PTB's "Hydrodynamic Test Field" - Investigations to Verify the Measurement Uncertainty Budget

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Abstract Establishing a national liquid flow standard that meets the accuracy requirements of modern industry makes necessary the application of up-to-date instrumentation devices in a calibration facility and appropriate test and verification procedures applied on this facility. The participation of PTB's new water flow facility in the international key comparison test of the CIPM; CCM.FF-K1, provided the opportunity to utilize the approved round-robin transfer standards in order to prove the accuracy, repeatability as well as the stability of the essential process parameters during the measurement and calibration procedures.

Keywords: Liquid flowmeter calibration; liquid flow reference standard; measurement uncertainty, calibration facility instrumentation

1. Introduction

PTB's new high-accuracy water flow calibration facility [1] has been commissioned. Therefore, a series of verification measurements have been performed and are still necessary to prove the claimed expanded uncertainty of measurement of 0.02 % - total flow calibration of a volumetric flowmeter - that was aimed at. This low uncertainty level is necessary as the facility serves as national liquid flow standard.

With a view to achieve minimum measurement uncertainty and to provide system-internal verification and comparison capabilities, the calibration facility was realized as a dual-reference flow standard that comprises balance and diverter based gravimetric references and a compact pipe prover as volumetric reference (see **Fig. 1** and **Table 1**, respectively). In **Fig. 2** the arrangement of the facility's essential component parts, the two different-size calibration lines (DN 400 in the foreground, DN 150 is located behind it) and the 30-tons weigh tank in the background, can be seen.
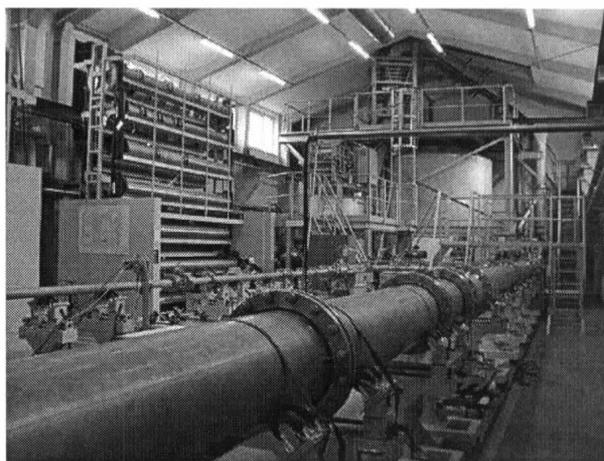

Fig. 2 View of the calibration hall (calibration lines with the weighing system in the background)

For a realistic estimation of the facility's measurement uncertainty capabilities at a level as low as 0.02%, the mathematical model of the measurement process should imply all relevant process quantities as well as the influences and imperfections that originate from the employed measurement devices and their calibration. For this analysis, the use of a special modeling element, a so-called generalized measurement device, is suggested.

The accuracy verification measurements, the paper refers to, were performed during an inter-comparison campaign from mid December 2003 through mid January 2004. As reference standard, the facility's 3-tons weighing system was incorporated. The transfer standard, which was circulated among the participating national metrological institutes, was realized as a tandem arrangement of Coriolis mass flowmeter and dual-rotor turbine
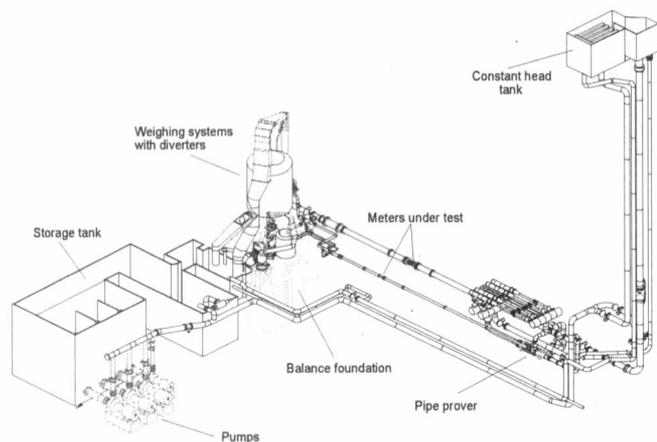

Fig. 1 Cutaway view of PTB's water flow calibration plant (constant head tank is located at a height of 35 m)

flowmeter [3], whose position in the pipe system, i.e. upstream and downstream position, was interchanged to determine the facility's repeatability and repro-ducibility capabilities and flow related impacts.

