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Modeling the uncertainty in liquid flowmeter calibration and application - Requirements and their technical realization for PTB’s national water flow standard

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Abstract

In this paper the model is derived which describes the processes of liquid flowmeter calibration and its utilization in meter applications. Subject of uncertainty analysis is the gravimetric calibration facility with the so-called flying-start-and-finish approach. The “hydrodynamic test field” at PTB Braunschweig, the national metrology institute (NMI) of Germany, is representing such a type of liquid flow calibration facility. It provides high accuracy for liquid flow measurands mean volume flow rate and totalized liquid flow. The calibration of a liquid flowmeter can only take into account meter characteristics under ideal flow conditions. Conditions occurring in flowmeter applications may be different from those in the calibration facility and, thus, contribute additional uncertainty effects.

1. Introduction

The measurement uncertainty analysis reveals as a means both of design support for realizing high-accuracy measurement facilities and of proving the appropriate operation of those facilities according to their measurement and accuracy specifications. So it was with PTB’s “hydrodynamic test field”, which serves as the German national standard facility for the measurands of liquid flow: volume flow rate, mass flow rate, total volume flow and total mass flow. According to the specific requirements to a national standard facility to provide traceability for state-of-the-art high-accuracy liquid flowmeters, the expanded total measurement uncertainty was derived to be as low as 0.02 %. Measurement analyses prior to the design process for the decisive component parts provided individual objectives of uncertainty contributions which had to be proved as a prerequisite to meet the low total uncertainty of the facility.

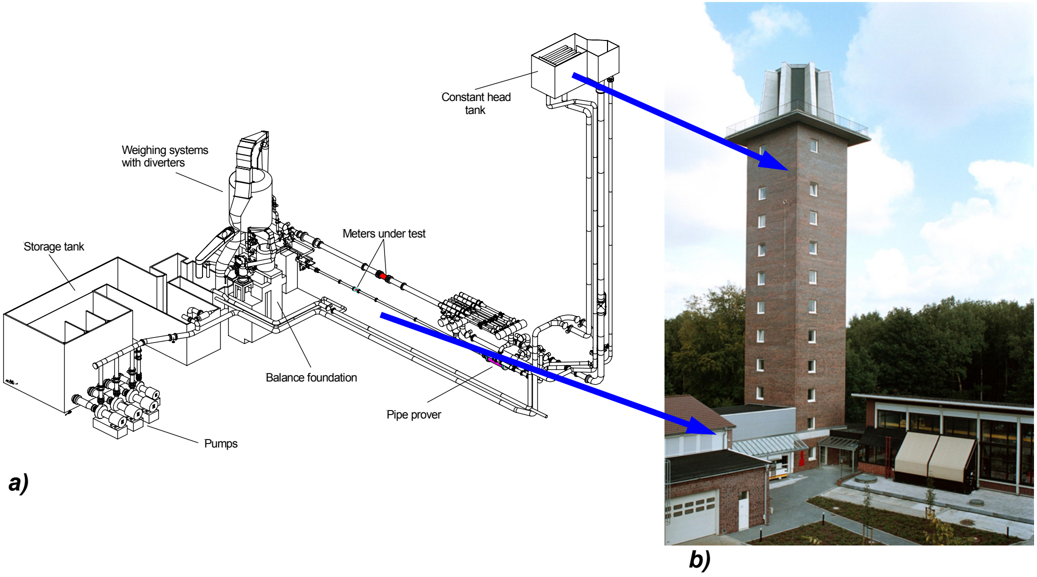


Figure 1 ***a)*** *Cutaway view of PTB's water flow calibration plant*
b) *PTB’s Willy Wien Tower*
(housing the constant-head tank of the standard flow facility on the 9th floor, at a height of 35 m)

