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This is the author's submitted version of the contribution published as:

Original

Field verification of thermal energy meters through ultrasonic clamp-on master meters / Ficco, G.; Frattolillo, A.; Malengo, A.; Puglisi, G.; Saba, F.; Zuena, F.. - In: MEASUREMENT. - ISSN 0263-2241. - 151:(2020), p. 107152. [10.1016/j.measurement.2019.107152]

Availability:

This version is available at: 11696/61476 since: 2021-01-24T11:13:18Z

Publisher:

elsevier

Published

DOI:10.1016/j.measurement.2019.107152

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

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3

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10

11

12 **Abstract**

13

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

24

25

26 **Keywords:**

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

29

30

31 **1. Introduction**

32

33 Thermal energy consumed in a building or in an apartment is measured through a thermal energy balance
34 wherein the flow rate of the working fluid, heat capacity and temperature are multiplied to yield heat flow
35 [1]. A thermal energy meter is then made up of a flow-meter, a temperature sensor pair (generally platinum
36 thermal resistance PT 500 or PT 1000) and a calculator module which processes volume and temperatures
37 measurements and calculates the thermal coefficient depending on the fluid density and specific heat

38 capacity. According to the harmonized technical standards [2, 3], a thermal energy meter is either a complete
39 instrument (consisting of embedded calculator and flow/temperature sensors) or combined (consisting of
40 flow sensor, temperature sensor pair and calculator as separate sub-assemblies). In almost all cases, complete
41 meters are used in the residential sector for sub-metering purposes (i.e. heat cost allocation and billing) when
42 a centralized heating plant is present. On the other hand, combined meters are generally used by large users,
43 both commercial and residential (e.g. directly in the district heating substation at the border with the supply
44 company). In EU countries, the spread of thermal energy meters for the measurement of heating and cooling
45 consumption has been recently pushed by Directive 2012/27/EU (EED) on energy efficiency [4], which has
46 set measurement of individual heat consumptions as a fundamental tool to increase efficiency and promote
47 energy savings.

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

54 Since thermal energy meters, as well as water and gas meters [11], are subject to natural drift of their
55 metrological performances, an adequate system of periodic in service inspections is required for consumer
56 protection. In Italy, for thermal energy meters and other instruments, the National Authority for legal
57 metrology instruments issued Decree n. 93 of 21 April 2017 [12] laying down the regulations for subsequent
58 and in service verification of measuring instruments regulated by legal metrology. For thermal energy meters
59 the frequency of subsequent verifications has been set, however the technical procedures in the field or in the
60 laboratory are still missing and they have not been punctually defined as instead for other categories of
61 instruments (e.g. for active electrical energy meters and non-automatic weighing instruments). In particular,
62 subsequent verification of thermal energy meters are mandatory, which frequency is variable between 5 and
63 9 years depending on the measuring principle of the flow sensor and on its permanent flow rate q_p . With
64 regard to the maximum permissible errors (MPE), it is established that for subsequent verifications they are
65 equal to those set for in-service verifications by the relevant Harmonized Standard or applicable OIML
66 Recommendation or, ultimately, those established for the initial verification (i.e. Annex VI MI-004 of the
67 MID directive). Subsequent verifications may be also performed in laboratory since, as a general principle,
68 whatever the reason for removal from the original place of installation, there is no obligation to reinstall the
69 instrument in the same place from which it was removed nor the impossibility or prohibition to reinstall the
70 same in a different place. Obviously, results of the verification in the field and in laboratory should be
71 comparable ensuring also metrological compatibility in terms of measured errors and related uncertainties.

72 In-field verification present the advantage that test are performed at the punctual installation conditions and
73 thus the effective metrological performances of the meter emerge. This is crucial for consumer protection,
74 however, in the field the particular actual operational conditions of use and the need to guarantee the

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

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

97
98

99 **2. Theory and Methods**

100

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

110

111 **2.1 Initial verification of thermal energy meters (EN 1434-5)**

112

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

117 Technical standard EN 1434-5 [18] specifies that verification of thermal energy meters shall be performed at
 118 the extremes and midpoints of its ranges and that, if the meter is a combined instrument, the flow sensor, the
 119 temperature sensors and the calculator shall each be tested separately. Moreover: i) the verification of the
 120 flow sensor is carried out according to the specifications of the EU type certificate (e.g. conductivity, fluid
 121 temperature, upstream and downstream straight sections); ii) the return temperature must be in the range
 122 (50 ± 5) °C for heating and (15 ± 5) °C for cooling (however, when specified in the EU-type certificate, tests
 123 can be performed with fluid at ambient temperature); iii) temperature sensor pair must be checked (without
 124 thermowell and with an immersion depth of at least 90% of the length) in the same thermostatic bath at three
 125 temperature values. According to EN 1434-5 [18], verification points for complete meters and combined are
 126 reported in Table 1 and 2, respectively.

