Quantifying impacts on the measurement uncertainty in flow calibration arising from dynamic flow effects

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Abstract:
Traceability of the measurement units in fluid flow metering, as the state-of-the-art approach, is practiced as a so-called element-by-element method which relies upon the idealistic assumption that the measurement process in a flow calibration facility can be run under exact steady-state conditions, i.e. absolutely no fluctuations of the flow quantities are assumed to occur during the flow measurement process. Practical experiences, combined with a model-based analytical view of the measurement process in a flow standard, have revealed that dynamic impacts on the measurement uncertainty due to flowrate fluctuations have to be taken into account, in addition to the steady-state traceability chain.

1 INTRODUCTION – MEASUREMENT DYNAMICS IN FLOWMETER CALIBRATION

The units or measurands that are estimated to be essential for the uncertainty estimation of flowmeter calibration as a part of a static measurement model are the following items: volume or mass, fluid density, fluid temperature during the measurement process, and time measurement [1]. There is one essential contribution to the measurement uncertainty which does not represent an SI unit, but which may cause uncertainty contributions whose magnitude can exceed those of the above quantities: the erroneous effect of the fluid diverting device [4][5][6].
As a general practice, this contribution is considered to represent a so-called diverter timing error on a liquid-flow calibration facility run in the flying-start-and-finish operation mode. This timing error can be determined by means of special test procedures [2][3]. As an outcome of those test procedures, a random-like set of timing error figures are calculated with a random-like scatter of values which have a deterministic effect on the measurement results.
Flowrate fluctuations represent a variation in mechanical energy, implicitly impacting the uncertainty of liquid flow calibration results.

Thus, it can be stated that flowrate induced impacts, which occur in the mathematical model of the measurement process, can be characterized as a primary cause as follows:

- Diverter-caused effect as an impact on the measurement analysis of a liquid-flow calibration facility run in the flying-start-and-finish operation mode;
- Erroneous effects due to the non-linear steady-state measurement response;
- Pressure changes in causative interactions due to flowrate fluctuations;
- Temperature changes caused by flowrate fluctuations;
- Time and spatial fluctuation of fluid properties, like density.

Even the operation of those flow calibration facilities that are run in the so-called standing-start-and-finish operation mode is significantly affected by the measurement process dynamics, though it does not seem so, as the start and the finish of the calibration measurements are defined under steady-state conditions, but the flow measurement startup and shutdown are dynamic system responses both with the flow system and the involved meter under test.

In this paper presented and a previous paper [1], the relevant cause-and-effect relationships are analyzed and quantified via which dynamic process effects impact the accuracy of the calibration results in liquid flow calibration facilities.

Owing to the above-mentioned dynamic impacts, which are not – as the state-of-art practice – a component part of the element-by-element traceability approach of the fluid flow units to the basic SI units, in not a few cases, the certified measurement uncertainty figures of accredited flow calibration laboratories have been revealed as being significantly and unrealistically too low - a fact that is not acceptable, as this unrealistic approach reduces correctness and comparability of flow measurement results tremendously, especially in the field of liquid flow metering [6].

2 MEASUREMENT DYNAMICS IN FLOWMETER CALIBRATION AND APPLICATION

In general, the calibration of flow meters is performed in a facility as depicted in **Fig. 1** by comparing the indication of the meter under test (MUT) to the mass which is collected in the tank on the weighing system. The actual calibration measurement is performed only after the process quantities of the water flow loop have been stabilized versus time, and steady state conditions have been achieved.

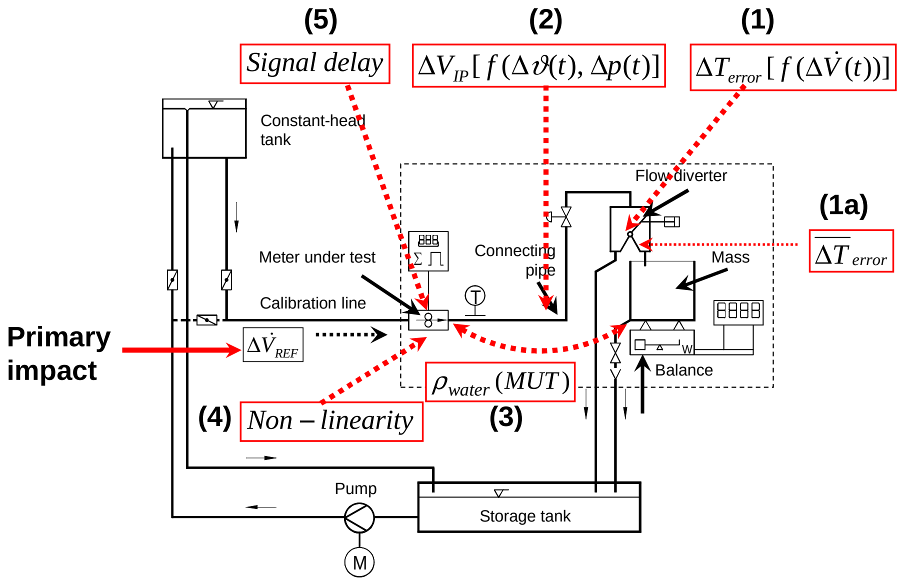


Figure 1 *Gravimetric liquid flow calibration facility – Uncertainty impacting items and impact of flowrate fluctuations*

