DETERMINATION OF LIQUID FLOWMETER CHARACTERISTICS FOR PRECISION MEASUREMENT PURPOSES BY UTILIZING SPECIAL CAPABILITIES OF PTB's 'HYDRODYNAMIC TEST FIELD'

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Abstract: In flow measurement applications with high-accuracy requirements, it is necessary to have an exact knowledge of the meter characteristics under different process conditions. Liquid flowmeters reveal both temperature and pressure dependence of their steady-state metering properties. So it requires the flowmeter error curves to be measured with the fluid temperature and pressure being varied as process parameters over their ranges in which the meters are to be applied. PTB's new national water flow standard and high-accuracy calibration facility provides unique capabilities to perform meter characterization measurements which meet those requirements. That has been proven in a series of calibrations.

1. INTRODUCTION

The accurate characteristic of a metering device, in general, is determined by calibration, i.e. defined values of the measurand, which are realized by a reference facility, are applied as a stimulus to the respective meter input and the corresponding meter reading, as a steady-state response, are acquired by calibration measurement equipment. A representative presentation of calibration results, very often utilized in fluid flow, is the so called error curve. In that case, the deviation values between the meter and the reference readings are displayed versa fluid flow rate. There are applications where calibration values are displayed versa Reynolds number, as a representative of the measurand.

Attempts were made to define a universal description of flowmeter characteristics, e.g. for turbine meters in [8]. On the other hand, there are also publications which state [5] that "a meter should be always calibrated in the fluids in which it is to be used", as there are significant effects on the meter characteristic due to viscosity and density variations. As well as the installation conditions, i.e. the flow velocity profile as it is shown in **Fig. 1** on principle, reveal impacts on the meter characteristics.

For flowmeter use, the adaptation to relevant process conditions can be achieved by characterizing the meter over the whole range of flow rate, temperature and, in certain cases, pressure. That means the meter K-factor or error curve is measured versus flow rate, with the respective parameter being varied over the range that is relevant for the meter's use.

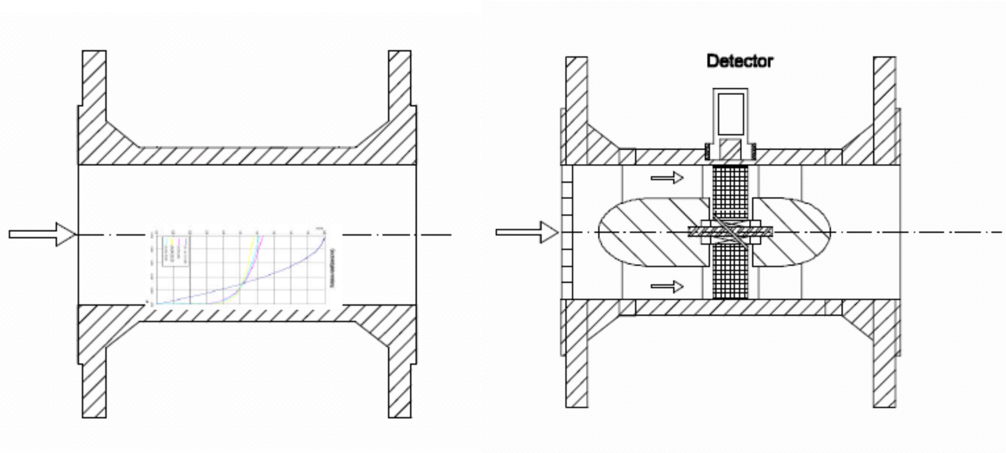
PTB's new high-accuracy water flow facility, the 'hydrodynamic test field', was designed to provide adequate capabilities both of flow rate and parameter adjustment and variation for water flow applications.

2. IMPACT OF FLUID AND METERS ON MEASUREMENT ACCURACY

Flowmeters often used in comparison measurement applications are turbine-type meters. The general primary design goal for turbine meters was to realize a function principle with a good linear steady-state meter response, i.e. rotational velocity of the turbine wheel versa volume flow rate through meter. That means meter operation with minimum energy extraction from the streaming fluid. Energy extraction is recognizable as a pressure drop across flow meter.

Thus, it is obvious that the meter characteristic and its parametric dependence from the respective fluid properties, like density, viscosity, fluid temperature and pressure, is not simply determined in a way, which is defined by the fluid flow, as we find it in a straight tube, but additionally by the flow sensing element inserted in such a ideal pipe flow. This additional meter component causes a more or less tremendous disturbance of the pipe flow profile, and, thus, it effects the meter characteristics.

