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In service verification of thermal energy meters through ultrasonic clamp-on master meters

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Abstract

The measurement of heat consumption in buildings through thermal energy meters presents numerous metrological issues due, for example, to the installation and operational conditions (e.g. presence of plant constraints, low flow rates, low temperature differences between flow and return) leading often to unacceptable measurement errors and uncertainties, both in laboratory and in the field. Therefore, in several EU countries, to guarantee consumer protection it is mandatory to carry out periodic inspection to assess their accuracy, while in service. In this work, the authors present the results of experimental campaigns performed both in the laboratory and in the field, aimed at analysing the key metrological concerns of the use of clamp-on master meter during in-field verification of thermal energy meters. The results showed that particular care should be paid to the meter configuration and installation of the transducer and that in-field legal metrology statutes in terms of permissible error and uncertainty are often very difficult to comply with.

Keywords:
thermal energy meter; in-field verification; ultrasonic clamp-on; master meter; maximum permissible error; uncertainty;

1. Introduction

Thermal energy consumed in a building or in an apartment is measured through a thermal energy balance wherein the flow rate of the working fluid, heat capacity and temperature are multiplied to yield heat flow [1]. A thermal energy meter is then made up of a flow-meter, a temperature sensor pair (generally platinum thermal resistance PT 500 or PT 1000) and a calculator module which processes volume and temperatures measurements and calculates the thermal coefficient depending on the fluid density and specific heat capacity. According to the harmonized technical standards [2, 3], a thermal energy meter is either a complete instrument (consisting of embedded calculator and flow/temperature sensors) or combined (consisting of flow sensor, temperature sensor pair and calculator as separate sub-assemblies). In almost all cases, complete meters are used in the residential sector for sub-metering purposes (i.e. heat cost allocation and billing) when a centralized heating plant is present. On the other hand, combined meters are generally used by large users, both commercial and residential (e.g. directly in the district heating substation at the border with the supply company). In EU countries, the spread of thermal energy meters for the measurement of heating and cooling consumption has been recently pushed by Directive 2012/27/EU (EED) on energy efficiency [4], which has set measurement of individual heat consumptions as a fundamental tool to increase efficiency and promote energy savings.

The estimation of the amounts of thermal energy consumed in single dwellings is certainly a current topic and debated given the related numerous technical, metrological and consumer protection issues [5-9]. To this end, thermal energy meters in EU are regulated by MID Directive on measuring instruments [10] which requires measuring instruments used for legal purposes shall fulfil essential metrological requirements, meaning that error and associated measurement uncertainty shall not exceed the limits allowed for the type of measurements.

Since thermal energy meters, as well as water and gas meters [11], are subject to natural drift of their metrological performances, an adequate system of periodic in service inspections is required for consumer protection. In Italy, for thermal energy meters and other instruments, the National Authority for legal metrology instruments issued Decree n. 93 of 21 April 2017 [12] laying down the regulations for subsequent and in service verification of measuring instruments regulated by legal metrology. For thermal energy meters the frequency of subsequent verifications has been set, however the technical procedures in the field or in the laboratory are still missing and they have not been punctually defined as instead for other categories of instruments (e.g. for active electrical energy meters and non-automatic weighing instruments). In particular, subsequent verification of thermal energy meters are mandatory, which frequency is variable between 5 and 9 years depending on the measuring principle of the flow sensor and on its permanent flow rate q_p . With regard to the maximum permissible errors (MPE), it is established that for subsequent verifications they are equal to those set for in-service verifications by the relevant Harmonized Standard or applicable OIML Recommendation or, ultimately, those established for the initial verification (i.e. Annex VI MI-004 of the MID directive). Subsequent verifications may be also performed in laboratory since, as a general principle, whatever the reason for removal from the original place of installation, there is no obligation to reinstall the instrument in the same place from which it was removed nor the impossibility or prohibition to reinstall the same in a different place. Obviously, results of the verification in the field and in laboratory should be comparable ensuring also metrological compatibility in terms of measured errors and related uncertainties.

In-field verification present the advantage that test are performed at the punctual installation conditions and thus the effective metrological performances of the meter emerge. This is crucial for consumer protection, however, in the field the particular actual operational conditions of use and the need to guarantee the continuity of the service often do not allow to test the meter at different verification points (i.e. for thermal energy meters at different flow-rates and heating fluid temperatures) as required by the applicable technical standards. On the other hand, it is known that in-field performance of the meter could depend on its metrological principle. Choi et al. [13] investigated the metrological performance of three types of heat flow-meters (turbine, electromagnetic and ultrasonic) in the field showing deviation of the turbine flow-meter and the ultrasonic within ±2.5% and of the electromagnetic within 6.9%. Furthermore, in-field verifications are critical due to the plant constraints determining installation requirements set by manufacturers are not always met, thus affecting metrological performance of the meter. As for example, the presence of elbows and other types of flow disturbances can cause a drift up to 5.0% for the flow sensor of a thermal energy meter [14], whereas the presence of an obstruction five diameters upstream of the flow meter can result in a drift between -0.6% and -7.9% [15]. Weissenbrunner et al. [16], through a Computational Fluid Dynamics simulation, analysed the systematic errors of ultrasonic flow meters due to uncertain inflow conditions, as caused by the presence of upstream flow disturbances like double elbows. In this case, systematic flow rate measurement errors have been found in the range from 1.5% to 4.5% if the distance between the meter and the upstream double elbow is smaller than 40 pipe diameters. Verifications performed in laboratory, conversely, allow more accurate results and lower uncertainties, together with the possibility to test the meter at different flow-rates and fluid temperatures. Furthermore, installation conditions are always ideal and several meters can be verified contemporarily, with consequent lower costs.

In this work, the authors present the results of two experimental campaigns aimed at analysing the metrological key concerns of the use of ultrasonic (US) clamp-on Master Meter (MM) both in laboratory and in-field for the verification of thermal energy meters. In particular, the effects of the presence of flow disturbances and of sludge in the flow have been investigated.

2. Theory and Methods

In Italy, decree 93/2017 in Annex III establishes specific verification procedures of legal instruments most commonly used (e.g. non automatic weighing instruments, electrical energy meters, gas volume conversion devices, etc.). For some other instruments (e.g. gas meters) national technical standards for in-field verification are available [17]. On the contrary, for thermal energy meters, standard procedures for subsequent in laboratory and in-field verifications are not available neither in EN harmonized standards nor in OIML Recommendations. Therefore, subsequent verification of thermal energy meters, in the field or in laboratory, shall conform the applicable requirements for verification of relevant national and European harmonized standards and, specifically, the EN 1434-5 [18] for initial verification, which is briefly described below.

2.1 Initial verification of thermal energy meters (EN 1434-5)

The initial verification of thermal energy meter is generally carried out at the manufacturer's laboratory. The instrument is tested at the so-called "*rated operating conditions*", i.e. at the conditions of use under the approved range of influence quantities (i.e. fluid temperature, temperature difference, flow-rate, heat output, working pressure and nominal pressure as reported in the EU-type examination certificate).