127

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

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

129

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

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

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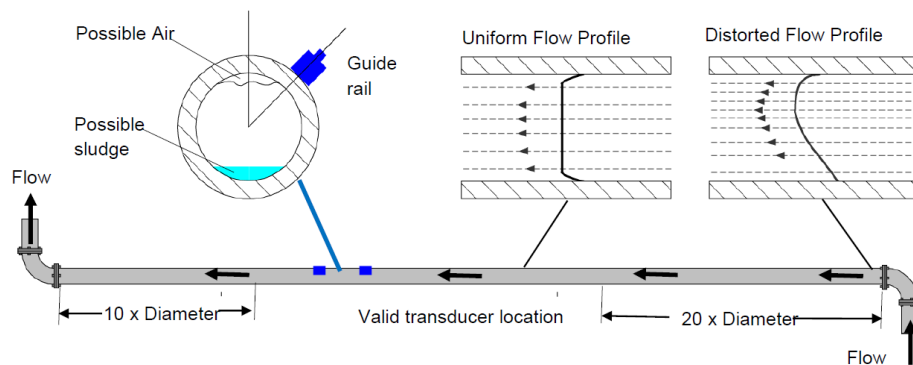
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* or $140 K < (\vartheta_{max} - 20 K) < \vartheta_3 < \vartheta_{max}$, if $\vartheta_{max} > 150 K$ ** for cooling applications verification is performed at $\Delta\vartheta_{min} \leq \Delta\vartheta \leq 1.2 \Delta\vartheta_{min}$ and $0.8 \Delta\vartheta_{max} \leq \Delta\vartheta \leq \Delta\vartheta_{max}$ 134 **2.2 Subsequent and in service verification of thermal energy meters**

135

136 Subsequent verification, in order to guarantee the continuity of supply as well as reliability of the result in
 137 congruence with the real installation and operational conditions, should be normally performed in the field.
 138 However, the in-field verification of thermal energy meters presents numerous technical and operational
 139 issues. In particular, the installation conditions of the meter, due to plant constraints (e.g. presence of
 140 upstream and downstream disturbances, connections and reductions in diameter, vertical/horizontal
 141 installation, availability of thermowells for the temperature probe on the return pipe, etc.), often do not meet
 142 the installation requirements referred to in type certificates. Furthermore, the installation of a reference MM
 143 is not always technically feasible. With regard to the operational procedures, in-field subsequent verifications

144 of thermal energy meters can be performed only through comparison method (both for flow and temperature
 145 sensors) whereas in laboratory more accurate methods (such as volumetric and gravimetric methods for the
 146 flow sensor) may also be applied. As a consequence, the strict metrological requirements in terms of error
 147 and uncertainty established by technical standards are generally met only in laboratory, whereas installation
 148 effects and critical operational conditions (i.e. low flow-rates and low temperature differences) may
 149 significantly influence in-field verification results, leading to unacceptable uncertainties.
 150 The in-field verification with clamp-on ultrasonic (US) MM seems to be the best from the point of view of
 151 ease of field operations, since flow and temperature sensors are installed directly on the external surface of
 152 the pipe without need to dismantle part of the plant and to interrupt the service. On the other hand, the
 153 clamp-on installation mode presents undoubted metrological key concerns, both for flow-rates and
 154 temperature measurements. In fact, to guarantee a correct installation of the flow sensor suitable straight
 155 undisturbed pipe lengths upstream and downstream of the flow sensor (up to 20 and 10 times the pipe
 156 diameter, respectively) are requested and particular attention must be paid to the possible presence of air and
 157 sludge in the pipeline (see Figure 1).
 158



159
 160 Figure 1 – Installation requirements of clamp-on US MMs
 161

162 As regards the temperature sensors verification, the typical configuration of thermal energy meters requires
 163 the use of specific thermowells, both on the flow and on the return pipes (this latter is generally mounted on
 164 board the flow sensor). The use of different systems during verifications (e.g. clamp-on temperature probes,
 165 thermostatically controlled baths) could lead to errors which are difficult to estimate and variable since they
 166 depend on the thermodynamic conditions and the velocity of the fluid in the pipeline. Finally, the contact
 167 resistance between the sensor and the pipe should be considered and this will depend on the material of the
 168 pipe.
 169

170 2.3 Maximum permissible errors and uncertainties

171
 172 Unfortunately, for thermal energy meters nor the harmonized standard EN 1434-1 neither the OIML R75
 173 Recommendation prescribe specific maximum permissible errors (MPE) for in service verifications. In this
 174 regard, a single reference is established in par. 3.23 of EN 1434-1 for the definition of "durability" in which

175 it is stated that "a measuring instrument will be designed to maintain an adequate stability of its metrological
 176 characteristics (e.g. to fulfil the double of MPE)". Table 3 and Figure 2 show MPEs for type approval and
 177 initial verification of thermal energy meters, as reported in EN 1434:1 [2] and OIML R75 [3].

