BRAZILIAN JOURNAL
OF
RADIATION SCIENCES
09-02C (2021) 01-13

Estimation of measurement uncertainty in an automated flowmeter calibration system

Deme[a] I.

[a] *National Institute of Metrology, Standardization and Industrial Quality – INMETRO/ Fluid Dynamics Metrology Division - Scientific Metrology/ Postal code: 25250-02, Xerém - Duque de Caxias, Rio de Janeiro, Brazil*
idrissdeme@yahoo.fr , deme.idrissa@posgraduacao.uerj.br

ABSTRACT

The aim of this work is to estimate and analyze the measurement uncertainty in the calibration of liquid flow meters by the gravimetric method, which is a primary method. The calibration system used in this work is the calibration system for liquid flow meters of the National Institute of Metrology Quality and Technology - INMETRO that gives traceability to liquid flow meters in Brazil. The system that was fully operated manually went through an automation process in some of the components. The measurements were made in five ranges for a mass meter and the uncertainty expression followed the procedures of the Guide to the Expression of Uncertainty in Measurement (Iso-Gum). The results were compared with each other and showed the performance of the meters according to the technology used in the measurement and the consistency of the calibration system.

Keywords: Calibration, measurement uncertainty, Flow measurement, gravimetric method.

ISSN: 2319-0612
Accepted: 2021-05-05

INTRODUCTION

The need to measure the flow rate of fluids has arisen since ancient times with the piping of water for domestic consumption. However, it was from the twentieth century that the need to measure the flow of fluids in general acquired a really high proportion and sophistication [1]. In fact, it became very common in industrial procedures the need for measurement and control of the quantity of liquids and gases due to the use of continuous processes [2]. Thus, flow rate has become one of the most measured quantities in industrial processes, along with temperature and pressure [3]. The applications are many, ranging from the simplest, such as water flow measurement in water treatment plants and homes, to measurement in medical applications, industrial gases and fuels [4]. Their multiple applications require the measured values to be reliable. Therefore, national and international standards, such as ISO-4185 [5] point out the need for calibration of the various types of meters that have emerged due to market needs and technological evolution, to ensure the reliability and quality of the measurements.

Calibration is the most important test for a flowmeter and is performed at all stages of meter development and production, as well as during its use. Calibration of liquid flow meters allows to ensure the reliability of these measuring instruments by comparing the measured value with a standard traceable to the International System of Units (SI) [6]. Based on the result of a calibration it is assessed how well an instrument meets the accuracy and operating range requirements to be used for its intended purpose. Calibrated instruments also enable the manufacturer or processor to produce quality goods, since the measurements are reliable and the uncertainty and error limits are known [6]. There are basically two measurement methods for calibrating liquid flow meters: volumetric and gravimetric.

The Division of Metrology in Fluid Dynamics (Dinam/Inmetro) of the National Institute of Metrology, Quality and Technology (INMETRO), which ensures reliability and traceability to the International System of Units (SI), has a bench for calibration of water flow meters using the gravimetric method of calibration which is the most reliable primary method. This device that was operated manually went through an automation process in the data acquisition procedures, control and drive of its pumps and scales [7].

The current work purpose of is to present a process for estimating measurement uncertainty in the calibration of a Coriolis mass flow meter with the automated gravimetric bench of the National Institute for Metrology, Quality and Technology (Inmetro). This estimation is done following the steps described by the ISO Guide for the Evaluation of Measurement Uncertainty (ISO-GUM) [8].

The methodology adopted, the main results obtained, and the conclusions are presented in the following lines.

1. MATERIALS AND METHODS

The calibration method used is gravimetric method, which consists in comparing the mass totalized by the meter with the mass totalized by the bench, through its scales, which serves as the primary calibration standard. The meter used in this work is a liquid mass flow meter.

The estimation of measurement uncertainty follows the steps of the ISO Guide to the expression of uncertainty in measurement (ISO-GUM) with the determination of the measurand, the input quantities, the cause-effect diagram (Ishikawa diagram), the sources of uncertainty and the evaluation of their standard uncertainties, the contribution of each source, as well as the presentation of the combined standard uncertainty, the degree of freedom, the coverage factor, and the estimation of the expanded uncertainty together with the expression of the result.

