified measuring instruments are mandatory. Biogas differs from natural gas by its composition and physical properties. Table 1 contains values for biogas. Thereby, a difference is made between raw biogas, which occurs directly after fermentation, and processed biogas, which has undergone a desulphurisation, drying and carbon dioxide reduction treatment by pressurised water wash, vacuum pressure-swing adsorption or other procedures. Raw biogas is used – after desulphurisation – directly to drive a gas engine or to fuel a combined heat and power plant. Biogas which has been refined up to the quality of natural gas is fed into natural gas distribution networks as additional gas or replacement gas.

According to [8], additional gases are gas mixtures which strongly differ from the base gas by their composition and their calorific properties. Such gases can be added to the base gas in limited quantities as long as the combustion behaviour of the mixture only changes minimally. Replacement gases are gas mixtures which, despite a composition and properties which differ

Table 1:
Composition (volume fraction in per cent) and properties of raw biogas and processed biogas for use as a replacement gas [8, 11–12]

	raw biogas	processed biogas
CH_4 / %	50 – 75	76 – 98
CO_2 / %	25 – 45	< 6
H_2O / %	2 – 7 (20°C – 40°C)	< dew point
H_2S / %	0.002 – 2	< 0.0005
N_2 / %	< 2	< 4
O_2 / %	< 2	< 3
H_2 / %	< 1	< 5
$H_{s,n}$ / kWh/m³	5.55 – 8.50	8.40 – 10.84
$W_{s,n}$ / kWh/m³	5.53 – 9.76	9.48 – 14.31
ρ_n / kg/m³	1.31 – 0.98	1.02 – 0.74

from the base gas, display a similar combustion behaviour to that of the base gas. They are used as a replacement of the base gas.

Since biogas plants are often operated in rural areas, it makes sense to feed the produced gas into the existing natural gas grid in order to transport it to the place where power and heat are needed. In order to ensure correct billing to the end customer, the worksheet G685 of DVGW [20] also applies in this case. It is particularly important to require compliance with the so-called "2% limit" with regard to calorific value deviations, i.e. the average calorific values measured at the feeding points may not deviate from the average calorific value prevailing in the distribution network during the billing period by more than 2%. Approved and verified calorific value reconstruction systems [9] which have proved their worth at the level of the long-distance gas supply grids cannot be used at the local level yet. Research is being done on this topic [10].

The volume of biogas at operating conditions is determined with classic gas meters which are usually suitable for biogas and have been granted approval. The methods which are widely used for the conversion to the volume at base conditions in the natural gas sector – via the equations of state SGERG-88 [5] or AGA-8-DC92 [6] – have, however, been derived for natural gases with typical components and their usual concentration ratios and are, therefore, a priori not suited for biogas and its mixtures with natural gas.

Volume conversion devices are in general approved for the use of natural gases. This limitation results – partly explicitly – from a corresponding passage in the type approval and – partly implicitly – from the conversion method implemented in the volume conversion device on the basis of the equation of state SGERG-88 which is applicable to natural gases only whose compositions comply with the so-called "1/3 rule", i.e. the fractions of the hydrocarbons decrease with increasing chain length in a geometrical row [5, p. 17]. Also the alternatively implemented equation of state AGA-8-DC92 is, as a matter of principle, not suited for biogases since this equation of state has not been developed for oxygenic gases, but for natural gases [6].

In the draft of the new Verification Ordinance (Draft EO 7-7 (2006), Section 2.3 [19]), maximum permissible errors on verification for the gas composition, as well as further gas properties parameters have been suggested. Thus, the use of commercially available gas chromatographs leads, in the case of oxygenic or hydrogenous gases, to an overstepping of the maximum permissible error on verification for the components "oxygen", "nitrogen" and "hydrogen" when certain concentration levels are exceeded. Gas chromatographs which differentiate oxygen and nitrogen are available; gas chromatographs with hydrogen analysis are in the process of development.

The limitations with regard to volume conversion and calorific value determination have de facto led to an impediment to feed biogas into the natural gas grid. In order not to impede the – politically supported – feeding of biogas into the grid until suitable measuring instruments have been developed and have undergone type approval, the verification authorities, together with PTB, have defined limit values for the undetected components below which also calorific value determination devices having an approval certificate for natural gas and volume conversion devices measure "correctly" from the verification point of view, i.e. the deviation is smaller than 10% of the maximum permissible error on verification. These regulations were adopted by the plenary meeting for legal metrology as *Technical Rule for Gas No. 14* and published by PTB. An explanation of these regulations has already been published [13, 14].