178

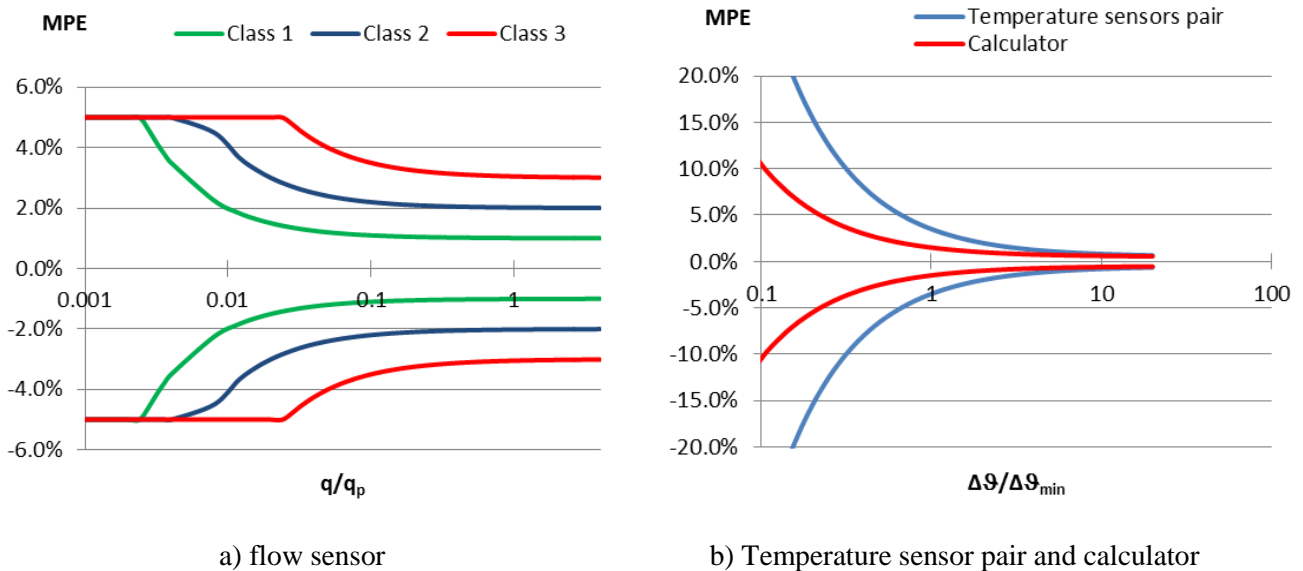
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Table 3 – MPE of thermal energy meters (initial verification)

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	$\left(3 + 0.05 \frac{q_p}{q}\right)^*$			$\left(3 + 0.05 \frac{q_p}{q}\right)^* + 1 + 4 \frac{\Delta\vartheta_{min}}{\Delta\vartheta}$

180
181

* but not more than 5 %



a) flow sensor

b) Temperature sensor pair and calculator

182

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

183

184 Among the relevant technical aspects set by Decree 93 [12], the error of the instruments used in the
 185 verification (e.g. Master Meter) must be lower than 1/3 of the maximum permissible error (MPE) allowed for
 186 the meter being tested. Furthermore, standard EN 1434-5 [18] prescribes uncertainties of the reference
 187 standards, the method and the instruments shall not exceed 1/5 of the MPE of the meter being tested or, if
 188 exceeding 1/5 of the MPE, the difference between the uncertainty and 1/5 of the MPE must be subtracted
 189 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
 190 is the measured error. Table 4 shows, as for example, for the accuracy Class 2 and up to size DN50 the
 191 applicable MPEs and the corresponding maximum uncertainties calculated at different q_p/q ratio
 192 considering the limit of 1/5 MPE in initial verification.

193

194

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

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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.