The measurements were performed in five flow ranges going from the lowest to the maximum of the meter used, corresponding to flow ranges of 20 kg/min, 60 kg/min, 80 kg/min, 100 kg/min and 120 kg/min. For each range six (6) measurements were taken, giving a total of thirty (30) measurements.

The measurand is the calibration factor Fm, a dimensionless number that represents the ration of the mass summed on the gravimetric bench scale and the mass summed by the meter. The mathematical model is as follows:

- General form of the equation for determining the measurand (Fm)

$$F_m = \frac{(Mc - Mv) \cdot \dfrac{\left(1 - \dfrac{\rho_{ab}}{\rho_b}\right)}{\left(1 - \dfrac{\rho_{ar}}{\rho_L}\right)}}{M_m} + \delta F_m \qquad (1)$$

- - Detailed form of the equation for determining the measurand (Fm)

$$F_m = \frac{(Mc - Mv) \cdot \dfrac{\left(1 - \dfrac{\rho_{AB}}{\rho_B}\right)}{\left(1 - \dfrac{\left(\dfrac{k_1.P_a - k_2.\varphi.\exp(k_3.T_a)}{k_4 + T_a}\right) + \delta\rho_a}{a_5.\left(1 - \dfrac{(T_L + a_1)^2.(T_L + a_2)}{a_3.(T_L + a_4)}\right) + \delta\rho_L}\right)}}{M_i} + \delta F_m \qquad (2)$$

Where:

Mc: Mass of the filled container measured on the scale (kg).

Mv: Mass of the empty container measured on the scale (kg).

$\rho_{AB:}$ Specific mass of air at the time of balance calibration (kg/dm^3)

$\rho_{B:}$ Specific mass of the standard weights that calibrated the balance (kg/dm^3)

M_i**:** Mass indicated by the meter (kg)

$\rho_{L:}$ specific mass of liquid at temperature T_L (°C)

T_L: temperature of the liquid TL (°C) and $T = T_L + \delta T_L$; δT_L: variation of T_L during a measurement series

a_1 = 3,983035 °C ; a_2 = 301,797 °C ; a_3 = 522528,9 °C ; a_4 = 69,34881 °C; a_5 = 999,97495 $kg.m^{-3}$

$\delta\rho_L$: error due to the difference between the liquid type of the standard equation and the working liquid

$\rho_{ar::}$ air specific mass $(kg)/m^3$

k_1: 0,34848; k_2 : 0,009024; k_3 : 0,0612; k_4 : 273,15

P_a: p barometric pressure in hPa

φ: air relative humidity in %

T_a: air temperature in °C

$\delta\rho_{ar}$: adjustment of ρ_a in equation (4.4) for the air specific mass evaluation.

δF_m**:** random variation of Fm

1.1. Step-by-step uncertainty estimation

- Input quantities

Table 1 shows the different input quantities, as well as the process for estimating the associated values.

Tabela 1: Input quantities

Quantity	**Value Estimation**
Mc : (kg)	$\overline{M_c} = \frac{1}{n}\sum_1^n M_{c_i}$ n = number of measurements
Mv: (kg)	$\overline{M_v} = \frac{1}{n}\sum_1^n M_{v_i}$ n = number of measurements
T_L:(°C)	$\overline{T_L} = \frac{1}{n}\sum_1^n T_{L_i}$ n = number of measurements
T_a: (°C)	$\overline{T_a} = \frac{1}{n}\sum_1^n T_{a_i}$ n = number of measurements
P_a: (Pa)	$\overline{P_a} = \frac{1}{n}\sum_1^n Pa_i$ n = number of measurements
φ: (%)	$\overline{\varphi} = \frac{1}{n}\sum_1^n \varphi_i$ n = number of measurements
ρ_{AB}:(kg/m³)	1,096
ρ_B: (kg/m³)	8000
ρ_L:(kg/m³)	$\rho_L(T_L) = a_5 \cdot \left[1 - \frac{(T_L + a_1)^2 \cdot (T_L + a_2)}{a_3 \cdot (T_L + a_4)}\right] + \delta\rho_L$ Tanaka equation [9]
ρ_{ar}: (g/m³)	$\rho_{ar} = \frac{k_1 \cdot P_a - k_2 \cdot \varphi \cdot \exp(k_3 \cdot T_a)}{k_4 + T_a} + \Delta\rho_{2007} + \delta\rho_{ar}$ [10]
M_m (kg)	$\overline{M_m} = \frac{1}{n}\sum_1^n M_{m_i}$ n = number of measurements
δF_m:	0

