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Traceability and measurement uncertainty of non-removable field flowmeters using clamp-on ultrasonic flowmeters as reference

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ABSTRACT
This study examines the traceability and measurement uncertainty of in situ hydraulic calibration of flowmeters using clamp-on ultrasonic flowmeters as reference. The procedure compares the equipment readings with the reference ones. Measurement uncertainty evaluation uses Guide to the expression of Uncertainty in Measurement (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.

Section: RESEARCH PAPER

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

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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 [1], [2], thus, requiring traceability [3]. It is common to find flowmeters installed in pipes [4] with physical constraints 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 in the measurement performance and its uncertainty the influence of local setup and flow conditions that affect locally the measurements [5], usually not considered in a laboratory setup where optimized calibration conditions reduce or eliminate many sources of error.

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 [6] must follow the specifications for operation of hydraulic calibration, namely, the characteristics of the fluid, the setup to install the sensors of the clamp-on flowmeter the material and characteristics of the piping, to ensure that the data is not disturbed by the conditions of the measurement. To notice that, currently, most of the systems do not allow to obtain directly digital information from the displays, being under development a method based on image processing to automate the acquisition process [7].

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 to estimate the inner diameter). Thus, the measurement procedure includes estimates of influence quantities (temperature, length, outside perimeter, and wall thickness) [4], [6]. Based on this information, the distance between the pair of transducers (emitter and receiver) can be established to the experimental setup to install in the pipe.

The relation of the setup conditions with these influence quantities mentioned allow to consider the four main sources of error, being those the following [8]:

- existing irregularities of the pipe along the sections
- installation of the transducers
- properties of the fluid and
- acoustic characteristics affecting the propagation of the ultrasonic wave.

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

2.1. Description and characteristics

The concept of ultrasonic flowmeters for liquids was firstly presented by [9].

Sanderson [10] highlighted the problems encountered using traditional flowmeters and suggested using 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 [11]. Lynnworth [12] 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 into 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 [13]-[14]. 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.

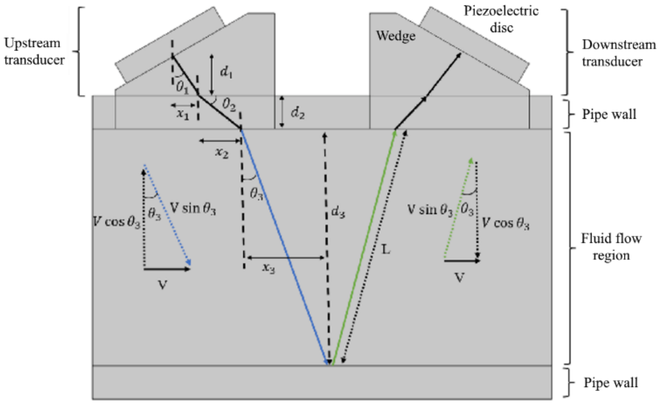

Figure 1. Schematic of the V-path method for Clamp-on ultrasonic flowmeters, adopted by [15].

Legend:

Θ_1, Θ_2, Θ_3 - angle of the ultrasonic wave in the wedge, pipe wall and the fluid, respectively

d_1 - vertical distance travelled by the wave in the wedge

d_2 - pipe thickness

d_3 - inner pipe diameter

v - the fluid flow velocity

x_1, x_2, x_3 - horizontal distances travelled by the wave in the wedge, pipe wall and fluid, respectively.

2.2. Mathematical models

The flow rate Q can be calculated by means of equation (1), based on the cross-sectional area of the pipe A

$$Q = v_\mathrm{a} \cdot A = \frac{v}{K} \cdot \frac{\pi \cdot d_3^2}{4}\,, \tag{1}$$

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 and
- 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 (2) and v_a (3) are presented below:

$$v = \frac{\Delta t}{t_\mathrm{up} + t_\mathrm{down} - 2\,t_\mathrm{delay}} \cdot \frac{c_\mathrm{wedge}}{\sin\theta_1} \tag{2}$$

and

$$v_\mathrm{a} = K \cdot \frac{\Delta t}{t_\mathrm{up} + t_\mathrm{down} - 2\,t_\mathrm{delay}} \cdot \frac{c_\mathrm{wedge}}{\sin\theta_1}\,. \tag{3}$$

The quantities found in these equations and some considerations related are the following

- $\Delta t = t_\mathrm{up} - t_\mathrm{down}$, 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 $w_{\mathrm{thickness}}$ and the pipe cross-section the perimeter P.