The experimental test and calibration results in **chapter 5** will be presented as measurement deviations both versa volume flow rate and versa Reynolds number, in order to check whether temperature depend meter effects can be neutralized by applying this approach. This was



a) *b)*

Fig. 1 *Flow conditions in a straight pipe and a pipe with inserted flow sensor*
a) *Flow velocity profile in straight pipe*
b) *Pipe with turbine as sensor sensing element*

made to see whether calibration measurement results can be referenced to a common reference temperature to make them comparable with each other.

There are a series of models that were developed to describe the performance of turbine flowmeters, e.g. references [1] through [3].

Viscosity effects on a turbine meter's characteristic had been tried to be treated by means of so called universal viscosity curves [4]. That approach represents a rough model of a turbine meter's operation, which takes only into account fluid flow through the tube-like meter body and explicitly the meter K-factor, which, aside by fluid properties, is determined by the meter design.

The flow conditions can be described by applying the Reynolds number, which is defined as follows:

$$Re = \frac{w \cdot D}{\nu} = \frac{w \cdot D \cdot \rho}{\eta} \tag{1}$$

where
- D = pipe diameter [m]
- w = mean flow velocity [m/s]
- ρ = fluid density [kg/m³]
- ν = kinematic viscosity [m²/s]
- η = dynamic viscosity [Pa s]

When vortices occur in a fluid flow, which were generated by a bluff body placed within the flow path, the resulting frequency of vortices will be given by the dimensionless quantity called Strouhal number St:

$$St = \frac{f \cdot d}{w} \tag{2}$$

where
- d = width of the bluff body [m]
- w = flow velocity [m/s]
- f = frequency of vortices [1/s]

For practical reasons, the flowmeter characteristic is described by a factor, which (like with metering devices used for any other measurand) characterizes the input-output signal response behavior.

Generally, the K-factor of a flowmeter is defined as the transfer ratio of the meter reading (output signal) versa flow rate. With meters which provide pulse-frequency signals f_{OUT} as a representative of the flow rate $\dot{V}$, the K-factor is defined as follows:

$$K = \frac{f_{OUT}}{\dot{V}} \qquad (3)$$

As the meter output frequency is measured in pulse counts per measurement time T_M, and the volume flow rate in unit volume per measurement time T_M, the meter K-factor's unit is pulse count per unit volume.

When a flowmeter is exposed to varying fluid temperature operating conditions, due to the thermal expansion of the meter material, the meter's component parts will change their dimensions. As a linear approximation the resulting change in meter K-factor can be describe by following equation [9]:

$$K_0 \approx K \cdot (1 + 3 \cdot \alpha \cdot (\vartheta - \vartheta_0)) \qquad (4)$$

where

- α = thermal expansion coefficient of meter material
- ϑ = temperature [°C]
- ϑ_0 = reference temperature [°C]

The above model does not take into account specific effects that are caused by the sensing element 'turbine wheel' like bearing friction and distortions of the flow profile [1][2].

Equation (4) had been applied on the calibration measurement data of a DN150 turbine flowmeter to check the feasibility and the accuracy of a temperature correction based upon such a simple

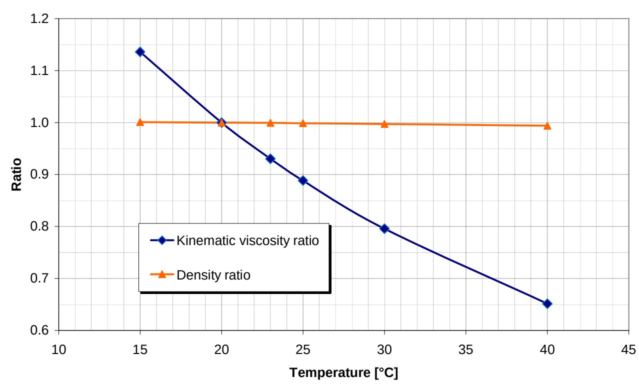


Fig. 2 *Ratios of kinematic viscosity and density of water vs. temperature (according to [6] and [7], respectively)*

linearized model approach (see **paragraph 5**).