Another quantity that may be subject to flow meter calibration and ,thus, to measurement uncertainty analysis is the meter K-factor K_{Meter}. In case of a

Table 1 Parameters of PTB's water flow facility

Plant features	Item(s)	Characteristics
Measurands	Volumetric/mass flow rate	Flow-rate meters
	Volume/mass (totalized)	Volume/mass flow totalizing meters
Calibration mode	Flying START / FINISH	Diverter
Reference standards	*Gravimetric calibration*	*Balances:* 0,3 t, 3 t and 30 t *(static weighing)*
	Volumetric calibration	Pipe prover
Operation modes	**Via constant-head tank**	Constant pressure in calibration line (approx. 0,3 MPa)
	Pump direct operation	Variable pressure in calibration line (max., approx. 0,6 MPa)
Meter / pipe sizes		DN 20 ... DN 400
Ranges of flow rate		0,3 m³/h ... 2100 m³/h
Expanded measurement uncertainty	Via constant-head tank	**0,02 %**

2. System measurement uncertainty analysis

2.1. Fundamental aspects

The verification of the measurement uncertainty of a measurement device, such like a liquid flow facility, requires the establishment of a model of the measurement process which describes analytically the relations between the measurand and the so-called input quantities, which contribute to the total uncertainty associated with respective calibration result.

In fluid flow applications, there occur four measurands:

- Volume flow rate (**Equ. 1a**),
- Mass flow rate,
- Total volume (volume passed measurement),
- Total mass (mass passed measurement).

The measurand which the claimed measurement uncertainty of PTB's water flow facility refers to is the fluid volume V_{MUT} having passed through the meter under test during measurement time T_{MEAS} or the deviation of the meter reading from reference volume V_{REF} (**Equ. 1b**).

$$\dot{V} = \frac{V_{REF}}{T_{MEAS}} \tag{1a}$$

$$\frac{\Delta V}{V_{REF}} = \frac{V_{MUT}(T_{MEAS}) - V_{REF}}{V_{REF}} \tag{1b}$$

flowmeter with a pulse signal output, the meter K-factor is measured in pulses per unit volume:

$$K_{Meter} = \frac{f_{Output}}{\dot{V}_{REF}} = \frac{N_{Pulses}/T_{MEAS}}{V_{REF}/T_{MEAS}} \tag{2a}$$

$$K_{Meter} = \frac{N_{Pulses}}{V_{REF}} \tag{2b}$$

For intercomparison purposes, the meter K-factor of the meter under test has proven to be the most suitable quantity for the facility's repeatability representation on the basis of which the facilities of the laboratories involved may be compared.

As the majority of flowmeter applications require volume reading as meter output, the central part of the measurement process model and measurement uncertainty budget is represented by determining a reference volume for meter deviation or K-factor calculation:

$$V_{REF} = \frac{m_1 - m_0}{\rho_{Water}(\vartheta, p)} - \Delta V_{IP}(\vartheta, p) \tag{3}$$

V_{REF} is the volume reference value which the meter reading is referred to in order to determine meter K-factor or meter deviation, respectively.

$\Delta V_{IP}(\vartheta, p)$ in **Equ. (3)** represents an error term, associated with an uncertainty, that is caused by differential volume changes of the interconnecting pipe's material and the enclosed fluid due to changes

in temperature and pressure.

It is obvious that, if the process quantities, i.e. temperature and pressure in the pipe section between meter location and the pipe outlet to reference (weigh tank), are unstable during a calibration run, there will be a remarkable impact on the reference value, which is delivered by the gravimetric reference.

The basis to describe the uncertainty propagation is formed by the theoretical model of the measurement process [5], which takes into account all input quantities (generally designated as X_1 through X_N) which are known and have been found to potentially contribute to the uncertainty associated with the measurand Y that is subject to measurement or meter calibration [4]:

$$Y = f_{Model}(X_1, X_2, .., X_N), \qquad (4)$$

with the X_i being represented by:

$X_1 : m_0$,
    mass of water in the weigh tank prior to measurement; is generally equal to zero;

$X_2 : m_1$,
    mass of water when measurement is finished;

$X_3 : \rho_{Water}$,
    density of the water collected in the weigh tank;

$X_4 : \vartheta_{Water, MUT}$,
    temperature of the water flowing through meter under test (MUT);

$X_4 : \vartheta_{Water, IP}$,
    ("representative") temperature of the water passing the interconnecting pipe section V_{IP} between MUT and the pipe outlet to the weigh tank;

$X_5 : T_{MEAS}$,
    period of time whose length is determined by diverter positions on its transitions across fluid stream [9][11];

...

X_N :the Nth input quantity to the mathematical model that causes contribution to the total measurement budget
    (a principal overview of the quantities that are to be taking into account in fluid flow measurement was given in [1], [2]and [9]).

According to [4], for a linearized model, an estimate

of the measurand Y, which is denoted by y, is obtained from the estimates of the input quantities x_i:

$$y = f_{Model}(x_1, x_2, .., x_N) \qquad (5)$$

Assuming that the relevant input quantities are independent of each other, the estimate for the standard uncertainty $u(y)$ is:

$$u^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f_{Model}}{\partial x_i} \right)^2 u^2(x_i) \qquad (6)$$

All input quantities whose measured values including the associated uncertainties are known or estimated can be applied directly on **Equ. (6)**. In case of input quantities whose measured values are acquired via chains of measurement devices, there are additional uncertainty contributions that originate from the uncertainty of the reference standard, they were calibrated on, and from the instability of the measurement characteristics of the respective device itself (see **Fig. 3a**).