(1) *Impact upon diverter timing error*

(1a) *Systematic effect: Diverter timing error* $\overline{\Delta T}_{error}$

(2) *Material and fluid effects within the interconnecting pipework*

(3) *Conversion of* m_{REF} *into* V_{REF}

(4) *Effects due to nonlinearities of the meter characteristics*

(5) *Time delay caused by the flow sensor or transmitter electronics*

Thus, as shown in **Fig. 2** (vertical cause-and-effect propagation lines), one is tempted to believe that time-dependant effects are not issues in the calibration process. But as depicted in **Fig. 1**, nevertheless there are several significant effects that originate from dynamic transitions during the measurement process. In the first place, the diverter actuations, which direct the liquid flow towards the weigh tank and, then, after the water collection back in the by-pass direction, are subject of dynamic impacts. Additionally, transient impacts resulting from variations of the interconnecting pipework and the enclosed liquid are caused by temperature and pressure fluctuations [1]. As a third impact, the conversion of the collected mass into the volume, represented by the meter reading, is to be mentioned here. Furthermore, the MUT nonlinearity effect is a characteristic which will cause measurement deviations on the occurrence of flowrate fluctuations [1]. Additionally, signal delays within the MUT's signal processing chain deliver contributions to the measurement uncertainty of the calibration measurements. But it has to be mentioned that the instability of the system's flowrate represents the primary impact which is the source of all dynamic effects. Thus, in **Fig. 2**, amendments with respect to the above-mentioned impacts have been added to a plain element-by-element traceability scheme (horizontal cause-and-effect propagation lines, dotted). In this figure, the positions where these impacts interfere are referenced in detail.

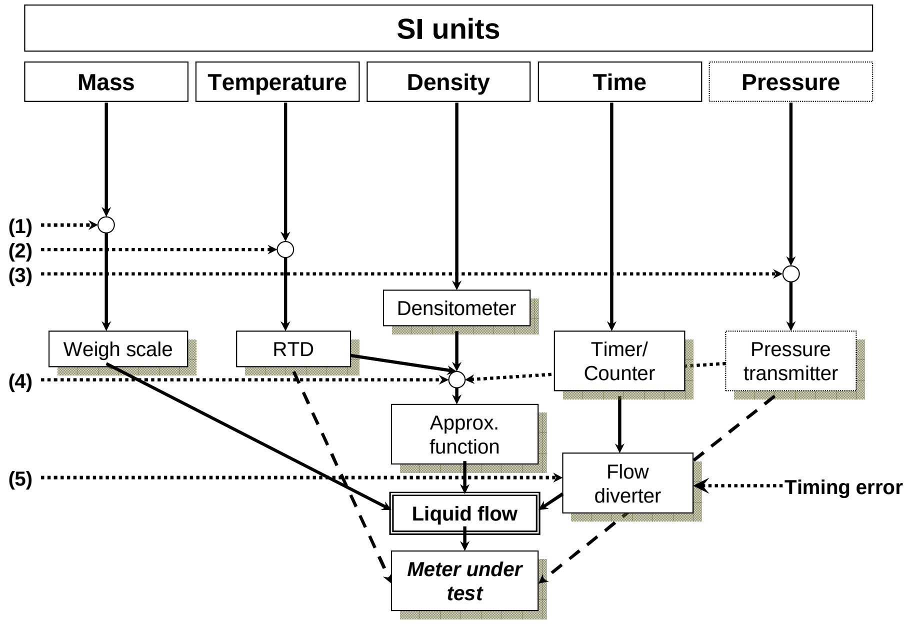


Figure 2 *"Comprehensive" traceability chain in fluid flow calibration - comprising dynamic process effects on the measurement uncertainty of liquid-flow standard facilities:*

(1) Dynamic impacts on weigh scale originating from mechanical vibration excitations;
(2) Variation in the temperature of the circulating water resulting from flowrate fluctuations and imperfect temperature control operation, respectively;
(3) Variation in the process pressure due to flowrate fluctuations;
(4) Fluctuations of the determined water density due to spatial and temporal changes in the water temperature within the water stream;
(5) Impact of flowrate variations on the diverter's timing error

3 SOURCES AND IMPACTS DUE TO DYNAMICS MEASUREMENT EFFECTS

3.1 Sources that cause dynamic impacts in flow calibration

The simplified model for the determination of the uncertainty of the measurement and calibration process is shown in **Fig. 3**. In a realistic measurement model, the acting signals now cannot be assumed as static, but as time-dependent quantities. Thus, the static system has to be transformed into a more comprehensive, dynamic system. Computations of those systems are, generally, performed by applying methods of the signal and system theory [7]. This will be explained in detail below.

3.2 Effects originating from the calibration facility's operation

Dynamic impacts are the consequences of fluctuations in the process quantities within the measurement system. Signal delays or other dynamic properties, like the transport time lag of the entire measurement system, characterize its dynamic behavior [1]. Thus, the uncertainty of the comparison of the readings of the MUT and the reference standard (both gravimetric and volumetric) is affected by time-dependent transients. Another additional erroneous effect results from the MUT's steady-state nonlinearity in the case where it is operated under fluctuating flowrate conditions. Both effects can be the source of additional meter errors.

3.3 Flowmeter-related dynamic effects

Under ideal conditions, the reading of a flowmeter is within the entire range of operation directly proportional to the input flowrate, even if further disturbing effects occur.
But in general, following characteristics can be assigned to a real flowmeter [1]:

- nonlinear steady-state flowmeter characteristics,
- time delay effects (at least, first-order time delay),
- dead-time delay effects.

