Aspects of traceability and comparisons in flow measurement

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Abstract: Key comparisons, in general, are necessary to prove and assure the measurement uncertainty entries in the CMC (calibration and measurement capabilities) data base held at the Bureau International des Poids et Mesures (BIPM). Due to the physical character of the measurands of fluid flow, the units of those cannot be directly transferred or traced back. Therefore, an element-by-element approach of traceability is applied. The measuring quantity that is implicitly transferring the flow units is the meter factor of the so-called transfer flowmeter that is utilized for comparison or traceability purposes. But, as fluid-flow and meter-installation effects reveal impacts on meter readings, flow comparison measurement data may, occasionally, be affected by several systematic effects. Those systematic effects can exceed in their results those that originate from general statistical processes and effects which are generally part of any measurement process. In those cases comparisons would result in inconsistent data sets among the participating laboratories. Thus, in flow unit traceability or comparison measurements, flowmeters with highly stable metering properties must be applied, whose meter factors have been qualified in a characterizing test process so that systematic factors of influence may be compensated for by applying correction factors.

1. INTRODUCTION

As a matter of principle, flow measurands, like volume or mass flowrate, are not represented by material measures, but they are solely existent as long as they are generated in a standard flow facility by circulating a test fluid, a gaseous or a liquid one, in the respective facility's pipework. Therefore, the question arises how to realize traceability to the SI system of units at an accuracy level as high as possible.

On principle, two alternative ways are possible and are applied:
1) - element-wise traceability to the basic SI units which are components of flow units, as m³/h or kg/s, respectively;
2) - traceability via flow transfer meter packages which represents a "true" comparison among flow standard facilities on the basis of the unit that is subject of flow measurement.

For practical reasons, the traceability performed element by element relies on the assumption that the model describing the analytical model of flow reference standard is comprehensive and implies all items that reveal an impact on the respective facility's measurement uncertainty. But, generally, those models applied do not take into account flow and test meter installation affects. That is the reason why comparisons are so essential for the realization and dissemination of the units in fluid flow measurement.

2. FLUID FLOW MEASUREMENT AND TRACEABILITY

2.1. Flow measurands

Units of fluid flow and the measurands generally to be acquired or metered by a flowmeter are:
- Volume flowrate
- Mass flowrate
- Total volume flow
- Total mass flow

According to the above measurands we can distinguish rate metering and totalizing flowmeters, the latter ones are, predominantly, in use for fiscal or budgeting applications.

The quantity which is always subject of a flowmeter's calibration is the so-called meter K-factor, though the meter is being calibrated in a flow standard facility against a reference volume or a reference mass. In any case, the flowmeter characteristics are implicitly represented by the meter K-factor: meter readings vs. stimulating meter inputs. Even if, in practical applications, the meter characteristics, i.e. the meter error curve, is displayed as volume or mass error vs. input flowrate, those results can be derived from a flowmeter operation description that based upon a meter K-factor representation.

Thus, in fluid flow measurement applications, there occur 4 types of measurands:

- (Average) Volume/volumetric flow rate:

$$\dot{V} = \frac{V_{REF}}{T_{MEAS}} = \frac{m_{REF}}{\rho_{Water} \cdot T_{MEAS}} \quad (1)$$

(standard or reference flow rate)

- (Average) Mass flow rate

$$\dot{m} = \frac{m_{REF}}{T_{MEAS}} \quad (2)$$

- Total(ized) volume measurement

$$V_M = \int_0^{T_{MEAS}} \dot{V}(t)dt = \overline{q}_V \cdot T_{MEAS} \quad (3)$$

(volume passed measurement)

- Total(ized) mass measurement

$$m_M = \int_0^{T_{MEAS}} \dot{m}(t)\,dt = \overline{q}_m \cdot T_{MEAS} \quad (4)$$

(quantity or mass passed measurement)

In general calibration tasks, the determination of the **flow rate** (**Equ. 1**) or the **measurement deviation** ΔV between **meter reading** V_{MUT} and **reference value** V_{REF} (**Equ. 5**) are subjects of calibration.

$$\frac{\Delta V}{V_{REF}} = \frac{V_{MUT}(T_{MEAS}) - V_{REF}}{V_{REF}} \quad (5)$$

With following symbols used:

$\dot{V}$	- Volume flowrate	[m³/h]
$\overline{q}_V$	- Average volume flowrate	[m³/h]
$\dot{m}$	- Mass flowrate	[kg/s]
$\overline{q}_m$	- Average mass flowrate	[kg/s]
ΔV	- Measurement deviation of meter reading	[m³]
V_{MUT}	- Volume reading of a totalizing flowmeter	[m³]
V_{REF}	- Reading of a reference volume standard	[m³]
m_{REF}	- Reading of a reference mass standard	[kg]
T_{MEAS}	- Period of time of measurement or fluid collection	[s]
ρ_{Water}	- Density of the test fluid (water)	[kg/m³]

2.2. Fluid flow standard facilities - Realization of the flow units

Fig. 1 presents an overview of principles that are in use for the realization of fluid flow standard facilities. For all of the **categories 1.1** through **2.2**, there are samples for both liquid and gaseous media. Basically, we have to distinguish between dynamic and static measuring principles that are characteristic for rate or total flow measurands as the respective primary unit to be measured or calibrated.

Sub-categories 1.2 and **2.2**, which are based upon the so-called “Standing start-and-finish” operation mode are widely in use for the calibration of consumption meters, e.g. for fiscal purposes. This measurement principle is not suitable for calibrating rate meters. Though being utilized for that purpose, in this case, it guaranties only a very poor accuracy or uncertainty level.

The high-lighted **items 1.1** and **2.3b** are representatives of **primary flow standards** that are in use in the fluid flow laboratories of several national institutes of metrology, run at the highest accuracy levels:

- **Gravimetric liquid flow** standard facilities based upon diverter operated static weighing;
- **Bell prover** based standard facilities for gas flow measurements.

