IMEKO TC8, TC11 and TC24 Joint Conference
October 11-13, 2023, Madeira, Portugal

ANALYSIS OF FLOW RATE MEASUREMENT ACCURACY AND TRACEABILITY OF FLOWMETERS IN FIELD CONDITIONS USING CLAMP-ON ULTRASONIC FLOWMETERS

C. Simões[1], A. Ribeiro[2], M. Almeida[3], Dídia Covas[4]

[1] LNEC – National Laboratory for Civil Engineering, Lisbon, Portugal, csimoes@lnec.pt
[2] LNEC – National Laboratory for Civil Engineering, Lisbon, Portugal, asribeiro@lnec.pt
[3] LNEC – National Laboratory for Civil Engineering, Lisbon, Portugal, mcalmeida@lnec.pt
[4] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal, didia.covas@tecnico.ulisboa.pt

Abstract:
This study examines the traceability and measurement uncertainty of *in situ* hydraulic calibration using clamp-on ultrasonic flowmeters as a reference. The procedure compares the equipment readings with the reference ones. Measurement uncertainty evaluation uses GUM formulation, considering the linearity conditions of the mathematical models applied. Experimental values are used to test the procedure and its suitability for actual cases where the expected accuracy needs to be achieved.

Keywords: Flow measurement; clamp-on ultrasonic flowmeter; measurement uncertainty; traceability; measurement accuracy.

1 INTRODUCTION

Many hydraulic infrastructures (e.g. supply pipes, drainage systems, pumping stations) have installed flowmeters to collect and provide data for monitoring and control systems and for the efficient management of systems, thus, requiring traceability. It is common to find flowmeters installed in pipes with physical constrains that prevent their removal for calibration in metrology laboratories, being needed to find alternative solutions to evaluate the accuracy of measurement equipment *in situ* using portable reference flowmeters.

Clamp-on ultrasonic flowmeters are a viable alternative for assessing the measurement accuracy in these locations, even if performance is lower when compared to metrology laboratories. An additional undeniable difficulty is to ensure stable flow conditions to define steps for testing. Thus, the basic principle of traceability is achieved, allowing to compare a reference standard and equipment to be calibrated. The method is based on the statistical analysis of time series.

This approach has the merit of incorporating the influence of local setup and flow conditions in the traceability evaluation, not considered in a laboratory setup with optimized calibration conditions.

This process of calibration has some advantages. It is non-invasive, since the quantities of interest (flow rate and velocity) are not disturbed, avoiding pressure drops in the pipe. Calibration equipment installation and readjustment are also easier. The procedure must follow specific rules to ensure the quality of the data using this method. The rules are related to the fluid characteristics, the installation setup, and the pipe characteristics.

The operation procedure of a clamp-on ultrasonic flowmeter, based on the transit-time differential method, requires an initial configuration using data related to the liquid (e.g., the type of liquid and its temperature) and pipe (e.g., material, coatings, outer diameter, and wall thickness allowing to calculate inner diameter). Thus, the measurement procedure includes estimates of influence quantities (temperature, length, outside perimeter and wall thickness). Usually, these systems can provide the distance between a couple of transducers, given the data mentioned above.

The relation of the setup conditions with these influence quantities allow to consider that the main sources of error are the following: existing irregularities of the pipe along the sections; installation of the transducers; properties of the fluid; and acoustic characteristics.

Flow behaviour and regimes of this type of flowmeters in non-laboratory conditions are typically not under control, and there is a need to study how, under those conditions, it is possible to provide traceability to the equipment under evaluation and, how the accuracy is affected in the comparison process and how it is possible to get correction functions and to assess its uncertainty from time series of flow data.

This paper describes how, under dynamic conditions, the contributions of the uncertainty sources are evaluated and propagated through probability distribution functions to calculate the measurement uncertainty. This information is crucial in determining whether calibrated equipment is suitable for a particular purpose and its impact on the measurement system.