3.2.3 Conventional liquid fuels

The quantity of liquid fuels is usually also determined by means of volumetric instruments. The conveying chain from the refinery to the end customer runs via 4 to 6 hand-over points which hand over the liquid at different temperatures, i.e. where volume conversion is also necessary. For handing over light fuel oil, volume conversion is mandatory and required by law, whereas for handing over other fuels, it is performed on a voluntary basis. The conversion methods are described in the PTB Requirements 5 [15]. Corresponding conversion factors for the different fuels are published at regular intervals in "PTB-Mitteilungen" [16].

3.2.4 Renewable liquid fuels

In trade with liquid fuels, the volumetric instruments used must also be adjusted to the properties of the alternative substances since these differ from fossil fuels through their density and viscosity and their particular temperature-dependence. Bio-fuels also differ from petroleum fuels with regard to their inferior calorific value; also amongst each other, there are differences depending on the raw material used.

The Law on the Share of Biofuel – as well as the EU Directive on which it is based [17] – define the required admixture via the energy content of the corresponding fuel. Contrary to the habit in the gas sector to use the superior calorific value to quantify the energy content, in the case of liquid fuels, the inferior calorific value is taken as a basis (the superior calorific value differs from the inferior calorific value by the condensation enthalpy occurring when the water vapour which forms during combustion condensates; the superior calorific value is, therefore, always higher than the inferior calorific value). Due to a lack of traceable measurements which would have to be open to the public and comprehensible, the inferior calorific values of biofuels and petroleum-based fuels have been established by virtue of decree by the Federal Ministry of Finance [18].

The lower inferior calorific values of biofuels compared to those of the fossil fuels express them selves by a higher fuel consumption. Furthermore, the extent of this increased consumption depends on the oil plant used to produce the biofuel in question. The inferior calorific value of biodiesel has not yet been subject to standardisation and is not indicated at petrol filling stations. Another – significant – difference between biofuels and petroleum-based fuels resides in their water absorption capacity. Whereas petroleum-based fuels can hardly solubilise any water at all, biodiesel can absorb considerable quantities of water and bioethanol is entirely miscible with water. It is therefore necessary to measure their water contents.

The density and viscosity of biofuels also deviate from the values of fossil fuels and furthermore, vary according to each biofuel. It is essential to know the density and its temperature dependence for the purpose of volume conversion which, in the case of liquid fuels, is performed to the base temperature of 15 °C. Viscosity is an important correction parameter for flowmeters whose read-out depends on the viscosity of the measured fluid. The density and viscosity of pure biofuels and of their mixtures with fossil fuels must therefore be determined as a function of the temperature. The measuring instruments used for the trade between the manufacturer, the wholesaler, the intermediary, the retailer at petrol filling stations and the consumer must also be adjusted, in order to ensure compliance with the maximum permissible error on verification and the operational error limit and to avoid a one-sided exploitation of the error limits.

3.3 PTB's measuring programme

PTB has launched a R&D programme for the determination of the energy content and the measurement of the density and viscosity of renewable fuels:

- Development of a gas chromatograph for the determination of the composition, calorific value, density and other parameters of raw biogas and processed biogas;
- Investigations on the uncertainty of the calorific values of gases in the public gas supply which have been determined by means of state reconstruction systems;
- Determination of the superior and inferior calorific values of liquid biofuels, and
- Measurement of the density and viscosity of liquid biofuels and their mixtures with fossil fuels. Particular attention is paid to the currently used mixture ratios as they are sold at petrol filling stations.

The investigations on liquid fuels extend to ethanol/petrol mixtures and to mixtures of (currently) rape oil methyl ester, soy oil methyl ester, cocos oil methyl ester and palm oil methyl ester with diesel. The mixtures with fossil fuels were, in all cases, investigated both as summer quality and as winter quality.

Due to the large number of mixtures, this investigation is particularly time-consuming. In order to provide data as quickly as possible, a pdf document with measurement data is made available on-line on the website of Department 1.5 "Liquid Flow" (http://www.ptb.de/de/org/1/15/index.htm).

4 Summary

Regenerative energy sources, such as wind power and bioenergy, are increasingly gaining in importance. It is expected that using such regenerative energy sources can reduce the greenhouse effect and the related global warming, as well as the dependence of the energy supply sector on petroleum products. In particular the variety of bioenergy sources and the currently still insufficient knowledge of the physical and chemical properties relevant for their envisaged use make it necessary to determine substance property data on the basis of measured values with known uncertainty, to adjust the techniques of measurement and to revise the relevant Technical Rules.