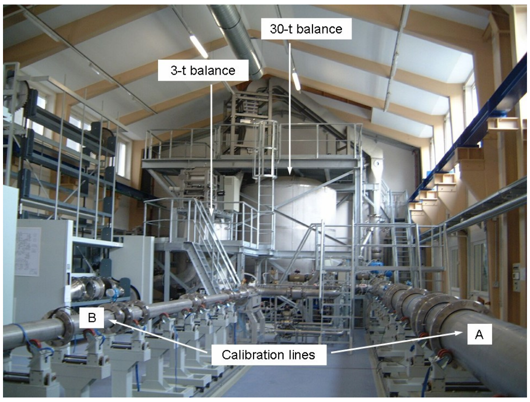


Figure 2 *View of calibration hall along the fluid's flow direction (calibration lines with the weighing systems in the background)*

Table 1 *Global plant parameters of PTB's new 'Hydrodynamic Test Field'*

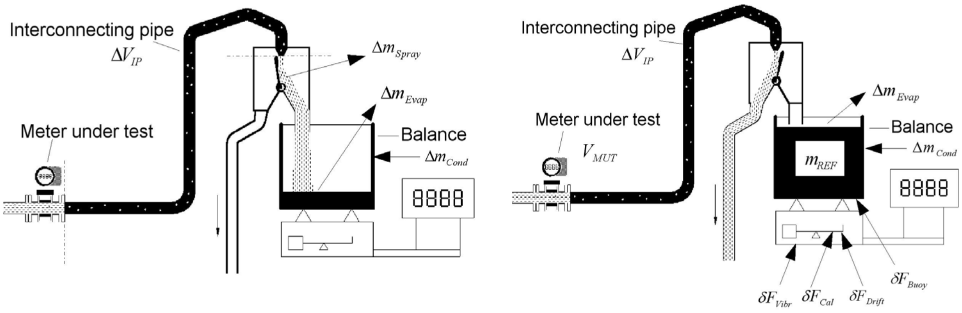
Plant features	Item(s)	Characteristics
Measurands	Volume / mass flow rate ***Volume*** / mass (totalized)	Flow-rate meters volume / mass flow totalizing meters
Calibration modes	Flying START / FINISH	***Diverter***
Reference standards	***Gravimetric calibration***	***Balances:*** 0.3 t, 3 t, 30 t
Operation modes	**Via constant-head tank** Pump direct operation	Const. pressure (3.5 bars) Adj. pressure (Max.: 6.0 bars)
Meter / pipe sizes	Line A / B	DN 20 ... DN 400
Ranges of flow rate	Line A / B	0.3 m³/h ... 2100 m³/h
Adjustability of water temperature	Line A / B	10°C … 35°C
Expanded measurement uncertainty	**0,02 %**	Operation via constant-head tank *(Temperature: 20°C … 25°C)*

2. The measurement process in a gravimetric liquid flowmeter calibration facility

The principle setup of PTB’s new gravimetric-reference water flow calibration facility, the “hydrodynamic test field” is depicted as a cutaway view in ***Figure 1a***. It shows the relevant component parts of a gravimetric liquid flow calibration facility that is run in the flying start-and-finish operation mode [1]:

- Speed-controlled set of pumps and constant-head tank for flow generation and precision flow rate stabilization, respectively.
- The two calibration lines that are run alternatively and which provide defined well-defined flow conditions to the installed meters under test (MUT) and adaptation for flowmeters of different sizes.
- The gravimetric reference system which comprises 3 weighing systems of different sizes, ranging from 300 kg through 30 t, each of them being equipped with a fluid diversion device (diverter) to provide capabilities for flying start and finish.