2 CLAMP-ON ULTRASONIC FLOWMETER

A. Description and characteristics

The concept of ultrasonic flowmeters for liquids was firstly presented by [1].

Sanderson [2] highlighted the problems encountered using traditional flowmeters and suggested the of ultrasonic flowmeters, which are not in contact with the fluid.

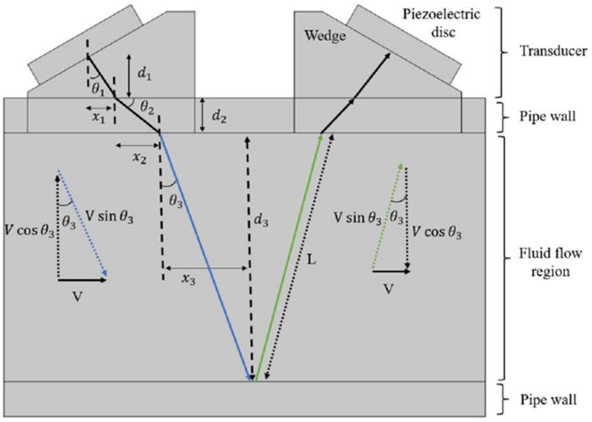
The performance of ultrasonic flowmeters with two pairs of transducers emitting and receiving ultrasonic signals has been largely experimentally studied [3]. Lynnworth [4] compared various types of ultrasonic flowmeters, their measurement processes and transducer mounting mechanisms.

When using ultrasonic flowmeters, depending on the propagation route of the ultrasonic waves, the measurement methods can be divided of two types: the Z-path method (the transmission method) and the V-path method (the reflection method).

The method applied by clamp-on ultrasonic flowmeters is the reflection method. An advantage of the reflection method is its ability to consistently obtain correct measurement values even when some flowing components move perpendicularly to the flow direction. However, since the ultrasonic wave propagation route is approximately twice the course length with the transmission method, a more considerable propagation loss occurs.

Figure 1 shows the schematic diagram of transit-time clamp-on ultrasonic flowmeters configured in a V-path arrangement, without being in contact with the fluid, as they are clamped on the outer side of an existing pipe, not disturbing the fluid flow.

The measuring principle consists of the upstream transducer transmitting an ultrasonic signal that travels in the fluid flow direction and reaches the downstream transducer [6-7]. After that, the downstream transducer transmits an ultrasonic signal which travels backwards, that is in the opposite direction to the fluid flow, and is received by the upstream transducer. This difference, called time of flight of both signals, is estimated and used to compute the velocity of the fluid integrated over the acoustic path. The integration of the fluid velocity in the pipe cross-section allows the estimation (i.e. measurement) of the flow rate.



Legend:
θ_1, θ_2, θ_3: the angle of the ultrasonic wave in the wedge, pipe wall and the fluid, respectively;
d_1: the vertical distance travelled by the wave in the wedge;
d_2: the pipe thickness;
d_3: the inner diameter of the pipe;
v: the fluid flow velocity;
x_1, x_2, x_3: the horizontal distances travelled by the wave in the wedge, pipe wall and fluid, respectively.

Figure 25: Schematic of the V-path method for Clamp-on ultrasonic flowmeters, adopted by [5].

b. Mathematical models

The flow rate – Q can be calculated by means of Equation 1, based on the cross-sectional area of the pipe, A:

$$Q = v_{\mathrm{a}} \cdot A = \left(\frac{v}{K}\right)\frac{\pi \cdot {d_3}^2}{4} \tag{7}$$

where (see Figure 1): d_3 is the inner pipe diameter; v is the velocity of the fluid integrated over the acoustic path; v_{a} is the velocity integrated over the pipe cross-section; K is a flow profile correction factor.