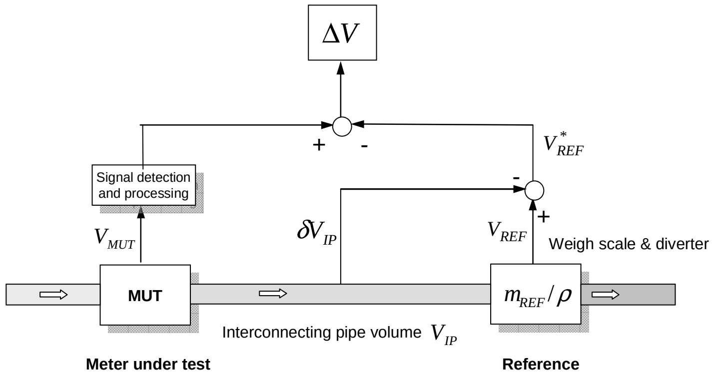


Figure 3 *Main elements of flow calibration facilities*
- Meter under test
- Interconnecting pipework
- Flow reference standard (gravimetric or volumetric)

4 ANALYTICAL UNCERTAINTY ANALYSIS AND SYSTEM SIMULATION

4.1 Characterization of the involved functional elements in the flow calibration facility

Summarizing, we can state that the measurement uncertainty of flow calibration facilities is influenced by effects as listed below

- fluctuating process quantities: flowrate, temperature, pressure;
- density-based mass-to-volume conversion;
- diverter;
- interconnecting pipework.

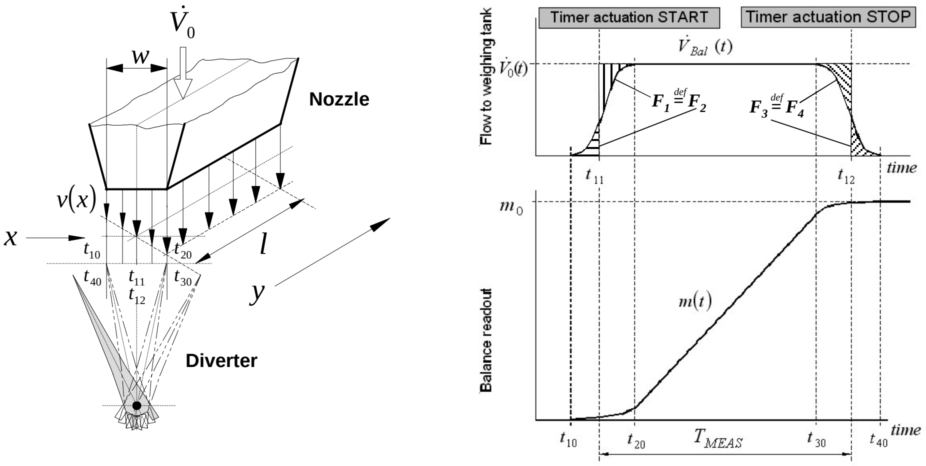
The dynamic interactions between the diverter operation and the MUT reading were described in [1] comprehensively as a more “realistic” measurement model.
For a clear demonstration, in **Fig. 4** the relations are plotted in stretched scales. As a matter of fact, both transitions of the diverter last only for fractions of a second. The plotted duration takes a couple of seconds here. During a measurement run, within the time slot between the times t_{10}, when the diverter starts to direct the liquid jet into the weigh tank, and t_{40}, when the entire flow is re-directed in the bypass direction again, the whole measurement, which is considered here, is completed. For further details, see **Fig. 4**.
Independent of the properties and the behavior of the reference flowrate (drift, fluctuation), the scale collects the amount of water which is directed into the weigh tank by the diverting device. But the reading of the MUT implies the above-mentioned dynamic impacts and, therefore, the reading will differ more or less from the reading of the scale.

Table 1 *Diverter-based liquid collection and signal acquisition – Model equations*

Reference liquid flow reported to weighing tank: $V_{REF} = V_{REF\_1} + V_{REF\_2} + V_{REF\_3}$ **(1)**		
Diverter transition: $t_{10} \ldots t_{20}$	Steady-state water collection: $t_{20} \ldots t_{30}$	Diverter transition: $t_{30} \ldots t_{40}$
$V_{REF\_1} = \int_{t_{10}}^{t_{20}} \int_{0}^{x(t)} l \cdot v(x,t)\, dxdt$ **(2)**	$V_{REF\_2} = \int_{t_{20}}^{t_{30}} \int_{0}^{x=w} l \cdot v(x,t)\, dxdt$ **(3)**	$V_{REF\_3} = \int_{t_{30}}^{t_{40}} \int_{x(t)}^{0} l \cdot v(x,t)\, dxdt$ **(4)**
Liquid flow reported to readings of the meter under test (MUT):		
	Diverter-actuated flow signal acquisition from MUT: $t_{11} \ldots t_{12}$	
	$V_{MUT} = \int_{t_{11}}^{t_{12}} \dot{V}_0(t)\, dt$ **(5)**	

The scope of this chapter encompasses the consideration of particular parts of a calibration facility, the complex interaction of both subsystems diverter and meter under test. This will be accomplished by a detailed look at the

single processes and the derivation of a couple of mathematical expressions, which describe the sequences of the operations and interactions, as well of the diverter as of the meter under test.
The principle of flow diversion is shown in **Fig. 4**.