2.2. Uncertainty estimates that adhere to input quantities from calibrated measurement devices

In order to investigate and budget the uncertainty of measurement for liquid flow reference standards, in case of total expanded uncertainties as low as 0.05%, the general practice to apply correction factors is satisfactory and is confirmed by experiences in practical measurement.

It should be mentioned that this approach relies on the mathematical model, which is described by **Equ. (3)**. Generally, from the very beginning of analyzing a system, this approach utilizes linearization of the equation, in order to receive analytical expressions whose correctness is given due to small-magnitude input quantities. This is well-handled in measurement practice.

In most cases, when the model of the measurement process in flow measurement is referred to, the equation, which is applied for analysis, is the total differential (first-order Taylor series expansion), i.e. a linear approximation, instead of the "exact" (non-linear) model equation. They represent function approximations based upon linearization in the operating point that is given by the steady-state quantities in **Equations (1)** through **(3)**:

$$m_{0,0} = m_0(m = 0t), \qquad (7a)$$

$$m_{1,0} = m_1(m = 3t), \qquad (7b)$$

$$\rho_{Water,0} = \rho_{Water}(\vartheta_0, p_0), \tag{7c}$$

$$V_{IP,0} = V_{IP}(\vartheta_0, p_0), \tag{7d}$$

with the defined process conditions, e.g.:

$$\vartheta_0 = 20\,°C$$

$$p_0 = 3\,bar$$

2.3. Generalized measurement device for measurement uncertainty analysis purposes

It is the author's suggestion, prior to applying any approximation to the measurement process model, to incorporate formulae that describe the steady-state response output vs. input quantities. That means, the respective input quantity or measurand is characterized by the sensor and transducer characteristics as it is given by data sheets and calibration measurements. In general these characteristics are linear or non-linear functions that are defined in standards and can be determined with a higher accuracy via calibration.

Typical examples of such parametric models are:
1) The platinum resistive temperature detector (RTD), whose resistance $R(\vartheta)$ as a function of temperature ϑ is based up **Equ. (8)** :

$$R(\vartheta) = R_{20}[1 + A \cdot \vartheta + B \cdot \vartheta^2], \tag{8}$$

with the temperature coefficients A and B.

But with respect to the sequence of the cause-and-effect chain [8][15], temperature has to be determined due the measured electric resistance, i.e. the inverse function of **Equ. (8)** has to be applied.

The temperature measurement chain, in addition to the RTD, also comprises resistance-to-voltage and analog-to-digital conversions. These auxiliary devices are also subject to calibration and, thus, they imply contributions to measurement uncertainties.

2) The weighing systems in PTB's water flow facility, which are equipped with calibration weights and automated calibration capabilities [3].

3) In-process density measurement to provide "real" measurement values of the test fluid in the water flow facility [2].

In order to provide means for incorporating the above mentioned sensors with the dedicated measurement chain in a comprehensive measurement process model, a "generalized measurement device" (GMD) is used. The principle of such a GMD is shown in **Fig. 3a** and **3b** to give an imagination what quantities

are applied to the input "terminals", what are internal variables and what is the informational contents of the output signal.
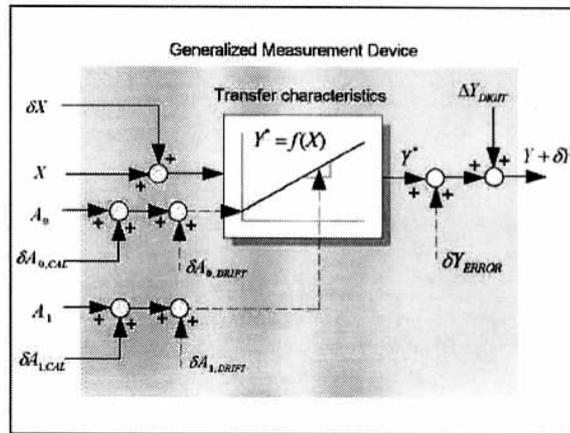
a)
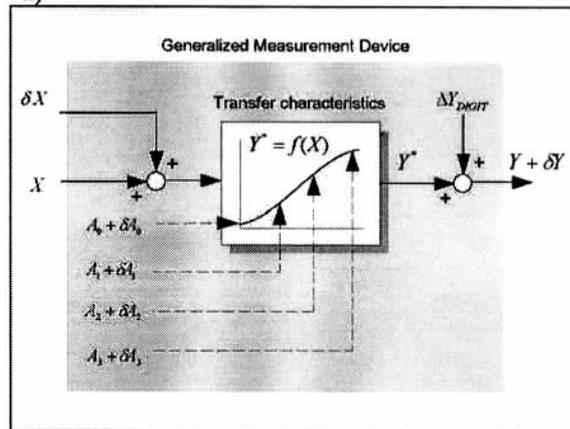
b)

Fig. 3 Generalized Measurement Device (GMD)
(cause-and-effect-chain: input signals cause GMD's output response)
a) Linear model of a GMD
b) Non-linear model

The intention of the approach suggested is:

- to provide a quantifiable system description of output quantity vs. input quantity ($Y^* = f(x)$);

- to take into account meter calibration results including their associated uncertainties that originate from the uncertainties of the standard(s) used (**Fig. 3a**: A_0, A_1, δA_0 and δA_1);

- to provide a signal input to uncertainty that originate from the measurement process (Type A or Type B evaluations [5]) in which the measurement device is applied (δX);

- to take into account the zero and span drifts of the

measurement device in use ($\delta A_{0,DRIFT}$ and $\delta A_{1,DRIFT}$).