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

$$d_{\mathrm{ext}} = \frac{P}{\pi} \tag{4}$$

and the inner diameter d_3 is given by

$$d_3 = d_{\mathrm{ext}} - 2 \cdot w_{\mathrm{thickness}} = \frac{P}{\pi} - 2 \cdot w_{\mathrm{thickness}} \,. \tag{5}$$

2.3. Traceability chain

The method developed to provide traceability to non-removable flowmeters in field by comparison with the clamp-on ultrasonic flowmeters need the support of a metrology infrastructure to provide the required metrological traceability to SI. This infrastructure is the Laboratory for Civil Engineering (LNEC) Hydraulic Metrology Unit (UHM).

This Unit is a R&DI infrastructure jointly coordinated by the Department of Hydraulics and Environment and the Scientific Instrumentation Centre, both LNEC in Lisbon, Portugal.

The hydraulic infrastructure can generate stable flow conditions in closed conduits by the primary gravimetric method, using four test rigs installed in parallel, each 15 m long and with a nominal diameter ranging from DN 80 to DN 400, as shown in Figure 2.

Each test rig has, among other characteristics, electromagnetic flowmeters acting as a secondary standard, telescopic connections, and valves to control the fluid pressure. The flow rate is obtained by measuring mass using two weighing platforms and time intervals using universal time counters. The fluid water is circulated from an underground reservoir with a volume of 340 m³ of water, using three vertical axis pumps controlled actuated by variable speed drives, providing operations up to:

- volumetric flow rate ≤ 0.500 m³/s and
- mass flow rate ≤ 400 kg/s.

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.

This facility allows the calibration of different types of flowmeters and counters, providing reference conditions for the measurement of mass and volumetric flow rate, and flow speed, with best measurement capabilities reaching 0.05 % to 0.3 %.

This infrastructure is part of the Portuguese quality infrastructure, being recognized since 2023 as the Portuguese Designated Institute for the measurement of liquid flow rate and flow speed.

The calibration performed *in situ* using the clamp-on ultrasonic flowmeter is intended to provide measurement traceability to the measurements performed by the non-removable flowmeters, by establishing a traceability chain described in Figure 3.

In this specific traceability chain, five levels are found, the higher one being related with the mass and time calibration (primary quantities for flow rate measurements) of Instituto Português da Qualidade (IPQ), the Portuguese NMI, by BIPM.

The second level is the calibration of LNEC's reference standards of mass (weighing platforms) and time (universal time counters), that establish the reference values of flow at laboratory level. The third level is the calibration of LNEC's transfer standards – electromagnetic flowmeters – installed in the test rigs of LNEC's infrastructure. The next level is for the calibration of the clamp-on ultrasonic flowmeters in comparison with the electromagnetic flowmeters, and the fifth level is the calibration of the client non-removable flowmeters in field, finally providing the measurement traceability to the measurement results obtained using these instruments.

Figure 2. LNEC's Hydraulic Metrology Unit (view).

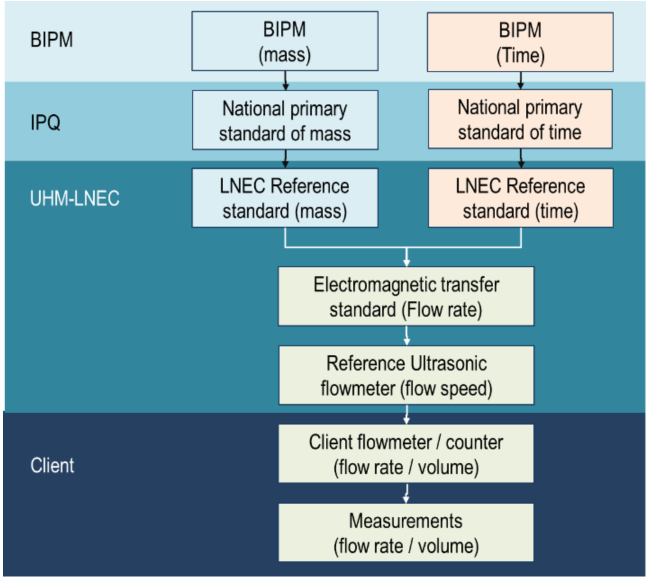

Figure 3. Traceability chain adapted to *in situ* calibration procedures of UHM-LNEC.