(a) ***(b)***

Figure 4 *Principle of flow diversion*
(a) Diverter and flow conditions
(b) Time responses of measurands

4.2 Character of the impacting effects

The question arises whether the sources of dynamic effects reveal a deterministic or a random character. It can be stated that the effects which cause dynamic contributions to the static measurement process propagate along a deterministic cause-and-effect relationship. But their random-like character results from the fact that their appearance is accidental due to imperfect system design and operation.

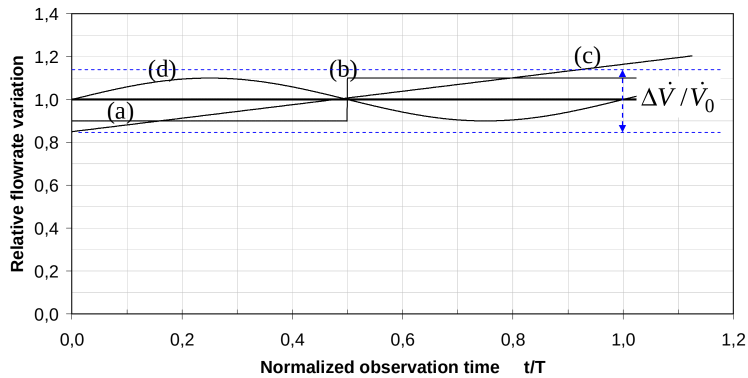


Figure 5 *Calibration facility: flowrate time characteristics*
a) Ideal, constant flowrate
b) Step-like time response, e.g. due to regulation valve instability
c) Drift of flowrate, e.g. induced due to temperature variations
d) Sinusoidal flowrate variations that may be caused by instabilities in the flowrate control loop

On principle, a liquid flow standard is to be run under quasi-static conditions, i.e. no fluctuations of the process parameters like flowrate, pressure or temperature occur. This is the ideal precondition for a low-uncertainty operation of such a flow standard facility. But, in reality, the involved flowmeters already deliver a noisy meter reading. This represents one of the sources of random contributions to the calibration measurement. According to **Fig. 5**, following random or random-like effects may be distinguished:

- Step-like time response, e.g. due to regulation valve instability;
- Drift of flowrate, e.g. induced due to temperature variations;
- Sinusoidal flowrate variations that may be caused by instabilities in the flowrate control loop.

Periodic variations in the flowrate, as the primary origin of succeeding pressure and temperature changes are treated here in this subparagraph, as they can be avoided generally. Their occurrence is due to instabilities in the flowrate control system. In cases where it is not recognized, of course, it is a random-like source of measurement uncertainty. The random-like character results from the fact that the liquid collection measurement process, initiated by the diverter's actuation, is run absolutely unsynchronized from the flowrate control loop's oscillations.
Thus, the stability of operation has to be provided by an appropriate control loop design and controller parameter tuning.

4.3 Diverter timing errors

The operation of a flow diverter in a liquid flow standard, which is run in the standing-start-and-finish operation mode, and its impact on the calibration results have been the subject of a number of publications. Thus, here, this issue can be referenced to a few of them, e.g. [2] through [4].
It is an obvious fact that the operation of the diverter causes a systematic volume error whose magnitude depends on the timer actuation adjustment, which is responsible for the actuation of the measurement acquisition from the MUT (See **Figs. 3** and **4**).
It can be stated that these effects, which cause a volume error in the calibration (or the gravimetric equivalent, respectively), are processes in a deterministic cause-and-effect chain. Thus, it could be expected that they are correctable in principle. But, in practice, this timing error effect of diverter operation is not directly accessible by measurement. What is the reason for this?

We can summarize the following facts and statements with respect to this issue:

1) The diverter's volume or timing error, respectively, is not directly accessible for a measurement of its magnitude. It has to be determined by two comparative measurement processes, with different numbers of diversions in either measurement procedure.
2) An exact, i.e. zero-error, timer actuation is only adjustable and valid, respectively, in case of absolutely stable flowrate conditions, which can only be achieved theoretically.
3) These requirements with respect to flowrate stability must be fulfilled both for measuring the timing error and for utilizing the diverter during a calibration measurement.

The general practice for determining this timing error, as described in [2] and [3], is to fill the gravimetric reference (weigh tank) in a single measurement step at flowrate $\dot{V}_0$, with the mass of water m_0 being collected in the gravimetric reference. In a second measurement process, the gravimetric standard is to be filled in a succession of N steps at flowrate $\dot{V}_1$, summarizing the individual masses Δm_i and $\Delta T_{M,i}$ timing errors. As the state of the art, the latter one is determined by this procedure as the effective total timing error ΔT_M. A quantitative analysis of the impact of a continuously varying flowrate effect is not possible in this way.
Two approaches or procedures to determine the diverter timing error are described in [2] and [3]. These approaches are summarized in the following section of this paragraph. For more detailed information, see the respective references. Both approaches are based upon a couple of idealizing simplifications, which comprise the following assumptions:

- flowrates are assumed to be constant during the measurement intervals T_M and $\sum_{i=1}^{N} T_i$;
- the duration of each measurement time interval T_i during the ***i*** repeated measurements is constant and equal to T_N.

The symbols and equation appearances of references [2] and [3] were slightly adapted to a unified, common representation in this paper.