Technical standard EN 1434-5 [18] specifies that verification of thermal energy meters shall be performed at the extremes and midpoints of its ranges and that, if the meter is a combined instrument, the flow sensor, the temperature sensors and the calculator shall each be tested separately. Moreover: i) the verification of the flow sensor is carried out according to the specifications of the EU type certificate (e.g. conductivity, fluid temperature, upstream and downstream straight sections); ii) the return temperature must be in the range (50±5) °C for heating and (15±5) °C for cooling (however, when specified in the EU-type certificate, tests can be performed with fluid at ambient temperature); iii) temperature sensor pair must be checked (without thermowell and with an immersion depth of at least 90% of the length) in the same thermostatic bath at three temperature values. According to EN 1434-5 [18], verification points for complete meters and combined are reported in Table 1 and 2, respectively.

Table 1: Temperature and flow values for complete thermal energy meters initial verification

Heating		*Cooling*	
Temperature difference	*Flow*	*Temperature difference*	*Flow*
$\Delta\vartheta_{min} \leq \Delta\vartheta \leq 1.2\ \Delta\vartheta_{min}$	$0.9\ q_p < q < 1.1\ q_p$	$\Delta\vartheta_{min} \leq \Delta\vartheta \leq 1.2\ \Delta\vartheta_{min}$	$0.9\ q_p < q < 1.1\ q_p$
$10\ K \leq \Delta\vartheta \leq 20\ K$	$0.1\ q_p < q < 0.11\ q_p$	$0.8\ \Delta\vartheta_{max} \leq \Delta\vartheta \leq \Delta\vartheta_{max}$	$0.1\ q_p < q < 0.11\ q_p$
$(\Delta\vartheta_{max} - 5\ K) < \Delta\vartheta < \Delta\vartheta_{max}$	$q_i < q < 1.2\ q_i$	$0.8\ \Delta\vartheta_{max} \leq \Delta\vartheta \leq \Delta\vartheta_{max}$	$q_i < q < 1.2\ q_i$

Table 2: initial verification of sub-assemblies of combined thermal energy meters

Flow sensor	*Temperature sensor pair*	*Calculator (for heating)***
$q_i < q < 1.2\ q_i$,	$\vartheta_{min} < \vartheta_1 < (\vartheta_{min} + 10\ K)$,	$\Delta\vartheta_{min} \leq \Delta\vartheta \leq 1.2\ \Delta\vartheta_{min}$,
$0.1\ q_p < q < 0.11\ q_p$	$\vartheta_2 = \frac{\vartheta_1+\vartheta_3}{2} \pm 5\ K$,	$10\ K \leq \Delta\vartheta \leq 20\ K$,
$0.9\ q_p < q < 1.1\ q_p$	$(\vartheta_{max} - 10\ K) < \vartheta_3 < \vartheta_{max}$ *	$(\Delta\vartheta_{max} - 5\ K) \leq \Delta\vartheta \leq 1.2\ \Delta\vartheta_{max}$

* or 140 $K < (\vartheta_{max} - 20\ K) < \vartheta_3 < \vartheta_{max}$, if $\vartheta_{max} > 150\ K$

** for cooling applications verification is performed at $\Delta\vartheta_{min} \leq \Delta\vartheta \leq 1.2\ \Delta\vartheta_{min}$ and $0.8\ \Delta\vartheta_{max} \leq \Delta\vartheta \leq \Delta\vartheta_{max}$

2.2 Subsequent and in service verification of thermal energy meters

Subsequent verification, in order to guarantee the continuity of supply as well as reliability of the result in congruence with the real installation and operational conditions, should be normally performed in the field. However, the in-field verification of thermal energy meters presents numerous technical and operational issues. In particular, the installation conditions of the meter, due to plant constraints (e.g. presence of upstream and downstream disturbances, connections and reductions in diameter, vertical/horizontal installation, availability of thermowells for the temperature probe on the return pipe, etc.), often do not meet the installation requirements referred to in type certificates. Furthermore, the installation of a reference MM is not always technically feasible. With regard to the operational procedures, in-field subsequent verifications of thermal energy meters can be performed only through comparison method (both for flow and temperature sensors) whereas in laboratory more accurate methods (such as volumetric and gravimetric methods for the flow sensor) may also be applied. As a consequence, the strict metrological requirements in terms of error and uncertainty established by technical standards are generally met only in laboratory, whereas installation effects and critical operational conditions (i.e. low flow-rates and low temperature differences) may significantly influence in-field verification results, leading to unacceptable uncertainties.

The in-field verification with clamp-on ultrasonic (US) MM seems to be the best from the point of view of ease of field operations, since flow and temperature sensors are installed directly on the external surface of the pipe without need to dismantle part of the plant and to interrupt the service. On the other hand, the clamp-on installation mode presents undoubted metrological key concerns, both for flow-rates and temperature measurements. In fact, to guarantee a correct installation of the flow sensor suitable straight undisturbed pipe lengths upstream and downstream of the flow sensor (up to 20 and 10 times the pipe diameter, respectively) are requested and particular attention must be paid to the possible presence of air and sludge in the pipeline (see Figure 1).

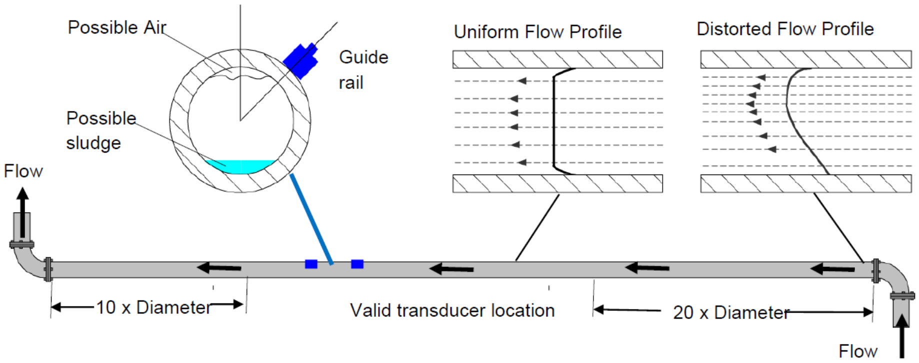


Figure 1 – Installation requirements of clamp-on US MMs

As regards the temperature sensors verification, the typical configuration of thermal energy meters requires the use of specific thermowells, both on the flow and on the return pipes (this latter is generally mounted on board the flow sensor). The use of different systems during verifications (e.g. clamp-on temperature probes, thermostatically controlled baths) could lead to errors which are difficult to estimate and variable since they depend on the thermodynamic conditions and the velocity of the fluid in the pipeline. Finally, the contact resistance between the sensor and the pipe should be considered and this will depend on the material of the pipe.