The categories or samples, presented in **Fig. 1**, may be the participants in the processes of traceability or key comparisons. Thus, measurement uncertainty models, characterizing the measuring properties of above flow standards, have to be necessarily developed for the purpose of the element-wise traceability process and making the different flow standards comparable.

2.3. Comparison measurements – Dissemination of the flow units

Generally in calibration tasks, the determination of the **flow rate** $\dot{V}$ (**Equa. 1**) or the **measurement deviation** ΔV between **meter reading** V_{MUT} and **reference value** V_{REF} (**Equa. 5**) are subjects of calibration.

In a key comparison the only "unique" device characteristic of the round-robin transfer meter, which is comparable, is represented by the meter K-factor. So, besides flow rate, the meter K-factor of a comparison test meter is subjects of measurement uncertainty analysis.

The meter K-factor of a measurement device, in general terms, is defined by the quotient of the meter reading divided by the "stimulus" which is the flow to be measured:

$$K_{Meter} = \frac{Meter\ reading}{Stimulus} \tag{6a}$$

Though being the performance characteristics of a flowrate meter, the meter K-factor is determined by the quantity collected by the reference standard and pulse counting during the finite period of time T_{MEAS}, the measurement or diversion time when the fluid flow is directed into the collecting (weigh) tank .

$$K_{Meter} = \frac{f_{Output}}{\dot{V}_{REF}} \tag{6b}$$

$$K_{Meter} = \frac{N_{Pulses} / T_{MEAS}}{V_{REF} / T_{MEAS}} \tag{6c}$$

$$K_{Meter} = \frac{N_{Pulses}}{V_{REF}} \tag{6d}$$

Owing to equation (6b), it is obvious that instability of the flow rate during collection time will, in case of a non-linear steady-state meter response, cause a contribution to the flowmeter calibration uncertainty. The measured meter K-factor applying equation (6c) is solely an average quantity.

Equations **(6a)** through **(6d)** refer to a flowmeter equipped with a pulse frequency output (representing "Meter reading" in Equa. (6a)) to whose "input" the reference flowrate $\dot{V}_{REF}$ is applied, with the meter pulse count N_{Pulses} accumulated during fluid-collection or measurement time T_{MEAS}.

3. PRACTICE OF COMPARISON MEASUREMENTS FOR TRACEABILITY PURPOSES

3.1. Practice of element-wise traceability

The basis for an element-by-element traceability approach is a measurement uncertainty model which relies on an analytical description of the measurement process that is realized in a flow standard facility.

As an example, here, we will refer to a gravimetric liquid-flow standard facility which is based upon static weighing with a diverter-actuated flying-start-and-finish measurement process [6].

The elements of the above measurement process and their interrelations are roughly described by **Equa. (7)**:

$$V_{REF} = \frac{m_1 - m_0}{\rho_{Water}} - \Delta V_{IP}(\vartheta, p) - \Delta V(\Delta T_{Error}) \tag{7}$$

With m_0 being zeroed balance reading prior to the beginning of fluid collection in the weigh tank, the following model of the measurement process results:

$$\dot{V} = \frac{V_{REF}}{T_{MEAS}} = \ \cdots \\ = \frac{\dfrac{m}{\rho_{Water}} - \Delta V_{IP}(\vartheta, p) - \Delta V(\Delta T_{Error})}{T_{MEAS}} \tag{8}$$

Aditional sources of uncertainty [6] in the measurement process originate from the flow diverter operations and from the physical processes in the connecting pipe section between meter under test and the gravimetric reference standard, due to temperature and pressure variations during the fluid collection time.

The resulting **uncertainty for flowrate measurements** is calculated according to **Equ. (9)**:

$$U_{\dot{V}}^{2}=\left(\frac{\partial\dot{V}}{\partial m}U_{m}\right)^{2}+\left(\frac{\partial\dot{V}}{\partial\rho_{Water}}U_{\rho}\right)^{2}+\left(\frac{\partial\dot{V}}{\partial(\Delta V_{IP})}U_{\Delta V}\right)^{2}+\left(\frac{\partial\dot{V}}{\partial(\Delta V_{T\_Error})}U_{T\_Error}\right)^{2}+\left(\frac{\partial\dot{V}}{\partial T_{MEAS}}U_{T}\right)^{2} \tag{9}$$

Or in relative figures following equation is obtained:

$$\left(\frac{U_{\dot{V}}}{\dot{V}_{0}}\right)^{2}=\left(\frac{U_{m}}{m}\right)^{2}+\left(\frac{U_{\rho}}{\rho_{Water}}\right)^{2}+\left(\frac{U_{\Delta V}}{V_{0}}\right)^{2}+\left(\frac{U_{T\_Error}}{V_{0}}\right)^{2}+\left(\frac{U_{T}}{T_{MEAS}}\right)^{2} \tag{10}$$

For **meter K-factor determination**, the inherent uncertainty is derived from **Equa. (6b)**:

$$K_{Meter}=\frac{f_{Output}}{\dot{V}_{REF}} \tag{6b}$$

Then, the standard uncertainty for the determination of the meter K-factor results as follows:

$$U_{K\_meter}^{2}=\left(\frac{\partial K_{Meter}}{\partial f_{Outout}}U_{f}\right)^{2}+\left(\frac{\partial K_{Meter}}{\partial\dot{V}}\cdot\frac{\partial\dot{V}}{\partial m}\,U_{m}\right)^{2}+\left(\frac{\partial K_{Meter}}{\partial\dot{V}}\cdot\frac{\partial\dot{V}}{\partial\rho_{Water}}\,U_{\rho}\right)^{2}+\left(\frac{\partial K_{Meter}}{\partial\dot{V}}\cdot\frac{\partial\dot{V}}{\partial(\Delta V_{IP})}\,U_{\Delta V}\right)^{2}+\left(\frac{\partial K_{Meter}}{\partial\dot{V}}\cdot\frac{\partial\dot{V}}{\partial(\Delta V_{T\_Error})}\,U_{T\_Error}\right)^{2}+\left(\frac{\partial K_{Meter}}{\partial\dot{V}}\cdot\frac{\partial\dot{V}}{\partial T_{MEAS}}\,U_{T}\right)^{2} \tag{11}$$