A clamp-on ultrasonic flowmeter transit-time, with single-path, and reflection transmitted indirectly measures the average velocity along the acoustic path, v, not the average flow velocity v_{a} needed to calculate the flow rate. The mathematical models associated with calculating v (Equation 2) and v_{a} (Equation 3) are presented below:

$$v = \frac{\Delta t}{t_{\mathrm{up}} + t_{\mathrm{down}} - 2t_{\mathrm{delay}}}\left(\frac{c_{\mathrm{wedge}}}{sin_{\theta 1}}\right) \tag{8}$$

and

$$v_{\mathrm{a}} = K\frac{\Delta t}{t_{\mathrm{up}} + t_{\mathrm{down}} - 2t_{\mathrm{delay}}}\left(\frac{c_{\mathrm{wedge}}}{sin_{\theta 1}}\right) \tag{9}$$

considering $\Delta t = t_{\mathrm{up}} - t_{\mathrm{down}}$, where t_{up} corresponds to the total time taken by the wave to propagate inside both transducers and the fluid for a wave which is propagating in the opposite direction of the fluid flow; t_{down} corresponds to the total time taken by the wave to propagate inside both transducers and the fluid for a wave propagating in the direction of the fluid flow; t_{delay} corresponds to the time taken by the wave to propagate inside the wedge and pipe wall; and c_{wedge} is to the speed of sound in the wedge. To obtain the inner diameter of the pipe's cross-sectional area, the values of two quantities are usually measured: the wall thickness, t; and the pipe cross-section the perimeter, P.

The outer diameter, d_{ext}, is obtained from the perimeter estimate,

$$d_{\mathrm{ext}} = \frac{P}{\pi} \tag{10}$$

and the inner diameter, d_3, is given by,

$$d_3 = d_{\mathrm{ext}} - 2\,t = \frac{P}{\pi} - 2\,t. \tag{11}$$

c. Traceability chain

The metrological activity requires resources of a metrology infrastructure to perform experimental comparisons with reference instruments with higher accuracy and traceability to SI.

Hydraulic Metrology Laboratory of the National Laboratory for Civil Engineering (HML-LNEC) has four closed conduits test rigs installed in parallel with lengths of 15 m, with nominal diameters from DN 80 to DN 400, as shown in Figure 2.

Each test rig has an electromagnetic flowmeter and is connected to two weighing platforms capable of storing from 1.7 and 17.6 ton of water. Additionally, it has a, underground water supply tank with 340 m^3, and three vertical axis pumps controlled using variable speed drives, capable of operating under the following conditions: volumetric flow rate ≤ 0,500 m^3/s; and mass flow rate ≤ 400 kg/s.

Figure 26: Hydraulic Metrology Laboratory (view).

Laboratory conditions are controlled with the aid of flow straighteners upstream, adjustable joint connections upstream, regulating valves, flow diverting systems and full bore shut-off valves.

The primary gravimetric flow rate measurement functional model is based on the measurement of mass using the weighing platforms and the measurement of time interval using universal time counters, being traceable to the Portuguese IPQ (the Portuguese National Metrology Institute) for the quantities of mass and time.

This facility allows the calibration of different types of flowmeters and counters, providing reference conditions for the measurement of mass flow rate and volumetric flow rate, and flow speed, being the reference obtained from the primary gravimetric standard (e.g. for electromagnetic flowmeters) or the secondary electromagnetic flowmeters (e.g. for the ultrasonic flowmeters), with best measurement capabilities reaching 0.05 % to 0.3 %.

It should be mentioned that HML-LNEC was recognized, since 2023, by EURAMET as the Portuguese Designated Institute for the measurement of liquid flow rate and flow velocities.

The calibration performed *in situ* is intended to provide traceability to the SI by establishing a traceability chain able to give confidence to the measurements obtained with the calibrated equipment. This is achieved using a clamp-on ultrasonic flowmeter of the Hydraulic Metrology Laboratory of LNEC, used as transfer standard.

The chain is obtained through comparisons with standards of higher accuracy to the top level of primary international standards of BIPM.