1) An "exact" numerical analysis of the diverter's timing error [8] relies on the following relations:

- Single-step filling: $$m_0 = \rho_0 \dot{V}_0 (T_M + \Delta T_M) \quad (5)$$

- i-th repeated step: $$\Delta m_i = \rho_i \dot{V}_i (T_i + \Delta T_M) \quad \{i = 1,2,...,N\} \quad (6)$$

- Over *N* steps: $$\sum_{i=1}^{N} [\Delta m_i] = \sum_{i=1}^{N} \left[\rho_i \dot{V}_i (T_i + \Delta T_M)\right] \quad (7)$$

The quantitative comparison (relation) between single-step and multi-step diverter-based liquid collection results in **Equ. (8)**:

$$\frac{m_0}{\sum_{i=1}^{N} [\Delta m_i]} = \frac{\rho_0 \dot{V}_0 \ (T_M + \Delta T_M)}{\sum_{i=1}^{N} \left[\rho_i \dot{V}_i T_i\right] \ + \ \Delta T_M \sum_{i=1}^{N} \left[\rho_i \dot{V}_i\right]} \quad (8)$$

Proceeding with transforming **Equ. (8)** delivers the diverter timing error as follows:

$$\Delta T_M = T_M \cdot \frac{\frac{m_1}{m_0}\rho_0 \dot{V}_0 - \frac{1}{T_M}\sum_{i=1}^{N}\left[\rho_i \dot{V}_i T_i\right]}{\sum_{i=1}^{N}\left[\rho_i \dot{V}_i\right] - \frac{m_1}{m_0}\rho_0 \dot{V}_0} \qquad (9)$$

2) Diverter timing error according to G. MATTINGLY [3]:
Starting from **Equ. (9)** and inserting the following equations with

$$\dot{m}_0 = m_0 / T_M \qquad (10)$$

$$\dot{m}_1 = \sum_{i=1}^{N}\Delta m_i \Big/ \sum_{i=1}^{N} T_i \quad , \qquad (11)$$

that equation is obtained which was derived by MATTINGLY:

$$\Delta T_M = T_M \cdot \frac{\frac{\dot{V}_0}{\dot{V}_1}\cdot\frac{\dot{m}_1}{\dot{m}_0} - 1}{N - \frac{\dot{V}_0}{\dot{V}_1}\cdot\frac{\dot{m}_1}{\dot{m}_0}} \qquad (12)$$

3) Diverter timing error according to ISO Standard 4185 [2]:
The diverter timing error given in ISO Standard 4185 relies on a further step of simplification:

$$\frac{\dot{V}_0}{\dot{V}_1}\cdot\frac{\dot{m}_1}{\dot{m}_0} \approx 1 \qquad \text{(See sample Table 2: = 0.999938)} \qquad (13)$$

$$N >> 1 \qquad (14)$$

Thus , we receive a formula (approximation) for calculating the diverter timing error as follows:

$$\Delta T_M \approx \frac{T_M}{N-1}\left[\frac{\dot{V}_0}{\dot{V}_1}\cdot\frac{\dot{m}_1}{\dot{m}_0} - 1\right] \qquad (15)$$

Inserting **Eqs. (13)** and **(14)**, **Equ. (15)** appears like the equation shown in ISO Standard 4185:

$$\Delta T_M = \frac{T_M}{N-1}\left[\frac{\dot{V}_0}{\dot{V}_1}\cdot\frac{\sum_{i=1}^{N}\Delta m_i \Big/ \sum_{i=1}^{N} T_i}{m_0 / T_M} - 1\right] \qquad (16)$$

The realization of the three measurement procedures as a spreadsheet is presented in **Table 2**. The comparison between approaches (1) through (3) reveals no significant difference between diverter timing errors, determined separately for the three approaches.

As the flow conditions in the diverter vary with the magnitude of the flowrate in the calibration system, the error level is impacted by the flowrate. Thus, it does not represent a constant quantity throughout the flowrate range in which the calibration facility is operated, but it varies with flowrate and other process conditions like temperature.

The input data structure of the spreadsheet in **Table 2** (see second column with symbols highlighted in red) provides the capability of applying the individual flowrates, $\dot{V}_0$ and $\dot{V}_i$, during each step of collecting the liquid in the gravimetric reference, instead of simply applying the mean flowrate $\overline{\dot{V}_1}$ (which is identical to $\dot{V}_1$ in **Eqs. (12)** through **(16)**) over ***N*** repeated measurements) which is the state-of-the-art practice [2][3].
PCS in the third column of **Tab. 2** represents the abbreviation for process control system. In this case, PCS refers to the flowrate readings displayed by the calibration facility's PCS. State-of-the-art control systems, generally, provide the capability of acquiring the flowrate values $\dot{V}_i$ in real time, in order to apply the precise calculation of the diverter timing error based on **Equ. (9)**. Due to EXCEL's limited typographic capabilities to display special symbols, in **Table 2**, Q_i stands for $\dot{V}_i$.