When referring to K_{Meter}, the relative standard uncertainty is obtained:

$$\left(\frac{U_{K\_Meter}}{K_{Meter}}\right)^{2}=\left(\frac{U_{f}}{f_{Output}}\right)^{2}+\left(\frac{U_{m}}{m}\right)^{2}+\left(\frac{U_{\rho}}{\rho_{Water}}\right)^{2}+\left(\frac{U_{\Delta V}}{V_{0}}\right)^{2}+\left(\frac{U_{T\_Error}}{V_{0}}\right)^{2}+\left(\frac{U_{T}}{T_{MEAS}}\right)^{2} \tag{12}$$

A glance on the measurement uncertainty equations **(11)** or **(12)** reveals that no flow or meter installation effects are part of this (analytical and theoretical) process of the measurement uncertainty analysis.

This is a lack of accuracy that is generally apparent with all uncertainty models which are applied in flow applications. And that is the reason why any flow related uncertainty entry to the CMC tables of BIPM must be verified and proven by traceability, i.e. comparison measurements, as it is illustrated in **Fig. 2**.

Flowrate dependencies in the operation of flow standards facilities due to systematic or deterministic physical effects are generally not taken into account as those processes and their interrelations are too complicated.

3.2. "Real" traceability via flow measurands

As show in **Fig. 2** on principle, the traceability of a flow unit should be performed via two different ways:

- Element-wise traceability, which the BIPM's flow CMC table entries rely on: a great number of flow related effects cannot, for practical reasons, be taken into account when deriving the measurement uncertainty budget of a flow standard facility.
- "Real" flow-based traceability measurements as they are performed in key comparisons; they are an indispensable requirement to prove CMC uncertainty entries.

As an experience from the practice in KC1 it revealed that the majority of the participating laboratories could not provide stable measurement conditions on predefined operating conditions: reference temperature 20°C.

Figures 4a and **4b** (which are solely one single example of test meter investigation data [3]) are to demonstrate that "plain" corrections on the basis of similarity relations, as they are expressed by the Reynolds number, will not provide corrected data results at a measurement uncertainty level that is necessary to prove uncertainty entries in the BIPM CMC data base.

Thus, flowmeter characterization [3] is an essential prerequisite for achieving consistent measurement data sets in a key comparison measurement campaign. Otherwise, it would be no wonder, as experienced in KC1; that the traceability measurements will not “hit” the target area, which is defined by the CMC entries of BIPM.

In practical flowmeter characterization tests[3], both temperature and pressure effects were recognized and proven which cause additional erroneous contributions in the meter characteristics which is represented by the K-factor error curve.

3.3. Techniques of comparisons – Cardinal flows vs. flow range comparisons

An essential question that always arises in measurement uncertainty issues is how to compare laboratory results with each other in order to derive a Key Comparison Reference Value (KCRV):

- One single measurement point or a set of a low number of so-called cardinal flowrate points, e.g. in the K1 water flow key comparison KCRVs were determined for two cardinal flowrates: ”Low flowrate” and “High Flowrate”;
- Applying several K-factors of a reference flowmeter so that the whole flowrate range is covered that is subject of the respective key comparison, as it was recommended by P. LAU [7][8][9]

Fig. 3 is a measurement data representation that displays the results of the K1 water flow key comparison for the turbine meter that one flowmeter of two in the transfer packge. It combines the “pure” data of that turbine meter, as they were delivered by the participating laboratories to the pilot laboratory, with the meter K-factor curves that were determined in PTB’s high-accuracy water flow test facility. During the characterization measurements the transfer meter package. The key comparison measurement from the labs had been applied for forming the KCRVs without taking into account the different operating conditions during the measurements in the labs. In the diagram areas high-lighted by rectangular areas those measurement data (meter K-factor deviations) were arranged according to the actual flowrates in the labs and dedicated to the temperatures under which the respective error curve value was measured in the respective laboratory.

As a résumé we can state that, without having the information of the “continuous” meter K-factor error curve, it would have been impossible to recognize that the scatter in the ordinate direction of the diagram does not result from stochastic sources but represents a systematic effect due to different operating temperature conditions in the participating laboratories.

This fact is an explanation that the KC1 measurement data did not represent a consistent set, so that the median had to be applied as a KCRV.

4. EXPERIENCES FROM PRACTICE – KEY COMPARISONS

4.1. Liquid flow – KC1 Water Flow

The measurements and the evaluation of data, which relied on those measurements during KC1 [4], were based on two cardinal flow rates on which the test meters of the transfer meter package were run during their round robin in the participating flow laboratories.

One obvious boundary condition that revealed during the round-robin measurement campaign [4] in 2003 and 2004 was the fact that the majority of the participating laboratories was not capable to adjust and stabilize the process parameter “fluid temperature” on predefined reference conditions at 20°C.

The sensitivity of the meter characteristics on fluctuations of the relevant process parameters: temperature and pressure may expressed by applying sensitivity coefficients upon the meter K-factor (i.e. its error curve vs. flowrate) that is assumed to be constant in a operating point of reference conditions.

