Flow meter calibration using the master meter method

Merima Čaušević[1], Maurice Cox[2], and Adriaan M.H. van der Veen[3]

[1]Institute of metrology of Bosnia and Herzegovina, merima.causevic@met.gov.ba
[2]National Physical Laboratory, maurice.cox@npl.co.uk
[3]Van Swinden Laboratorium, the Netherlands, avdveen@vsl.nl

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1 Summary

This example demonstrates the calibration of a gas flow measuring instrument by the so-called "master meter" method, i.e. by comparing the measured flow on a master meter (reference standard) and the measured flow on the device under test. The measurements in this example were performed by using three measurement standards with different measuring ranges and one device under test in the "SARAJEVOGAS" Laboratory. The measurements were performed at 10 different flow rates, where each flow rate was measured three times, which gives in total 30 measurements of flow rate. As a result, this example gives the uncertainty of measurement of the meter under test at each of ten flow rates within this set-up.

2 Introduction of the application

The test facility operates on the so-called "master meter" principle where the meter under test (MUT) is located downstream from the standard meter (figure 1). Ambient air is sucked by a fan and the flow rate is adjusted by regulation of the fan and electromotive valve. The testing procedure is controlled by software. The measurement of flow rate for this kind of set-up first starts with entering the desired flow rate into the flow computer. After the first recorded pulse from the MUT, the volume flow rate from the MUT and the reference measurement standard (master meter or MM) are measured and recorded separately on the indicating devices of these measuring instruments. After two or more MUT pulses (depending on the selected volume) the measurement stops automatically. The volume flow rates from the MUT and the MM are calculated by dividing the number of pulses by the pulse value for each measuring instrument. Figure 1 shows the location of the master meter, the meter under test and the measuring instruments for temperature and pressure measurements in the laboratory set-up.

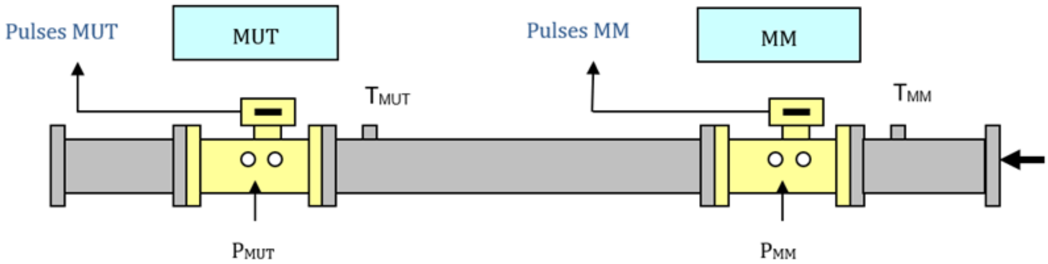

Figure 1: Set-up in the SARAJEVOGAS laboratory

3 Specification of the measurand(s)

The measurement, which in this case was for calibration purposes, was performed at atmospheric conditions with air temperature around 22 °C. The absolute pressure was measured directly with the standard and the meter under test, while the temperatures were measured downstream. Single tests lasted a minimum of 200 s to reach a stable flow rate. The calibration was performed with three standard/master meters with the following measuring ranges given in table 1.

Table 1: Volume flow rate ranges of the meters involved

G40 Rotary gas meter	G250 Turbine gas meter	G1000 Turbine gas meter
$20\,\mathrm{m^3\,h^{-1}}$–$50\,\mathrm{m^3\,h^{-1}}$	$100\,\mathrm{m^3\,h^{-1}}$–$350\,\mathrm{m^3\,h^{-1}}$	$450\,\mathrm{m^3\,h^{-1}}$–$1\,000\,\mathrm{m^3\,h^{-1}}$

4 Measurement model

4.1 Main effects

The basic procedure within this example differentiates between two types of quantities that influence the measurement uncertainty. The first type refers to the measurement error of the meter under test and the second type to the measurement standard, repeatability of measurement as well as any other additional influence quantity. The measurement error of the device under test is considered to be the main effect since it includes measurement effects of pressure, temperature and impulses.