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Micro-flowrate – Flowrates in the Range "Microliter per Minute"

Henning Wolf[1], Rainer Kramer[2], Bodo Mickan[3]

1 Introduction

The recording of very small flowrates has been increasingly gaining in importance over the past few years. While so far, flows with flowrates in the range of μl/min have been used only in very few applications such as, e. g., in chromatographic procedures, the spectrum of possible applications has increased due to apparatuses which are manufactured in micro-system technology. This development can be observed in both gas flows and liquid flows. PTB has reacted to these changes by developing standard measuring apparatuses and transfer standards which are dedicated to the range of small flowrates.

2 Liquids

Applications in the chemico-analytical field are already wide-spread – the term "lab-on-a-chip" has meanwhile become well-known for this development [1, 2]. Miniaturisation enables analyses with very small sample quantities, and different sensors on one chip make it possible to perform several analyses at the same time. The measuring time is often much shorter than when using classic equipment, without the measurement uncertainty being increased.

Microdosing has become widespread in the medical field [3]. Drug doses no longer need to be distributed over the whole body in administrations once or several times a day but can be dispensed at a constant dose round the clock, in the ideal case close to the target area. This makes it possible to reduce the quantity of drugs dispensed as well as the undesirable side-effects. Drug depots can be transported out of and into the body via ports, but they are increasingly implanted directly in the body. Implanted depots thus dispense liquid at a pre-defined dosing over several years. In addition, systems for the administration of boluses are being tested which are remote-controlled by radio signals.

2.1 Generation and measurement of small flowrates

In the applications mentioned, flowrates typically lie in the range between 1 μl/min and 1000 μl/min; it is to be expected that even smaller flowrates in the nano-range will soon be used.

In order to generate very small flowrates, numerous micro-pumps have been developed; we will not go further into details with regard to these pumps, [4] provides an overview. The measurement of flowrates is generally performed by means of thermal sensors. Thereby, a pipe section through which the flowing liquid streams, is heated. When the liquid is not flowing, the temperature distribution is symmetrical around the heated spot. Due to heat transport in the direction of flow, an asymmetry occurs as soon as the liquid flows; this asymmetry is used as a measure for the flowrate. Such systems can be constructed in classic precision engineering but can also be very strongly miniaturised thanks to microsystems technology [5]. Since the importance of the temperature asymmetry depends on the thermal conductivity and heat capacity of the liquids, the devices must be adjusted and calibrated according to the type of liquid used in each individual case.

2.2 Standard measuring apparatus for small flowrates

Small flowrates are often measured by means of gravimetric methods. In the case of simple set-ups, the increase of the balance reading of a laboratory balance serves as a measure for the flowrates. Volumetric apparatuses have also been realised [6]. In order to enable traceable measurements of very small flowrates with low uncertainty, a series of additional parameters must, however, be measured and kept constant. At PTB, a corresponding standard measuring apparatus is presently being set up for the flowrate range between 1 μl/min (and smaller) and 1 ml/min. This apparatus will – similar to the large flowrate measuring facilities which have already been realised at PTB (Hydrodynamic Test Field; heat meter test rig) – work gravimetrically, i. e. the liquid is led onto a balance where its mass is determined and the volume of the liquid is calculated by means of its density.

Contrary to the large facilities which are operated in a start-stop way and determine an

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integral flowrate, the micro-flowrate facility can measure flowrates continuously ("dynamic operation"). The time-dependent resolution of the measurement thereby lies – due to the integration time of the balance used – at around 1 second. In the case of the large facilities, a constant flowrate is also generated by means of a reservoir which is mounted in a superelevated position together with an adjustable throttling valve. In order to prevent the formation of drops and to minimise losses by evaporation, the fluid flow is led from the reservoir into the weighing vessel through a leak-tight pipe. The projected measurement uncertainty for the mass flow determination will lie clearly below 1 %. Besides the uncertainty contributions which also occur in the case of the large facilities, in the case of the facility for very small flowrates, the uncertainty in the determination of the evaporation rate is decisive. The evaporation rate is necessary for the correction of the measured flowrate. Besides the balance sensitivity, evaporation is THE effect which determines the lower measuring limit of the apparatus. Since the evaporation rate cannot be measured at the same time as the flowrate, but must be detected before and after the actual measurement, its time-dependent constancy is of paramount importance. This constancy is, however, influenced by numerous parameters, such as temperature, ambient pressure, convection, free surface of the fluid, height of the vessel and degree of saturation of the surrounding gas [7]. All these parameters must be kept constant.