Figure 2 presents an overview of essential components of the calibration facility: the two calibration lines and two of the three weighing systems. The constant-head tank with the overflow weir at a height of 35 m is located on the ninth floor of the Willy Wien Tower (***Figure 1b***), which was erected in close proximity to the plant building. ***Table 1*** presents a summary of the essential plant features and characteristics.



a) ***Phase 2*** ***b)*** ***Phase 3***

Figure 3 *Main section and system components with quantities revealing an impact on the system’s measurement uncertainty*
a) *Phase of measurement*
b) *Phase of system’s settling time prior to “meter” reading*

The section of the facility which has a direct impact on the accuracy of flowmeter calibration is shown in ***Figure 3***, it comprises MUT, interconnecting pipe section, fluid diverter and balance as the gravimetric reference. A single calibration run at a given flow rate can, principally, be characterized by three phases. Depending on the process conditions prior to measurement (***Phase 1***, not depicted), during (***Phase 2***) and after the diverter-actuated water collection into the weigh tank (***Phase 3***), different disturbing effects determine the accuracy of measurement. A qualitative overview of those quantities is presented in ***Table 2***.

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

$$K_{Meter} = \frac{N_{Pulses}}{V_{REF}} \qquad (2)$$

Quantities or meter characteristics that are subject of flowmeter calibration are:

- **Meter deviation** (***Eq. 1***), or
- **Meter K-factor** (***Eq. 2***); with meters that provide pulse signal outputs, it is measured in pulse count per unit volume or mass.

3. The measurement uncertainty model for a gravimetric-reference liquid flow calibration facility

Based upon the measurement principle in ***Figure 3*** and the measurands according to ***Eq. (1)*** or ***(2)***, respectively, the model for measurement uncertainty analysis can be established. ***Table 2*** contains a summarized overview of quantities and measurands that exert an influence on the total measurement uncertainty in liquid flowmeter calibration.

Table 2 *Measurement deviation ΔV_{Meas} in flowmeter calibration (factors of influence)*

$$\Delta V_{Meas} = V_{MUT} + \Delta V_{IP} + m_{REF} / \rho_{Water} \qquad (3)$$

- **A)** **Fluid density**
  - **Density measurement**
  - **Temperature measurement**
  - Calibration fluid sampling
- **B)** **Gravimetric reference** (weighing system)
  - **Mass of water** (collected in weighing tank)
  - **Balance parameters/calibration**
  - **Density of** environmental **air** (buoyancy)
  - Density of water
  - Diverter operation
  - Evaporation of collected water
  - Condensing moisture on weighing tank's wall
- **C)** **Change in volume contents of interconnecting piping**
  - **Temperature change** during a calibration run
  - **Compressibility of water** (test fluid)
  - Pressure change during a calibration run
  - Leakage flow from/to neighboring pipe system(s)
- **D)** **MUT's reading**
  - **Density of water** (test fluid)
  - **Time measurement** of diversion (flow diverter)
  - **Temperature change** during a calibration run
  - **Compressibility of water** (test fluid)
  - **Change in flow rate**
  - Pressure change during a calibration run
  - Meter readability
  - Velocity profile of test fluid flowing through flowmeter
  - and others

The analysis, starting from ***Eq. (2)*** and applying the respective formulas for physical effects of influence, results in ***Eq. (4)***.

Following quantities were taken into account as they produce significant contributions to the system's total measurement uncertainty:

- Mass determination m_{Water},
- Density of water ρ_{Water},
- Variation of interconnecting pipe volume $\Delta V_{IP}(\vartheta, p)$,
- Fluid diversion time error,
- Uncertainty due to effects originating from MUT, e.g. quantization effect in signal pulse counting.

Temperature of the process fluid and temperature variation, revealing a tremendous effect on system accuracy, occur implicitly in terms of water density and the variations of the interconnecting piping (***Eq. (5)*** and ***(6)***).