The item δY_{ERROR} in **Fig. 3a** summarizes all imperfections of a (fictitious) linear meter: linearity error, hysteresis and other, which are generally given in data sheets.

As an option, the GMD approach comprises an internal source of uncertainty ΔY_{DIGIT}, which originates from analog-to-digital conversion [10]. This "signal" source is only active or valid if the respective element or device, the GMD refers to, contains an analog-to-digital converter.

Whether the linear (**Fig. 3a**) or the non-linear (**Fig. 3b**) GMD model should be applied, depends on whether the measurement device that is to be modeled reveals a linear or a non-linear characteristic and whether linearization of the transfer function is acceptable. In an analytical approach the linearized approximation will reduce the sophistication of the model of the whole system.

From the technical point of view, the linear transfer function is described by the following equation:

$$Y^* = A_0 + A_1 \cdot X \qquad (9)$$

Equ. (10) presents a 3rd-degree transfer function, which is characteristic for the steady-state responses of the balances and the density metering facility [2].

$$Y^* = A_0 + A_1 \cdot X + A_2 \cdot X^2 + A_3 \cdot X^3 \qquad (10)$$

It should be mentioned that, even when a linearized transfer function (**Equ. 9**) is applied, the generalized measurement device implies non-linearity due to multiplication (**Fig. 3a**). For low-amplitude input quantities, this non-linearity due to multiplication can be linearized at the operating point:

$$Y_0^* = f(A_{0,0}, A_{1,0}, X_0) \qquad (11)$$

for analytical investigation purposes, with $A_{0,0}$, $A_{1,0}$ and X_0 as the steady-state parameters and input quantity, respectively, in the operating point.

Thus, for low-amplitude uncertainty input quantities the resulting system behavior is as follows:

$$
\begin{aligned}
Y^* = {} & A_{0,0} + A_{1,0}X_0 + \delta A_{0,CAL} + \delta A_{0,DRIFT} \\
& + X_0(\delta A_{1,CAL} + \delta A_{1,DRIFT}) + A_{1,0}\delta X \qquad (12) \\
& + (\delta A_{1,CAL} + \delta A_{1,DRIFT})\delta X
\end{aligned}
$$

with the last term, as a product of two small quantities; being neglected (see also [15]).

Based upon [7], the utilization of generalized measurement devices can be the basis for digital system simulation with distinct probability distributions of uncertainty inputs, in future works.

When a flowmeter or its calibration, i.e. the determination of the meter K-factor, is subject of a measurement uncertainty analysis , the generalized measurement device approached can be extended to the description of a flowmeter when its steady-state input-output behavior is characterized by a linear or non-linear transfer function, as it is outlined in an ISO standard draft [6].

2.4. Uncertainty model – final remarks

Generally, not all process quantities in a flow standard facility that may have an impact on the measurement and accuracy capabilities or inherent correlations will be recognized and, thus, they will not be considered in the measurement uncertainty budget of a standard facility.

For that reason, it is an urgent necessity to perform comparison measurements. The provision of a dual-reference implementation: gravimetric and volumetric, in the new water flow facility at PTB, provides means to perform intercomparison measurements in one and the same standard facility.

As a step in system accuracy performance verification, the transfer standard meter package, which was circulated during the CPIM initiated intercomparison, was utilized to investigate the repeatability and reproducibility capabilities of PTB's water flow facility.

3. Practical measurement investigations

3.1. Test equipment and procedures

The participation of PTB's high-accuracy water flow facility in the international key comparison of the CIPM: CCM.FF.K1, and the circulation of a set of proven transfer meters provided the opportunity to utilize this test equipment and the test program [4], designed for this key comparison, to verify the

Table 2 Transfer standard package for comparison measurements [4]

Item No.	Component	Type/make	Task	Position in flow direction	Specification (meter K-factor)
[?]1	*Flowmeter #1*	Coriolis mass flowmeter	*Transfer standard*	2 *or* 4	12.0 pulses/L
2	*Flowmeter #2*	Turbine flowmeter	*Transfer standard*	4 *or* 2	10.3 pulses/L
3	*Auxiliary flowmeter*	5-beam ultrasonic flowmeter	Monitoring the pipe flow profile to meter at position #2	1	
4	*Flow conditioner*	Tube-bundle flow conditioner	Improvement of flow profile to meter at position #4	3	
5	*Pressure and temperature taps*	Pressure and temperature transmitters	Measurement of water pressure and temperature	5	

repeatability performance of the PTB facility. By interpreting measurement data, acquired in the test programs, it was tried to find facility characteristics, especially due to the application of YOUDEN plot data representation [12].