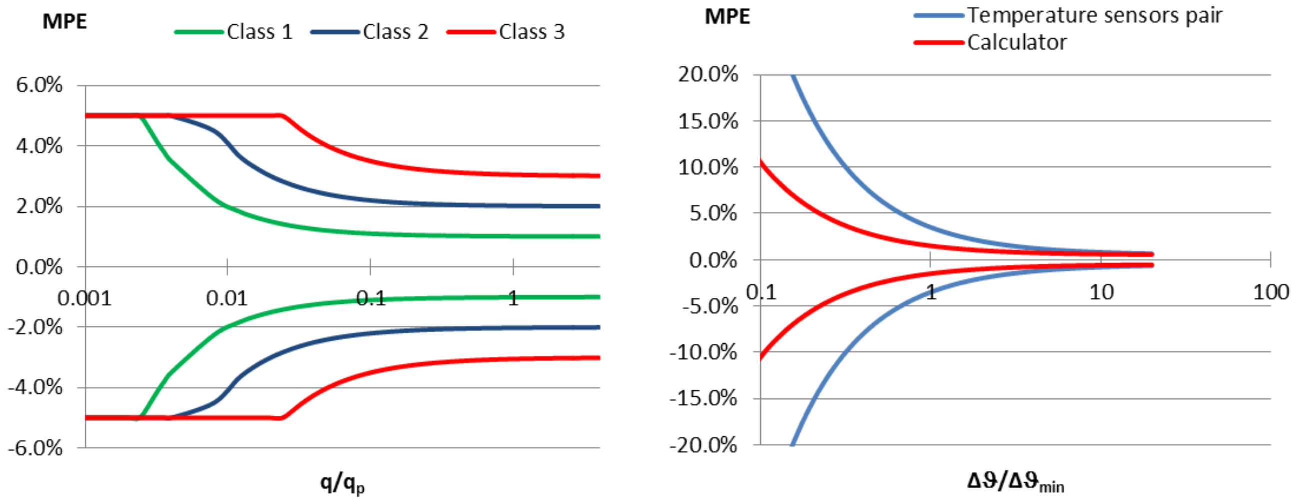
2.3 Maximum permissible errors and uncertainties

Unfortunately, for thermal energy meters nor the harmonized standard EN 1434-1 neither the OIML R75 Recommendation prescribe specific maximum permissible errors (MPE) for in service verifications. In this regard, a single reference is established in par. 3.23 of EN 1434-1 for the definition of "*durability*" in which it is stated that "*a measuring instrument will be designed to maintain an adequate stability of its metrological characteristics (e.g. to fulfil the double of MPE)*". Table 3 and Figure 2 show MPEs for type approval and initial verification of thermal energy meters, as reported in EN 1434:1 [2] and OIML R75 [3].

Table 3 – MPE of thermal energy meters (initial verification)

MID class	*Sub-assemblies of combined meter*			*Complete meter*
	Flow sensor	*Temperature sensor pair*	*Calculator*	
1	$\left(1+0.01\,\frac{q_p}{q}\right)^*$	$0.5+3\frac{\Delta\vartheta_{min}}{\Delta\vartheta}$	$0.5+\frac{\Delta\vartheta_{min}}{\Delta\vartheta}$	$\left(1+0.01\,\frac{q_p}{q}\right)^*+1+4\frac{\Delta\vartheta_{min}}{\Delta\vartheta}$
2	$\left(2+0.02\,\frac{q_p}{q}\right)^*$			$\left(2+0.02\,\frac{q_p}{q}\right)^*+1+4\frac{\Delta\vartheta_{min}}{\Delta\vartheta}$
3	$\left(3+0.05\,\frac{q_p}{q}\right)^*$			$\left(3+0.05\,\frac{q_p}{q}\right)^*+1+4\frac{\Delta\vartheta_{min}}{\Delta\vartheta}$

* but not more than 5 %



a) flow sensor

b) Temperature sensor pair and calculator

Figure 2 - MPE of single sub-assemblies of combined thermal energy meter

Among the relevant technical aspects set by Decree 93 [12], the error of the instruments used in the verification (e.g. Master Meter) must be lower than 1/3 of the maximum permissible error (MPE) allowed for the meter being tested. Furthermore, standard EN 1434-5 [18] prescribes uncertainties of the reference standards, the method and the instruments shall not exceed 1/5 of the MPE of the meter being tested or, if exceeding 1/5 of the MPE, the difference between the uncertainty and 1/5 of the MPE must be subtracted from the MPE of the meter being tested to obtain a lower MPE (i.e. $e<\left(1+\frac{1}{5}\right)MPE-U$), in which e is the measured error. Table 4 shows, as for example, for the accuracy Class 2 and up to size DN50 the applicable MPEs and the corresponding maximum uncertainties calculated at different q_p/q ratio considering the limit of 1/5 MPE in initial verification.

Table 4 –MPE and uncertainty of flow sensors of thermal energy meters (initial verification)

q_p/q	*MPE*	*U*	*Flow rate (m^3h^{-1})*						
			DN15		*DN20*	*DN25*	*DN32*	*DN40*	*DN50*
250	5%	1.0%	0.0024	0.006	0.010	0.014	0.024	0.040	0.060
100	4%	0.8%	0.006	0.015	0.025	0.035	0.060	0.100	0.150
50	3%	0.6%	0.01	0.03	0.05	0.07	0.12	0.20	0.30
25	3%	0.5%	0.02	0.06	0.10	0.14	0.24	0.40	0.60
10	2%	0.4%	0.06	0.15	0.25	0.35	0.60	1.0	1.5
1	2%	0.4%	0.6	1.5	2.5	3.5	6.0	10	15

From table 4 it can be highlighted that the maximum admitted uncertainty depends on the ratio q_p/q. This leads the reference MM flow sensor to show a maximum expanded uncertainty lower than 0.4% for flow rate above 0.6 m^3h^{-1}, whereas for lower ones the uncertainty increase up to 1%. Such low uncertainties very rarely occur in the field, due to frequent critical operational conditions (e.g. low flow-rate and temperature differences) and to not adequate installation conditions (e.g. limited straight pipe lengths, presence of obstructions, valves). Therefore, at the state of the art, only if MPEs double of the ones of initial verification are set or higher uncertainties are allowed, in-field verification could be adequate in terms of requested uncertainty. On the other hand, the WELMEC Guideline 11.1 [19] on utility meters is less restrictive, since for market surveillance the Best Measurement Capability, which is the expanded uncertainty of the measurand without the uncertainty contribution of the instrument under test, is recommended to be lower than 1/3 MPE. The meter is then declared to be non-conforming if at any point the average error of several repetitions for one verification point exceeds the sum of MPE and the estimated expanded uncertainty.

2.4 Test volumes and duration

A crucial parameter to define is the test volume required for verification: the greater the volume of fluid passed during the verification, the lower the relative uncertainty contribution due to the resolution of the meter. On the other hand, high volumes result in longer test durations and can give rise to drift of some influence quantities (e.g. the fluid temperature). The principles for defining the minimum volume of fluid to be used for the verification are unfortunately not explicitly established in technical standards for thermal energy meters, but to this aim consolidated rules of legal metrology for other types of meters (e.g. gas meters) are available, such as:

1. the meter resolution is not adequate when volume/mass corresponding to the last digit or division is not at least one order of magnitude below the uncertainty of the meter itself [20];
2. the volume/mass of a one-minute run at the maximum meter flow-rate is adequate [21].