In this specific case, there are five levels, the lower one is between the equipment to be calibrated and the secondary standard (electromagnetic flowmeter); the next one represents the internal calibration of these secondary standards with the primary gravimetric system, which considers the flow rate traceable to mass and time measurement standards. These two internal standards are traceable to the Portuguese NMI followed by the traceability to BIPM. Figure 3 shows the traceability chain related with the calibration *in situ* performed by HML-LNEC.

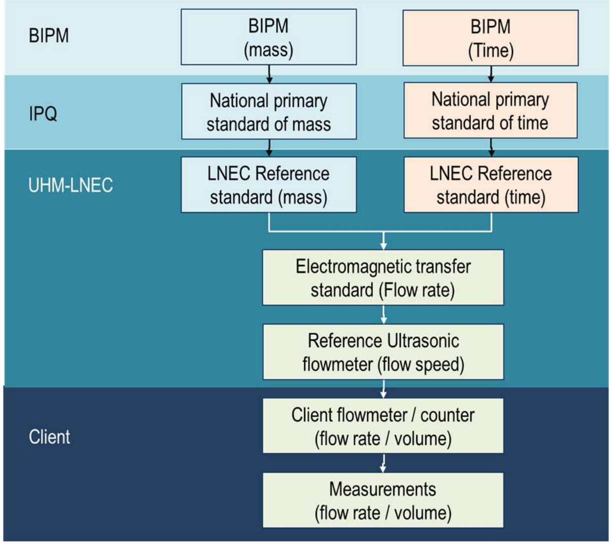


Figure 3 – Traceability chain adapted to *in situ* calibration procedures of HML-LNEC.

3 DATA ACQUISITION APPROACH

The proposed method uses clamp-on ultrasonic flowmeters as reference standard in on-site calibrations.

The traceability chain internal first step is to calibrate the electromagnetic transfer standard using the primary gravimetric method [8].

The second internal step to establish the traceability of the clamp-on ultrasonic flowmeters is obtained in the LNEC hydraulic metrology laboratory facilities, under ideal conditions, where the transducers are mounted in the clean (not painted) surface of a reference pipe (whose internal geometry is also evaluated using a 3D coordinate measuring machine) and the setup assures good acoustic coupling between the transducer faces and the pipe surface.

The calibration method consists of a direct comparison between the readings of the clamp-on ultrasonic flowmeter and of an electromagnetic flowmeter used as a standard. In laboratory conditions, the major influencing factors that affect the uncertainty of clamp-on flowmeters are the area of the measurement cross-section [7], the velocity profile, the path-velocity measurement, and the resolution and repeatability.

The clamp-on ultrasonic flowmeters also require the definition of operational parameters to be able to properly use internal algorithms. These includes operational data regarding the fluid (e.g. the type of fluid) and the installation pipe (e.g. material, coatings, inner diameter and wall thickness) with which the signal conditioner calculates the appropriate distance of the transducers.

The third internal step of the traceability chain is obtained by performing the calibration procedure *in situ*. This process is highly dependent on the nature of the flow and its operational conditions, sometimes allowing to change its magnitude using valves and other elements in the pipeline, but often without any means to change the conditions of the flow. The approach usually followed considers the sample observation of more than 20 pairs of readings (reference flow rate, Q_{S}, and equipment's flow rate, Q_{R}), if it is possible to change the flow magnitude in three or more steps and, at least, 50 pairs of readings otherwise. Typically, both readings are taken in intervals of 10 or 15 s, to capture the dynamics of the flow. The procedure usually generates two time series, being required to process the data to assure synchronization.

The practice of this approach shows that, In many cases, non-ideal conditions can affect the quality of readings, always requiring some caution about measurement results, examples of these conditions are::

- unknown inner condition of the pipe, often with encrustations (see Figure 4);
- upstream flow disturbances due to pipe tightness;
- the pipe is not working in closed conditions.