Table 3 Key comparison: test configurations and procedures

No.	Test [1]	Configu-ration [2]	Flow rate [3]	Conditions [4]
1	A1	1	H	ON
2	A2	1	L	OFF
3	B1	1	L	ON
4	B2	1	H	OFF
5	C1	2	L	ON
6	C2	2	H	OFF
7	D1	2	H	ON
8	D2	2	L	OFF
/	/			Disassemble & Reassemble
9	E1	2	H	ON
10	E2	2	L	OFF
11	F1	2	L	ON
12	F2	2	H	OFF
13	G1	1	L	ON
14	G2	1	H	OFF
15	H1	1	H	ON
16	H2	1	L	OFF

[1] Each test comprises 5 test runs

[2] **Sequence of meters in flow direction:**
Configuration   #1:   Coriolis - Turbine
             #2:   Turbine - Coriolis

[3] **L = Low flow:**   73 m³/h
H = High flow: 161 m³/h

[4] **ON:**   Switch on equipment prior to test
OFF: Switch off after test
Disassemble: transfer package from pipeline and separate components

The transfer standard package comprised a Coriolis mass flow meter and a turbine meter as transfer meters with signal output characteristics (meter K-factors) that were comparable, so that analysis procedures to determine certain facility-caused impacts on meter outputs were applicable.

In addition to the two transfer standard meters, the transfer standard package comprised (see **Table 2**):
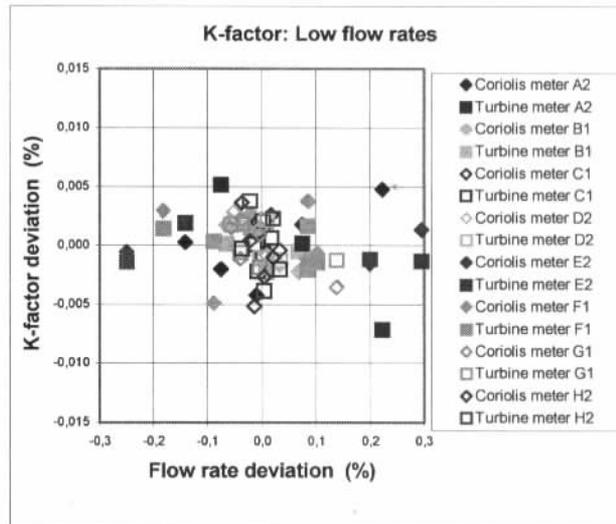
- an auxiliary 5-beam ultrasonic flowmeter that serves for flow profile monitoring purpose at the package inlet section (within the key comparison program),
- a flow conditioner to avoid or reduce influences between the two transfer meters.

Fig. 4a   Meter K-factors vs. flow rate: repeatability at 73 m³/h
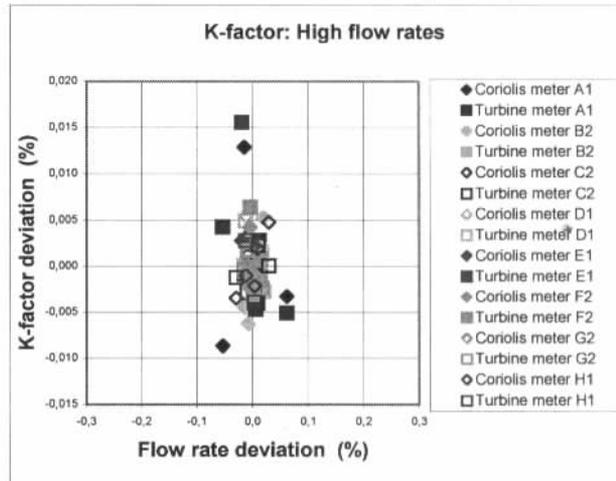

Fig. 4b   Meter K-factors vs. flow rate: repeatability at 162 m³/h

Parameters of the test programs were (**Table 3**):
- Flow rate: "Low" and "High"
- Position of test meter #1 and #2 (upstream or

downstream to each other). The position of the two transfer meters was changed according to configuration #1 and #2, as indicated in **Table 3**.
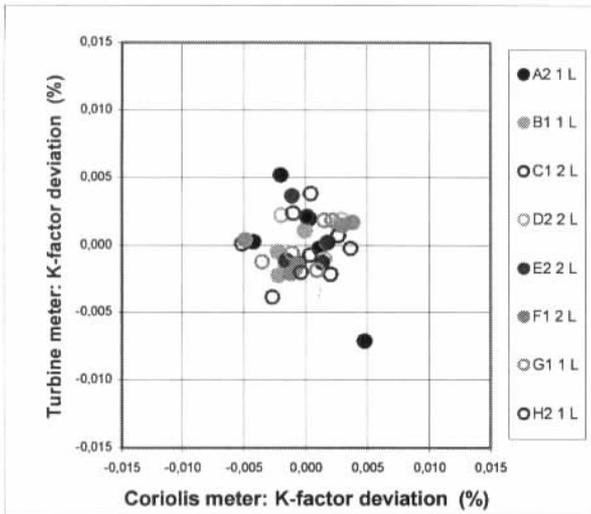

Fig. 5a   Meter K-factors: Turbine meter vs. Coriolis meter (repeatability at 73 m³/h)

Fig. 5b   Meter K-factors: Turbine meter vs. Coriolis meter (repeatability at 162 m³/h)

Each of the **tests A1** through **H2** (see: **Table 3**) comprised 5 test runs, with the electronic equipment being switched on prior to the respective test **#1** and being switched off after having finished the respective test **#2** (e.g. **A1** and **A2**).