Also the fluid which is subject of flow measurement reveals changes of its properties like density and viscosity [6][7] when the fluid temperature is changing. As the fluid is water in the measurements, which were performed on PTB's high-accuracy flow facility, the diagram in **Fig. 2** is to show the relative change of water density and viscosity when the temperatures vary in the range from 15 °C through 40 °C [6][7]. With PTB's water flow facility the water temperature can be varied by means of computer-based set-point control from 10 °C through 35 °C.

3. IMPACT OF FLOWMETERS DEPENDING ON METER TYPE

3.1. Flow sensors without electronics

According to the utilization of different physical effects as flow sensing principles and the methods of signal acquisition, conditioning and processing, we can distinguish flowmeters whose sensing element delivers an output signal that is strictly proportional to the fluid flow rate to be measured (type A) and meters that comprise a flow sensing element with a dedicated signal processing unit to provide linear flow rate measurement capabilities (type B).

These two basic realizations of flowmeters are represented by the signal flow diagram in **Fig. 3**. Type-A meters, on principle, do not require additional signal processing of the senor "raw" signal to deliver a signal whose magnitude is proportional to the flow rate on the sensor input.

These type-A class flowmeters comprise e.g. turbine, vortex, electromagnetic and thermal mass flowmeters. And by some authors [10] these meters are called linear flowmeters because their meter characteristic is represented by linear function whose slope is defined by the meter K-factor.

Additional electronics to the sensor output simply provide signal conditioning to adopt the sensor "raw" signal level to subsequent indicating or controlling devices.

Two examples of such a flowmeter type: a turbine meter and a vortex meter, were investigate in order to determine meter error curves with the fluid temperature being varied as a parameter of meter characteristics. The results of these calibrations will be discussed in **paragraph 5.1** and **5.2**, respectively.

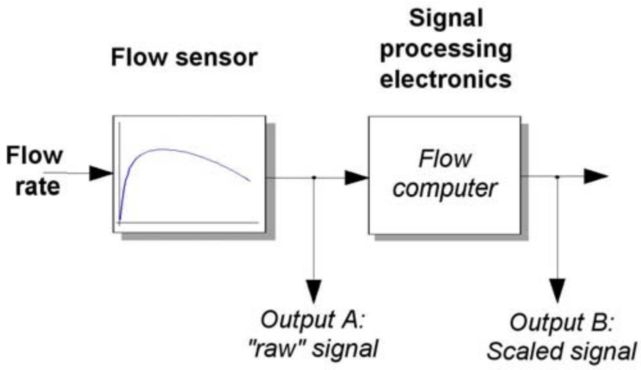


Fig. 3 *Flow measurement data acquisition*

3.2. Electronic output flow meters

Unlike type-A flowmeters, type-B or electronic output flowmeters need, due to their flow sensor characteristics, additional signal processing capabilities in their electronics to transform the “raw” signal into a linear signal meter characteristic (See **Fig. 3**). Depending on whether this “add-on” electronics is a component part of a flowmeter, it is considered to be a functional part of the so called measurement transmitter. Separate, optional multi-functional units are designated as flow computers.

In some cases the addition of a signal processing unit to a type-A meter improves or enhances the overall meter performance. One example of such an application is given by [14] where the add-on flow computer extents the accuracy of turbine-based flow measurement to multiple viscosity meter capability.

Though the functions of electromagnetic and coriolis flowmeters are based on sensor principles that reveal linear characteristics each, they are always equipped with electronics that inherently comprises signal processing functions (including temperature compensation) in addition to plain signal condition capabilities. Generally, there are no provisions that a customer has access to the “raw” signal output of the meter. Thus, what can be measured only is always the overall meter characteristic.

As samples of electronic output flowmeters, an electromagnetic and a coriolis meter were tested under varying operating temperature conditions. The measurement results of these tests will be presented and discussed in paragraphs **5.3** and **5.4**.

4. RELEVANT CHARACTERISTICS OF PTB’s WATER FLOW FACILITY

In the design and construction of PTB’s ‘hydrodynamic test field’ and its component parts, special provisions were made to realize a measurement uncertainty as low as 0.02 % in calibrating total volume flow meters [13] and to reach a good adoptability to special calibration and measurement requirements, as they arise from application conditions of a flowmeter under varying temperature and line pressures [13]. For those purposes, e.g., the test facility was equipped with a temperature control system that provides highest temperature stability during calibration runs to guarantee minimum measurement uncertainty capabilities. As an essential option, set-point adjustable temperature selection capabilities were implemented into the computer-based process control system of the test facility to adopt test temperatures to future application conditions of the meters under test.