The mathematical model for the measurement error of the MUT can be expressed as follows [1]:

$$e = \frac{V_{\mathrm{MUT}} - V_{\mathrm{REF}}}{V_{\mathrm{REF}}} \tag{1}$$

$$= \frac{V_{\mathrm{MUT}}}{V_{\mathrm{REF}}} - 1, \tag{2}$$

where

e is the measurement error of the MUT,
V_{MUT} is the volume of the gas flow that is measured with the MUT,
V_{REF} is the reference volume, i.e. the volume of the gas flow measured with the MM.

The reference volume V_{REF} is not the same as V_{MM}, which is the volume of the gas flow measured with the MM, because it is corrected for the reference conditions (temperature and pressure) at the measurement point where the MUT is placed. V_{REF} is calculated by using the the gas equation [2]

$$pV = ZRT, \tag{3}$$

where

p is the pressure of the gas,
V is the volume of the gas,
Z is the compressibility factor of the gas,
T is the absolute temperature of the gas,
R the ideal gas constant.

Z and R are considered to remain constant for both the measurement point of the MM and the MUT [1]:

$$\frac{p_{\mathrm{MUT}} V_{\mathrm{REF}}}{T_{\mathrm{MUT}}} = \frac{p_{\mathrm{MM}} V_{\mathrm{MM}}}{T_{\mathrm{MM}}} = ZR, \tag{4}$$

$$V_{\mathrm{REF}} = V_{\mathrm{MM}} \frac{p_{\mathrm{MM}}}{p_{\mathrm{MUT}}} \frac{T_{\mathrm{MUT}}}{T_{\mathrm{MM}}}, \tag{5}$$

where

V_{MM} is the volume of gas measured with the MM,
p_{MM} is the gas pressure measured with the MM,
p_{MUT} is the gas pressure measured with the MUT,
T_{MUT} is the gas temperature measured with the MUT,
T_{MM} is the gas temperature measured with the MM.

By substituting equation (5) into equation (2),

$$e = \frac{V_{\mathrm{MUT}}}{V_{\mathrm{MM}}} \frac{p_{\mathrm{MUT}}}{p_{\mathrm{MM}}} \frac{T_{\mathrm{MM}}}{T_{\mathrm{MUT}}} - 1. \tag{6}$$

By using a slightly different notation from that in [1] the volume of the measured gas can be expressed in terms of the number of pulses and the K-factor (pulse value) of the measuring instrument:

$$V_{\mathrm{MUT}} = \frac{I_{\mathrm{MUT}}}{K_{\mathrm{MUT}}}, \tag{7}$$

$$V_{\mathrm{MM}} = \frac{I_{\mathrm{MM}}}{K_{\mathrm{MM}}(1 + f_{\mathrm{MM}})}, \tag{8}$$

where

I_{MUT} is the number of pulses recorded on the MUT,
K_{MUT} is the pulse value directly given on the label of the MUT (a constant value for the individual measuring instrument),
I_{MM} is the number of pulses recorded on the MM,
K_{MM} is the pulse value directly given on the label of the MM (a constant value for the individual measurement standard),
f_{MM} is the MM error according to the calibration certificate.

After substitution, equation (6) becomes

$$e = \frac{I_{\mathrm{MUT}}}{I_{\mathrm{MM}}} \frac{K_{\mathrm{MM}}(1 + f_{\mathrm{MM}})}{K_{\mathrm{MUT}}} \frac{p_{\mathrm{MUT}}}{p_{\mathrm{MM}}} \frac{T_{\mathrm{MM}}}{T_{\mathrm{MUT}}} - 1. \tag{9}$$

4.2 Other influencing factors

Other factors that influence the measurement results are considered to be related to the calibration of the MM, i.e. the measurement standard (Q_{MM}), repeatability of measurement (Q_{REP}) and additional influencing quantities (Q_{AUX}). The additional influencing factors on the measuring results are as follows:

MASTER METER

- Location of the MM (some MMs are located directly under the ceiling),
- Drift of the MM.