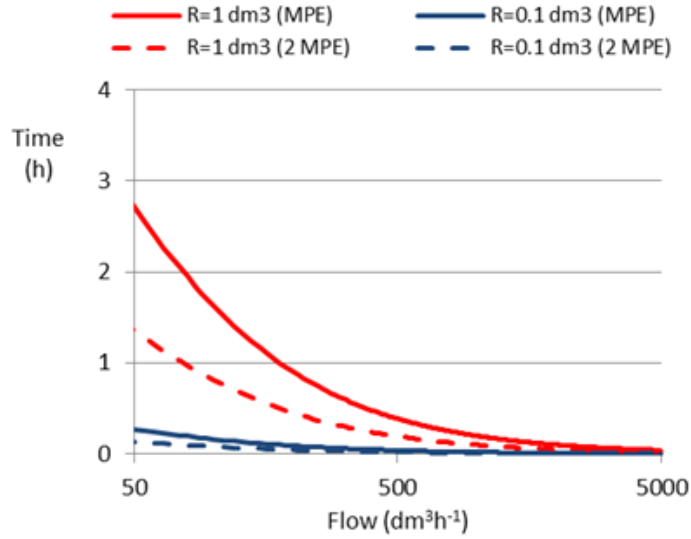
2.4 Test volumes and duration

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 $2 \frac{u_R}{Q} \leq \frac{MPE}{100 f}$, in which $Q = n R$ is the

227 minimum amount and n is the number of scale intervals and, finally, $n \geq 100 \frac{2f}{\sqrt{6} MPE}$. Therefore, since the
 228 resolution in volume of thermal energy meters for residential use is often equal to 1 dm^3 , significant fluid
 229 volumes are needed for tests to comply with the applicable MPE limits and related uncertainties, thus
 230 resulting in a considerable effort in terms of duration and costs. Figure 3 shows the trend of the minimum
 231 test duration of the flow sensor verification of a thermal energy meter (MID class 2 with $q_p = 2.5 \text{ m}^3\text{h}^{-1}$) as a
 232 function of the resolution and of the flow-rate, considering $U < 1/5 MPE$.
 233



234
 235 Figure 3 – Minimum test duration for a MID class 2 thermal energy meter
 236

237 The above described issue is valid also for temperature measurements, since at $\Delta\vartheta=3 \text{ K}$ (which is the $\Delta\vartheta_{min}$
 238 homologated value of numerous thermal energy meters on the market), the MPE of the temperature sensor
 239 pair is 3.5% (in the case of errors equal to the initial verification ones) corresponding to about $0.1 \text{ }^\circ\text{C}$.
 240 Therefore, to meet EN 1434-5 requirement ($U < 1/5 MPE$), the expanded uncertainty of the temperature
 241 difference should be lower than $0.03 \text{ }^\circ\text{C}$, meaning the expanded uncertainty of single temperature sensors
 242 should not exceed $0.02 \text{ }^\circ\text{C}$, which is a particularly critical value. As a consequence, statutory accuracy
 243 requirements may be unreasonable, especially in the field.
 244

245 2.5 Uncertainty estimation of clamp-on flow measurement

246
 247 As far as the mean volumetric fluid flow rate q_v is concerned, the mathematical model of the measurement
 248 can be expressed in the following form:

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

249 where t_b and t_f are the measurements of total times of flight of ultrasounds from transmitter to receiver
 250 transducers in backward and forward flow directions respectively, Δt_{bf} is the difference between backward

251 and forward total times of flight, τ is the delay time spent by the ultrasound beam to pass through the pipe
 252 wall and the external supports (wedges) for ultrasonic transducers, α is the wedge angle (equal to the
 253 transmission angle of ultrasounds through wedges), c_w is the speed of sound in the wedge material, D_e is the
 254 pipe external diameter and s_p is the pipe wall thickness.

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

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

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

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

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

265

266

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

267

268 Similarly, for a mean fluid velocity (water at 20 °C) of 0.3 m s⁻¹ (corresponding to about 2.3 m³h⁻¹),
269 expanded uncertainty increases up to 1.86%. The estimated uncertainties are consistent with the ones
270 provided by Annex C of the ISO Standard 12242 [22], although different approach, meter size and
271 measurement conditions have been considered for the uncertainty analysis. Since for fluid velocity above 1.0
272 ms⁻¹ the relative uncertainty is practically constant, the value of about 1.3% represents the typical best
273 uncertainty of ultrasonic Clamp-on MM at laboratory conditions. It can be also highlighted that the main
274 uncertainty contributions on volumetric flow rate measurement are due to measurements of pipe external
275 diameter, pipe wall thickness, forward-backward times of flight difference and separation distance between
276 transmitter and receiver ultrasonic transducers.