Figures 1 and 2 show an experimentally obtained result with regard to evaporation. Figure 1 shows the mass loss caused by evaporation in a weighing vessel filled with water. Figure 2 shows the deviation of the measured values shown in Figure 1 in a fitted straight. The long-term behaviour of the curve shape is due to evaporation which is not constant in time, whereas the scattering of the measured values and some outliers can be clearly attributed to the balance. A parameter which significantly influences the change in evaporation is the temperature in the weighing chamber whose curve is

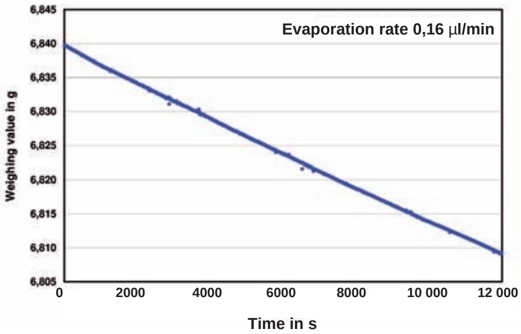

Figure 1:
Mass loss due to the evaporation of water in a weighing vessel

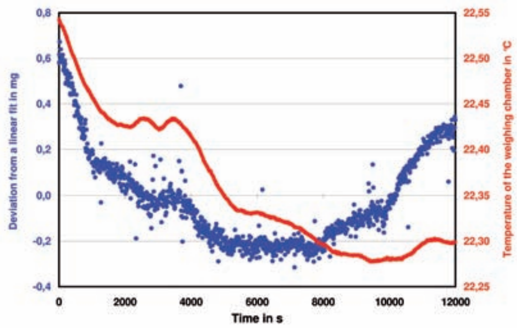

Figure 2:
Deviation of the evaporation rate from a linear behaviour.
Blue curve: deviation of the mass loss due to evaporation from a linear adaptation to the data (left ordinate).
Red curve: temperature in the weighing chamber (right ordinate).

also plotted in Fig. 2 (red curve). Further possible influences on the evaporation are changes in the ambient pressure, in the degree of saturation of the air with water vapour and the convection of the air caused by temperature change.

2.3 Outlook

On the basis of the results obtained up to now, it is expected that evaporation rates with values smaller than 0.05 µl/min can be achieved in the standard measuring apparatus by means of constructive measures. This value can also be considered as a reference value for the smallest flowrate which can be reasonably measured with the apparatus so that the above-mentioned flowrate range could be extended down to this smaller flowrate. The completion of the apparatus is expected in 2009.

3 Gases

When determining small gas flowrates, one must distinguish between applications for which the flowrate measurement is used for the assessment of device or system properties and such for which flows of different gases are to be measured as a process input or output quantity. An example of the first group of applications would be leakage tests of apparatuses and systems which are extremely important in vacuum technology – amongst others. For the quality assurance of products, increasingly, investigations on hermetic encapsulations or on packages are carried out. In order to be able to detect extremely small leakage rates, leak measurements are mainly performed with helium or hydrogen. For the calibration of the leakage meters, test leaks are used which release almost constant flows over longer periods of time.

The second application group, which deals with gas flow measurements in chemical and biological processes, will be considered in more detail in the following. An example of this is the generation of gas mixtures for combustion investigations. Thereby, relatively large gas streams are to be mixed with small gas streams. The generation of test gases for the calibration of analysers is increasingly gaining in importance. At present, these test gases are often produced gravimetrically, i. e. by weighing the elements into a gas cylinder. In order to cover the full measuring range of the analysers, a wide variety of calibration gas mixtures is used. Another possibility is to generate each component of the calibration gas according to its proportion as the gas stream of a pure gas, to measure it and to finally homogenise the mixture. The miniaturisation of the analysers leads to a need for small calibration gas quantities, it is thus necessary to be able to use, as far as possible, also small gas streams of the sometimes very expensive ultra-high-purity gases.