METER UNDER TEST

- Unknown characteristics.

LABORATORY

- Inadequate thermal insulation,
- For large flows, air is drawn from adjacent rooms whose temperature is different from that in the laboratory,
- Low interconnecting room,
- Flow computer,
- Separated pressure and temperature probes from the related transmitters/converters (the probes are on the test bench and the converters are remote and located in the control cabinet).

The measurement model used for the evaluation of measurement uncertainty is obtained by summing all influencing quantities on the measurement result as follows:

$$e_{\mathrm{flow}} = e + Q, \tag{10}$$

where Q denotes other influencing quantities and

$$Q = Q_{\mathrm{MM}} + Q_{\mathrm{REP}} + Q_{\mathrm{AUX}}. \tag{11}$$

5 Uncertainty propagation

Uncertainty propagation follows the procedure described within GUM [3] (although we validate the results obtained using the propagation of distributions in section 7). The measurement model used for the uncertainty propagation is described by equation (**??**), where it is assumed that the quantities Q_{MM}, Q_{REP} and Q_{AUX} have zero mean values and standard deviations equal to the standard uncertainties that will be explained in the following subsections. The standard uncertainty of e_{flow} given in equation (10) can be expressed using the law of propagation of uncertainty [3] as follows:

$$u^2(e_{\mathrm{flow}}) = \left[\left(\frac{\partial e_{\mathrm{flow}}}{\partial e} u(e) \right)^2 + \left(\frac{\partial e_{\mathrm{flow}}}{\partial Q} u(Q) \right)^2 \right], \tag{12}$$

where

partial derivatives denote sensitivity coefficients of the measurement error (e) and other influencing quantities Q,
$u(e)$ is the standard uncertainty of the measurement error,
$u(Q)$ is the standard uncertainty of other influencing quantities.

5.1 Standard measurement uncertainty $u(e)$ of the measurement error of the meter under test

The standard measurement uncertainty of the measurement error can be obtained from the mathematical model (9), and can be expressed as follows:

$$
\begin{aligned}
u^2(e) = &\left[\frac{\partial e}{\partial I_{\mathrm{MUT}}} u(I_{\mathrm{MUT}})\right]^2 + \left[\frac{\partial e}{\partial I_{\mathrm{MM}}} u(I_{\mathrm{MM}})\right]^2 + \left[\frac{\partial e}{\partial p_{\mathrm{MUT}}} u(p_{\mathrm{MUT}})\right]^2 \\
&+ \left[\frac{\partial e}{\partial p_{\mathrm{MM}}} u(p_{\mathrm{MM}})\right]^2 + \left[\frac{\partial e}{\partial T_{\mathrm{MUT}}} u(T_{\mathrm{MUT}})\right]^2 + \left[\frac{\partial e}{\partial T_{\mathrm{MM}}} u(T_{\mathrm{MM}})\right]^2 .
\end{aligned} \tag{13}
$$

The uncertainties of the pulse values (K) for the MM and the MUT, as well as the uncertainties of the error of the MM in this example were considered negligible.

Using (9), let

$$S = e + 1 = \frac{I_{\mathrm{MUT}}}{I_{\mathrm{MM}}} \frac{K_{\mathrm{MM}}(1+f_{\mathrm{MM}})}{K_{\mathrm{MUT}}} \frac{p_{\mathrm{MUT}}}{p_{\mathrm{MM}}} \frac{T_{\mathrm{MM}}}{T_{\mathrm{MUT}}}.$$