At reference conditions, e.g. temperature 20°C, is defined as follows:

$$K_{Meter} = \left. \frac{f_{Output}}{\dot{V}_{REF}} \right|_{20°C} \tag{13}$$

But, practically, the meter K-factor of a flowmeter is affected due to variations in fluid temperature ϑ and line pressure p:

$$K_{Meter} = f(\vartheta, p) \tag{14}$$

In cases when it is not guaranteed during a flow comparison that all participating laboratories are capable to run their flow standard facilities at predefined reference temperatures, corrections terms must be applied in order to refer the measurements to reference conditions. Those corrections are assumed to be applied for measurements in Laboratory No. “N”:

$$K^{REF}_{Lab\_\#N} = K^{\vartheta\_\#N}_{Lab\_\#N} + \Delta K_{Correct}\left(\vartheta_{Lab\_\#N} - \vartheta_{REF}\right) \tag{15}$$

With items as follows:

$K^{\vartheta\_\#N}_{Lab\_\#N}$	- Meter K-factor determined in Lab No. “N” under local temperature conditions
$K^{REF}_{Lab\_\#N}$	- Corrected K-factor to reference temperature conditions
$\Delta K_{Correct}\left(\vartheta_{Lab\_\#N} - \vartheta_{REF}\right)$	- Correction term

Correction terms of the meter K-factor $\Delta K_{Correct}$ have to be determined in a participating laboratory that provides a flow standard facility with capabilities of characterizing flowmeters with respect to their sensitivity upon deterministic temperature variations.

Equivalent corrections are necessary when a transfer flowmeter reveals sensitivity impacts due to variations in line pressure [3].

It must be emphasized, here, that the introduction of the above mentioned correction terms, which were determined in one of participating laboratories (pilot laboratory) of a key comparison (KC) by means of meter characterization tests, will induce implicit correlations amongst the measurement data of those labs in a KC.

4.2. Gas flow – KC5

The key comparisons for high pressure gas organized up to now have all the same common concept for the measurand. It was the agreement to compare those results which were determined under nearly identical conditions[1], i.e. gas composition, pressure and flowrate. Secondly, the test matrix should cover a large part of the flow rate range of the meters under test with a convenient density of test points per flowrate range.

The first restriction was chosen to avoid any unknown impact to the comparison results due to the dependency of the meter on these fluid flow properties because the characterization and modeling of these dependencies is difficult. In the consequence, the CMM.FF-K5 for high pressure gas was split into two different parts: K5a for high pressure natural gas and K5b for pressurized air/nitrogen.

The second agreement (to cover a flowrate range with an reasonable test matrix) has given the bases to investigate the inter-comparison results with respect to impacts which had not been considered in advance sufficiently.

In the following, we explain first some basic relations about the measurand and the key reference value. At second we summarize our experience with the application of meter modeling to reach inter comparability between the test results determined in air/nitrogen and natural gas.

The central expression used to quantify the meter under test in relation to the fluid quantity is the relative deviation f of the indicated quantity[2] Q_{MuT} to the reference quantity $Q_{Lab\#i}$ provided by the Lab #i for the measurement (meter deviation f_i)

$$f_i = \frac{Q_{MuT}}{Q_{Lab\#i}} - 1 \tag{16}$$

The concept of the relative meter deviation f is very close to the concept of meter factor K_{Meter} (**Equa. 6a**), therefore all what will be said below about the handling of comparison results based on the relative meter deviation f can be easily transformed to expressions using the meter factor K_{Meter}.

Based on all results for the meter deviation f at the different laboratories the key comparisons reference value f_{KCRV} was calculated as a weighted mean (w_{i} is the weight for Lab #i based on the reported uncertainties for the results).

$$f_{KCRV} = \Sigma w_i \cdot f_i = \frac{Q_{MuT}}{Q_{KCRV}} - 1 \tag{17}$$

Formally, the key reference value for the meter deviation can also be expressed as a relative deviation of the meter indication to the key reference quantity.

To express the degree of equivalence, the difference d_{i} (and its accompanied uncertainty) between the

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[1] This means here to keep the test conditions concerning (absolute) temperature, flow rate and pressure within 5% and to use standard compositions of natural gas, air or nitrogen.

[2] Please note that here the quantity can be total volume, total mass, volume flow rate or mass flow rate according to the indication of the meter under test. The meter under tests in the CCM.FF-KC5 are turbine meters.

measured value f_i at Lab #i and the key reference value f_{KCRV} is calculated:

$$d_i = f_i - f_{KCRV} \tag{18}$$

The interest is finally the relative deviation $\Delta Q_{\#i,rel}$ of the quantity $Q_{Lab\#i}$ to the key reference quantity Q_{KCRV}:

$$\Delta Q_{\#i,rel} = \frac{Q_{Lab\#i}}{Q_{KCRV}} - 1 . \tag{19}$$

The relationship of this to the usually used difference d_i **Equa. (18**) shall be shown here. Even this was the common understanding among the flow experts it was never expressed in detail in the CCM.FF-protocols up to now.

The relation is easily shown if we expand the expression **Equa. (19)** by a unity Q_{MuT}/Q_{MuT}. Furthermore we make use of **Equations (16)** and **(17)** as well as some small approximation due to the fact that f_i as well as f_{KCRV} are much smaller than 1.[3] The final outcome is that the usual used value d_i is the negative value of the original interest $\Delta Q_{\#i,rel}$.

$$\Delta Q_{\#i,rel} = \frac{Q_{Lab\#i}}{Q_{MuT}} \cdot \frac{Q_{MuT}}{Q_{KCRV}} - 1 = \frac{1 + f_{KCRV}}{1 + f_i} - 1 \tag{20}$$
$$\approx \left(1 + f_{KCRV}\right) \cdot \left(1 - f_i\right) \approx f_{KCRV} - f_i = -d_i$$

The expansion by Q_{MuT}/Q_{MuT} in **Equa. (20)** is made on the background that the dependency of the meter deviation f on the fluid quantity Q is normally negligible small, at least, for small changes of quantity[4]. It has to be emphasized here that the expansion is independent to a special value of Q_{MuT} and therefore also independent to the meter under test. This means the independence of the $\Delta Q_{\#i,rel}$ to the meter under test used for comparison which was utilized in the past CCM.FF-KCs (1 to 6 except 4) by silent agreement of the flow experts. Within the comparison rounds the results coming from at least two different meters under test were combined.