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

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

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

296

297

298 **3 Experimental campaign**

299

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

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

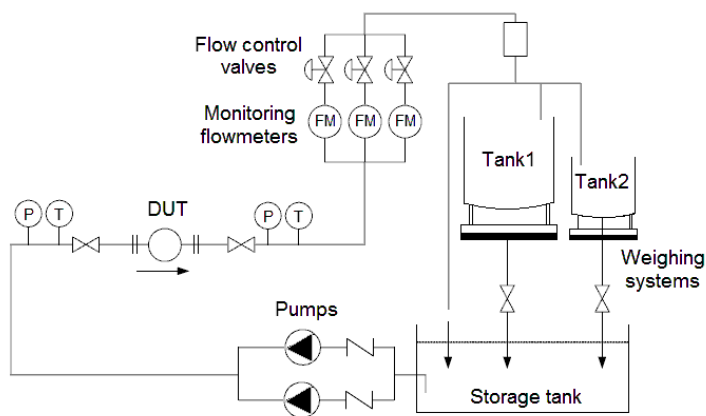
308

309 **3.1 In laboratory verification of a complete thermal energy meter**

310

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

315 The liquid flow calibration bench of LAMI operates with the gravimetric principle in the flow-rate range
316 from 0.01 to 20.0 m³h⁻¹. The main components of the bench are: i) a 1000 dm³ tank with electric heaters to
317 allow test temperature of the heating fluid variable between 15 and 90 °C; ii) a flow regulation system; iii) a
318 straight test section suitable for DN15 to DN40 nominal diameters. The liquid volume measured by the meter
319 under test (MUT) is then compared to the mass of the fluid conveyed alternatively in two measuring tanks,
320 which capacity is 600 and 60 dm³, and measured through two precision scales below the tanks. The best
321 relative expanded uncertainty of the bench ranges between 0.25% and 0.50% depending on the flow-rate and
322 water temperature. Figure 4 shows the sketch of the LAMI test bench.



323

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

325

326 The MUT is made up of a turbine flow sensor (DN 20 MID approved in precision class 2) which permanent
327 flow-rate is 2.5 m³h⁻¹. The MUT resolution in the "TEST" mode, via an optical probe, is 0.001 dm³. It is
328 worthy to note that during the normal use in the field this mode is prohibited by specific physical and
329 software seals in order to prevent fraudulent access to the software of the meter. The MM used is made up of
330 a clamp-on transit time ultrasonic meter and a pair of PT 1000 4 wires temperature sensors. The declared

331 accuracy of the flow-rate MM is 3% above 0.3 m s^{-1} . In Table 6 the nominal verification points and the
 332 related minimum volumes are shown, together with the corresponding MPEs and uncertainties.

333

334 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

335

336 Considering that the resolution of the MUT in the field is equal to 1 dm^3 , the total duration of the verification
 337 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
 338 case of double MPE and uncertainty. To this aim the possibility to access a better resolution during
 339 verifications, when available on board the meter, should be crucial.

340

341 3.2 In-field and in laboratory verification of the flow sensor of a combined thermal energy meter

342

343 Tests carried out at INRIM were aimed at assessing both the in laboratory and in-field performance of the
 344 electromagnetic flow sensor of a combined thermal energy meter, installed at the heat exchange substation of
 345 a large building supplied by the district heating network of Turin. The investigated flow sensor is a MID
 346 class 2 DN 25 which permanent flow-rate is $16 \text{ m}^3\text{h}^{-1}$. Tests have been conducted firstly in the field by
 347 comparison with a US clamp-on MM, owned by the district heating company and which declared calibration
 348 expanded uncertainty is 1.6%. Subsequently, the MUT has been tested at the INRIM laboratory of liquid
 349 flow which maintains the national reference standard of volume and liquid flow (water). The primary
 350 measurement method, adopted at INRIM is the so-called "weighing and timing" gravimetric method,
 351 consisting in the realization of a constant flow of liquid through the MUT and in the deviation of the flow,
 352 for a fixed time interval, into a tank for the subsequent accurate weighing. This method is compliant with EN
 353 24185 [25]. The measurement range for flow-rates is from 0.01 to $7 \text{ dm}^3\text{s}^{-1}$, with water temperature values
 354 ranging from $20 \text{ }^\circ\text{C}$ to $80 \text{ }^\circ\text{C}$. The best relative expanded uncertainty ($k=2$) is about 0.1%. In Figure 5 a
 355 sketch of the INRIM test bench is reported.