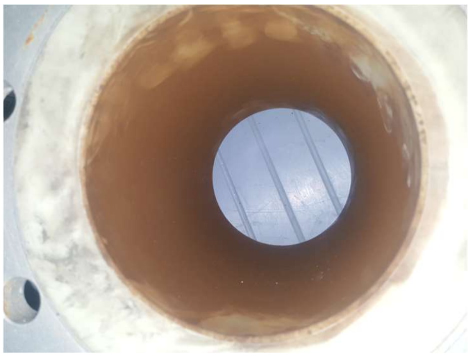


Figure 4: Inner pipe with encrustations

Other factors can be mentioned as affecting the performance of flowmeters in local setups:

- distortion in the fluid flow profile due to disturbances related to bends, contractions, expansions, valves and pumps, air bubbles or fluid contamination; and
- unknown pipe condition, such as, pipe roughness or incrustation due to corrosion on the inner side of the piping and parametric errors .

a. Uncertainty analysis

The general method used for the evaluation of measurement uncertainty is presented in [9], known as the GUM, firstly published by ISO, IEC and other organizations in 1993. This method states that, for a functional relation *f* of the type,:

$$y = f(x_1, \dots, x_n) \qquad (12)$$

being *y* the output quantity calculated from *n* input quantities, x_i. The development of the function as a 1st order Taylor series gives the formulation for the measurement standard uncertainty of the output quantity, *u(y)*:

$$u^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right) u(x_i, x_j) \qquad (13)$$

The first part of the second term of Equation 7 is related to the variance of each input quantity, whereas the second part of the second term is related to the contributions resulting from the correlation between input quantities, providing an exact solution only for linear functions. For non-linear mathematical models, computational approaches are used.

For the studied *in situ* calibration method, the starting point for the mathematical model is given for the average calibration error, $\bar{\varepsilon}$:

$$\bar{\varepsilon} = \frac{\Sigma(Q_{r,i} - Q_{s,i})}{n} \qquad (14)$$

where $Q_{r,i}$ represents the readings obtained with the flowmeter to be calibrated, $Q_{s,i}$ represents the readings of the reference flow rate (clamp-on ultrasonic flowmeter) and *n* is the number of pairs of observations.

This mathematical model should also include the contributions for the uncertainty budget related with the time dependent method. Taking into account another variable associated with the data time series, $\delta\varepsilon_{\Delta\mathrm{t}}$, the mathematical model is described as follows:

$$\bar{\varepsilon} = \frac{\Sigma(Q_{r,i} - Q_{s,i})}{n} + \delta\varepsilon_{\Delta\mathrm{t}}. \qquad (15)$$

This equation can be simplified considering,

$$\left(Q_{r,i} - Q_{s,i}\right) = \Delta Q_i. \qquad (16)$$

being the uncertainty of the differences obtained using Equation (7),

$$u^2(\Delta Q_i) = u^2\left(Q_{r,i}\right) + u^2\left(Q_{s,i}\right). \qquad (17)$$

and that the uncertainty of each difference value has identical uncertainty given by Equation (14) being calculated using Equation (15),

$$u(\Delta Q_i) = u(\Delta Q). \qquad (18)$$

$$u^2(\Delta Q_i) = u^2(Q_r) + u^2(Q_s). \qquad (19)$$

Regarding the uncertainty associated with the measurement of the reference flow rate, $u^2(Q_s)$, it should be noted that the contributions for uncertainty are included in the calibration certificate associated with the clamp-on ultrasonic flowmeter.

The uncertainty associated with the flow rate to be calibrated, $u^2(Q_r)$, can be estimated considering the following sources of uncertainty:

- *repeatability*, $\delta Q_{r,\mathrm{rep}}$, given by the calibration error experimental standard deviation of the mean;
- *resolution* of the equipment associated with the measurable quantity, $\delta Q_{r,\mathrm{res}}$; and
- *stability*, $\delta Q_{r,\mathrm{sta}}$, obtained from the magnitude of variation of the measurement results of the flow rate to be calibrated.