The corresponding sensitivity coefficients were determined, in a well-known manner, by applying derivative operations with respect to the input quantities, i.e. factors of influence.

$$\left(\frac{U_{K\_Meter}}{K_{Meter}}\right)^2 = \left(\frac{U_f}{f_{Output}}\right)^2 + \left(\frac{U_m}{m}\right)^2 + \left(\frac{U_\rho}{\rho_{Water}}\right)^2 + \left(\frac{U_{\Delta V}}{V_0}\right)^2 + \left(\frac{U_{T\_Error}}{V_0}\right)^2 + \left(\frac{U_T}{T_{MEAS}}\right)^2 \qquad (4)$$

$$\Delta V_{IP}(\vartheta) = \left[V_1 \cdot (\gamma_{Water} - 3\alpha_1) \quad + \quad V_2 \cdot (\gamma_{Water} - 3\alpha_2)\right] \cdot \Delta\vartheta \tag{5}$$

$$\frac{\Delta V_{IP}}{V_0} = \gamma_{effective} \cdot \Delta\vartheta \tag{6}$$

Equations (5) and ***(6)*** discard how water temperature variations during a calibration run (diverter-actuated water collection into weigh tank), due to different thermal expansion coefficients of the materials (fluid water, piping of stainless steel, diverter nozzle from plastics) involved in this thermal process cause a volumetric error with a dedicated uncertainty.

In order to minimize the above thermal effects, the facility was equipped with a computer-based process control and measurement system providing high accuracy and stability of the process quantities: flow rate, temperature, and pressure [8]. The process control system provides assistance to the operators to monitor the proper operation of the calibration plant with its 500 sensors and actuators and to detect system malfunctions.

Eq. (3) in ***Table 2*** is a representative model for uncertainty analysis in cases when the meter reading deviation is considered to be the measurand instead of the meter K-factor.

4. Component realization to meet the requirements for a national liquid flow standard

The core component of PTB's "hydrodynamic test field", which guarantees outstanding accuracy in water flow calibration, is represented by the gravimetric reference system which comprises three dual-balance weighing systems, with weighing ranges as follows: 300 kg, 3 tons, 30 tons [7]. To guarantee long-term stability of mass determination, each of the weighing systems was equipped with a mass calibration facility, which is monitored and actuated by the plant-wide process control system

Another decisive component part of the gravimetric system, which reveals a tremendous impact on system accuracy, is the fluid diverter. The diverters of the "hydrodynamic test field" [4][5] was optimized that it combines a short diversion time with good repeatability capabilities.

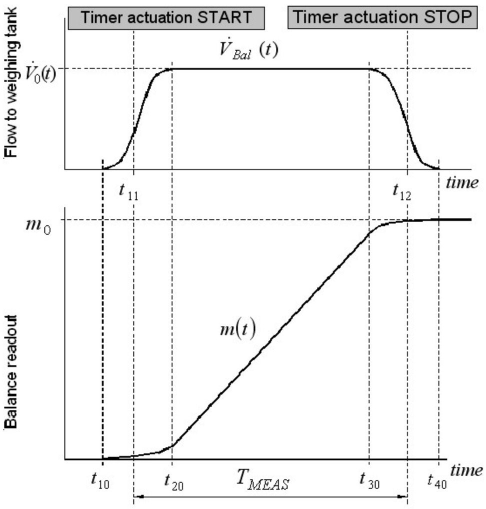


Figure 4 *3-tons weighing system with fluid diverter (highlighted by the circular marker)*

Figure 5 *Principle of flow diversion: - time response of measurands*

The diversion error analysis was performed according to **ISO standard 4185** [8]. Those investigations on the three diverters of the gravimetric reference were made with the flow rate being varied over the full range that was specified for the calibration facility ranging from 0.3 m³/h through 2,100 m³/h.

The standard uncertainty contributions originating from the different components of the calibration facility are presented in ***Table 3.*** Those values are valid for a set of parameters, which is displayed in ***Table 4***. The graphical visualization of the uncertainty analysis data in ***Figure 6*** provides assistance as an indicator for parameters or components, respectively, that have a dominant effect on the total measurement uncertainty and implies potentials for system improvement.