Test meter **configuration #1** (Coriolis meter located upstream, turbine meter downstream) was applied during **tests A** through **B** as well as **G** through **H**, **configuration #2** (turbine meter upstream, Coriolis meter downstream) being applied in **tests C** through **F**.

Conditions that simulate reproducibility were enforced by shutting down the system after **test D2**, disassembling the whole transfer package (standard meters and auxiliary devices, see **Table 3**) and separating all components. Afterward the package was reassembled in the calibration line and the test facility was started up again to proceed with **test F1**.

2.3. Key comparison measurement results

The essential results of the test measurements that were performed with the key comparison transfer standard are presented as graphs in **Figures 4** through **8**.

As it was stated in [13], in order to determine system repeatability of a flow calibrator, it is a necessary prerequisite to exclude correlations between the measurement data of the two comparison meters as well as deterministic influences due to variation in flow rate and temperature.
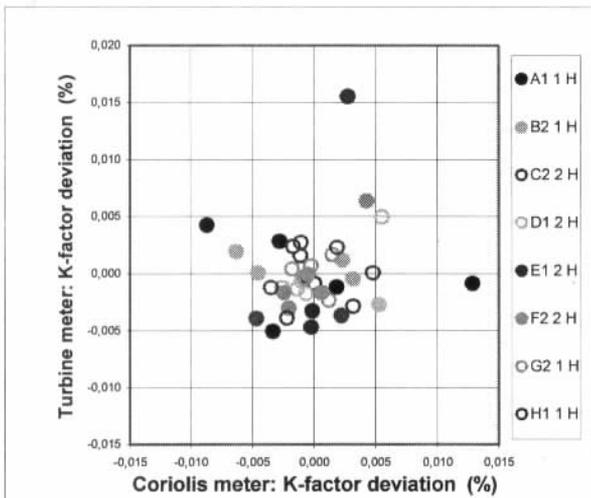
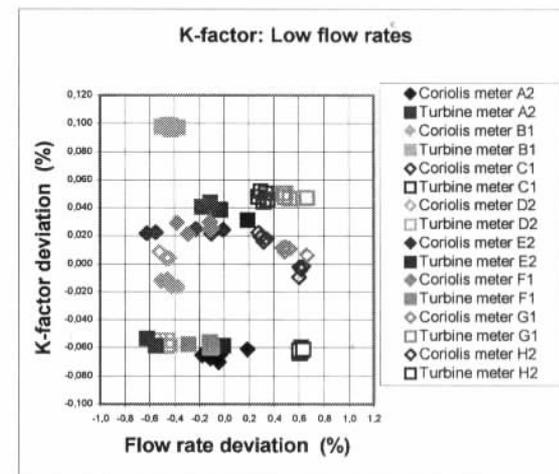Fig. 6a   Meter K-factors vs. flow rate: reproducibility at 73 m³/h
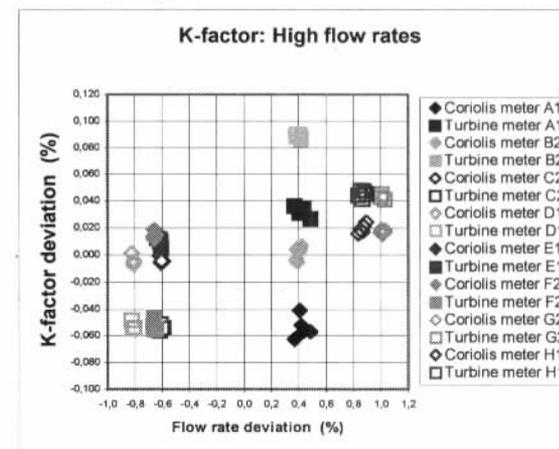
Fig. 6b   Meter K-factors vs. flow rate: reproducibility at 162 m³/h

Flow rate stability during comparison tests can be extracted from **Fig. 4a**: low flow rate, and **Fig. 4b**: high flow rate. All relative deviations in flow rate and meter K-factor depicted represent figures that refer to the respective "local" average over 5 test runs during the test **A1** through **H2**.

The graphs reveal that the flow rate stability at higher (162 m³/h) flow rates is obviously better than at low flow rate (73 m³/h), as a matter of fact.