- Ishikawa Diagram

Figure 1 shows the quantities that influence the measurand Fm and their types of uncertainties.

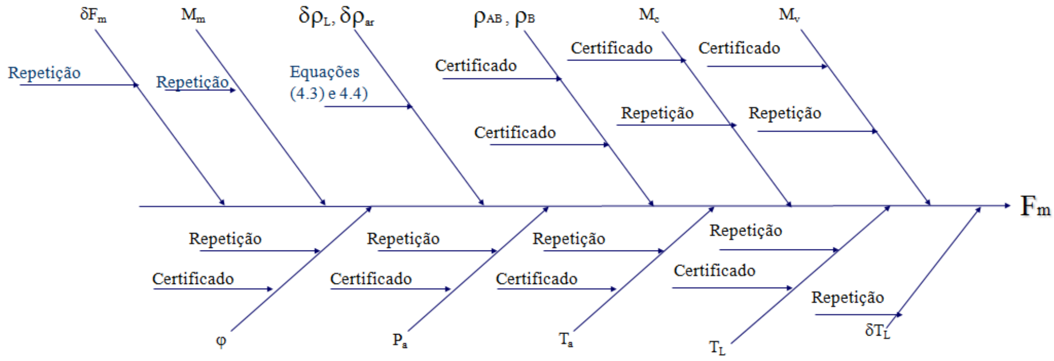

Figura 1: Ishikawa cause-effect diagram

- Sensitivity Coefficients $c_i = \frac{\partial Fm}{\partial x_i}$

The sensitivity coefficients and their calculation modes are shown here in Table 2.

Table 2: Sensitivity coefficients

Quantity	**Sensitivity Coefficients (c_i)**
Mc : (kg)	$\frac{\rho_L(\rho_B-\rho_{AB})}{M_m.\rho_B(\rho_L-\rho_{ar})}$
Mv: (kg)	$\frac{-\rho_L(\rho_B-\rho_{AB})}{M_m.\rho_B(\rho_L-\rho_{ar})}$
T_L:(ºC)	$-\frac{\partial\rho_L}{\partial T}\frac{F_m\rho_{ar}}{\rho_L-\rho_{ar}}$
δT_L: (ºC)	$-\frac{\partial\rho_L}{\partial(\delta T)}\frac{F_m\rho_{ar}}{\rho_L-\rho_{ar}}$
T_a: (ºC)	$\frac{\partial\rho_L}{\partial(T_a)}\frac{F_m}{\rho_L-\rho_{ar}}$
P_a: (kPa)	$\frac{\partial\rho_L}{\partial(P_a)}\frac{F_m}{\rho_L-\rho_{ar}}$
φ: (%)	$\frac{\partial\rho_L}{\partial(\varphi)}\frac{F_m}{\rho_L-\rho_{ar}}$
ρ_{AB}: (kg/m^3)	$\frac{-(M_c-M_v)\rho_L}{V_m\rho_B(\rho_L-\rho_{ar})}$

ρ_B: (kg/m³)	$\frac{-(M_c - M_v)\rho_L\rho_{AB}}{V_m(\rho_B)^2(\rho_L - \rho_{ar})}$
$\delta\rho_L$: (kg/m³)	$-\frac{F_m\rho_{ar}}{\rho_L(\rho_L - \rho_{ar})}$
$\delta\rho_{ar}$:(kg/m³)	$\frac{F_m}{(\rho_L - \rho_{ar})}$
V_m:(L) Ou M_m:(kg)	$\frac{(M_c - M_v)\rho_L(\rho_B - \rho_{AB})}{(M_m)^2.\rho_B(\rho_L - \rho_{ar})}$
δF_m:	1

The contribution uc(i) of each source was evaluated by making the product of the standard uncertainty associated with it with the corresponding sensitivity coefficient. Therefore, from the product of the elements of tables 1 and 2.