356

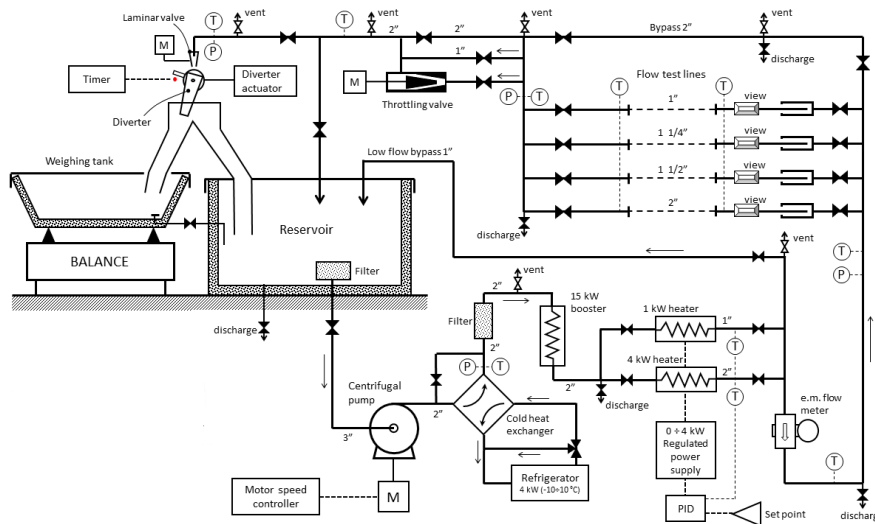


Figure 5 – Sketch of the gravimetric test bench for cold and hot water meters of INRIM

357

358

359

360 The in laboratory verification of the MUT has been performed “as found” at water temperatures of 20 °C and
 361 50 °C, with expanded uncertainties ranging between 0.1 % and 0.3 % respectively. In order to evaluate drift
 362 due to the presence of sludge, the MUT has been tested again at 20 °C after the cleaning of the inner surface.

363

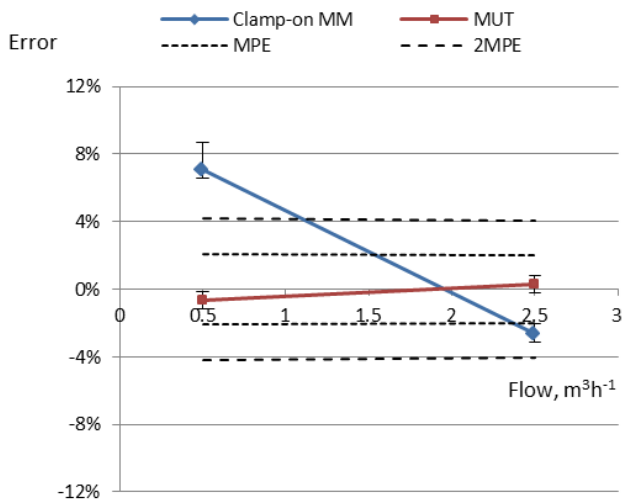
364

4. Results and discussion

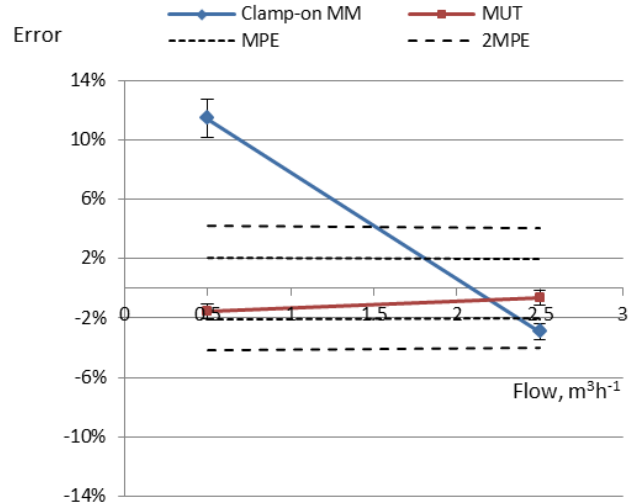
366

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

376 At high fluid temperatures, the thermal expansion of the flow meter body plays an important role, leading to
 377 systematic error. In this case $q_{v,true} = q_{v,meas}(1 + 3\alpha\Delta T)$ [26]. Thus, considering a linear thermal
 378 expansion coefficient α of the pipe of $17 \cdot 10^{-6} \text{ }^\circ\text{C}^{-1}$, the correction is about 0.15 % at $\Delta T = 30 \text{ }^\circ\text{C}$. The results
 379 obtained with the MUT are consistent with this correction, but the fluid temperature seems to affect
 380 significantly the MM at low flow-rate, since a bias of about +4.4% has been observed at $\vartheta = 50 \text{ }^\circ\text{C}$ in respect
 381 to $\vartheta = 20 \text{ }^\circ\text{C}$. This effect is probably ascribed to systematic errors on the time of flight in the fluid, in
 382 particular at low velocity.