3. CALIBRATION PROCEDURE

The procedure adopted for the calibration of non-removable flowmeters by comparison with clamp-on ultrasonic flowmeters as reference standard in field conditions requires several operations described in the following steps.

The first operational step of this procedure is to calibrate the electromagnetic flowmeter of the rig to be used for the calibration of the clamp-on ultrasonic flowmeter, being this operation made according to the primary gravimetric method [14], [16].

The second step is to install the clamp-on ultrasonic flowmeter in the testing rig under ideal conditions, with the transducers mounted on the clean (not painted) surface of a reference pipe (whose internal geometry is also evaluated using a 3D coordinate measuring machine). This ensures that the setup provides a good acoustic coupling between the transducer faces and the pipe surface. The calibration method consists of a direct comparison between the readings of the flow rate and flow speed of the clamp-on ultrasonic flowmeter and the electromagnetic flowmeter used as a transfer standard. In laboratory conditions, the major influencing factors considered to contribute to the measurement uncertainty of clamp-on flowmeters are the area of the measurement cross-section [17], the velocity profile, the path-velocity measurement, the resolution, and the 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 step of the procedure is related with 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 adopted considers variable sample size because of local stability conditions. Experience shows that a sample size lower than 20 pairs of readings (reference flow rate Q_s and equipment's flow rate Q_r) should be avoided to assure a reasonable statistical representativeness of the behaviour of the performance of the method. It is also recommended to obtain different magnitudes of flow, although in many cases, the variability of the measuring interval is relatively small (e.g. when flow is mainly used to fill water reservoirs). Regarding sample rate, measures are typically taken in intervals of 10 s to 15 s, which is usually enough to capture the dynamics of the flow. This procedure usually generates time series, which is required to process the data to ensure synchronization. The practice of this approach shows often that non-ideal conditions can affect significantly the quality of readings, always requiring a critical analysis and some caution, examples of these negative influential conditions are:

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

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

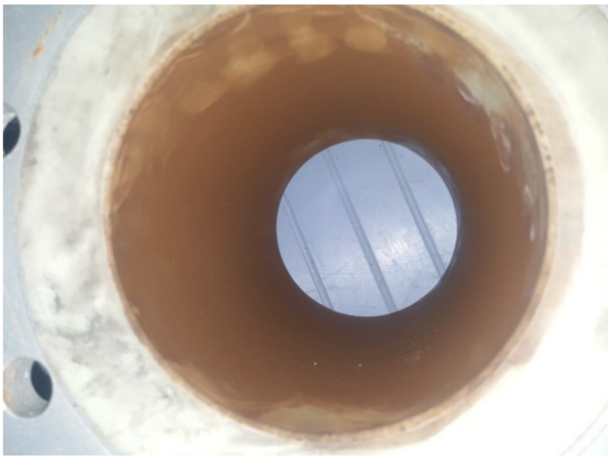

Figure 4. Inner pipe with encrustations.

- unknown pipe condition, such as pipe roughness or incrustation due to corrosion on the inner side of the piping and parametric errors.

3.1. Uncertainty analysis

The general method used to evaluate measurement uncertainty is presented in [17], known as the GUM [18], first published by ISO, IEC and other organizations in 1993. This method states that, for a functional relation *f* of the type,

$$y = f(x_1, \ldots, x_\mathrm{n}), \tag{6}$$

where y is 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 $u(y)$

$$u^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right) u(x_{i,}x_j)\,. \tag{7}$$

The first part of the second term of (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 higher level non-linear mathematical models [19], computational approaches might be required to avoid bias and other types of deviations related to measurement uncertainties estimates.