The standard deviations of the respective flow rates,

adjusted for calibration, vary:
- from $\approx 1.2 \cdot 10^{-4}$ to $\approx 2.7 \cdot 10^{-3}$ at low flow rates,
- from $\approx 7.8 \cdot 10^{-5}$ to $\approx 4.2 \cdot 10^{-4}$ at high flow rates.

It should be mentioned that variations in flow rate cause an uncertainty contribution to the budget of the flow calibration facility [14, chap. 8].

Predominantly, these disturbing variations in flow rate originate from improper operation of the flow regulation instrumentation, i.e. the respective regulating valve that is active in the flow control loop is operating out of optimum region of the valve
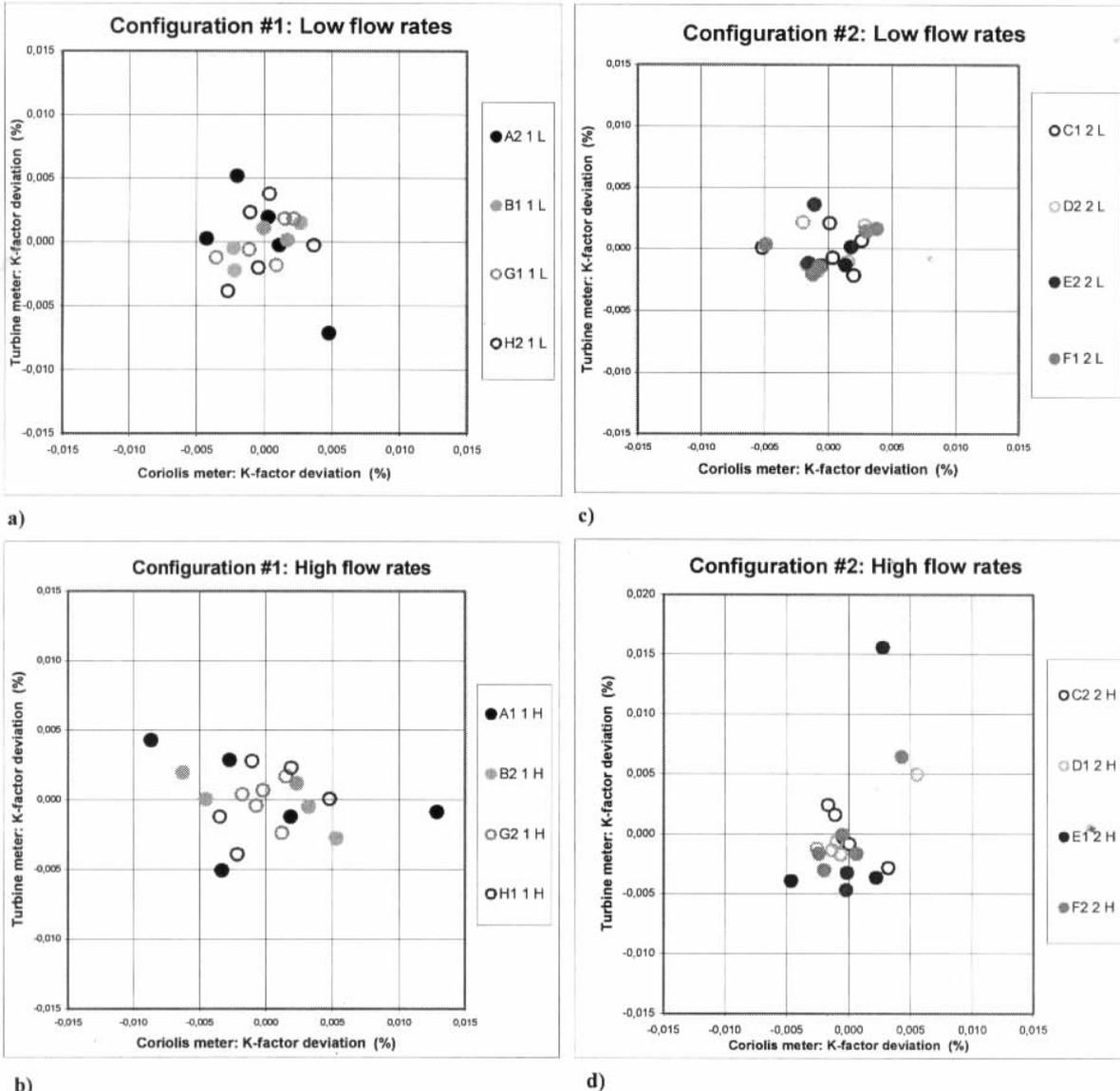

a)

b)

c)

d)

Fig. 7   YOUDEN plots of key comparison measurements distinguishing:

1)   - **Configuration #1:**   Coriolis flowmeter *upstream*, Turbine flowmeter *downstream*   [**a)** and **b)**]
       - **Configuration #2:**   Turbine flowmeter *upstream*, Coriolis flowmeter *downstream*   [**c)** and **d)**]
2)   - **Low flow rates:** 73 m³/h   [**a)** and **c)**]
       - **High flow rates:** 162 m³/h   [**b)** and **d)**]

characteristics. In case of comparison measurements, this effect definitively appeared at the low flow rates (see **Fig. 4a** and **4b**).