Then, sensitivity coefficients are calculated from equation (9) as follows:

$$\frac{\partial e}{\partial I_{\mathrm{MUT}}} = \frac{S}{I_{\mathrm{MUT}}}, \tag{14}$$

$$\frac{\partial e}{\partial I_{\mathrm{MM}}} = -\frac{S}{I_{\mathrm{MM}}}, \tag{15}$$

$$\frac{\partial e}{\partial p_{\mathrm{MUT}}} = \frac{S}{p_{\mathrm{MUT}}}, \tag{16}$$

$$\frac{\partial e}{\partial p_{\mathrm{MM}}} = -\frac{S}{p_{\mathrm{MM}}}, \tag{17}$$

$$\frac{\partial e}{\partial T_{\mathrm{MM}}} = \frac{S}{T_{\mathrm{MM}}}, \tag{18}$$

$$\frac{\partial e}{\partial T_{\mathrm{MUT}}} = -\frac{S}{T_{\mathrm{MUT}}}. \tag{19}$$

The standard measurement uncertainty of the following individual measurement quantities can be determined as the standard deviations of the according rectangular probability distributions:

$$u(e_{n_i}) = \frac{L_{n_i}}{\sqrt{3}}, \tag{20}$$

$$u(e_{p_i}) = \frac{L_{p_i}}{\sqrt{3}}, \tag{21}$$

$$u(e_{T_i}) = \frac{L_{T_i}}{\sqrt{3}}, \tag{22}$$

where

- e_{n_i} is the presumed error due to reading the number of pulses on the measuring instrument. According to [3] it is expected that the value of this error to lie within the interval $[n_{i-}, n_{i+}] = [-0.5, 0.5]$ pulse with length $L_{n_i} = n_{i+} - n_{i-} = 1$ pulse,
- e_{p_i} is the presumed error due to measurement with pressure tubes, where, as in the previous case for e_{n_i}, the length of the interval is $L_{p_i} = 0.2\,\mathrm{mbar}$,
- e_{T_i} is the presumed error due to measurement with temperature tubes, where again as for e_{n_i} the length of the interval is for the MM $L_{T_{\mathrm{MM}}} = 0.132\,\mathrm{K}$ and for the MUT $L_{T_{\mathrm{MUT}}} = 0.163\,\mathrm{K}$.

Since the location of the pressure and temperature probes on the test bench can be changed, in the measurement uncertainty budget two probes for each quantity and their combination on the test bench are considered. In this way measurement uncertainty is slightly increased, but the measurement uncertainty calculation is simplified and kept on the “safe side” (despite its being not in keeping with the GUM, which recommends the use of realistic values).

The calculated values of the standard measurement uncertainty of individual quantities, accompanied by sensitivity coefficients, are used in equations (14)–(19).

5.2 Standard measurement uncertainties of other influencing quantities Q_{REP}, Q_{MM}, Q_{AUX}

5.2.1 Standard measurement uncertainty u_{REP} of the mean value, obtained by a series of consecutive measurements — repeatability of the measurement

The method used for obtaining the standard deviation follows the principle described within the GUM [3]. The repeatability of measurement is calculated using

$$u_{\mathrm{REP}} = \frac{s}{\sqrt{n}}, \tag{23}$$

where s denotes the standard deviation of the series of n consecutive measurements.

5.2.2 Standard measurement uncertainty u_{MM} of the standard used -– master meter

The standard measurement uncertainty of the MM is calculated by using the expanded measurement uncertainty and a coverage factor, both obtained from the calibration certificate, i.e.

$$u_{\mathrm{MM}} = \frac{U_{\mathrm{MM}}}{k}, \tag{24}$$

where

U_{MM} is the expanded measurement uncertainty of the MM during the calibration procedure,
k is the coverage factor ($k = 2$).