To illustrate this last statement, we like to present here again the results for the differences to the reference value out of the CCM.FF.K5a for high pressure natural gas and out of the determination of the Harmonized European Cubic Meter 2004. They already published in [5].

Table 1 presents the overview of all the meters and pressures used in the mentioned inter comparisons. In total, 10 different meters were used. The **Fig. 5** shows the differences *d* to the reference values for each of the participants (LNE, NMi and PTB) distinguishing the two comparison loops CCM.FF-K5a and the harmonization. The values for the differences d are quite closed for each of the participants and there is no significant difference between both comparison loops to be obtained. Such a reproducibility of the results is one of the most important preconditions for establishing and maintaining the Harmonized European Cubic Meter.

Another example of the inter-comparability of results using different meters (also different principles of meters like rotary meters and critical nozzles) can be found in a survey of 12 inter-comparisons given in the paper [13] of these proceedings.

As mentioned above, we got very stable and consistent results but it was strictly different between natural gas and air/nitrogen. It was quite a nice opportunity to overcome this situation as PTB as the pilot lab for CCM.KC5b (air/nitrogen) performed additional measurements with natural gas. These measurements were documented in the protocol of CCM.FF-K5b [14] but were not used for the determination of the key comparison value.

For including these additional results into the evaluation, it was necessary to consider an enhanced model for the meter (turbine meter) and to apply the tools of the least square fitting [15] to determine all parameters of the model out of the comparison results. Therefore, the key reference value was determined in this case as a best fitting function.

The enhanced model for the meter deviation of a turbine meter was formulated as a simple sum of three parts:

$$f_{turbine} = f_{flow\_forces} + f_{bearing\_friction} + f_{p,T-sys\_dev} \tag{20}$$

The meter deviation f_{flow_forces} caused by the fluid flow through the wheel and around the blades can be assumed as a function of Reynolds number.

The next part $f_{bearing\_friction}$ is caused by the bearing friction. The bearing friction itself is dominated by the viscous flow of lubrification inside of the bearings. As this flow is laminar, the torque M_B being caused by

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[3] E.g. if the deviations *f* are in the order of 0.5%, the final error of the approximations used in **Equa. (20)** can reach ±0.005% in maximum. This is of course an additional uncertainty which has to be considered but in the field of high pressure gas measurement definitely insignificant compared to the CMC uncertainties.

[4] This assumption is of course not exactly fulfilled and leads again to additional uncertainties. If these uncertainties are not acceptable , the next level can be the expression the dependency of *f* to *Q* by an appropriate analytical function to apply an small correction (as it was done e.g. in the CCM.FF-KC6) to reduce these additional uncertainties.

the friction is in first order proportional to the rotational speed ω of the wheel. Experiments of manufacturers shows that this model can be enhanced in practise by a small additional constant to reflect the real behaviour more properly. The part $f_{\mathrm{bearing\_friction}}$ is proportional to the relation between the torque M_{B} and the dynamic pressure of the flow attacking the wheel.

The third part $f_{\mathrm{p,T\text{-}sys\_dev}}$ deals with the systematic deviations between the values for pressure $p_{\mathrm{M,meas}}$ and temperature $T_{\mathrm{M,meas}}$ being measured at the meter and the true one at the turbine wheel p_{M} and T_{M}.

The first part $f_{\mathrm{flow\_forces}}$ is dominating for so-called Reynolds balanced meters. Such an ideal meter would have a consistent error curve versus the Reynolds number as shown by the corresponding curve for $f_{\mathrm{flow\_forces}}$ in **Fig. 6**. The real turbine meters can be close to this ideal behaviour approximately in the flow rate range of 0.25 Q_{max} to 0.7 Q_{max}. In this range the deviations from the ideal behavior are typically insignificant comparing to uncertainties of the measurements.[5]

But below 0.25 Q_{max} and above 0.7 Q_{max} the parts $f_{\mathrm{bearing\_friction}}$ and $f_{\mathrm{p,T\text{-}sys\_dev}}$ can reach values in the order of 0.2%.

The delicate point of the problem is that the determination of these parts, before starting a comparison like the K5, would need the investigation of the meters in all the expected test conditions (what is practically impossible for single pilot laboratory).

Nevertheless, the evaluation of the comparison results, using the linear model according to **Equa. (20)** and the tools of the least square fitting was successfully applied afterwards. It demonstrates all the issues about the systematic deviations of metering results between natural gas and air nitrogen. An illustration of this issue is given in **Fig. 7**. The outcome here, which is given in detail in [15], will be summarized in the following chapter.

5. CONCLUSIONS

Based upon practical experiences acquired in flow metering applications, especially in comparison measurements, following statements and recommendations, respectively, can be derived:

Gas flow (see also [15])**:**

- The application of detailed models for the dependency of meter indication on the fluid properties and the tools of least square fitting allows to combine measurements in a wider range of test conditions.
- The modelling is one critical point and it is recommendable to restrict to meters which can be described by simple models. The example shown here for turbine meters seemed to be the upper limit of complexity.
- There is a large test matrix necessary to get a sufficient input to the fitting process.
- Another critical point is the correct treatment of the test results concerning correlations among them. The conventional point-to-point evaluation could ignore this because for each point only one value for each participant was used and the participants had to be independent (uncorrelated) from precondition of the key comparison. But in the case of evaluation of all results simultaneously by least square fitting, the correlation between the different results on one participants are important.[6]

Liquid flow (water flow), but, partly, it may be also relevant for gas flow:

- Element-wise traceability is not sufficient in order to proof reliability of uncertainty estimations in flow applications.
- Comparison measurements should cover continuously the flow rate range of the flow test facilities which are subject of the comparison, of course, under the aspect of the meters serving as transfer flow standards.
- Special metering procedures and measurement data evaluation algorithms are applicable to isolate the uncertainty effects, represented by standard deviation of the acquired measurement data, to those which can be dedicated to facility impacts and to those which originate from meter related effects [8][9] (See also [10]).
- Corrections of varying process conditions cannot be compensated for by applying similarity relations like the Reynolds number.
- Variations in the process parameters, like temperature and line pressure, as well as flow conditions reveal an impact upon meter calibration

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[5] In high pressure gas measurements we have to consider measurement uncertainties of about 0.15%. Insignificant means therefore impacts below 0.05%.