Another accuracy-limiting factor was - and still is - friction in the valve actuation that prevents the valve's position to follow exactly the sequence of tiny increments of the valve actuation signal from the electronic control or manually operator-initiated valve actuation. Sequences of small-increment input signals to the respective control valve are "accumulated" by mechanical friction effects, this accumulated valve position is "stored" in the air-actuated valve positioner, i.e. no valve re-positioning is actuated due to signal input, but mechanical vibration from the valve's surroundings may cause an unintended flow actuation by the respective valve; an effect that caused "scattered" flow rate values as it is visualized in **Fig. 4b**.

Improvements of flow rate stability during a test run can be achieved by an auxiliary add-on facility with the valve that, when activated during test run, blocks valve action mechanically. An alternative solution is the utilization of electrically powered valve actuators.

Repeatability capabilities of the water flow facility can be derived from the magnitude of meter K-factor variations in the graphs of **Figures 6** and **7**, respectively, with all values being referred to the average of the 5 tests of the respective **tests A1** through **H2**. Additionally, the YOUDEN plot representation of the test measurement results, depicted in **Fig. 5**, reveals no significant functional interdependence of **meter #1** K-factor vs. **meter #2** K-factor that could be interpreted as an impact of the calibration facility [12]. That means that we cannot extract any influence of the test facility from the measurement data, all the scatter of the measurement data can be dedicated to the "imperfect" capabilities of the standard meters: Coriolis mass flow meter and turbine flow meter.

The majority of standard deviation values (meter K-factor deviations) related to the 5 runs of a single test were better than $3.5 \cdot 10^{-5}$.

In [1], a repeatability for total volume flow calibration as low as $4.0 \cdot 10^{-5}$ had been estimated to be satisfactory for the system's total expanded measurement uncertainty not to exceed 0.02%.

Information on **reproducibility**, which implies capabilities of the calibration facility and transfer standards as well as skills and abilities of the operating personnel, is visualized, on principle, in **Fig. 8**. The graphs shown there rely on the same data

as in **Fig. 7**, but all deviations of the meter K-factors were referred to the "global" average over all **tests A1** through **H2**.

If the measurement data were extracted in order to provide separate graphical representation for meter arrangement **configurations #1** and **#2** (**Figures 7a** through **7d**), it can be recognized that with configuration #2, where the turbine meter is in the upstream and the Coriolis mass flow meter is in the downstream position, the spread of the deviation values of meter K-factors under this operation conditions reveals a lower standard deviation.

As expected, the undisturbed flow profile, the turbine flowmeter was facing in the upstream position with configuration #2, provided optimum operating conditions to the meter and caused a reduced spread of the K-factor deviations in comparison with standard meter configuration #1 (see **Fig. 7**).
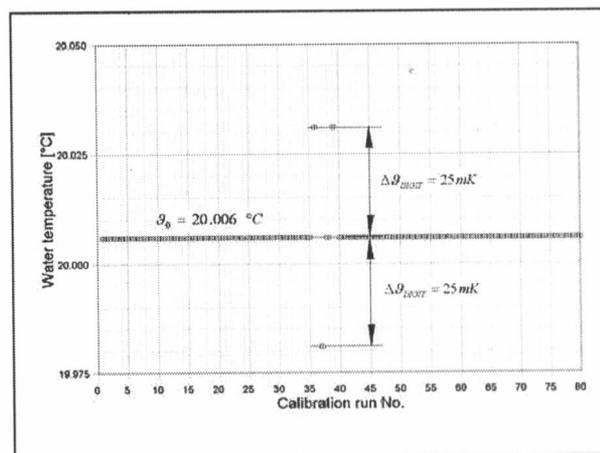

Fig. 8   Temperature stability of the test fluid during the key comparison
(period of time: Dec. 17, 2003 through Jan. 5, 2004)

4. Conclusions

The detailed and model-based interpretation of the measurement results, achieved with the transfer meter package (consisting of a turbine flowmeter and a Coriolis flowmeter) during international intercomparison measurements, demonstrates that the new high-accuracy water flow facility at PTB offers an accuracy characteristic that meets the objective target stated as a design goal of the facility's repeatability capabilities [1]. Based upon YOUDEN plot data representation [12] (see **Fig. 7**; if ignoring outliers of the results), there was no visible correlation between upstream turbine and downstream Coriolis flowmeters that might have originated from the plant's characteristics. Therefore, there is an urgent need to

the availability of transfer meters which provide a higher accuracy than those that are available in the market today.

Essentially, the good repeatability capabilities of the PTB facility relies on the extensive process measurement and control instrumentation equipment and the specific measurement and control algorithms that guarantee an excellent stability of the accuracy relevant process quantity: fluid pressure and temperature. The variation of the water temperature in the meter under test, during the vast majority of single measurements, did not exceed the digital resolution of the temperature measurement chain of 25 mK (**Fig. 8**).

Acknowledgment

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