5.2.3 Standard measurement uncertainty u_{AUX} of additional influence factors

When evaluating measurement uncertainty it is necessary to include additional factors, which have influence on the measurement results and which influence is hard to quantify. The combined standard measurement uncertainty of other influence factors can be calculated from the estimated measurement error contribution, as well as from the assumption of rectangular distribution for influence factors, i.e.

$$u_{\mathrm{AUX}} = \frac{e_{\mathrm{AUX}}}{\sqrt{3}}, \tag{25}$$

where e_{AUX} is the estimated error, which is usually bounded by $|e_{\mathrm{AUX}}| \leq 0.1\,\%$.

Since the sensitivity coefficients in equation (12) have the value 1,

$$u(e_{\mathrm{flow}}) = \sqrt{u^2(e) + u^2_{\mathrm{REP}} + u^2_{\mathrm{MM}} + u^2_{\mathrm{AUX}}}. \tag{26}$$

6 Reporting the result

The measurements were carried out according to the requirements set out in standards [4] and [5] for turbine and rotary gas meters. During the calibration process the measurement data presented in tables 2 and 3 were obtained.

Table 2: Data on flow, pressure and temperature parameters obtained by involving measurement standards G1000, G250 in the calibration procedure

Standard	G1000	G1000	G1000	G250	G250
Flow/(m^3/h)	995.832	800.404	650.997	452.394	349.768
I_{MM}	91 330.33	73 804	59 990	206 280.67	159 517.67
I_{MUT}	25 379.67	20 477.33	16 625	11 539.67	8 907.6
K_{MM}	1 630.75	1 630.75	1 630.75	8 100	8 100
K_{MUT}	450.238	450.238	450.238	450.238	450.238
f_{MM}/%	−0.021 2	0.004 962	0.018 9	0.130 0	0.120 0
p_{MM}/mbar	957.5	958.83	959.74	947.51	952.75
p_{MUT}/mbar	954.6	956.93	958.48	942.43	949.59
T_{MM}/K	295.010	294.920	294.980	294.970	295.000
T_{MUT}/K	295.080	294.990	294.980	295.030	295.050

Table 3: Data on flow, pressure and temperature obtained by involving measurement standards G250, G40 in the calibration procedure

Standard	G250	G250	G250	G40	G40
Flow/($m^3\,h^{-1}$)	251.649	159.545	100.092	50.232	20.015
I_{MM}	115 029.33	73 059.67	45 954	9 452.33	7 564
I_{MUT}	6 413.67	4 066.67	2 553.33	1 277.67	1 022
K_{MM}	8 100	8 100	8 100	3 338.82	3 338.82
K_{MUT}	450.238	450.238	450.238	450.238	450.238
f_{MM}/%	0.117 1	0.160 4	0.279 6	0.100 0	−0.027 6
p_{MM}/mbar	956.67	959.35	960.47	960.41	961.03
p_{MUT}/mbar	954.96	958.67	960.23	958.31	960.79
T_{MM}/K	295.060	295.12	295.20	295.370	295.470
T_{MUT}/K	295.070	295.100	295.140	295.170	295.200

In tables 2 and 3 'Flow' represents the mean value of three observations of flow rate. One flow rate value was selected among the results in these tables in order to present step-by-step calculation of measurement uncertainty in this example. The selected flow rate is 251.649 m^3/h and it was measured by turbine gas meter G250. The data used for calculation appear in Tables 2 and 3. The error of the measuring instrument for this measuring point can be calculated according to equation (9) as follows:

$$e = \left(\frac{6\,413.67}{115\,029.33}\frac{8\,100(1+0.117\,1/100)}{450.238}\frac{954.96}{956.67}\frac{295.06}{295.07} - 1\right) \times 100\,\% \tag{27}$$

$$= 0.244\,1\,\%. \tag{28}$$

The standard measurement uncertainty of the measurement error of the MUT can be calculated from equation (13). However, it is necessary first to calculate the sensitivity coefficients of each influencing parameter, which can be carried out according to formulæ (14) and (15). The value of S was calculated as 100.243.