Table 3 *Measurement uncertainty budget of the water flow calibration facility*

Sources of uncertainty	Relative standard uncertainty [%]			
Mass				***2,09E-03***
Calibration of standard weights			4,60E-05	
Discrimination of balance			1,16E-05	
Repeatability of balance			2,08E-03	
Drift of balance			2,31E-04	
Bouyancy				***2,19E-05***
Ambient air density			2,19E-05	
Water density			3,18E-11	
Density of calibration weights			7,56E-09	
Temperature of fluid		1,54E+00		
Discrimination of temp.meas.	7,23E-02			
Sensor/meter calibration	5,20E-01			
Temp. gradient in water (estim.)	1,45E+00			
Density of fluid				***3,31E-03***
Temp. Meas. for appr. function			3,33E-09	
Density meas. for appr. function			8,51E-04	
Temp. downstream of MUT		1,54E+00	3,20E-03	
Numeric approx. Error			1,16E-04	
Time (Measurement/Diversion)				***2,31E-05***
Calibration of Timer (5x10-9)			2,00E-15	
Discrimination of Timer display			4,62E-07	
Discrmination of Diverter Time			2,31E-05	
Diverter timing error				***7,99E-03***
Diverter timing error				
Flowrate				
Diversion error volume			7,99E-03	
Interconnecting piping volume				***1,02E-04***
Temp. Variation during calibr.		1,54E+00		
IP volume				
effektive TC				
IP volume error			1,02E-04	
Meter under test (MUT)				***1,92E-04***
Discr. of frequency meas.			1,92E-04	
Repeatability uncertainty				3,50E-03
u_c(K-factor)	**Combined uncertainty**			***0,010***
U(K-factor)	**Expanded Uncertainty (k=2)**			**0,019**

Table 4 *Parameters of the calibration facility having an impact to the facility's operating conditions*

System item	Quantity	Value		Explenation	Condition
Facility	Flowrate:	**72,0**	m³/h		Operation parameter
- Balance	Target weight:	**2500,0**	kg		dito
- Cal. weights	Density	7845,0	kg/m³	Carbon steel	Material parameter
- Diversion time	(derived quantity)	125,1	s		Operation parameter
- Ref. Volume	(derived quantity)	2,5030	m³		dito
- Ambient air	Air density	**1,1800**	kg/m³		Ambient condition
- Interc. piping	IP volume:	0,5008	m³	steel, plastics	Design parameter
	"effective" TC	1,7689E-04	1/K		Design/material para.
	delta Temp.:	**0,050**	K	During measm.	Operation parameter
- Diverter	Timing error:	**20,0**	ms	Standard dev.	dito
Fluid	Water density:	998,8173	kg/m³	(at 20 °C)	Material parameter
	Water temp.:	**20,000**	°C		Operation parameter
Meter under test	Pulse frequency	**209,00**	Hz	Turbine meter	Sample meter
Repeatability		**3,50E-05**			Op./design param.

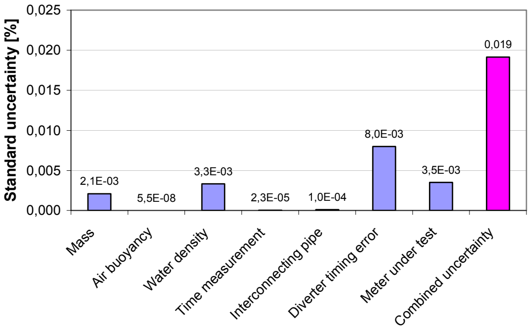


Figure 6 *Individual uncertainty contributions of the main quantities of impact to the total uncertainty of the calibration facility*

In **Table 3** and **Figure 6**, respectively, the representative estimate of the standard uncertainty for the fluid diverter device seems to be relatively high a value, but that value represents the uncertainty behavior of the diverter time measurement operation over a wide range of fluid flow rate. Small uncertainty values are only valid within a narrow bandwidth of flow rate. Over a wider range, the optimized flow conditions, having been found on the basis digital flow simulation [4], are exceeded. This fact has been taken into account with that higher magnitude of the uncertainty estimate.