- Combined uncertainty

$$u_c(F_m) = \sqrt{u_C^2(M_c) + u_C^2(M_v) + u_C^2(T_L) + u_C^2(\delta T_L) + u_C^2(T_a) + u_C^2(P_a) + u_C^2(\varphi) + u_C^2(\rho_{AB}) + u_C^2(\rho_B) + u_C^2(\delta\rho_L) + u_C^2(\delta\rho_{ar}) + u_C^2(M_m)} \quad (3)$$

- Effective freedom degree

It was calculated by the Welch-Satterthwaite formula as recommended by ISO-GUM..

$$\nu_{eff} = \frac{u_c{}^2(F_m)}{\frac{u_C^4(M_c)}{\nu(M_c)} + \frac{u_C^4(M_v)}{\nu(M_v)} + \frac{u_C^4(T_L)}{\nu(T_L)} + \frac{u_C^4(\delta T_L)}{\nu(\delta T_L)} + \frac{u_C^4(T_a)}{\nu(T_a)} + \frac{u_C^4(P_a)}{\nu(P_a)} + \frac{u_C^4(\varphi)}{\nu(\varphi)} + \frac{u_C^4(\rho_{AB})}{\nu(\rho_{AB})} + \frac{u_C^4(\rho_B)}{\nu(\rho_B)} + \frac{u_C^4(\delta\rho_L)}{\nu(\delta\rho_L)} + \frac{u_C^4(\delta\rho_{ar})}{\nu(\delta\rho_{ar})} + \frac{u_C^4(M_m)}{\nu(M_m)}} \quad (4)$$

- Coverage factor, expanded uncertainty and result expression

The coverage factor k was evaluated to a probability of 95.45% using Excel's INVT(1-0.9545;υeff) function.

The expanded uncertainty for these conditions is given as:

$$U = k.u_c \quad (5)$$

The result of Fm is expressed as a dimensionless number because it represents the quotient of the mass totalized on the scale and the mass totalized on the gauge, that is, it is the ratio of magnitudes of the same nature.

2. RESULTS AND DISCUSSION

The main results achieved are presented below. Table 3 presents the values of Fm, the expanded uncertainty and the combined uncertainty as a function of the flow range and Table 4 shows the sources of uncertainty and the determination of the standard uncertainty associated with each one. The table shows the influence factors and their respective contributions in percent in the combined uncertainty for each flow range. The contribution uc(i) of each source was evaluated by making the product of the standard uncertainty associated with it with the corresponding sensitivity coefficient.

Table 3: Fm values and uncertainties per range

Flow Range (kg/min)	20	60	80	100	120
F_m	0,97749	0,99204	0,99375	0,99436	0,99490
U	0,0018	0,00030	0,00021	0,00016	0,00016
u	0,00068	0,00012	0,00009	0,00007	0,00007
k (95,45% coverage)	2,649	2,429	2,284	2,320	2,255
γ_{eff}	5	8	11	10	12
U%	0,16	0,030	0,021	0,016	0,016
N° de corridas.	6	6	6	6	6

Table 3: Sources of uncertainties and their estimates

Quantity	**Evaluation of the source of uncertainty**	**Estimate**
M_c : (kg)	- Scale certificate (type B): - Repetition (type A) (Degree of freedom υ = 87)	u = U/k = 0,002 $s_{\overline{M_c}} = \sqrt{\frac{\sum_1^n \left(\overline{M_c} - M_{c_i}\right)^2}{n(n-1)}}$
M_v: (kg)	- Scale certificate (type B) - Repetition (type A) (Degree of freedom υ = 87)	u = U/k = U: 0,002 $s_{\overline{M_v}} = \sqrt{\frac{\sum_1^n \left(\overline{M_v} - M_{v_i}\right)^2}{n(n-1)}}$