Table 2 *Spreadsheet for calculating the diverter's timing error [8]*

RUN No.	Flowrates	Average flow rate (PCS reading)	Average mass flow rate (PCS reading)	Balance reading	True mass	Mass difference dM	Measurement time T_M	Mass flow rate	Water temp.	Water density	$RHO_i * Q_i$	$RHO_i*Q_i*T_i$
		[m³/h]	[t/h]	[kg]	[kg]	[kg]	[s]	[kg/s]	[°C]	[kg/m³]	[kg/s]	[kg]
0	**Q0**	**9,855**	**9,826**	**983,709**	**984,894**	**-**	**360,238**	**2,734**	**24,767**	**997,101**	**2,730**	**983,297**
1	**Q1**	9,871	9,845	**99,111**	99,230	99,230	36,240	2,738	23,764	997,351	2,735	99,104
2	**Q2**	9,864	9,837	**198,235**	198,473	99,243	36,239	2,739	24,272	997,225	2,732	99,021
3	**Q3**	9,903	9,875	**297,539**	297,898	99,424	36,238	2,744	24,357	997,204	2,743	99,404
4	**Q4**	9,883	9,856	**396,835**	397,313	99,415	36,241	2,743	24,355	997,205	2,738	99,216
5	**Q5**	9,881	9,852	**496,230**	496,827	99,514	36,285	2,743	24,704	997,117	2,737	99,301
6	**Q6**	9,876	9,847	**595,475**	596,193	99,365	36,239	2,742	24,945	997,055	2,735	99,124
7	**Q7**	9,892	9,863	**694,731**	695,568	99,375	36,238	2,742	24,931	997,059	2,740	99,285
8	**Q8**	9,887	9,858	**794,049**	795,006	99,438	36,264	2,742	24,945	997,055	2,738	99,304
9	**Q9**	9,892	9,863	**893,266**	894,343	99,337	36,238	2,741	24,945	997,055	2,740	99,280
10	**Q10**	9,877	9,848	**992,498**	993,693	99,351	36,241	2,741	24,945	997,055	2,736	99,139
	Sums			**992,498**		*993,693*	***362,464***				***27,373***	***992,180***
	MIN	*9,864*	*9,837*	*99,111*	*99,230*	*99,230211*	*36,238*	*2,738*	*23,764*	*997,055*	*2,732*	*99,021*
	MAX	*9,903*	*9,875*	*992,498*	*993,693*	*99,514250*	*36,285*	*2,744*	*24,945*	*997,351*	*2,743*	*99,404*
	AVG	*9,883*	*9,854*	*545,797*	*546,454*	*99,369350*	*36,246*	*2,741*	*24,616*	*997,138*	*2,737*	*99,218*
	STD	*1,137E-02*	*1,104E-02*	*3,006E+02*	*3,009E+02*	*8,664E-02*	*1,573E-02*	*1,808E-03*	*4,108E-01*	*1,032E-01*	*3,066E-03*	*1,174E-01*
	relSTD	***1,151E-03***	***1,120E-03***	***5,507E-01***	***5,507E-01***	***8,719E-04***	***4,341E-04***	***6,595E-04***	***1,669E-02***	***1,035E-04***	***1,120E-03***	***1,183E-03***
	q/q'	*-0,279*										

ISO International Standard 4185: *[2]*

$S(m_i)$ =	**993,693**	kg
$S(T_i)$ =	**362,464**	s
m_0 =	**984,894**	kg
t_0 =	**360,238**	s
q =	**9,855**	m³/h
q' =	**9,883**	m³/h
$S(m_i)/S(t_i)$ =	**2,741**	
m_0/t_0 =	**2,734**	
N =	***10***	
Timing error:		
deltaT =	$[t_0/(N - 1)] * [(q/q') *((S(m_i)/S(T_i))/(m_0/t_0)) - 1]$	
deltaT =	**-2,469**	ms

NIST/Mattingly: *[3]*

$S(m_i)$ =	**993,693**	kg
$T = S(T_i)$ =	**362,464**	s
m_0 =	**984,894**	kg
t_0 =	**360,238**	s
$Q_1 = q$ =	**9,855**	m³/h
$Q_2 = q'$ =	**9,883**	m³/h
$w_2 = S(m_i)/S(t_i)$ =	**2,741**	
$w_1 = m_0/t_0$ =	**2,734**	
N =	***10***	
Q_1*w_2/Q_2*w_1 =	0,999938	
Timing error:		
deltaT =	$[(Q_1*w_2/Q_2*w_1 - 1) / (N - Q_1*w_2/Q_2*w_1)]*S(T_i)$	
deltaT =	**-2,484**	ms

PTB/Engel: *[8]*

$m_1 = S(m_i)$ =	**993,693**	kg
m_0 =	**984,894**	kg
Q_0 =	**9,855**	m³/h
$T_M = t_0$ =	**360,238**	s
Rho_0*Q_0 =	**2,730**	kg/s
SUM(Rho_i*Q_i)=	**27,373**	kg/s
$Rho_0*Q_0*T_0$ =	**983,297**	m³/h
SUM($Rho_i*Q_i*T_i$) =	**992,180**	m³/h
m_1/m_0 =	**1,009**	
Timing error:		
deltaT =	See Equ.(9)	
deltaT =	**-3,997**	ms

5 EXPERIMENTAL ANALYSIS OF THE CALIBRATION SYSTEM'S DYNAMIC BEHAVIOR

5.1 Device for test signal generation and response signal acquisition

In order to determine the dynamic response of a flow calibration facility, a test setup has been developed which comprises, as the essential part, hardware and software components that acquire frequency signals of flow sensors and compute the instantaneous frequency f_i, as the equivalent of flowrate, from the spacing time T_i between two succeeding signal pulses directly into real time: $f_i = 1/T_i$. This test equipment provides capabilities of acquiring the signals from 3 flow sensors (as frequency signals) and, additionally, analog current signals, as it is show in **Fig. 6**, as a schematic diagram.