3.1 Generation and measurement of gas flows

For the measurement of small gas flowrates, mainly thermal mass flow meters or controllers (MFCs) as well as laminar flow elements (LFEs) are used. Devices for minimum flowrates of up to Q_{min} = 0.1 ml/min are commercially available. The principle of the thermal mass flow meters is basically comparable with that of the devices for liquids described in Section 2.2. The dependence on the type of gas is given here as well.

In the case of LFEs, the drop in the pressure is determined which occurs when streams flow through one or several parallel channels having suitable dimensions. The channels can be designed as capillary tubes, clearances or circular gaps; it is thus possible to investigate laminar flows in the channels with small Reynolds numbers (Re < 2000). The flowrate depends on the type of gas and is, as a first approximation, proportional to the differential pressure and to the viscosity of the gas.

At present, the link-up of the calibration of these measuring instruments is performed mainly with air. Conversion factors are necessary to use these devices with other gases; these factors are calculated experimentally or theoretically on the basis of the gas properties. The relative uncertainty values are expected to amount to several per cents. Due to PTB's experience with the critical operation of nozzles, which show a very good long-term stability, the use of micro-nozzles has been promoted. Investigations on the transferability of calibrations with air to other gases, especially to natural gas, have shown that uncertainties of U < 0.5 % can be achieved [7] if the thermodynamic gas properties are known. Compared with the standardised shape specified in ISO 9300 [11], micro-nozzles, for production reasons, have a simplified geometry. Figure 3 shows an REM recording of a micro-nozzle

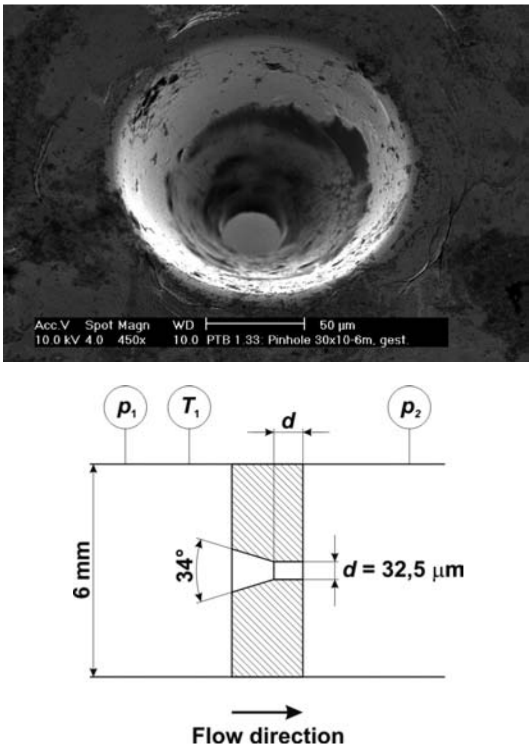

Figure 3:
REM recording and drawing of a PTB micro-nozzle with a neck diameter of d = 32.5 µm

which was calibrated with air, methane and hydrogen and can be used for a Reynolds number range between Re = 5 and Re = 900.

In the same way as for LFEs, in the case of quantity determination by means of a micro-nozzle, besides the temperature also the input pressure and the differential pressure must be measured via the nozzle. The measurement results are shown in Fig. 5. For differential pressures Δp > 900 mbar, the nozzles become critical, i. e. the flowrate only depends on the input pressure, the input temperature and the gas composition.

The results of the investigations have shown that the influence of the gas type can be well represented by means of a standardisation based on the physical properties of the flow [8]. Due to the laminar flow conditions and the simple geometry, micro-nozzles are very well suited for investigations by means of numerical simula-

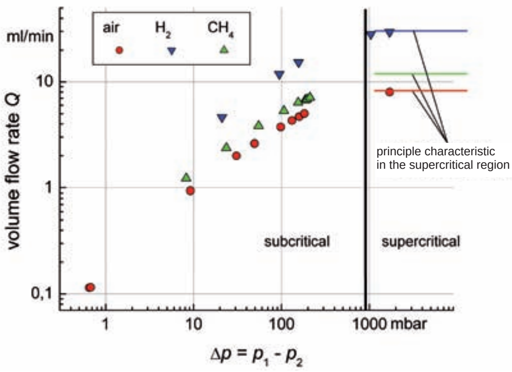

Figure 4:
Flow through a micro-nozzle as a function of the differential pressure between input and output for air, hydrogen (H_2) and methane (CH_4) (Q depending on the input pressure $p1$ and the input temperature $T1$).

tions [9]. Since this requires considering the compressibility of the gas, metrological investigation results which were obtained from micro-nozzles can be used for optimising numerical solution algorithms for compressible flow problems.