The control loop structure of the temperature stabilization system can be seen in **Fig. 4** [12] [13]. In order to tackle the problem of control dynamics that arise from the huge quantity of water contained and circulated in the pipe work of the facility, the temperature control system had to be subdivided into a so called course control (dedicated to the storage tank) and a fine control loop (dedicated to the calibration line pipe work). This control loop structure had been necessary, to combine high temperature stability with a reasonable settling time of the temperature control system.

To combine good flow rate stability as one prerequisite for minimum uncertainty of measurement with pressure adjustable plant capabilities, the test fluid can be run across the constant-head tank to achieve highest flow stability or, alternatively, the test fluid can directly be pumped into the calibration line, with flow rate and pressure being adjustable independently from each other. In latter case, the two measurands are adjusted both via pump speed and valve control in a multi-variable control loop structure [13].

Fig. 5a illustrates the temperature adjustment capabilities of the test facility, as it had been utilized during the characterization measurements of a dual-rotor turbine meter and a coriolis flowmeter. Those meters were used as a transfer meter package in the CIPM KC-1 key comparison [15]. For meter characterization purposes the fluid temperature had

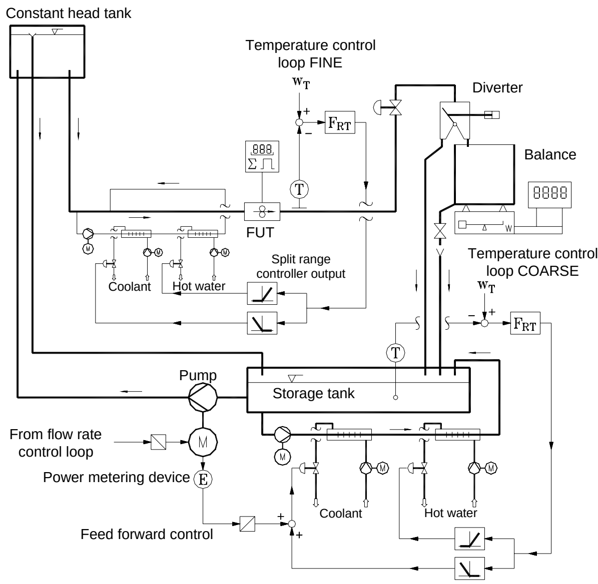
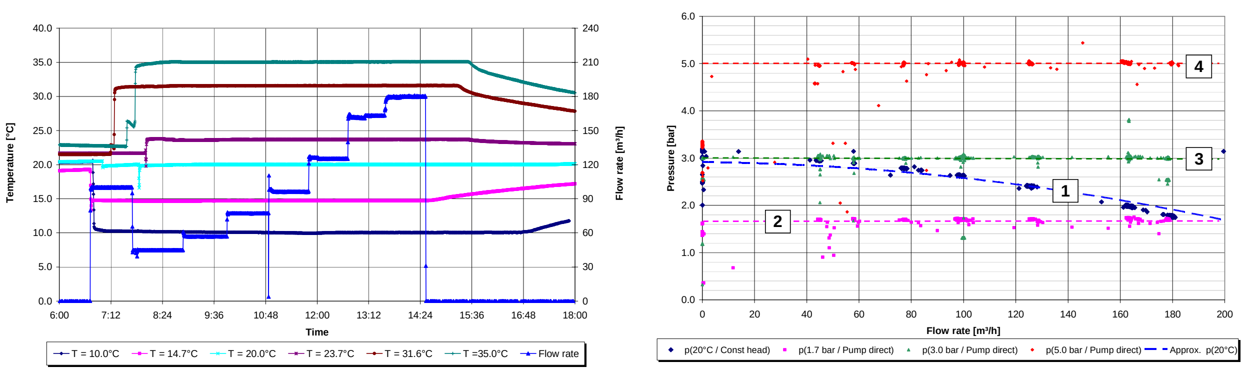


Fig. 4 *Temperature control loops*

been varied within the range from 10 °C through 35 °C. Some of the temperature values were chosen according to the operating temperatures that occurred in the facilities of the participating laboratories during the comparison measurements.