The measurement results, which are displayed in **Figures 7** and **8**, rely on the utilization of this measurement equipment.

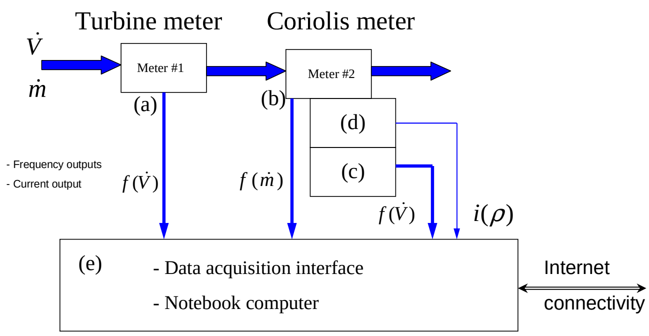


Figure 6 *Calibration facility: monitoring the flowrate time characteristics - auxiliary electronics for monitoring the dynamics of process flowrate*

a) ***Meter #1****: turbine meter with frequency output signal*
b) ***Meter #2****: Coriolis meter with* ***mass flowrate-related*** *frequency output signal*
c) ***Meter #2****: Coriolis meter with* volume flowrate-related *frequency output signal*
d) ***Meter #2****: Coriolis meter with* volume flowrate-related *current output signal (4 mA … 20 mA)*
e) ***Auxiliary electronics****: Acquisition of flowmeter signals, calculation of the instantaneous flowrate-related values from measured pulse spacings*

5.2 “Natural” system immanent flowrate disturbances occurring in a flow standard

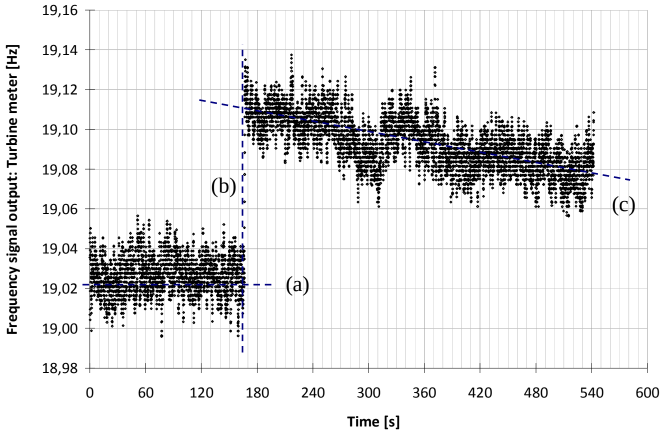


Figure 7 *Calibration facility: flowrate time characteristics*
a) Stable, constant flowrate
b) Step-like time respons
c) Drift of flowrate

By utilizing the signal acquisition capabilities of the test equipment which was described in the previous section, the flowrate stability in a flow standard facility has been investigated. The results of such an investigational measurement are presented in **Fig. 7**. These results reveal the typical characteristic system behavior as it has already been categorized in **Paragraph 4.2**.

5.3 Experimental simulation of flowrate fluctuations by external disturbance stimulation

For the purpose of verifying the analytical investigation of flowrate variation effects in a flow standard by a experimental investigations, dedicated test signals [7] have to be applied to the flow regulation valve, as it is shown in **Fig. 8**. In a test experiment, step-like control signals (signal: **Vale_scaled_60**) have been applied to the valve’s control signal input in order to stimulate a modulation of the flowrate magnitude (represented by signal **AVG_frequency**).

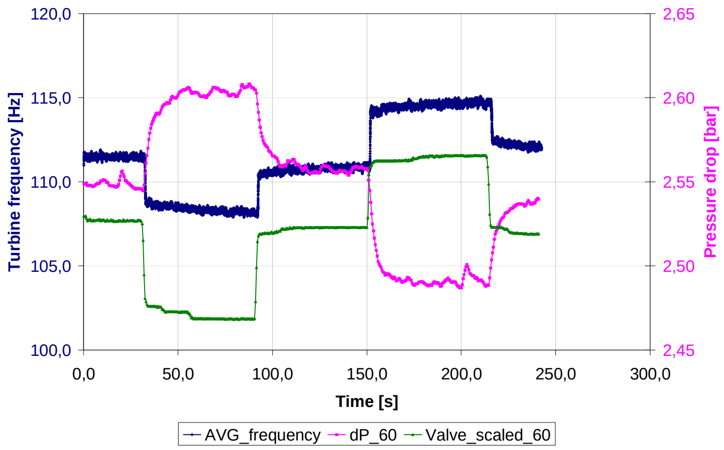


Figure 8 *System reactions upon step-like variations of control valve position:*
*a) Control valve position (***Valve_scaled_60***)*
*b) Response of the turbine frequency signal output (***AVG_frequency***)*
*c) Time function of the differential pressure across control valve (***dP_60***)*

Of course, besides the flowrate magnitude, other process quantities are affected by the test signals generation. One of these process quantities is the pressure drop across the control valve (signal **dP_60**). Figure 60 in the signal designators refers to the flowrate of 60 m³/h at which the test was carried out.