3.2 Standard measuring apparatus for small flowrates

For the traceability of the flowrate measurement, also for the flowrates considered here, gravimetric and volumetric fundamental apparatuses are used. Also pvTt methods have been developed for the smallest flowrates in which the pressure and temperature changes in a known volume V were used to determine the flowrate. In the case of the gravimetric method, the mass loss of a container is determined out of which gas flows during calibration. Over the last few years, standard apparatuses have thus been developed which analyse mass loss directly during calibration, i. e. perform a dynamic weighing. On principle, it is also possible to measure the mass of the container at the beginning and at the end of a calibration. The coupling and decoupling of the container from the object under test is technically difficult to realise but would avoid side forces during the weighing. In the case of dynamic weighing, uncertainty influences are caused by the connection capillary tubes towards the test object, by buoyancy effects, the leak tightness of the system as well as the uncertainty of the balance itself.

For traceability, a displacer system was developed at PTB which is traced back to the SI unit of length via the calibration of the plungers. The peculiarity of the set-up shown in Fig. 5 is that the comparator principle was realised by the coupling of the two displacer systems. During the acceleration of the two displacers by means of the stepper motor, displacer system 1 acts as a flowrate sink and displacer system 2 acts as the flowrate source. At a certain speed of the stepper motor, the same amount of gas flows into the “sink” as is released out of the “source”. At this speed, no flowrate is detected in the connection pipe between the two displacers and the comparator is balanced. A particular advantage of this device resides in the fact that it enables a practically unlimited stabilisation of the pressure and temperature at the desired calibration flowrate at the test object. In a flowrate range of Q_{min} = 0.05 ml/min up to Q_{max} = 100 ml/min, with the double-piston comparators of PTB, volume rates can be represented with an uncertainty of 0.05 % (k = 2).

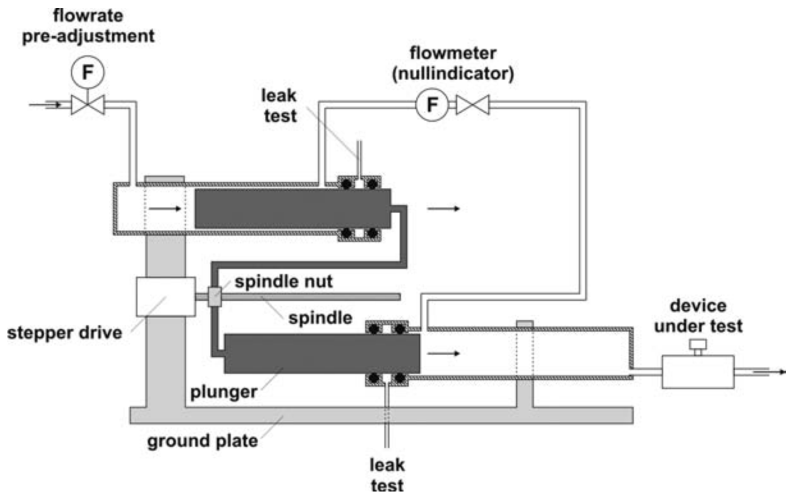

Figure 5:
Set-up of the double-piston comparator

3.3 Outlook

Due to the increasing demand regarding the traceability of working standards at DKD laboratories and in industry, PTB has developed a gas supply with the most important technical gases. It is thus possible, by means of displacer standards, to realise the traceability of these gases and to perform calibrations for third parties. Within the scope of quality assurance, further validations must be realised on the standard apparatuses for the quantification of uncertainty influences such as, e. g., leak tightness. With regard to the micro-nozzles, the transferability of calibration results from one gas to other gases must be further investigated, with a particular focus on the achievable uncertainties. In order to promote a use as transfer standard, also long-term investigations are envisaged.

4 Summary

In order to ensure the traceable measurement of very small flowrates, fundamental investigations for the measurement of both fluid flows and gas flows are being performed and standard measuring apparatuses are set up at PTB. Starting at the end of 2009, the calibration of flow meters for water in the flowrate range from 1 ml/min to 1 µl/min can be offered as a service. An extension to other liquids is planned.

At PTB, flow meters from 0.1 ml/min can be calibrated with different technical gases by means of displacer devices. An improvement of the uncertainty of the standards, especially for flowrates below 1 ml/min, and the development of transfer standards on the basis of micro-nozzles are our future focuses of work.

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