As above mentioned, in-field expanded uncertainty of thermal energy meters under verification should be less than 1/5 MPE, including the contribution of the meter resolution R, to which a rectangular probability distribution can be associated. Similarly, OIML R 140 [21] for the measuring systems for gaseous fuel establishes $U < 1/3\ MPE$. Since the measurement is performed by difference between two values, then the sole uncertainty contribution of the meter resolution is $u_R = R/\sqrt{6}$. As a general rule, considering a reduction coefficient f of the MPE (e.g. f equal to 3 or 5), it derives $2\frac{u_R}{Q} \le \frac{MPE}{100\,f}$, in which $Q = n\,R$ is the minimum amount and n is the number of scale intervals and, finally, $n \geq 100 \frac{2f}{\sqrt{6}\, MPE}$. Therefore, since the resolution in volume of thermal energy meters for residential use is often equal to 1 dm^3, significant fluid volumes are needed for tests to comply with the applicable MPE limits and related uncertainties, thus resulting in a considerable effort in terms of duration and costs. Figure 3 shows the trend of the minimum test duration of the flow sensor verification of a thermal energy meter (MID class 2 with $q_p = 2.5$ m^{3}h^{-1}) as a function of the resolution and of the flow-rate, considering $U < 1/5\, MPE$.

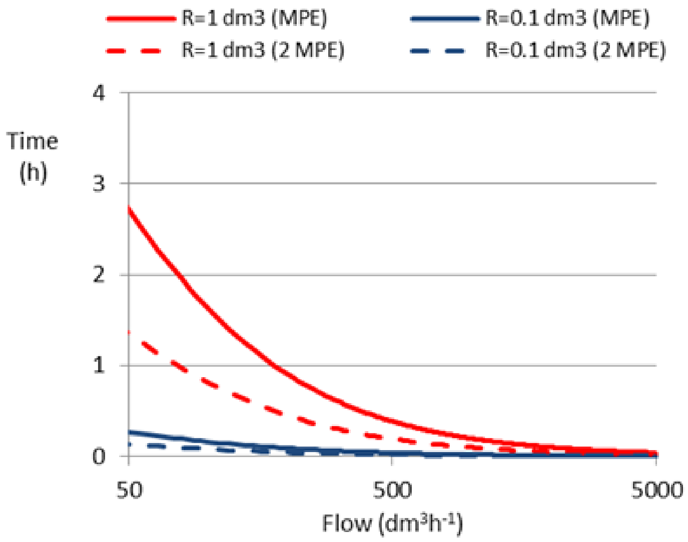


Figure 3 – Minimum test duration for a MID class 2 thermal energy meter

The above described issue is valid also for temperature measurements, since at $\Delta\vartheta$=3 K (which is the $\Delta\vartheta_{min}$ homologated value of numerous thermal energy meters on the market), the MPE of the temperature sensor pair is 3.5% (in the case of errors equal to the initial verification ones) corresponding to about 0.1 °C. Therefore, to meet EN 1434-5 requirement ($U < 1/5\, MPE$), the expanded uncertainty of the temperature difference should be lower than 0.03 °C, meaning the expanded uncertainty of single temperature sensors should not exceed 0.02 °C, which is a particularly critical value. As a consequence, statutory accuracy requirements may be unreasonable, especially in the field.

2.5 Uncertainty estimation of clamp-on flow measurement

As far as the mean volumetric fluid flow rate q_v is concerned, the mathematical model of the measurement can be expressed in the following form:

$$q_v = \frac{\pi (D_e - 2s_p)^2 c_w}{4 \sin \alpha} \left(\frac{\Delta t_{bf}}{t_f + t_b - 2\tau} \right) \quad (1)$$

where t_b and t_f are the measurements of total times of flight of ultrasounds from transmitter to receiver transducers in backward and forward flow directions respectively, Δt_{bf} is the difference between backward and forward total times of flight, τ is the delay time spent by the ultrasound beam to pass through the pipe wall and the external supports (wedges) for ultrasonic transducers, α is the wedge angle (equal to the transmission angle of ultrasounds through wedges), c_w is the speed of sound in the wedge material, D_e is the pipe external diameter and s_p is the pipe wall thickness.

The delay time τ can be evaluated using the following relation:

$$\tau = 2\left(\frac{s_w}{c_w \cos\alpha} + \frac{s_p}{c_p \cos\beta}\right) + \frac{\delta L \sin\alpha}{c_w} \qquad (2)$$

where s_w is the wedge thickness, namely the distance between the ultrasonic transducers and the external pipe surface, c_p is the speed of sound in the pipe material, δL is the error associated to the distance between ultrasonic transducers and β is the ultrasound propagation angle through the pipe wall, which can be determined by the Snell's relation for the acoustic refraction at the wedge-pipe interface:

$$\frac{\sin\beta}{c_p} = \frac{\sin\alpha}{c_w} \qquad (3)$$

An example of uncertainty budget for a DN25 clamp-on flow meter, characterized by an ultrasound V-path configuration, for a mean fluid velocity (water at 20 °C) of 1.0 m s^{-1} is shown in Table 5. To evaluate the uncertainty budget of the flow rate measurement through ultrasonic clamp-on flow meter, according to Eq. (1) typical values, best uncertainties and probability density functions have been assumed for the input quantities.

Table 5 –Uncertainty budget for a clamp-on flow-meter at v=1.0 m s^{-1}

Quantity	*Symbol* X_i	*Mean value* $\mu(X_i)$	*Standard uncertainty* $u(X_i)$	*Probability density function*	*Sensitivity coefficient* $\partial q_v/\partial X_i$	*Relative standard uncertainty contribution* $\lvert u_i(q_v)\rvert/\mu(q_v)$
Pipe external diameter	D_e	3.37·10^{-2} m	5.0·10^{-5} m	Normal	4.5·10^{-2} m^{2}s^{-1}	0.358 %
Pipe wall thickness	s_p	2.90·10^{-3} m	3.0·10^{-5} m	Normal	-7.2·10^{-2} m^{2}s^{-1}	0.343 %
Error of the distance between US transducers	δL	0 m	5.0·10^{-4} m	Normal	4.1·10^{-3} m^{2}s^{-1}	0.322 %
Forward US total time of flight	t_f	7.82·10^{-5} s	3.0·10^{-9} s	Normal	-7.6 m^{3}s^{-2}	0.004 %
Backward US total time of flight	t_b	7.82·10^{-5} s	3.0·10^{-9} s	Normal	-7.6 m^{3}s^{-2}	0.004 %
Backward-forward US times of flight difference	Δt_{bf}	2.30·10^{-8} s	5.0·10^{-11} s	Normal	2.7·10^4 m^{3}s^{-2}	0.217 %
Wedge angle	α	0.663 rad	9.0·10^{-4} rad	Normal	-2.3·10^{-4} m^{3}s^{-1}rad^{-1}	0.033 %
Wedge thickness	s_w	3.00·10^{-2} m	2.5·10^{-5} m	Normal	1.7·10^{-2} m^{2}s^{-1}	0.066 %
Speed of sound in the wedge material	c_w	2300 ms^{-1}	2.31 ms^{-1}	Uniform	-7.9·10^{-9} m^2	0.003 %
Speed of sound in the pipe material	c_p	3200 ms^{-1}	2.77 ms^{-1}	Uniform	2.9·10^{-8} m^2	0.013 %
Volumetric flow rate	q_v	Mean value, q_v				6.32·10^{-4} m^{3}s^{-1}
		Standard uncertainty, $u(q_v)$				4.00·10^{-6} m^{3}s^{-1}
		Relative standard uncertainty, $\lvert u(q_v)\rvert/q_v$				0.63 %
		Relative expanded uncertainty (k=2), $\lvert U(q_v)\rvert/\mu(q_v)$				1.26 %

Similarly, for a mean fluid velocity (water at 20 °C) of 0.3 m s^{-1} (corresponding to about 2.3 m^3h^{-1}), expanded uncertainty increases up to 1.86%. The estimated uncertainties are consistent with the ones provided by Annex C of the ISO Standard 12242 [22], although different approach, meter size and measurement conditions have been considered for the uncertainty analysis. Since for fluid velocity above 1.0 ms^{-1} the relative uncertainty is practically constant, the value of about 1.3% represents the typical best uncertainty of ultrasonic Clamp-on MM at laboratory conditions. It can be also highlighted that the main uncertainty contributions on volumetric flow rate measurement are due to measurements of pipe external diameter, pipe wall thickness, forward-backward times of flight difference and separation distance between transmitter and receiver ultrasonic transducers.