For the studied *in situ* calibration method, the starting point for the mathematical model is given for the average calibration error, $\bar{\varepsilon}$ [20]

$$\bar{\varepsilon} = \frac{\sum\left(Q_\mathrm{r,i} - Q_\mathrm{s,i}\right)}{n}\,, \tag{8}$$

where $Q_\mathrm{r,i}$ represents the readings obtained with the flowmeter to be calibrated, $Q_\mathrm{s,i}$ 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 to the time-dependent method. Considering another variable associated with the data time series, $\delta_{\varepsilon_{\Delta\mathrm{T}}}$, the mathematical model is described as follows

$$\bar{\varepsilon} = \frac{\sum\left(Q_\mathrm{r,i} - Q_\mathrm{s,i}\right)}{n} + \delta_{\varepsilon_{\Delta\mathrm{T}}}\,. \tag{9}$$

This equation can be simplified considering

$$\left(Q_{\mathrm{r,i}} - Q_{\mathrm{s,i}}\right) = \Delta Q_{\mathrm{i}} \,, \tag{10}$$

where the uncertainty of the differences obtained using equation (7),

$$u^2(\Delta Q_{\mathrm{i}}) = u^2\left(Q_{\mathrm{r,i}}\right) + u^2\left(Q_{\mathrm{s,i}}\right) \tag{11}$$

and that the uncertainty of each difference value has identical uncertainty given by (12) being calculated using (13)

$$u(\Delta Q_{\mathrm{i}}) = u(\Delta Q) \tag{12}$$

$$u^2(\Delta Q_{\mathrm{i}}) = u^2(Q_{\mathrm{r}}) + u^2(Q_{\mathrm{s}}) \,. \tag{13}$$

Regarding the uncertainty $u(Q_{\mathrm{s}})$ associated with the measurement of the reference flow rate, it should be noted that the contributions for uncertainty are included in the calibration certificate associated with the clamp-on ultrasonic flowmeter.

The uncertainty $u(Q_{\mathrm{r}})$ associated with the flow rate to be calibrated, can be estimated considering the following sources of uncertainty:

- *repeatability* $\delta Q_{\mathrm{r,rep}}$ given by the calibration error experimental standard deviation of the mean [17], [21];
- *resolution* $\delta Q_{\mathrm{r,res}}$ of the equipment associated with the measurable quantity and
- *stability* $\delta Q_{\mathrm{r,sta}}$ obtained from the magnitude of variation of the measurement results of the flow rate to be calibrated.

The combined uncertainty is given by

$$u^2(Q_{\mathrm{r}}) = u^2\left(\delta Q_{\mathrm{r,rep}}\right) + u^2\left(\delta Q_{\mathrm{r,res}}\right) + u^2\left(\delta Q_{\mathrm{r,sta}}\right) . \tag{14}$$

Using the approach mentioned above, the mathematical model (12) using the equivalent formula (13) generates equation (15) and the respective uncertainty (16)

$$\bar{\varepsilon} = \frac{\sum(\Delta Q_{\mathrm{i}})}{n} + \delta_{\varepsilon_{\Delta\mathrm{T}}} \tag{15}$$

$$u^2(\bar{\varepsilon}) = \sum_{i=1}^{n} \frac{u^2(\Delta Q_{\mathrm{i}})}{n^2} + u^2\left(\delta_{\varepsilon_{\Delta\mathrm{T}}}\right). \tag{16}$$

Applying the simplified relation given by (16) results in

$$u^2(\bar{\varepsilon}) = \frac{1}{n^2} \sum_{i=1}^{n} u^2(\Delta Q_{\mathrm{i}}) + u^2\left(\delta_{\varepsilon_{\Delta\mathrm{T}}}\right), \tag{17}$$

and,

$$u^2(\bar{\varepsilon}) = \frac{u^2(\Delta Q_{\mathrm{i}})}{n^2} + u^2\left(\delta_{\varepsilon_{\Delta\mathrm{T}}}\right) . \tag{18}$$

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, see (14): *acquisition method* $\delta\varepsilon_{\mathrm{met}}$, *synchronization* $\delta\varepsilon_{\mathrm{sync}}$ and *repeatability* $\delta\varepsilon_{\mathrm{rep}}$ obtained through the experimental standard deviation of the mean error of calibration

$$u^2\left(\sum \delta\varepsilon_{\Delta\mathrm{T}}\right) = u^2(\delta\varepsilon_{\mathrm{met}}) + u^2\left(\delta\varepsilon_{\mathrm{sync}}\right) + u^2\left(\delta\varepsilon_{\mathrm{rep}}\right) . \tag{19}$$

3.2. 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 $Q_{\mathrm{s,i}}$ and read flow rate $Q_{\mathrm{r,i}}$ 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.