T_L:(^oC)	- pt100 certificate (type B) - Repetition (type A) (Degree of freedom υ =∞)	u = U/k = 0,005 $s_{\overline{T_L}} = \sqrt{\frac{\sum_1^n(\ \overline{T_L} - T_{L_i})^2}{n(n-1)}}$
δT_L: (^oC)	- Repetition (type A) (Rectangular distribution υ =∞)	$(T_{Lmax} - T_{Lmin})/2.\sqrt{3}$
T_a: (^oC)	- Weather station certificate (type B) - Repetition (type A) (Degree of freedom υ =∞)	u = U/k = 0,15 $s_{\overline{T_a}} = \sqrt{\frac{\sum_1^n(\ \overline{T_a} - T_{a_i})^2}{n(n-1)}}$ ...
P_a: (kPa)	- Weather station certificate (type B) - Repetition (type A) (Degree of freedom υ =∞)	- u = U/k = 1 $s_{\overline{P_a}} = \sqrt{\frac{\sum_1^n(\ \overline{P_a} - P_{a_i})^2}{n(n-1)}}$ ...
φ:(%)	-Weather station certificate (type B) - Repetition (type A) (Degree of freedom υ =∞)	u = U/k = 0,981246 $s_{\overline{\varphi}} = \sqrt{\frac{\sum_1^n(\overline{\varphi} - \varphi_i)^2}{n(n-1)}}$, ...
ρ_{AB}: (kg/m^3)	- Certificate (type B) (Degree of freedom υ =∞)	u = U/k = 0,014
ρ_B: (kg/m^3)	- Certified -weights (type B) (Degree of freedom υ =∞)	u = U/k = 0,115
$\delta\rho_L$: (kg/m^3)	- Tanaka equation (type B) (degree of freedom υ =∞)	u = U/k = 0,012
$\delta\rho_{ar}$:(kg/m^3)	- Equation for determining the specific mass of air (type B) (Degree of freedom υ =∞)	u = U/k = $1,15.10^{-5}$
V_m:(L) Ou M_m:(kg)	- Repetition (type A) (n-1 degree of freedom)	$s_{\overline{M_m}} = \sqrt{\frac{\sum_1^n(\ \overline{M_m} - M_{m_i})^2}{n(n-1)}}$
δF_m:	- Fm (type A) repetition (degree of freedom n-1)	$s_{\overline{\delta F_m}} = \sqrt{\frac{\sum_1^n(\ \overline{F_m} - F_{m_i})^2}{n(n-1)}}$

Table 4: Influencing factors and their contributions

Input variables i	Flow Rate (kg/min)				
	20	**60**	**80**	**100**	**120**
	$100 \cdot c_i \cdot u_i/u$				
δFm	74,00%	43,73%	35,64%	34,72%	32,42%
M_c	8,70%	15,50%	17,20%	15,25%	16,66%
M_v	8,70%	15,50%	17,20%	15,25%	16,66%
T_a	3,55%	13,04%	15,65%	19,36%	18,66%
δρar	1,27%	4,59%	5,50%	6,92%	6,73%
m_{ini}	1,52%	2,74%	3,05%	2,71%	2,96%
m_{fim}	1,52%	2,74%	3,05%	2,71%	2,96%
ρ_{ab}	0,20%	0,71%	0,86%	1,08%	1,05%
φ	0,14%	0,54%	0,64%	0,76%	0,72%
T_{Lm}	0,14%	0,50%	0,61%	0,78%	0,77%
δT_{Lm}	0,25%	0,29%	0,47%	0,30%	0,27%
Pa	0,029%	0,11%	0,13%	0,16%	0,16%
$\delta\rho_L$	0,0015%	0,0055%	0,0066%	0,0082%	0,0080%
ρ_b	0,00021%	0,00078%	0,00094%	0,0012%	0,0011%
Total	100,00%	100,00%	100,00%	100,00%	100,00%