The combined uncertainty is given by,

$$u^2\,(Q_r) = u^2\,(\delta Q_{r,\mathrm{rep}}) + u^2(\delta Q_{r,\mathrm{res}}) + u^2(\delta Q_{r,\mathrm{sta}}) \qquad (20)$$

Using the approach mentioned above, the mathematical model (Equation 11) using the equivalent formula (Equation 12) generates Equation (17) and the respective uncertainty (Equation 18).

$$\bar{\varepsilon} = \frac{\Sigma(\Delta Q_i)}{n} + \delta\varepsilon_{\Delta\mathrm{t}}, \qquad (21)$$

$$u^2(\bar{\varepsilon}) = \textstyle\sum_{i=1}^{n} \frac{u^2(\Delta Q_i)}{n^2} + u^2(\delta\varepsilon_{\Delta\mathrm{T}}). \qquad (22)$$

Applying the simplified relation given by Equation (14) results in:

$$u^2(\bar{\varepsilon}) = \frac{1}{n^2}\sum_{i=1}^{n} u^2(\Delta Q_i) + u^2(\delta\varepsilon_{\Delta\mathrm{T}}), \qquad (23)$$

and,

$$u^2(\bar{\varepsilon}) = \frac{u^2(\Delta Q)}{n} + u^2(\delta\varepsilon_{\Delta\mathrm{T}}). \qquad (24)$$

To determine the uncertainty associated with the deviation associated with the data time series, $\delta\varepsilon_{\Delta\mathrm{T}}$, the following sources of uncertainty are considered (shown Equation 16): acquisition method, $\delta\varepsilon_{\mathrm{met}}$; synchronization, $\delta\varepsilon_{\mathrm{sinc}}$; and *repeatability*, $\delta\varepsilon_{\mathrm{rep}}$, obtained through the experimental standard deviation of the mean error of calibration.

$$u^2\,(\Sigma\delta\varepsilon_{\Delta\mathrm{T}}) = u^2\,(\delta\varepsilon_{\mathrm{met}}) + u^2(\delta\varepsilon_{\mathrm{sinc}}) + u^2(\delta\varepsilon_{\mathrm{rep}}) \qquad (25)$$

B. Case study and data

The case study corresponds to the hydraulic calibration carried out *in situ* without control of the flow, being used a sample of 25 pairs of reference flow rate, $Q_{s,i}$, and read flow rate, $Q_{r,i}$, shown in Figure 5. Figure 6 shows the time variation of the error of calibration (difference between readings and reference values). For the remaining calibration levels, the evaluation of the measurement uncertainties is performed in the same way.

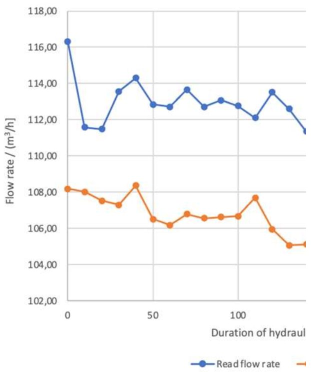


Figure 5: Reference flow rate and readings of flow rate of the hydraulic equipment under calibration.

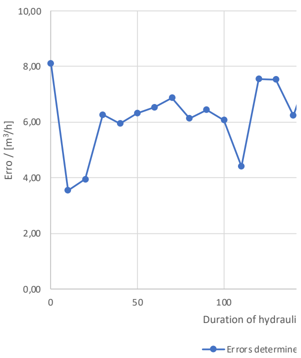


Figure 6: Errors obtained in the hydraulic calibration.

To calculate the standard uncertainty, $u(\bar{\varepsilon})$, using Equation (19), the contributions of the input quantities needed to be determined applying Probability Distribution Functions (PDF) and their parameters are presented in Table 1 and Table 2, respectively.