[6] In the practise of gas measurements, the reproducibility of results in one Lab is usually significant smaller than the total uncertainty of the results (factor about 1.5 to 2). This indicates the dominance of the non-stochastic systematic parts in the uncertainty budgets which causes correlations.

conditions which are, in general, not incorporated in a measurement model due to the sophisticated interrelations among the involved physical processes. Thus, modeling those processes, with all relevant process parameters being involved, is practically not feasible.

- In order to provide the basis for achieving consistent measurement data in comparisons, all flow test facilities participating should be described and analyzed in a way that they are dedicated to or based upon a standard model as any flow standard facility can be related to.
- To avoid systematic effects on comparison measurement data the involved transfer flowmeters must be characterized prior to their utilization in a comparison measurement campaign. In such a case, meter characterization comprises an exact experimental analysis of the relevant impacts of temperature and fluid line pressure in a flow calibration facility which is capable to adjust and stabilize the magnitude of those effecting process quantities and acquire the dedicated test meter reading.
- Due to the characterization measurements the respective meter characteristics, i.e. the so-called meter K-factor, can be quantitatively described as functions vs. temperature and vs. pressure, respectively. Once having determined the deterministic meter characteristics or sensitivity coefficients, “exact” correction factors can be applied, thus, avoiding systematic effects in cases when in calibration facility conditions should occur, diverting from defined standard conditions
- As it is obvious that applying corrections on the basis of characterization measurements implicitly involves an additional source of uncertainty, it is recommended to run flow standard facilities in a comparison under identical conditions in order to avoid correction procedures and, thus, additional uncertainty contributions to comparison measurement results.
- For a realistic estimation of calibration uncertainty, aside establishing a correct and detailed measurement uncertainty model, there is a necessity to isolate uncertainty effects that originate from inherent effects in the respective flow standard from those that must be dedicated to the metering properties of the meter under test, which is, in cases of comparison measurements, represented by the transfer meter or set of meters in a transfer package [10][11][12].
- As systematic laboratory effects [10], absolutely, cannot be excluded in flow applications, due to flow related installation effects and due to a non-ideal flowmeter installation, appropriate approaches must be proved and applied in a traceability or comparison measurement campaign as an add-on in the test program.

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Table 1 *Overview of the test meters used and the pressures applied during the CCM.FF-K5a and the determination of the Harmonized European Cubic Meter 2004*

	Harmonized European Cubic Meter LNE-LADG (BNM)/NMi/PTB				BIPM/CIPM KC5a
Nominal diameter DN/mm (inch)	100 (4“)	150 (6“)	250 (10“)	400 (16“)	150 (6“)
pressures (bar)	8, 20, 50	8, 20, 50	20, 50	20, 50	10, 20, 47
No. of meters	2	2	2	2	2
Type of meter	turbine/ turbine	turbine/ turbine	turbine/ turbine	turbine/ turbine	turbine/ ultrasonic

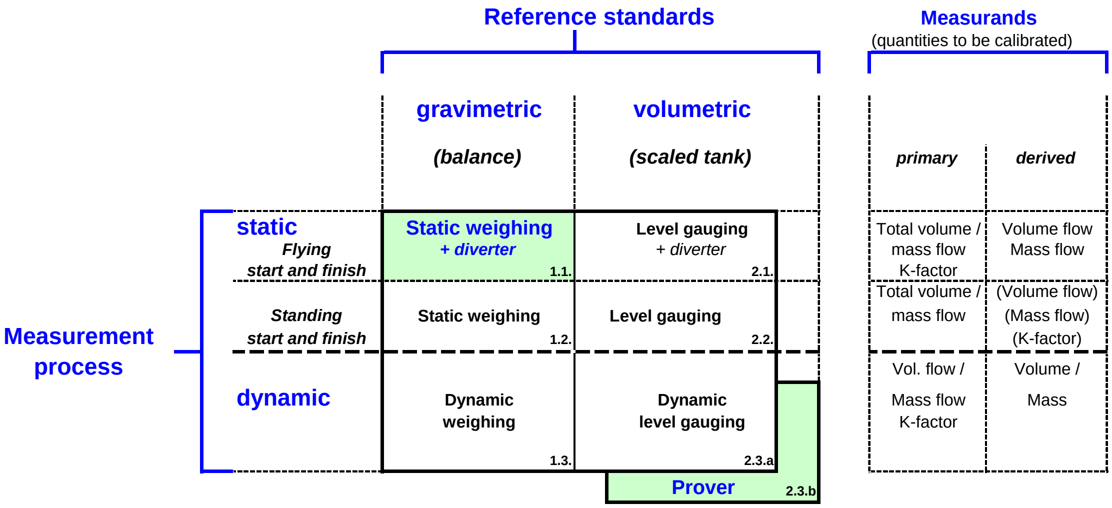

Figure 1 *Overview of flow standard facilities – Basic operating principles (applicable for both liquid and gaseous fluids)*