installed, the process pressure is going down about one third when the applied flow rate is varied from minimum through maximum value during meter calibration. That means, in this plant operation mode, both temperature and pressure variations occur coincidently so that pressure and temperature



a) ***b)***

Fig. 5 *Test flow rate, temperature and pressure capabilities of PTB's water flow facility*
a) *Temperatures and flow rates vs. time during flowmeter characterization measurements*
b) *Flow rate and pressure adjustability:*
*operation via constant-head tank **(1)** and pump-direct operations*

The curves in **Fig. 5b** are to demonstrate the different operating conditions that occur depending on whether the test facility is run via the constant-head tank or in the direct pump operation mode. Curve **#1** indicates that, due dynamic pressure losses in the pipe work of the facility, on the location in the calibration line where the meter under test is

caused meter effects cannot be isolated from each other. That might be important in cases when coriolis flowmeters are to be investigated.

For that reason it is recommendable that for meter characterization purposes the calibration facility, generally, should be run in the direct pump operation mode. So it is possible to recognize which meter effects were caused due to temperature or due to pressure variations.

The curves **#2** through **#4** in **Fig. 5b** prove that the stability of pressure on different calibration flow rates revealed to be adequately stable to provide stable flow conditions that were comparable with those of the operation via constant-head tank.

Finally, we can resume from a series of calibrations that the above plant features had proven to be very useful in analyzing flowmeter characteristics as it is necessary for precision meter applications like laboratory inter-comparison measurements.

5. MEASUREMENT RESULTS AND DISCUSSIONS

5.1. Turbine-type flowmeters

The first results to be discussed were acquired when a DN150 turbine flowmeter was calibrated upstream of an electromagnetic flowmeter (See **paragraph 5.3**). The measurement conditions during calibration were the same for both meters: temperature variations from 10 °C through 35 °C.

as pipe bends or similar disturbing factors were avoided in the upstream pipe work.

By transforming the meter input quantity "volume flow rate" into a Reynolds number representation, it was tried to eliminate temperature error effects in a representation displaying error curves versa Reynolds numbers. But in **Fig. 6b** it can be seen that such an input variable transformation still reveals temperature dependence of the meter error curves. That fact could be expected as such a simple transformation of flow quantities does not take into account thermal effects on the sensing element "turbine wheel".

For that reason another attempt was made by applying **Equ. (4),** which takes into account thermal expansion of as well as meter tube and turbine wheel. It can be recognized in **Fig. 7a** that in the higher flow rate region of the turbine meter operation a temperature effect in the meter error curves could be eliminated by that approach. Remaining divergent error curves at low flow rates are estimated to arise from effects other than thermal expansion of meter tube and sensor [3].

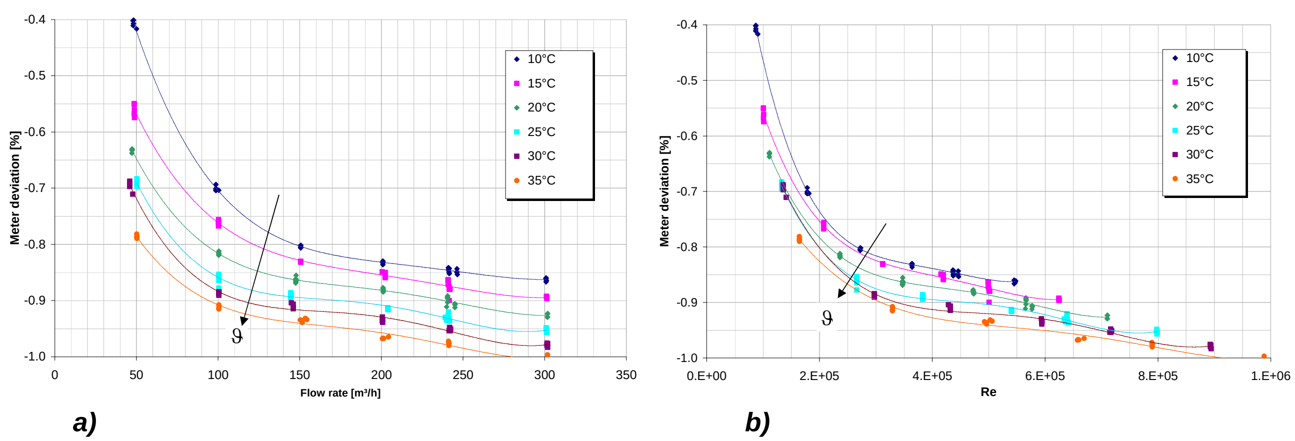
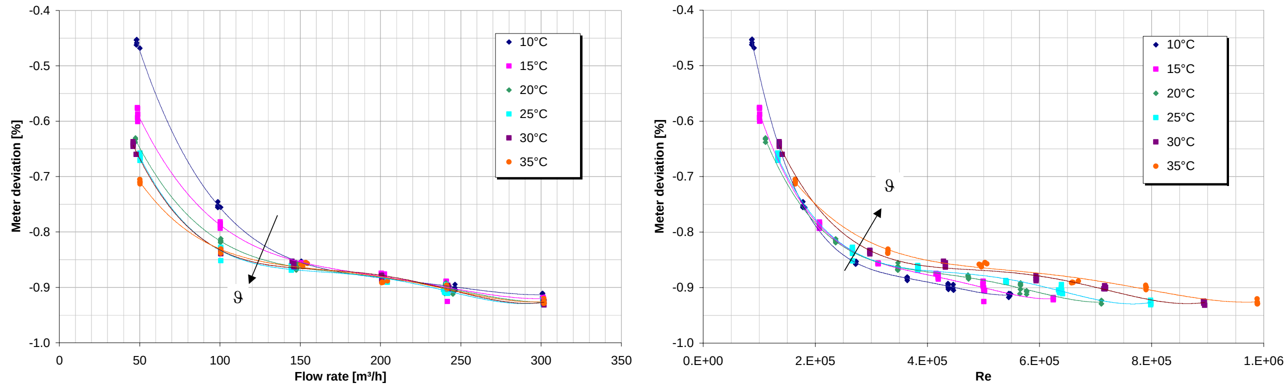