Table 8: PDF's of input quantities related to Q_{r}

Quantity	**PDF**	**Parameters**
$\delta Q_{r,\mathrm{sta}}$	Uniform	$[-0{,}1; +0{,}1]$
$\delta Q_{r,\mathrm{res}}$	Uniform	$[-5 \cdot 10^{-3}; +5 \cdot 10^{-3}]$
$\delta Q_{r,\mathrm{rep}}$	Normal	$N(\mu;\sigma) = N(0; 0{,}33)$

Table 9: PDF's of input quantities related to $\delta\varepsilon_{\Delta\mathrm{T}}$

Quantity	**PDF**	**Parameters**
$\delta\varepsilon_{\mathrm{met}}$	Uniform	$[-0{,}2; +0{,}2]$
$\delta\varepsilon_{\mathrm{sinc}}$	Normal	$N(\mu;\sigma) = N(0; 0{,}1)$
$\delta\varepsilon_{\mathrm{rep}}$	Normal	$N(\mu;\sigma) = N(0; 0{,}32)$

Using the values presented in Table 1, the value of the standard uncertainty of the clamp-on ultrasonic flowmeter (taken from the calibration certificate), $u(Q_{s,i}) = 6{,}9 \cdot 10^{-2}$ m³/h, and by applying Equation 14, an estimate of the standard uncertainty associated with average calibration error the can be obtained given by:

$$u(\bar{\varepsilon}) = 0{,}07\ \mathrm{m}^3/\mathrm{h} \tag{26}$$

The expanded uncertainty, $U_{95}(\bar{\varepsilon})$, is calculated by,

$$U_{95}(\bar{\varepsilon}) = k_{95} \cdot u(\bar{\varepsilon}) \tag{13}$$

with k_{95} being the expansion factor. Using a value of 2.05 for this parameter (an alternative could be used considering a t-student PDF with the degrees of freedom analysis based on the Welch-Satterthwaite formula, as described in the GUM), the expanded uncertainty is:

$$U_{95}(\bar{\varepsilon}) = 0{,}15\ \mathrm{m}^3/\mathrm{h} \tag{14}$$

4 CONCLUSIONS

This study allowed to assess the accuracy of the results of hydraulic calibration tests performed *in situ* using a clamp-on ultrasonic flowmeter as a reference.

The measurement uncertainty related to the average calibration error was determined using the conventional Uncertainty Propagation Law, showing that in non-ideal conditions (sometimes it is complicated to obtain data variability), HML-LNEC has instrumentation necessary to meet the accuracy requirements associated with this type of test. These accuracy requirements are achievable through careful statistical analysis, by using numerical methods, for the uncertainty evaluation, reflecting that the quality of the measurement result depends on this analysis.

Considering that the approach presented for the quantification of uncertainty sources associated with calculating the measurement uncertainty of the average calibration error is presented in a simplified way, it is expected that other sources of uncertainty will be quantified in future work. Additionally, it is also planned to study approaches based on FDP and the uncertainty associated with its parameters as an alternative to the method presented herein.

5 REFERENCES

J. Kritz, "An ultrasonic flowmeter for liquids", International Society of Automation, vol. 10, 1955.

M. L. Sanderson, "Electromagnetic and ultrasonic flowmeters: their present states and future possibilities", Electronics and Power, vol. 28, pp. 161-164, 1982.
DOI: 10.1049/ep.1982.0071

E. Thompson, "Two beam ultrasonic flow measurement", Imperial College of Science and Technology, University of London, 1978.

L. C. Lynnworth, "Ultrasonic flowmeters", Transactions of the Institute of Measurement and Control, vol. 3, pp. 217-223, 1981.
DOI: 10.1177/014233128100300405

M. Ali, "Evaluation of clamp-on ultrasonic liquid flowmeters", University of Western Ontario, 2022.

A. Scwery, T. Staubli, A. Abgottspon, "Field and laboratory experience with a clamp-on acoustic transit time flowmeter", 2012.

ISO 12242, "Measurement of fluid flow in closed conduits – Ultrasonic transit-time meters for liquid", 2012.

ISO 20456, "Measurement of fluid flow in closed conduits – Guidance for the use of electromagnetic flowmeters for conductive liquids", 2017.

JCGM 100, "Evaluation of measurement data. guide to the expression of uncertainty in measurement (GUM 1995 with minor corrections)", 2008.