Sensitivity coefficients are calculated as follows:

$$\frac{\partial e}{\partial I_{\mathrm{MUT}}} = \frac{100.243}{6\,413.67} = 0.015\ 6, \tag{29}$$

$$\frac{\partial e}{\partial I_{\mathrm{MM}}} = -\frac{100.243}{115\,029.33} = -0.000\ 871, \tag{30}$$

$$\frac{\partial e}{\partial p_{\mathrm{MUT}}} = \frac{100.243}{954.96} = 0.149\ 70, \tag{31}$$

$$\frac{\partial e}{\partial p_{\mathrm{MM}}} = -\frac{100.243}{956.67} = -0.147\ 80, \tag{32}$$

$$\frac{\partial e}{\partial T_{\mathrm{MM}}} = \frac{100.243}{295.06} = 0.339\ 74, \tag{33}$$

$$\frac{\partial e}{\partial T_{\mathrm{MUT}}} = -\frac{100.243}{295.07} = -0.339\ 729. \tag{34}$$

From equations (20)–(22) and information on errors given in subsection 5.1, we obtain

$$u(I_i) = \frac{1}{\sqrt{3}} = 0.5780, \tag{35}$$

$$u(p_i) = \frac{0.2}{\sqrt{3}} = 0.1156, \tag{36}$$

$$u(T_{MUT}) = \frac{0.163}{\sqrt{3}} = 0.0942 \tag{37}$$

$$u(T_{MM}) = \frac{0.132}{\sqrt{3}} = 0.0763. \tag{38}$$

Results (35)–(37) combined with equation (13) give the standard uncertainty of the measuring system measurement error:

$$u(e) = 0.045\,\%. \tag{39}$$

The relative standard deviation (s) of the measured values at this point is $s = 0.003\ 1\,\%$, which gives the relative standard uncertainty due to repeatability of measurements:

$$u_{\mathrm{REP}} = 0.001\ 8\,\%. \tag{40}$$

The standard measurement uncertainty u_{MM} of the standard used -– master meter – is calculated according to equation (24), where the the expanded measurement uncertainty of the MM (obtained from the calibration certificate) is $U_{\mathrm{MM}} = 0.25\,\%$, giving

$$u_{\mathrm{MM}} = \frac{0.25}{2} \tag{41}$$

$$= 0.125\,\%. \tag{42}$$

The relative standard uncertainty u_{AUX} of other influence factors can be calculated according to equation (25), where it is assumed the estimated error is $e_{\mathrm{AUX}} = 0.1\,\%$ and to have a rectangular probability distribution:

$$u_{\mathrm{AUX}} = \frac{0.1}{\sqrt{3}}\,\% \tag{43}$$

$$= 0.057\ 8\,\% \tag{44}$$

By substituting the uncertainty contributions obtained in (40), (42), (39) and (44) into equation (26), the combined relative standard uncertainty becomes

$$u(e_{\mathrm{flow}}) = (0.045^2 + 0.001\ 8^2 + 0.125^2 + 0.057\ 8^2)^{1/2}\,\%, \tag{45}$$

$$u(e_{\mathrm{flow}}) = 0.144\ 9\,\%. \tag{46}$$

The expanded measurement uncertainty, with coverage factor $k = 2$ is

$$\begin{aligned} U &= 2 \times u(e_{\text{flow}}) \qquad (47) \\ &= 0.29\,\%. \qquad (48) \end{aligned}$$

The results for the uncertainty contributions at every flow rate, as well as the combined and expanded measurement uncertainty ($k = 2$) are presented in table 4.