Fig. 6 *Error curves of a DN150 turbine flowmeter: "raw" data*
a) *Meter error vs. flow rate*
b) *Meter error vs. Re number*

The error curves of the turbine meter in **Fig. 6a** reveal that there is a tremendous impact of temperature on meter error. This temperature effect can be explained as a result of changes of density and viscosity [1][2][3][11]. Effects caused by a distorted flow profile can be neglected in this case,

Applying Reynolds number instead of volume flow rate as the independent variable of the error curve presentation does not improve the situation. A reversal of the tendency in the temperature dependence of meter errors could be interpreted as an "overcompensation" effect.



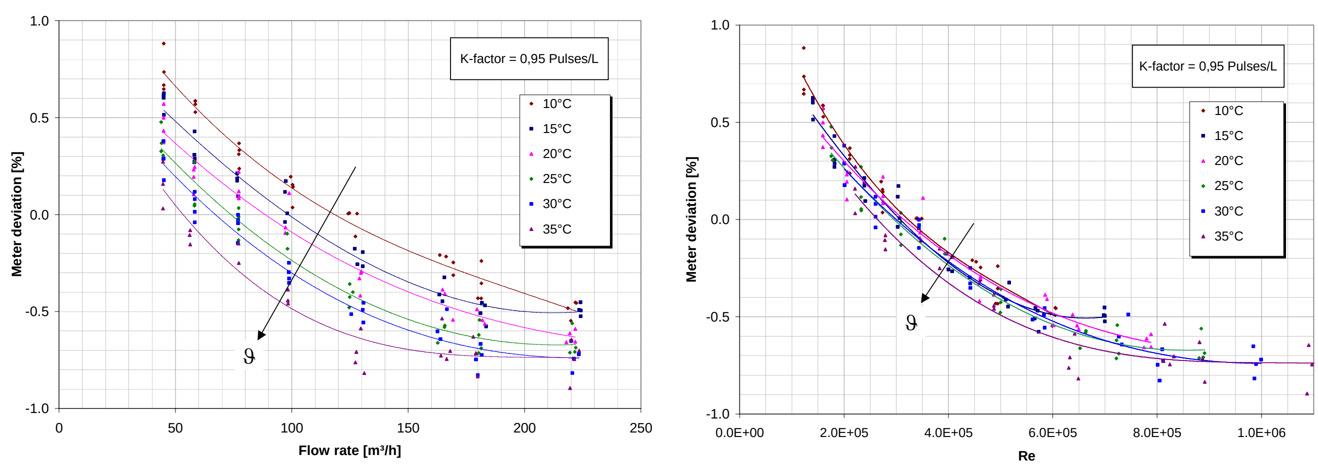
a) ***b)***

Fig. 7 *Error curves of a DN150 turbine flowmeter: temperature correction applying* ***Equ. (4)***
a) *Meter error vs. flow rate*
b) *Meter error vs. Re number*