It is worth to observe that the standard uncertainty of the difference between forward and backward ultrasonic times of flight, since it is usually obtained through the cross correlation function of the two ultrasonic signals, has been evaluated equal to 50 ps considering the absolute measurements of times of flight as strongly correlated. Furthermore, the uncertainty of the separation distance between the ultrasonic transducers takes into account the possible errors in the placement of transmitter and receiver wedges, which is one of the most critical part of the installation of clamp-on flow meters [23]. Finally, the uncertainties associated to pipe and wedges dimensions are likely to be the ones expected for a best practice installation and configuration of the ultrasonic clamp-on flow meter. Other uncertainty sources, like the thermal expansion of the meter body, the misalignment of the ultrasonic transducers with respect to the pipe axis and the imperfect acoustic coupling between the transducers and the pipe wall, the presence of impurities in the flow [24] have not been taken into account in this work because of the assumptions related to constant and uniform temperature conditions and best practice installation, which occur only in laboratory.

Nevertheless, the high uncertainty values associated to US clamp-on flow measurement can result unacceptable for in-field verifications, both for Welmec 11.1 [19] and EN 1434-5 [18] requirements. Therefore, a different approach should be considered, as for example, admitting the sum of the error and expanded uncertainty of the MM to be lower than the double of the initial verification MPE. At the same time the MM expanded uncertainty, including the main contribution in the field (pipe diameter and thickness measurement, velocity profile, resolution of the MUT) should not exceed the MPE. This situation is represented by

$$(e + U) \leq 2\,MPE \text{ and } U \leq MPE \qquad (4)$$

3 Experimental campaign

The authors performed two experimental campaigns aimed at analysing the in-field verification of thermal energy meters by comparison with a clamp-on US MM and in laboratory by the gravimetric method. The first experimental campaign was carried out at the LAMI, the industrial measurement laboratory of the

University of Cassino and Southern Lazio on a complete meter, but, for the sake of simplicity, separate tests on the flow sensor and the temperature sensor pair have been carried out. The second investigation has been performed at INRIM, the Italian national institute for research in metrology, and concerned the electromagnetic flow rate sensor of a combined meter installed in the district heating substation of a large building.

3.1 In laboratory verification of a complete thermal energy meter

The authors specifically designed and implemented an experimental test layout to evaluate the metrological performance of a complete thermal energy meter in the laboratory configuration through the primary gravimetric test bench of the LAMI and by comparison with a clamp-on US MM. Temperature sensor pair has been tested by comparison with a reference thermometer in a thermostatic bath.

The liquid flow calibration bench of LAMI operates with the gravimetric principle in the flow-rate range from 0.01 to 20.0 m^{3}h^{-1}. The main components of the bench are: i) a 1000 dm^3 tank with electric heaters to allow test temperature of the heating fluid variable between 15 and 90 °C; ii) a flow regulation system; iii) a straight test section suitable for DN15 to DN40 nominal diameters. The liquid volume measured by the meter under test (MUT) is then compared to the mass of the fluid conveyed alternatively in two measuring tanks, which capacity is 600 and 60 dm^3, and measured through two precision scales below the tanks. The best relative expanded uncertainty of the bench ranges between 0.25% and 0.50% depending on the flow-rate and water temperature. Figure 4 shows the sketch of the LAMI test bench.

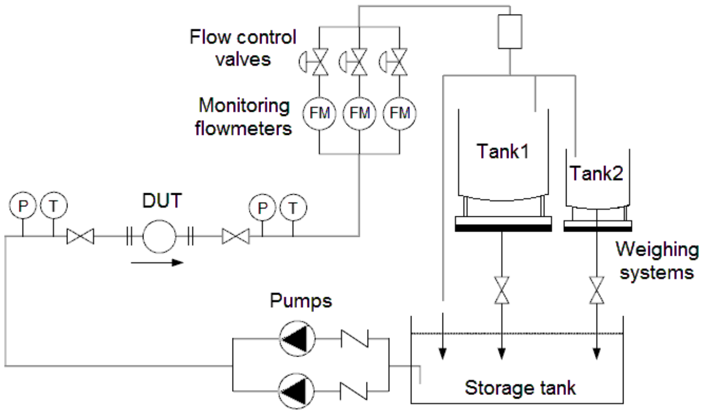


Figure 4 – Sketch of the gravimetric test bench for liquid flows at LAMI

The MUT is made up of a turbine flow sensor (DN 20 MID approved in precision class 2) which permanent flow-rate is 2.5 m^{3}h^{-1}. The MUT resolution in the "TEST" mode, via an optical probe, is 0.001 dm^3. It is worthy to note that during the normal use in the field this mode is prohibited by specific physical and software seals in order to prevent fraudulent access to the software of the meter. The MM used is made up of a clamp-on transit time ultrasonic meter and a pair of PT 1000 4 wires temperature sensors. The declared accuracy of the flow-rate MM is 3% above 0.3 m s^{-1}. In Table 6 the nominal verification points and the related minimum volumes are shown, together with the corresponding MPEs and uncertainties.

Table 6 – Nominal verification conditions for the MUT and related minimum test volume and duration

ϑ *Fluid temp.°C*	$\Delta\vartheta$ *Temp diff. °C*	q *flow* m^3h^{-1}	*Single MPE*				*Double MPE*			
			MPE	*U*	V_{min} *(dm^3)*	*Time (h)*	*2 MPE*	*U*	V_{min} *(dm^3)*	*Time (h)*
50	3	2.5	2.0%	0.4%	202	0.1	4.0%	0.8%	101	0.04
50	15	0.25	2.2%	0.4%	186	0.7	4.4%	0.8%	93	0.40
80	65	0.05	3.0%	0.6%	136	2.7	6.0%	1.2%	68	1.40

Considering that the resolution of the MUT in the field is equal to 1 dm^3, the total duration of the verification would be more than 3 h in the case of single MPE with uncertainty equal to 1/5 MPE and about 2 h in the case of double MPE and uncertainty. To this aim the possibility to access a better resolution during verifications, when available on board the meter, should be crucial.