a) $\theta=20^\circ\text{C}$



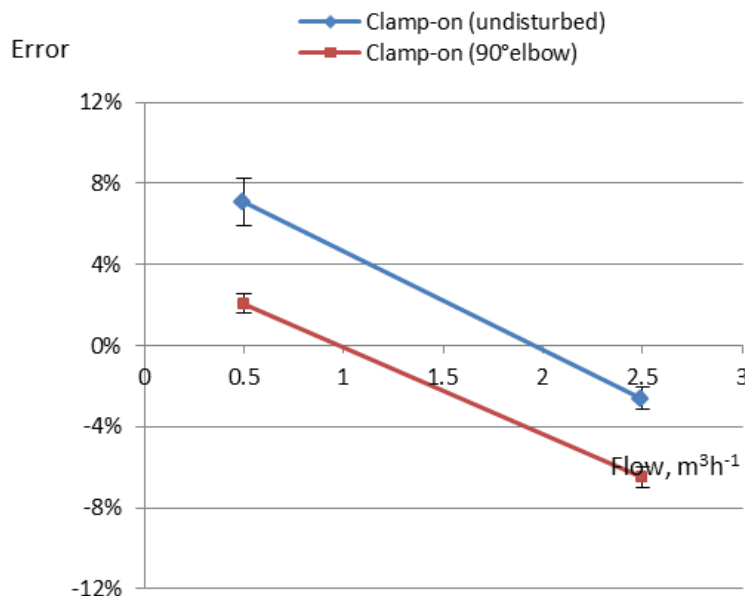
b) $\theta=50^\circ\text{C}$

383

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

384

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



389

Figure 7 –Results with disturbed (90° elbow) and undisturbed US clamp-on MM at $\theta=20^\circ\text{C}$

391

392 From the experimental results obtained, the following considerations emerge:

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

395 2. the clamp-on MM shows quite good repeatability at high flow rates regardless the fluid temperature,
 396 whereas at low flow rates error increases as temperature increases (from about + 7.1% at $\vartheta = 20\text{ }^{\circ}\text{C}$ to
 397 about + 11.3% at $\vartheta = 50\text{ }^{\circ}\text{C}$);

398 3. in presence of a 90° elbow flow disturbance the clamp-on MM showed a constant drift of about -4%.

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

405
 406 Table 7 – Verification results for temperature sensor pair (insulated pipe)

Flow m^3h^{-1}	ϑ fluid $^{\circ}\text{C}$	$\Delta\vartheta$ Ref. $^{\circ}\text{C}$	Clamp-on MM			MUT			MPE	2 MPE
			$\Delta\vartheta$, $^{\circ}\text{C}$	E , $^{\circ}\text{C}$	E	$\Delta\vartheta$, $^{\circ}\text{C}$	E , $^{\circ}\text{C}$	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%

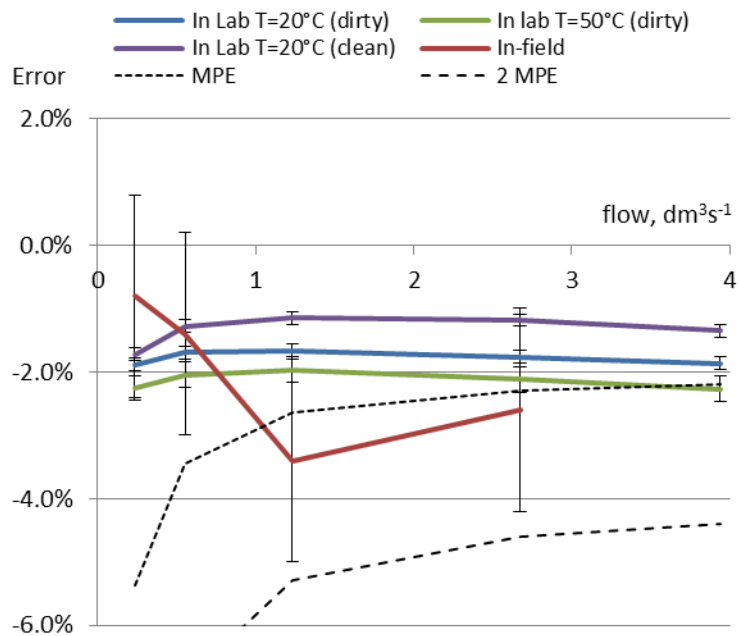
407
 408 It can be pointed out that: i) negative results were found both for the clamp-on MM and for the MUT at all
 409 test conditions with single MPE (except for the MUT at high flow and high $\Delta\vartheta$ condition), ii) results were
 410 positive for clamp-on MM only at low $\Delta\vartheta$ (at low and high flow-rates) and at high $\Delta\vartheta$ and high flow-rate for
 411 the MUT with double MPE. Further experiments were carried out both with insulated piping (i.e. sensor
 412 installed under the insulation) and with not insulated (i.e. sensor installed on the external surface of the pipe
 413 directly immersed in the external environment), in order to evaluate the influence of the ambient temperature
 414 on the accuracy of the probes. In the case of not-insulated pipe, in fact, the measurement of the temperature
 415 on the outside of the pipe can be significantly different from that measured directly in the fluid (as in the
 416 laboratory bench) or through a thermowell (as in the MUT), and this difference may depend on the fluid flow
 417 rate in the pipeline. The results of these tests are shown in Table 8.