5.2. Vortex flowmeters

The second example of a type-A flowmeter (See **chapter 3**), which was investigated in a temperature test, was a vortex meter DN100. Though the make of the meter comprises signal transmitter electronics with standardized signal output, for the test purposes the flow rate signal was tapped directly on the vortex sensor output. Thus, this electric signal corresponds to vortex frequency, without any signal processing or sensor signal corrections being applied.

The steady-state characteristic of a vortex flowmeter is described by **Equ. (2)**. Due to that equation, the temperature dependent error curves (**Fig. 8a**) result from thermal expansion effects of the meter tube cross section and bluff body width, as a good approximation. The meter error representation versa Reynolds number with the resulting good elimination of temperature effects proves that **Equ. (2)** represents an adequate model of the meter characteristics.

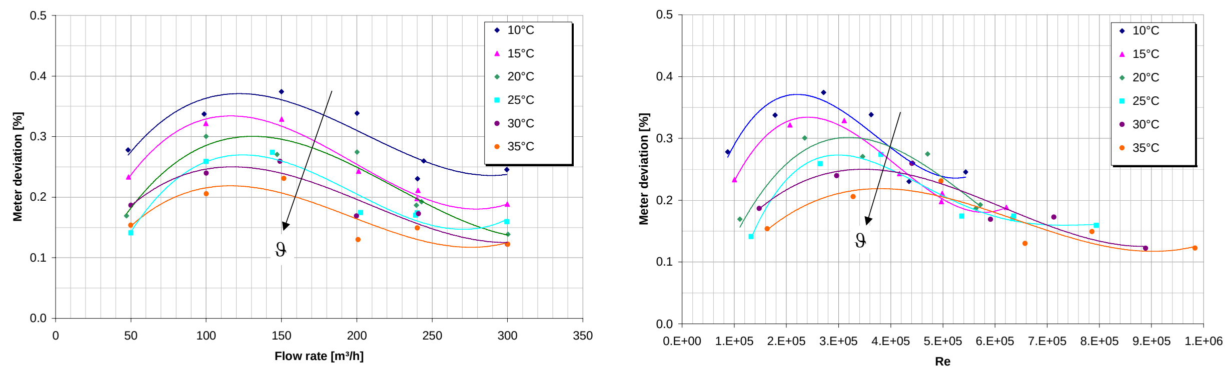


a) ***b)***

Fig. 8 *Error curves of a DN100 vortex-shedding flowmeter: "raw"' signal*
a) *Meter error vs. flow rate*
b) *Meter error vs. Re number*

5.3. Electromagnetic flowmeters

One example of an electronic output flowmeter which was investigated on PTB's water flow facility to determine the temperature meter characteristics was an electromagnetic flowmeter DN150. For that purpose the set-point of the facility's temperature control had been varied automatically by the supervisory computer system from 10 °C through 35 °C in steps of 10 Kelvins to acquire measurement data for meter error curves.



a) *b)*

Fig. 9 *Error curves of a DN150 electromagnetic flowmeter*
a) *Meter error vs. flow rate*
b) *Meter error vs. Re number*

As this type of a flow metering device comprises flow sensor and signal processing capabilities, to provide linear measurement characteristics and compensation of temperature effects, it could be estimated that flow effects which occur in the meter's pipe flow, similar to those in a turbine meter, would not be recognizable in the error curves of the meter characteristic. As it was part of the meter design strategy of R&D engineers to compensate for those temperature and pressure dependent effects.

Fig. 9 shows that this specific flowmeter still reveals an systematic influence vs. temperature. And even the representation of the respective temperature errors versa Re numbers cannot reduce these effects, see Figures **9a** and **9b**.

5.4. Coriolis flowmeters

Fig. 10 presents another good example of an electronic output flowmeter, a Coriolis meter DN100. The error curves, which represent the temperature characteristics, reveal that the meter's overall temperature response was compensated for nearly ideally. The temperature set-point values for the test series in **Fig. 10** were derived from conditions of the water flow key comparison KC-1 of the CIPM FFWG, under which the participating laboratories had performed their comparison measurements [16].