Table 3 *Legend of symbols applied in text*

Symbol	Meaning	Unit
i	Index	/
m	Mass	*kg*
m_0	Mass collected during single-step filling	*kg*
m_1	$\sum_{i=1}^{N} \Delta m_i$ Mass accumulated over ***i*** measurement steps	*kg*
Δm_i	Mass collected during ***i***-th repeated measurement	*kg*
$\dot{m}$	Mass flowrate	*kg/s*
$\dot{m}_0$	Mass flowrate during single-step filling, measured by monitoring flowmeter	*kg/s*
$\dot{m}_0^*$	m_0 / T_M Mass flowrate during single-step filling	*kg/s*
$\dot{m}_i^*$	$\Delta m_i / T_i$ Mass flowrate during ***i***-th repeated measurement	*kg/s*
$\dot{m}_1^*$	$\frac{1}{T_M} \sum_{i=1}^{N} \Delta m_i$ Mean mass flowrate over ***i*** measurements	*kg/s*
N	Number of repeated measurements	/
T_M	Measurement time over single-step filling	*s*
T_N	$T_N = T_M / N$ Ideal, constant measurement time over each measurement step	*s*
T_i	***i***-th measurement time	*s*
ΔT_M	Diverter timing error	*s*
$\dot{V}$	Volume flowrate	*m³/h*
$\dot{V}_0$	Volume flowrate during single-step filling	*m³/h*
$\dot{V}_1$	$\frac{1}{N} \sum_{i=1}^{N} \dot{V}_i$ Mean volume flowrate over N measurements	*m³/h*
$\dot{V}_i$	Volume flowrate during ***i***-th measurement	*m³/h*
ρ_0	Liquid density during single-step filling	*kg/m³*
ρ_i	Liquid density during ***i***-th measurement	*kg/m³*

6 SUMMARY AND CONCLUSIONS

This paper reveals, among other things, the cause-and-effect relationships as to how dynamic effects caused by random-like fluctuations of the process quantities fluid flowrate, fluid temperature and pipe pressure impact the measurement uncertainty of a flow calibration facility via plant components, like the interconnecting pipework and die flow diverter, and the meter under test (MUT). Thus, arguments are delivered as to why the MUT effects have to be taken into account with the CMC entries of a calibration facility. The measurement uncertainty budget, therefore, has to be extended by additional uncertainty contributions that originate from the dynamic impacts (See **[1]**).

The investigation of the dynamic impacts caused by time variations in the process parameters can be performed to a certain level of precision, by a model-based theoretical analysis or, more realistically, by experimental analysis, with the fluid flowrate varied or “modulated” around the “stable” operating point of flowrate at which the calibration measurement is run under assumed stable conditions. By varying the magnitude of this modulation amplitude, with the different types of test signal time functions according to **Fig. 5** being applied to the process flowrate as an external excitation impact, the sensitivity of the calibration measurement results with respect to this quantity can be determined quantitatively.

A special device has been developed which provides capabilities of acquiring, in high-resolution real time, the frequency signals (pulse trains) delivered by the flowmeters under test in the flow standard installation and the signals from the process transmitters acquiring pressure and temperature data in the flow standard’s pipework, as illustrated in **Fig. 6**. This test device also generates and delivers the test signals which are utilized for system analysis purposes, as described above.

Based upon these systematic investigations, significant characteristic figures can be determined for a flow calibration standard which represents influence or correction factors on uncertainty, respectively, and which has to be taken into account in addition to those uncertainty values that had been determined by applying the element-by-element static traceability approach, as represented by the vertical cause-and-effect paths in **Fig. 2**.

But as a fundamental requirement for low-uncertainty operation purposes it is an unavoidable necessity that a flow standard facility has to be run at steady-state flowrate conditions with any random-like scatter, drift or variation due to an imperfect operation of the flowrate and temperature control systems being limited to predefined low levels.

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REFERENCES

[1] R. Engel, H.-J. Baade: *Impacts upon the measurement uncertainty of liquid-flow facilities originating from random-like variations of the flow parameters*, Proceedings of the 8th ISFFM, Colorado Springs, CO, USA 2012

[2] ISO International Standardization Organization: *Measurement of liquid flow in closed conduits – Weighing Method*, ISO Standard 4185, First edition, 1980-12-15

[3] R.J. Goldstein (editor): *Fluid mechanics measurements*, 2nd edition, Taylor & Francis, 1996, Chapter 6, G.E. Mattingly: *Volume flow measurement, Appendix D: Diverter evaluation and correction*

[4] R. Engel, H.-J. Baade: *Model-based flow diverter analysis for an improved uncertainty determination in liquid flow calibration facilities*, Measurement Science and Technology 21(2010) pp. 11

[5] R. Engel, H.-J. Baade: *Water density determination in high accuracy flowmeter calibration - Measurement uncertainties and practical aspects*, Flow Measurement and Instrumentation 25(2012) pp. 40-53

[6] R. Engel: *Aspects and requirements of traceability in fluid flow measurement*, Simposio de Metrología, Plenaría V (plenary session), Querétaro, Mexico, October 29, 2010

[7] R.C. Dorf, R.H. Bishop: *Modern Control Systems*, 11th edition, Prentice Hall, 2008

[8] R. Engel: *Timing error of flow diversion in liquid flow calibration*, unpublished internal research report, Physikalisch-Technische Bundesanstalt, Department Liquid Flow, Braunschweig, 2013