418
 419 Table 8 – Error analysis of insulated and not insulated pipes

Flow m^3h^{-1}	ϑ fluid $^{\circ}\text{C}$	Insulated pipe ($^{\circ}\text{C}$)		Not-insulated pipe ($^{\circ}\text{C}$)		Deviation ($^{\circ}\text{C}$)	
		$E_{Clamp-on}$	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

420
 421 It can be pointed out that the MM shows a drift of $0.30\text{ }^{\circ}\text{C}$, from a positive value (insulated pipe) to a
 422 negative one (not-insulated pipe) and that the higher is the fluid temperature the higher is the drift (at 50°C
 423 this is equal to about $1\text{ }^{\circ}\text{C}$). On the other hand, the MUT showed limited deviation (about $0.1\text{ }^{\circ}\text{C}$) at low

424 temperature while at high temperature the effect is opposite and more significant (equal to about -0.2 °C).
 425 The test flow-rate appears to be a less significant influence parameter for both clamp-on MM and MUT.
 426 Concerning the tests carried out by INRIM, Figure 8 shows the results for both in laboratory and in the field
 427 conditions.
 428



429
 430 Figure 8 - Experimental results of the verification of the flow sensor of a combined thermal energy meter in
 431 laboratory at different temperatures and conditions and in the field
 432

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

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

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

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

464
 465 Table 9 – In-field and in laboratory typical uncertainties and statutory ($U < 1/5 MPE$) for subsequent
 466 verification of a thermal energy meter (class 2 MID $q_p=2.5 \text{ m}^3\text{h}^{-1}$ and $\Delta\vartheta_{\min}=3 \text{ }^\circ\text{C}$)

Verification point		MPE	Statutory uncertainty		Typical uncertainty	
			1/5 MPE	2/5 MPE	in-field	in-lab
Flow-rate	2.5 m ³ h ⁻¹	2.02%	0.40%	0.81%	1-3%	0.2-1%
	0.5 m ³ h ⁻¹	2.10%	0.42%	0.84%	1.5-4%	0.2-1%
	0.05 m ³ h ⁻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

467
 468 From the experimental evidence, it is clear that compliance with the statutory uncertainty limits is very
 469 challenging in some operational (e.g. low flow-rates, high fluid temperature, low temperature difference) and
 470 in-field conditions. Therefore, it should be preferable to carry out verifications in the laboratory, especially in
 471 disputes. On the other hand, larger MPEs and uncertainties should be admitted for in-field verifications, due
 472 to the unavoidable installation effects. In this latter case, the criterion of equation (4) could be considered.
 473 This could allow the use of US clamp-on MMs for in-field verifications.

474 475 476 5. Conclusions

477
 478 The use of Clamp-on MM can greatly simplify the operational procedures of the verification of thermal
 479 energy meters in the field, but particular attention must be paid to the plant constraints and to the different
 480 behaviour in respect to the rated operating conditions in laboratory. On the operational hand, very strict

481 limits in terms of uncertainty are established by applicable technical standard, both for in the field and in
482 laboratory verification. To this aim, unfortunately, clamp-on flow meters show significant uncertainties of
483 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
484 to the uncertainties associated to the characteristic dimensions of the pipe (diameter and thickness), the
485 measurement of the difference between forward and backward ultrasound times of flight and the separation
486 distance between transmitter and receiver ultrasonic transducers.

487 The obtained experimental results show:

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

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

503

504

505 **Acknowledgments**

506

507 This work has been developed under the project “Ricerca di Sistema Elettrico PAR 2017” funded by ENEA
508 (grant number I12F16000180001).

509

510

511 **Acronyms and Symbols**

512

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

<i>MUT</i>	Meter Under Test
<i>OIML</i>	Organisation Internationale de Métrologie Légale
<i>PT</i>	Platinum Thermoresistance
<i>R</i>	Meter Reading
<i>US</i>	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 ³ h ⁻¹
q_p	permanent flow-rate, m ³ h ⁻¹
q_i	minimum flow-rate, m ³ h ⁻¹
q_s	Upper flow rate limit, m ³ h ⁻¹
q_v	Volumetric flow rate, m ³ h ⁻¹
s_p	Pipe wall thickness, mm
s_w	Wedge thickness, mm
t_b	Backward US total time of flight, μ s
t_f	Forward US total time of flight, μ s
V_{min}	Minimum fluid volume, dm ³

513

514

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516

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