Table 4: Uncertainty contributions for individual flow rates

Standard	$u_{\text{REP}}/\%$	$u_{\text{MM}}/\%$	$u(e)/\%$	$u_{\text{AUX}}/\%$	$u(e_{\text{flow}})/\%$	$U/\%$
G1000	0.044 65	0.125	0.000 25	0.057 73	0.144 74	0.29
G1000	0.044 67	0.125	0.000 87	0.057 73	0.144 76	0.29
G1000	0.044 69	0.125	0.001 50	0.057 73	0.144 77	0.29
G250	0.044 85	0.125	0.002 36	0.057 73	0.144 83	0.29
G250	0.045 01	0.125	0.000 39	0.057 73	0.144 86	0.29
G250	0.045 41	0.125	0.001 78	0.057 73	0.144 99	0.29
G250	0.046 68	0.125	0.005 42	0.057 73	0.145 48	0.29
G250	0.049 82	0.125	0.001 27	0.057 73	0.146 43	0.29
G40	0.063 70	0.125	0.001 82	0.057 73	0.151 72	0.30
G40	0.072 42	0.125	0.001 32	0.057 73	0.155 57	0.31

7 Interpretation of results

The approach for uncertainty evaluation described within this example can be generally used for calibration of gas flow meters by the ‘master meter’ method, when the meter under test is located downstream of the master meter. Depending on the costumer needs, it can be decided earlier how many flow rate points are necessary for the calculation of the measurement uncertainties.

In this example the uncertainties due to additional influence factors (u_{AUX}), which were not exactly known, were quantified. One way of improving this example would be to quantify other uncertainty sources and include them to the overall uncertainty budget.

According to [3], if the measurement model is linear in the input quantities and the dominant contributions have normal probability distributions, the GUM uncertainty framework (GUF) will provide reliable results. In order to validate the GUF, the Monte Carlo method (MCM), described within GUM Supplement 1 (GUM-S1) [6] was used for the evaluation of measurement uncertainty for the measurement model described by equation (10). For this method the number of Monte Carlo trials was prescribed to be 10^8. Values for the input quantities, their associated standard uncertainties and their probability distributions remained the same as described in section 6.

The results of the applied method are shown in table 5.

Table 5: Results obtained by two approaches for measurement uncertainty evaluation: GUF–GUM uncertainty framework, MCM–Monte Carlo method, CI–Coverage interval (lower limit, higher limit)

Approach	Estimate/%	Std. unc./%	CI (95%)/%
GUF	0.024 41	0.144 9	(−0.045 9, 0.534 1)
MCM	0.024 41	0.140 2	(−0.030 9, 0.518 5)

Figure 2 shows the probability density functions as a result of the evaluation of uncertainty by following the principles described within GUM and GUM Supplement 1 (Monte Carlo method) [6].

It can be noticed, both in table 5 and from figure 2 that the obtained results for the methods differ insignificantly. The 95 % coverage interval for the MCM method is slightly shorter than that obtained by the GUM method, while the estimates of the flow measurement error are the same.

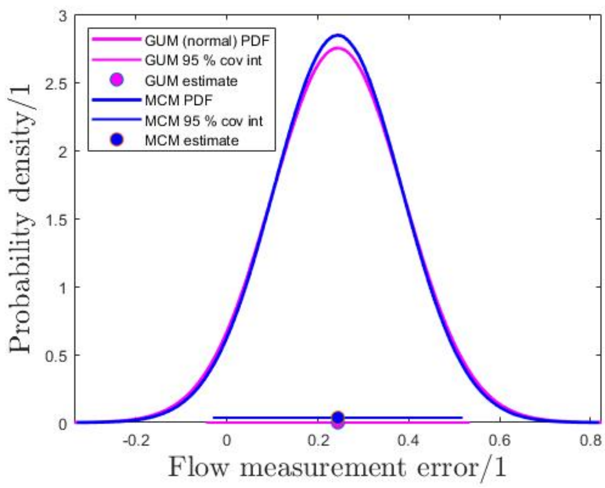

Figure 2: Probability density functions for Monte Carlo and GUM approach

Due to the sufficiently large number of Monte Carlo trials and even though the measurement model was not linear in this example, the GUM method provided accurate results.

The GUM approach for evaluation of measurement uncertainty in terms of the measurement error described in previous sections is followed by several national metrology institutes in Europe.

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