Figure 6 reveals that, with the present operation and uncertainty parameters of the calibration facility, predominantly the reduction of the diverter timing error uncertainty as a factor of system improvement would significantly reduce the facility's total measurement uncertainty.

5. Summary and final remarks

Generally, liquid flow calibration facilities, which are based upon static weighing and diverter-based flying-start-and-finish method, are affected by several different factors of influence that can be categorized to be of first-order and second-order effects.

First-order factors of influence, which comprise quantities like mass determination, temperature measurement, temperature stability during calibration run, water density measurement, time determination of fluid diversion, appear explicitly in the equation that represents the measurement uncertainty model of the calibration process (See **Table 2**: quantities highlighted by bold letters). These quantities and their associated standard uncertainty contributions were listed in ***Table 3***. The corresponding operation and material parameters of the facility that represent the initial causes of measurement accuracy and uncertainty can be seen in ***Table 4***. These were the factors of influence that were primarily be influenced by an appropriate and accurate system and component design ([3] through [7]).

Second-order factors of influence, like fluid flow rate stability during a calibration run, are implicitly taken into account in the analysis of the diverter operation [4], and it also determines the flowmeter reading due to non-linearity effects in the flowmeter's steady state response characteristics.

A symbiosis-like interaction of uncertainty analysis and system and component design steps resulted in a water flow calibration facility which provides outstanding characteristics: total measurement uncertainty of meter calibration as low as 0.02 %, adjustability of fluid temperature from 10°C through 35°C, and pressure adjustability ranging from 2 bars through 6 bars.

The measurement analysis, presented in this paper, was subject of accounting the measurement and calibration capabilities (CMC's) of the national metrological institutes (NMI's) by BIPM [9]. ***Figure 7*** depicts the CMC data base of the NMI's in water flow measurement in a 3-D chart, with the flow rate range being displayed vs. expanded measurement uncertainty and NMIs' country ID, respectively. The data of the "hydrodynamic test field" reveal that PTB's water flow facility occupies an outstanding position with respect to low uncertainty values.

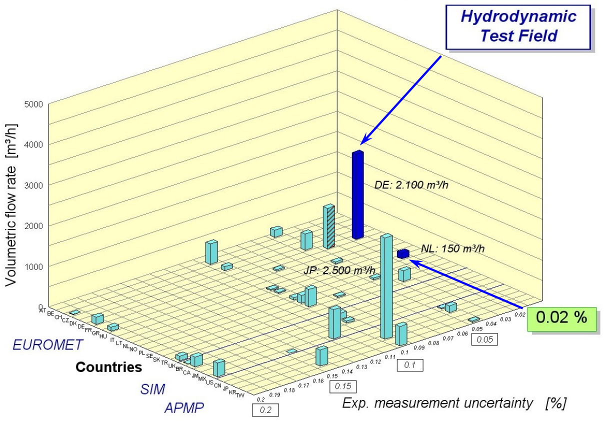


Figure 7 *Calibration and measurement capabilities (CMCs) of the national metrological institutes (NMIs) in the field of water flow (according to the BIPM data base [9])*

During an international key comparison (Key Comparison Water Flow CCM.FF-K1 of BIPM [10]) the PTB facility could prove its outstanding position with respect to smallest measurement uncertainty in liquid flow calibration. Additionally, during the KC measurement campaign the special capabilities of this facility [6] were utilized in order to determine the meter K-factor sensitivities of the two meter artifacts of the transfer meter package. This was a necessary measure as the majority of those laboratories could not guarantee a predefined fluid temperature during measurement operation. Among the participating NMI laboratories, the "hydrodynamic test field" was the only one that could provide exact fluid temperature adjustability and stability. Thus, it was possible, due to characterization measurements, to determine sensitivity coefficients of the meter factors which served as a basis to apply corrections and make results comparable.

References

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