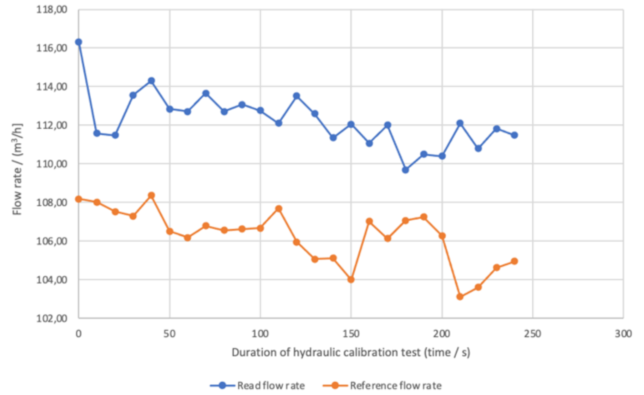

Figure 5. Reference flow rate and readings of flow rate of the hydraulic equipment under calibration.

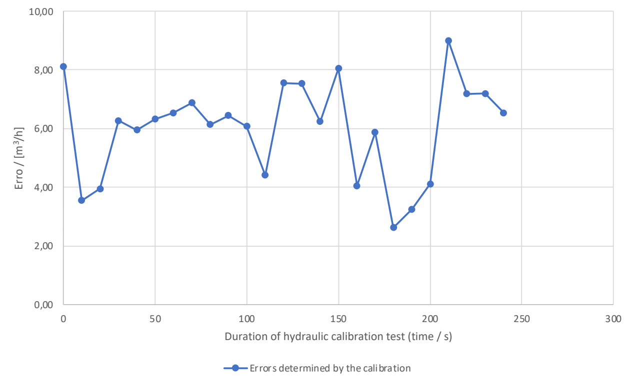

Figure 6. Errors obtained in the hydraulic calibration.

To calculate the standard uncertainty $u(\bar{\varepsilon})$ using (18), 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.

Using the values presented in Table 1, the value of the standard uncertainty of the clamp-on ultrasonic flowmeter (taken from the calibration certificate), $u\left(Q_{\mathrm{s},i}\right) = 6.9 \cdot 10^{-2}$ m³/h, and by applying (14), an estimate of the standard uncertainty associated with average calibration error the can be obtained by

$$u(\bar{\varepsilon}) = 0.07\ \mathrm{m}^3/h \,. \tag{20}$$

Table 1. PDFs of input quantities related to Q_{r}.

Quantity	PDF	Parameters
$\delta Q_{\mathrm{r,sta}}$	Uniform	[-0.1; +0.1]
$\delta Q_{\mathrm{r,res}}$	Uniform	[-5·10⁻³; +5·10⁻³]
$\delta Q_{\mathrm{r,rep}}$	Normal	*N (μ; σ)* =*N* (0; 0.33)

Table 2. PDFs of input quantities related to $\delta_{\varepsilon_{\Delta\mathrm{T}}}$.

Quantity	PDF	Parameters
$\delta\varepsilon_{\mathrm{met}}$	Uniform	[-0.2; +0.2]
$\delta\varepsilon_{\mathrm{sync}}$	Normal	*N (μ; σ)* =*N* (0; 0.1)
$\delta\varepsilon_{\mathrm{rep}}$	Normal	*N (μ; σ)* =*N* (0; 0.32)

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

$$U_{95}(\bar{\varepsilon}) = k_{95} \cdot u(\bar{\varepsilon}) \quad (21)$$

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

$$U_{95}(\bar{\varepsilon}) = 0.15\ \frac{\mathrm{m}^3}{\mathrm{h}}. \quad (22)$$

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), LNEC has the 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 PDF and the uncertainty associated with its parameters as an alternative to the method presented herein.

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