3.2 In-field and in laboratory verification of the flow sensor of a combined thermal energy meter

Tests carried out at INRIM were aimed at assessing both the in laboratory and in-field performance of the electromagnetic flow sensor of a combined thermal energy meter, installed at the heat exchange substation of a large building supplied by the district heating network of Turin. The investigated flow sensor is a MID class 2 DN 25 which permanent flow-rate is 16 m^3h^{-1}. Tests have been conducted firstly in the field by comparison with a US clamp-on MM, owned by the district heating company and which declared calibration expanded uncertainty is 1.6%. Subsequently, the MUT has been tested at the INRIM laboratory of liquid flow which maintains the national reference standard of volume and liquid flow (water). The primary measurement method, adopted at INRIM is the so-called "weighing and timing" gravimetric method, consisting in the realization of a constant flow of liquid through the MUT and in the deviation of the flow, for a fixed time interval, into a tank for the subsequent accurate weighing. This method is compliant with EN 24185 [25]. The measurement range for flow-rates is from 0.01 to 7 dm^3s^{-1}, with water temperature values ranging from 20 °C to 80 °C. The best relative expanded uncertainty (k=2) is about 0.1%. In Figure 5 a sketch of the INRIM test bench is reported.

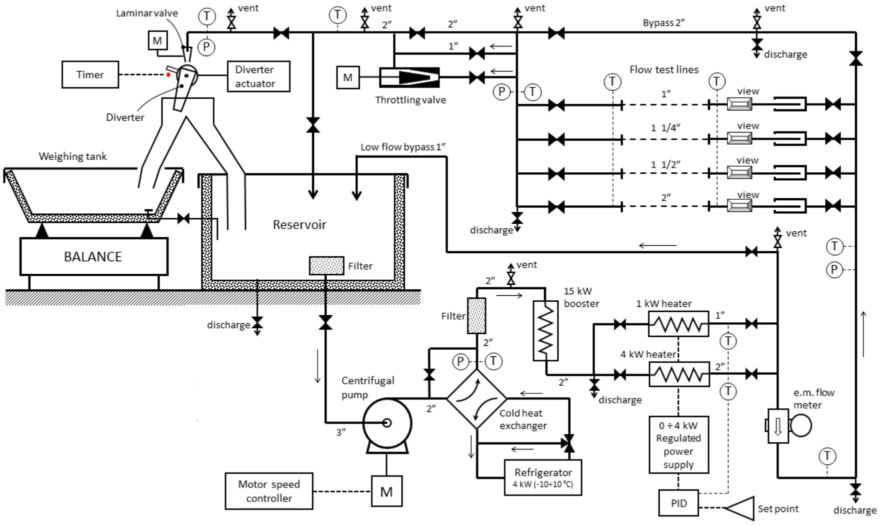


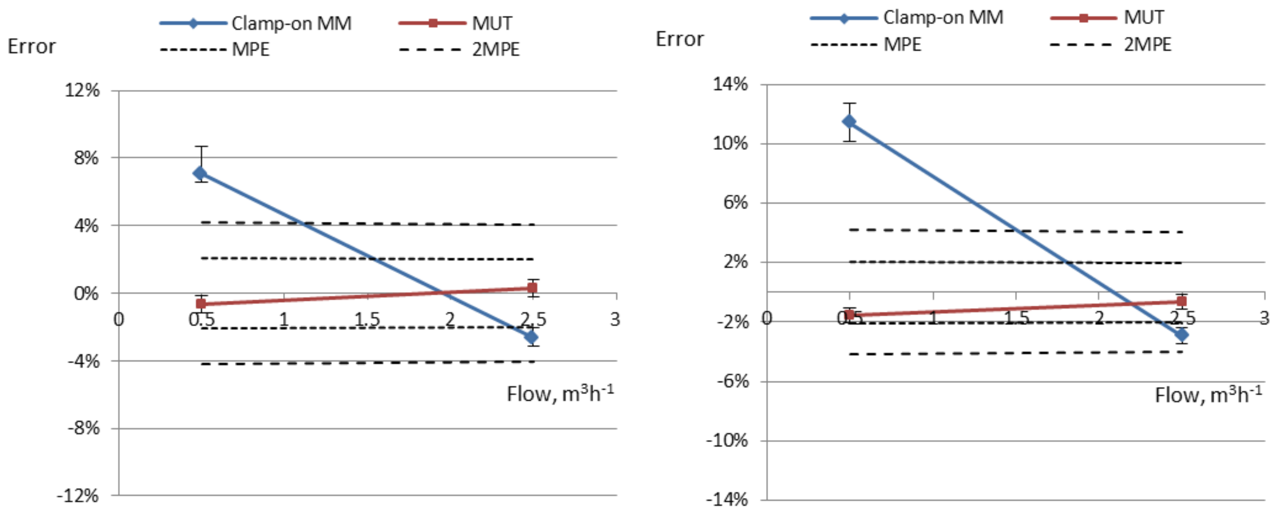
Figure 5 – Sketch of the gravimetric test bench for cold and hot water meters of INRIM

The in laboratory verification of the MUT has been performed "as found" at water temperatures of 20 °C and 50 °C, with expanded uncertainties ranging between 0.1 % and 0.3 % respectively. In order to evaluate drift due to the presence of sludge, the MUT has been tested again at 20 °C after the cleaning of the inner surface.

4. Results and discussion

During the preliminary operations of the in laboratory verification of a complete thermal energy meter, some issues were found that led to a high variability of the MM performance. In particular: i) at low test flow rates (i.e. q<0.5 m^{3}h^{-1}), the clamp on MM shows a very low repeatability; ii) the coupling gel used presented an evident degradation of the performance at a fluid temperature of 50 °C, so as not to guarantee an effective coupling of the sensors on the pipe. It was therefore necessary to replace the gel with a high temperature resistant one and to carry out the verification tests at a minimum flow rate of 0.50 m^{3}h^{-1}, due to the instability of the MM at lower flow-rates. Consequently, authors performed tests at 0.50 and 2.50 m^{3}h^{-1}, with fluid temperature 20 and 50 °C and the related results are shown in Figure 6. As far as possible, a test volume of approximately 250 dm^3 was used.

At high fluid temperatures, the thermal expansion of the flow meter body plays an important role, leading to systematic error. In this case $q_{v,true} = q_{v,meas}(1 + 3\alpha\Delta T)$ [26]. Thus, considering a linear thermal expansion coefficient α of the pipe of $17\cdot10^{-6}$ °C^{-1} , the correction is about 0.15 % at ΔT=30 °C. The results obtained with the MUT are consistent with this correction, but the fluid temperature seems to affect significantly the MM at low flow-rate, since a bias of about +4.4% has been observed at ϑ=50 °C in respect to ϑ=20 °C. This effect is probably ascribed to systematic errors on the time of flight in the fluid, in particular at low velocity.



a) ϑ=20°C b) ϑ=50°C

Figure 6 – Test results with US clamp-on MM correctly installed (straight pipe)

Subsequently, in order to verify the performance of the MM in non-optimal installation conditions, tests were repeated with the MM installed immediately downstream to a 90° elbow, that is a situation which could be frequent in the field due to particular plant constraints. In this case the MM showed a significant bias (i.e. about -4%) in respect to the undisturbed flow condition (see Figure 7).