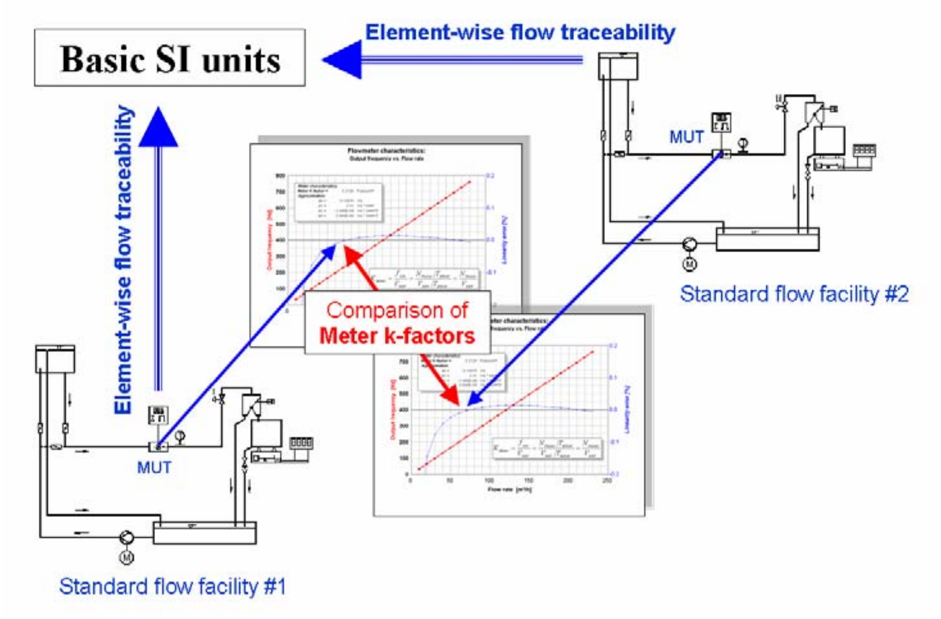

Figure 2 *Traceability in fluid flow measurement – Comparison measurements (MUT meter under test)*

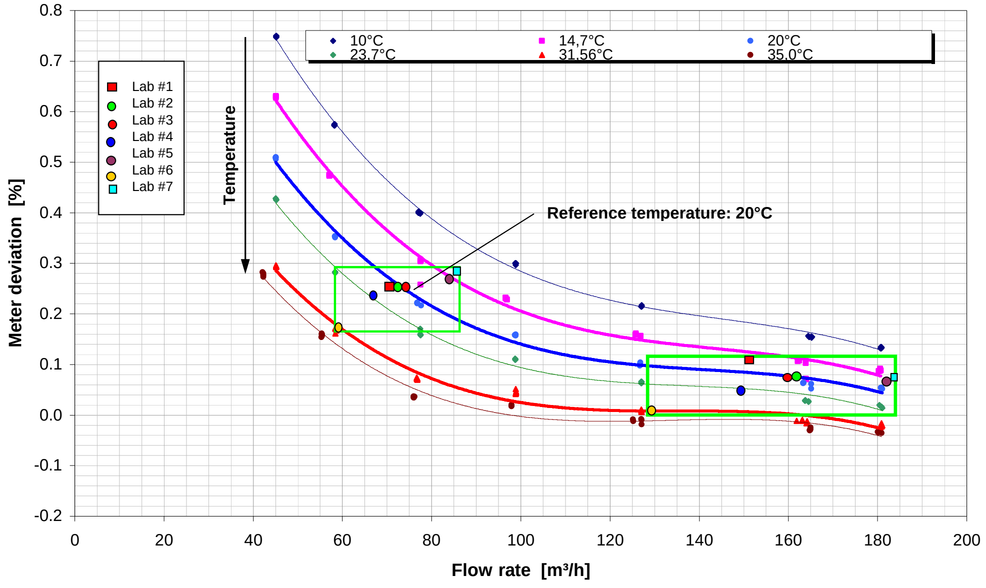

Figure 3 *Systematic temperature effects turbine meter: Cardinal flow points (turbine meter DN100, WGFF, Key comparison KC1 [4])*

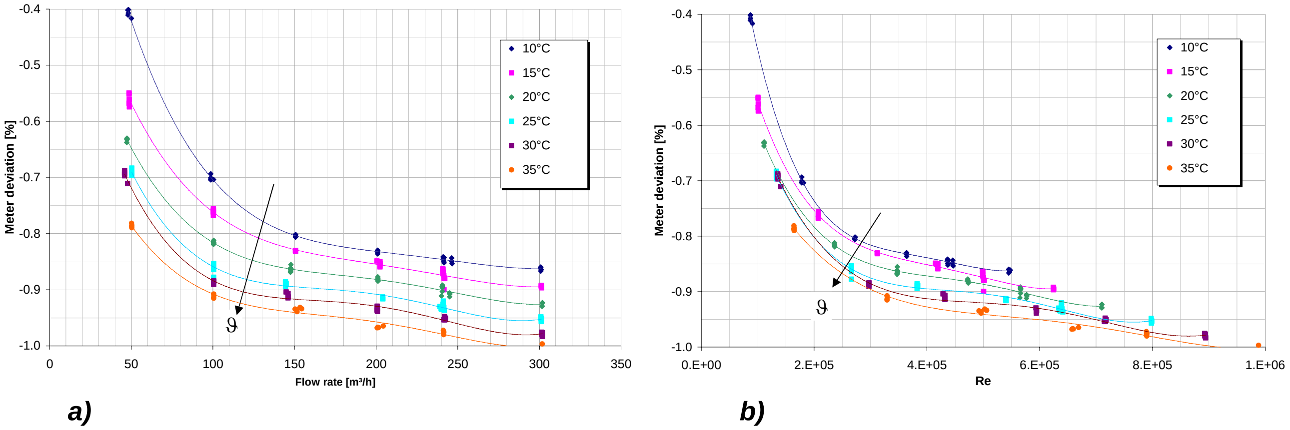

Figure 4 *Error curves of a DN150 turbine flowmeter – Transfer flowmeter characterization*
Fluid temperature as factor of influence
a) *Meter error vs. flow rate*
b) *Meter error vs. Reynolds number*