The uncertainty reaches smaller values as the flow rate increases as shown in Table 3. However, in the higher ranges, the uncertainty has values close to each other. As the repeatability does not vary considerably in the higher flow rates, a tendency towards stability in the flow rate is observed, which is expected. This case would be equivalent to the situation of a constant level reservoir. It can be seen from Table 5 that the repeatability (indicated by the random variation of

Fm, δFm) is the main influencing factor in all ranges. The totalized masses on the scale (Mc, Mv) are important factors, but they are surpassed by the ambient temperature (Ta) from the range of 60 kg/min and by the ambient temperature (Ta) and the temperature variation of the liquid at the gauge (δTL) in the ranges of 80 kg/min and 100 kg/min where the contribution of δFm is at the lowest thresholds. The lower flow rate range (20 kg/min) is the one that presents a higher relative uncertainty due to difficulties in controlling the parameters in this range because the flow is less developed. The decrease in the contribution of δFm ends up emphasizing the contributions of the ambient temperature and the variation of the specific mass evaluated as well as the variation of the liquid temperature in the uncertainty. Thus, factors that do not depend on the test system such as the ambient temperature start to have an important contribution in the uncertainty, thus showing the importance of controlling the environmental effects for the optimal operation of the flow meter. These influences that were not highlighted with manual calibration highlight a line of investigation for future work.

3. CONCLUSIONS

This study allowed the presentation of a method that enables the estimation of the different sources of uncertainty in a dynamic measurement system and their contributions to the measurement uncertainty. It also made it possible to highlight the ideal operating conditions of the flow meter by comparing the uncertainty values in different flow ranges. The results obtained are in agreement and with the values obtained with the manual system and other systems in the literature. The influences of environmental factors that do not depend directly on the system and that were not highlighted with the manual calibration were highlighted and open an important line of investigation for future work.

THANKS TO

Thanks to the National Institute of Metrology, Quality and Technology that allowed this work to be done.

REFERENCES

[1] DELMÉ, G. J. **MANUAL DE MEDIÇÃO DE VAZÃO**. 3ª. ed. São Paulo: EDGARD BLÜCHER , 2003.

[2] CASSIOLATO, C.; ALVES, E. O. A. Medição de Vazão. **Controle & Instrumentação**, São Paulo, n. 138, 2008.

[3] FRENZEL, F. et al. Industrial Flow Measurement Basics and Practice. Ladenburg: **ABB Automation Products GmbH**, 2011.

[4] FIGUEIREDO DE ANDRADE, P. M.; ROCHA, P.; FERREIRA, L. E. A. Medição de vazão para sistemas de medição de petróleo e gás natural. **Revista Analytica**, n. 23, Junho/Julho 2006

[5] ISO - INTERNATIONAL STANDARD ORGANISATION. ISO 4185: **Measurement of liquid flow in closed conduits weighing method**. 1. ed. Berlin, 1980.

[6] ALDER, K. The Measure of All Things: The Seven-Year Odyssey and Hidden Error That Transformed the World. **the free presss**, New York, 2002.

[7] DEME, I. Automatização e controle da bancada de calibração de medidores de vazão de líquidos do Inmetro. 2017. 153f. Dissertação (Mestrado) – Programa de Pós-graduação em Metrologia e Qualidade – **Instituto Nacional de Metrologia, Qualidade e Tecnologia**, Duque de Caxias, 2017.

[8] (JCGM), J. C. F. G. I. M. Avaliação de dados de Medição - Guia para a expressão de incerteza de medição (ISO- GUM). 1ª edição brasileira. ed. Rio de Janeiro: **Instituto Nacional de Metrologia, Qualidade e Tecnologia (INMETRO)**, 2012.

[9] TANAKA, M. et al. Recommended table for density of water between 0 ºC and 40º. **Metrologia**, Paris, v. 38, p. 301-309, Janeiro 2001.

[10]. GIACOMO, P. Equation for the determination of the density of moist air (1981). **Metrologia**, Paris, v. 18, n. 1, p. 33 -40, Janeiro 1982.