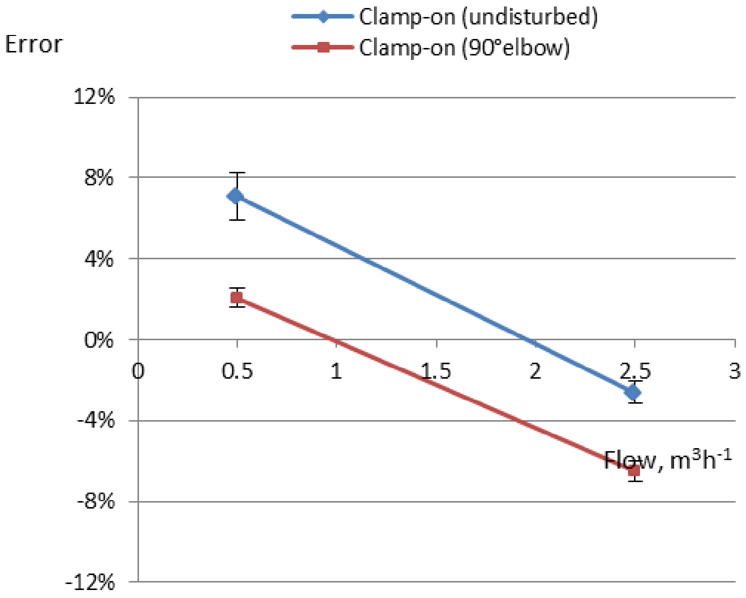


Figure 7 –Results with disturbed (90° elbow) and undisturbed US clamp-on MM at ϑ=20°C

From the experimental results obtained, the following considerations emerge:

1. the clamp-on MM shows significant errors especially at low flow rates and this is due to the impossibility of working below 0.3 m/s;

2. the clamp-on MM shows quite good repeatability at high flow rates regardless the fluid temperature, whereas at low flow rates error increases as temperature increases (from about + 7.1% at ϑ= 20 °C to about + 11.3% at ϑ= 50 °C);
3. in presence of a 90° elbow flow disturbance the clamp-on MM showed a constant drift of about -4%.

The authors finally verified the temperature sensor pair at different ϑ (50°C and 20°C) and q (2.50 m^3h^{-1} and 0.50 m^3h^{-1}). In the experimental campaign, reference values of return temperature (ϑ_{low}) are given by the outlet temperature of the bench (installed upstream of the weighing tanks and immersed in the heating fluid flow). A PT100 reference sensor immersed in a thermostatic bath was also used as reference flow temperature (ϑ_{high}). Both reference PT100 show a resolution of 0.01 °C and the expanded uncertainty of the temperature difference is about 0.03°C. The verification results are shown in Table 7.

Table 7 – Verification results for temperature sensor pair (insulated pipe)

Flow *m^3h^{-1}*	*ϑ fluid* *°C*	*$\Delta\vartheta$* *Ref. °C*	*Clamp-on MM*			*MUT*			*MPE*	*2 MPE*
			$\Delta\vartheta$, °C	*E, °C*	*E*	*$\Delta\vartheta$, °C*	*E, °C*	*E*		
0.5	20	6.30	6.10	-0.20	-3.17%	6.00	-0.30	-4.76%	1.93%	3.86%
2.5	20	6.30	6.10	-0.20	-3.17%	6.00	-0.30	-4.76%	1.93%	3.86%
0.5	50	24.86	24.20	-0.66	-2.65%	25.91	1.05	4.22%	0.86%	1.72%
2.5	50	24.66	23.90	-0.76	-3.08%	24.65	-0.01	-0.04%	0.86%	1.73%

It can be pointed out that: i) negative results were found both for the clamp-on MM and for the MUT at all test conditions with single MPE (except for the MUT at high flow and high $\Delta\vartheta$ condition), ii) results were positive for clamp-on MM only at low $\Delta\vartheta$ (at low and high flow-rates) and at high $\Delta\vartheta$ and high flow-rate for the MUT with double MPE. Further experiments were carried out both with insulated piping (i.e. sensor installed under the insulation) and with not insulated (i.e. sensor installed on the external surface of the pipe directly immersed in the external environment), in order to evaluate the influence of the ambient temperature on the accuracy of the probes. In the case of not-insulated pipe, in fact, the measurement of the temperature on the outside of the pipe can be significantly different from that measured directly in the fluid (as in the laboratory bench) or through a thermowell (as in the MUT), and this difference may depend on the fluid flow rate in the pipeline. The results of these tests are shown in Table 8.

Table 8 – Error analysis of insulated and not insulated pipes

Flow *m^3h^{-1}*	*ϑ fluid* *°C*	*Insulated pipe (°C)*		*Not-insulated pipe (°C)*		*Deviation (°C)*	
		$E_{Clamp-on}$	E_{MUT}	$E_{Clamp-on}$	E_{MUT}	Clamp-on MM	MUT
0.5	20	0.20	0.20	-0.10	0.10	0.30	0.10
2.5	20	0.20	0.20	-0.10	0.10	0.30	0.10
0.5	50	0.50	0.05	-0.40	0.23	0.90	-0.18
2.5	50	0.60	0.11	-0.40	0.26	1.00	-0.15

It can be pointed out that the MM shows a drift of 0.30 °C, from a positive value (insulated pipe) to a negative one (not-insulated pipe) and that the higher is the fluid temperature the higher is the drift (at 50°C this is equal to about 1 °C). On the other hand, the MUT showed limited deviation (about 0.1 °C) at low temperature while at high temperature the effect is opposite and more significant (equal to about -0.2 °C). The test flow-rate appears to be a less significant influence parameter for both clamp-on MM and MUT. Concerning the tests carried out by INRIM, Figure 8 shows the results for both in laboratory and in the field conditions.

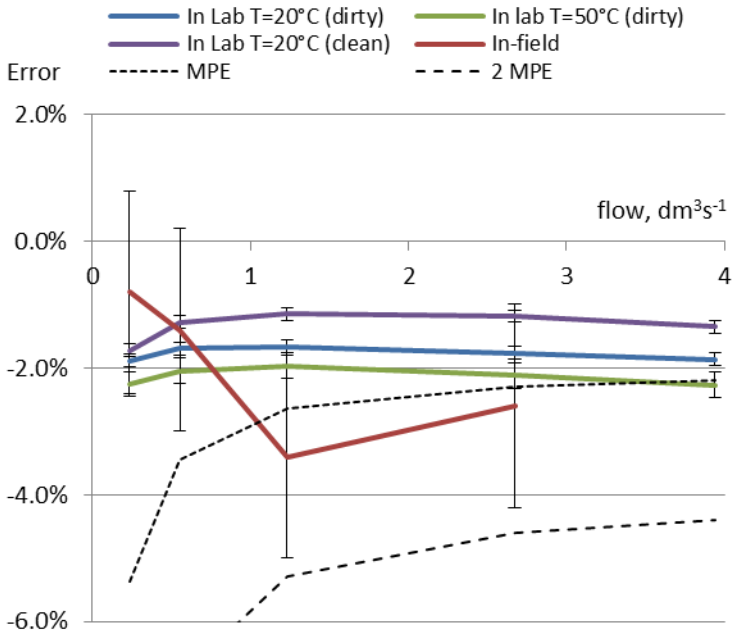


Figure 8 - Experimental results of the verification of the flow sensor of a combined thermal energy meter in laboratory at different temperatures and conditions and in the field

From the analysis of the results it can be pointed out that:

- in-field results at $q > 4$ m^{3}h^{-1} showed the MUT exceeds MPEs of initial verification, whereas in laboratory results are always compliant with MPEs of initial verification except for the dirty sensor at high temperature and high flow-rate;
- at about 4 m^{3}h^{-1} the sum of the error and the uncertainty exceeded in the field the 2 MPE limit and this is due to the large uncertainty of the clamp-on MM
- related differences up to 2% between in-field and in laboratory results have been found, except at 1.8 m^{3}h^{-1}, where a good agreement occur;
- compared to a substantially constant behaviour in the laboratory (errors in the range between -1.6% and -1.9%), the MUT showed higher variability in the field (between -0.7% and -3.4%) which can be reasonably attributed to the plant constraints and to the method's reliability;
- in the laboratory a constant bias of the MUT (on average equal to about -1%) has been found as the temperature of the fluid increases from 20 to 50 °C;
- the presence of sludge causes a performance decay of about 0.8% on average.