Though the compensation of erroneous effects caused by factors of influence, like temperature or pressure, is a systematic (~ally designed) control of the steady-state meter response, no systematic temperature influence or temperature dependent tendency are recognizable, as it could be seen with the electromagnetic flowmeter in the last preceding paragraph.

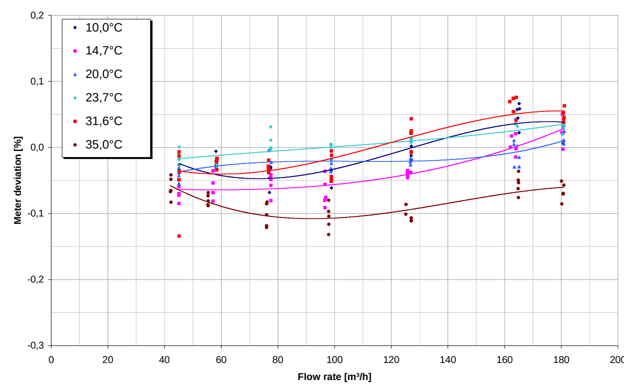


Fig.10 *Error curves of a DN100 Coriolis flowmeter: Temperature: 10°C … 35°C*

Also in this case, the parameter adjustability capabilities of the ‘hydrodynamic test field’ represent a powerful tool to investigate flowmeter characteristic, it proves the proper operation of the flow computer subassembly of a flow metering device.

6. CONCLUSIONS

Test measurements on PTB’s water flow calibration facility [12], comprising several different-type flowmeters, have revealed that measurements for high-accuracy or laboratory inter-comparison purposes require stability of the process conditions, like water temperature and pressure. It had been proven that those parameters may have, in general, a more or less tremendous impact on the steady-state meter characteristics, represented by the error curves. This is due to both by the changed fluid properties and the measurement properties of the flow sensing elements in the meters.

When applying an error curve representation versus Reynolds number as an independent variable or meter ‘input’ quantity, the impact of the fluid properties on the meter characteristics are seemingly compensated for. But this is only valid for the theoretical assumption that the meter is simply represented by a straight pipe section, as it was shown in **Fig. 1**. One should be aware that such a rough model of a flow sensor operation is not taking into account that - with a few exceptions - the completion of a flowmeter is realized by inserting the primary flow sensing element in a more or less ideal straight tube-like meter flow path. This obviously has a functional feedback on the flow conditions in the meter section and, thus, on the whole meter characteristics.

Additionally to the fact that the presence of a ‘realistic’ flow sensing element within the meter pipe section is a primary factor which is predominantly responsible for the meter characteristics, flow-rate dependent effects and the process parameters temperature and pressure coincidentally have an effect on the respective meter characteristics. For instance, the turbine wheel as sensing element in a meter reveals additional effects due to flow distortions and temperature dependent friction in the wheel’s bearings.

In coriolis-type flowmeters, the sensing effect is based on tube vibrations, so the Eigenvalues of the vibrating-tube resonant frequencies are, additionally, influenced by the fluid pressure in the sensor tubes.

In one case, it was tried to isolate the ‘rough’ characteristics of the sensing element. That was a DN100 Vortex flowmeter, where the flow signal was directly tapped from the sensor output, with the signal processing electronics being bypassed. Also in this case, the Reynolds number referenced representation of the error curve could not compensate temperature effects, over an essentially wide range of temperature variations.

Thus, it is obvious that, for high-accuracy as it is required in case of laboratory inter-comparison measurements or traceability purposes, that differences in the measurement conditions, characterized by different fluid temperatures and/or fluid pressures at the locations of measurement or calibration, cannot simply be compensated by applying Reynolds number referenced error curve meter representations or other normalizations like Strouhal or Roshko number [8][14].

On PTB’s new water flow facility, the implemented features of set-point temperature and pressure controls have proven to fulfill the requirements of enhanced meter characterization measurements.

The dedicated investigation of flowmeter characteristics, which was initiated during the last year, will be continued and its scope will be widened. That appears to be necessary as improved meter accuracies that are possible with the state of the art in electronics and microcontroller-based signal conditioning required the meter performance to be characterized as exactly as possible.

ACKNOWLEDGEMENTS

The authors would like to thank A. Eggestein and K. Mittelstädt, both from PTB Braunschweig, for having performed the extensive measurement programs which delivered the measurement data basis for this paper.

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