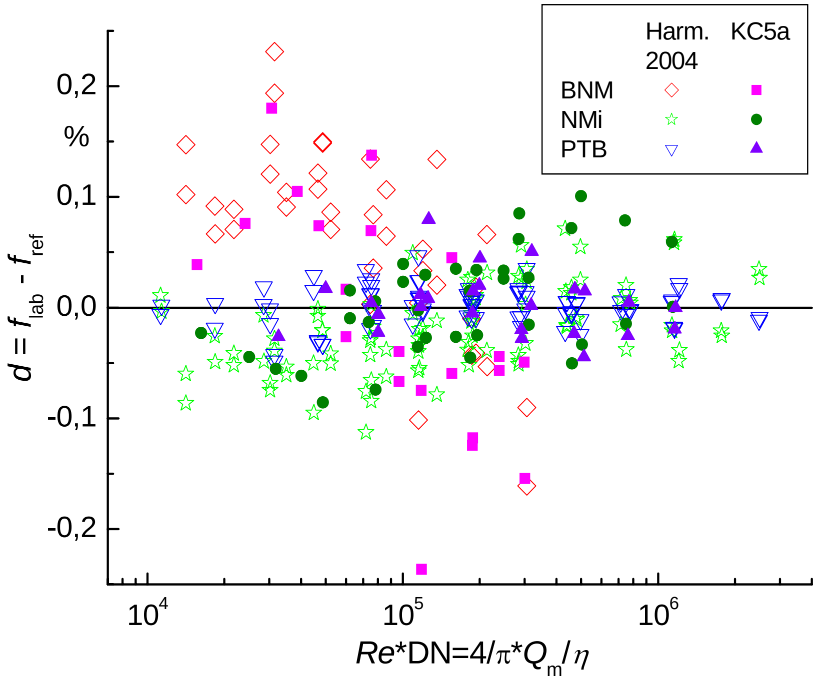

Figure 5 *Overview of differences values between all laboratories and the reference values of the CCM.FF-K5a (determination of the Harmonised European Cubic meter 2004), see also Table 1*

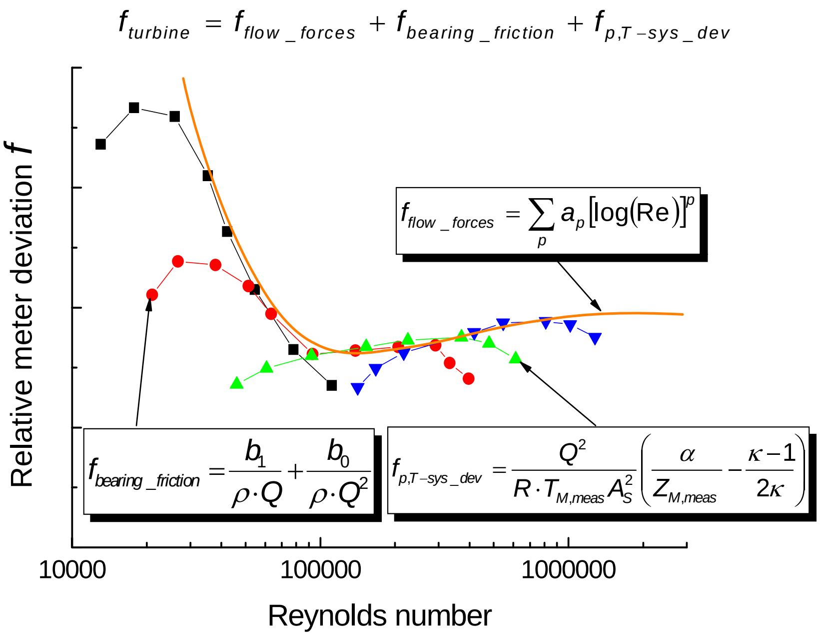

Figure 6 *Schematic plot of the meter deviation of a turbine meter versus the Reynolds number The curves for different pressures (indicated by the colours) deviate from an ideal Re-curve at the low and high flow rates due to the additional dependencies of the meter deviation on the fluid properties like dynamic pressure, Mach number and isentropic exponent*

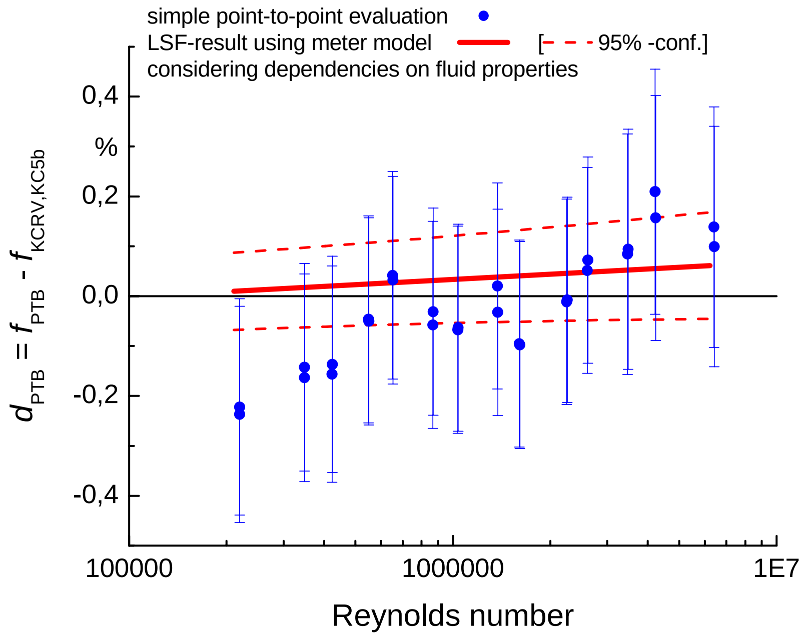

Figure 7 *The difference for PTB results within CCM.FF-KC5b being determined:*
- as a simple point-to-point difference at the same Reynolds number at the same pressure level
- using a meter model (see Fig. 6) considering dependencies on fluid properties.