Therefore, to get better performance in the field, the MM readings should be corrected with the calibration errors estimated in the laboratory (e.g. with the gravimetric method for flow and in thermostatic bath for

temperature sensor pair). In this case, to meet the strict legal metrology statutes, the MM should be adjusted and the calibration results “as found” reported in the calibration certificate together with the “as left” ones.
Moreover, as well known, the calibration results in terms of error and uncertainty of the MM in the laboratory (as well as that of any other measuring instrument) are worth only at the punctual calibration conditions described in the certificate. Unfortunately, in the field, the calibration conditions are difficult to replicate (e.g. straight pipe lengths upstream and downstream not fully developed, presence of debris, rust and inhomogeneity in the pipe, deposit of dust and other obstructions on the bottom of the pipe with consequent narrowing of the section, etc.) and the related correction factors are very difficult to estimate. Thus, in addition to the environmental conditions during test, the characteristics of the pipe on which the ultrasonic clamp-on MM is installed (e.g. finish, material and tube thickness) must also be considered. In this regard, the application of suitable correction coefficients both for the flow sensor and the temperature sensor pair (i.e. deriving from calibration errors and from the analysis of the real in service conditions) should be useful to enhance the reliability of in-field verification.
In the following table 9 the statutory uncertainty limit is compared with the typical uncertainty performance in the field and in the laboratory when a clamp-on MM is used.

Table 9 – In-field and in laboratory typical uncertainties and statutory ($\boldsymbol{U} < 1/5\ MPE$) for subsequent verification of a thermal energy meter (class 2 MID $q_{\mathbf{p}}$=2.5 m^3h^{-1} and $\Delta\vartheta_{\mathbf{min}}$=3 °C)

Verification point		*MPE*	*Statutory uncertainty*		*Typical uncertainty*	
			1/5 MPE	*2/5 MPE*	*in-field*	*in-lab*
Flow-rate	2.5 m^3h^{-1}	2.02%	0.40%	0.81%	1-3%	0.2-1%
	0.5 m^3h^{-1}	2.10%	0.42%	0.84%	1.5-4%	0.2-1%
	0.05 m^3h^{-1}	3.00%	0.60%	1.20%	2-5%	0.5-2%
Temperature difference	3 °C	3.50%	0.02 °C	0.04 °C	> 0.1 °C	0.02-0.05 °C
	15 °C	1.10%	0.03 °C	0.07 °C	> 0.1 °C	0.02-0.05 °C

From the experimental evidence, it is clear that compliance with the statutory uncertainty limits is very challenging in some operational (e.g. low flow-rates, high fluid temperature, low temperature difference) and in-field conditions. Therefore, it should be preferable to carry out verifications in the laboratory, especially in disputes. On the other hand, larger MPEs and uncertainties should be admitted for in-field verifications, due to the unavoidable installation effects. In this latter case, the criterion of equation (4) could be considered. This could allow the use of US clamp-on MMs for in-field verifications.

5. Conclusions

The use of Clamp-on MM can greatly simplify the operational procedures of the verification of thermal energy meters in the field, but particular attention must be paid to the plant constraints and to the different behaviour in respect to the rated operating conditions in laboratory. On the operational hand, very strict limits in terms of uncertainty are established by applicable technical standard, both for in the field and in laboratory verification. To this aim, unfortunately, clamp-on flow meters show significant uncertainties of flow rate measurement (e.g. ranging from about 1.3% to 1.9% at 1.0 and 0.3 m s^{-1}, respectively), mainly due to the uncertainties associated to the characteristic dimensions of the pipe (diameter and thickness), the measurement of the difference between forward and backward ultrasound times of flight and the separation distance between transmitter and receiver ultrasonic transducers.

The obtained experimental results show:

- US clamp-on are significantly affected by flow disturbance and by temperature effect which can lead to unpredictable systematic errors probably due to the measurement of the time of flight;
- a significant variability of the accuracy in the field occurs which can be reasonably attributed to the test conditions and to the method's reliability (i.e. comparison with clamp-on MM), whereas a constant behaviour in the laboratory has been observed;
- the presence of dirt and sludge causes a decay of the metrological performance of the flow sensor.

Furthermore, in-field verifications require high test volumes in order to minimize the influence of the meter readings, leading to long test durations and high costs. To this aim the possibility to access a better reading in test-mode configuration of the meter should be very useful together with a different approach in respect to the uncertainty limits in the field (e.g. admitting the sum of uncertainty and error not exceeding MPEs, together with the possibility to apply the correction of the main influences in the field). Finally, tests carried out show the need to provide, both in the new buildings and in the retrofit of existing plants, suitable configurations for the proper installation of additional verification systems (e.g. MM flow sensor, thermowells for reference themometers) in order to avoid plant constraints to significantly influence the outcome of the verification.

Acknowledgments

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Acronyms and Symbols

DN	Nominal Diameter
EED	Energy Efficiency Directive
e	Measured error
EU	European Union
INRIM	Istituto Nazionale per la Ricerca Metrologica
MID	Measuring Instruments Directive
MM	Master Meter
MPE	Maximum Permissible Error

MUT	Meter Under Test
$OIML$	Organisation Internationale de Métrologie Légale
PT	Platinum Thermoresistance
R	Meter Reading
US	Ultrasonic
α	Wedge angle, °
c_p	Speed of sound in the pipe material, m s^{-1}
c_w	Speed of sound in the wedge material, m s^{-1}
D_e	Pipe external diameter, mm
δL	Separation distance between US transducers, mm
Δt_{bf}	Backward-forward US times of flight difference, ns
ϑ	Fluid temperature, K
$\Delta\vartheta$	temperature difference, K
$\Delta\vartheta_{max}$	maximum temperature difference, K
$\Delta\vartheta_{min}$	Minimum temperature difference, K
q	flow-rate, m^3h^{-1}
q_p	permanent flow-rate, m^3h^{-1}
q_i	minimum flow-rate, m^3h^{-1}
q_s	Upper flow rate limit, m^3h^{-1}
q_v	Volumetric flow rate, m^3h^{-1}
s_p	Pipe wall thickness, mm
s_w	Wedge thickness, mm
t_b	Backward US total time of flight, µs
t_f	Forward US total time of flight, µs
V_{min}	Minimum fluid volume, dm^3

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