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Abstract

Individual metering for heating and cooling application has been recognized as an effective tool to improve energy efficiency in buildings in EU. Hence, thermal energy meters are widely spreading in district heating networks and in buildings served by a central heating/cooling source. By a legal metrology point of view, while type approval and initial verification of thermal energy meters are regulated by MID and harmonized standards EN 1434, no technical common procedure is still available in EU for subsequent verifications both in laboratory and on the field and member states are tackling this issue with different approaches. Nevertheless, the verification of thermal energy meters is a difficult task, due to the complex measuring chain and to the need to set appropriate verification points combined in flow-rate and temperature difference values. In this paper, the authors present the results of an experimental campaign aimed at analysing the key metrological issues and the compatibility between the results of subsequent verification of a thermal energy meter performed in the laboratory and on the field.

1. Introduction

Measurement and billing of thermal energy in residential and commercial buildings is a very debated topic among the scientific community since several technical, metrological and consumer protection issues are involved [1-6]. Individual heat metering, in fact, is considered an effective tool to improve energy savings in the residential sector, and the Energy Efficiency Directive 2012/27/EU (EED) has set the obligation for buildings supplied by central heating sources, or served by district heating/cooling networks, to install individual metering systems for sharing cost of space heating/cooling and domestic hot water.

Thermal energy meters (TEMs) must fulfil essential metrological requirements showing error and associated measurement uncertainty not exceeding maximum permissible errors (MPE). However, MID only provides strict regulation of type approval and initial verification of such kind of meters, leaving EU member states the task to regulate subsequent verification, in continuity with the potential existing rules. Furthermore, nor harmonized technical standards (i.e. EN 1434 [7]) neither legal metrology recommendations (i.e. OIML R75) set specific requirements for subsequent verification of TEMs and only a hint of increased permissible error limit in service is generally given by OIML.

In theory, master meters for flow measurement could allow effective on-field verifications when plant configuration is such as to allow the installation according to the related manufacturers' instruction. Unfortunately, these installation conditions are still rare to find. Thus, the most appropriate type of master meter available for on-field verifications of flow-meters would be the ultrasonic (US) clamp-on since the disruption of the flow is not necessary. However, clamp-on flow-meters are significantly affected by flow disturbance and by temperature effect which can lead to systematic errors related to the time of flight measurement. Furthermore, the uncertainties associated to the knowledge of the material and of the dimensional characteristics of the pipe (i.e. diameter and thickness) cannot be neglected when measured on the field. For these reasons, their use in the field is critical and only through the careful evaluation of all the influence quantities, overall uncertainties can be within about 2-3 %.

In [8] the authors designed and developed an experimental campaign aimed at investigating the metrological issues related to the use of US clamp-on flow sensor as reference meters during in field verification of TEMs. It has been demonstrated the clamp-on transducer installation (vertical/horizontal, straight pipes, etc.) and configuration (pipe material and dimensions, fluid characteristic) play a crucial role and that legal metrology verification requirements in terms of permissible error and uncertainty in some cases are very challenging.

In [9] three flow-sensors for TEMs (turbine, electromagnetic and ultrasonic) have been investigated in the field showing a different behaviour (i.e. errors below 2.5% for turbine and ultrasonic sensors and within 6.9% for the electromagnetic). Other kind of flow disturbances have been investigated in [10] and [11] showing deviations up to 5% downstream to an elbow and ranging -0.6% to -7.9% due to a pipe obstruction five diameters upstream of the sensor, respectively. In a CFD simulation study [12], errors in the range from 1.5% to 4.5% have been found when the distance between the flow-sensor and a double elbow is lower than 40 straight pipe diameters.

As far as calibration of temperature sensors pair is concerned, wide traceability is available both within accredited laboratories and primary metrology institutes, with expected expanded uncertainties on single sensor within 0.1°C. However, the strict metrological requirements in terms of uncertainty especially at particular operative conditions (e.g. low temperature difference between flow and return pipes) impose particular care in designing the calibration process of the temperature sensors pair [13].

In this paper, the authors present the results of an experimental campaign aimed at analysing the key metrological issues related to subsequent verification of TEMs performed both in the laboratory (with gravimetric and volumetric methods) and on the field. Finally, the outcome of the verification was assessed both in the case of the complete meter (i.e. in energy units) and of separate sub-assemblies, as allowed by the harmonised technical standard for initial verification.

2. Materials and Methods

In reference to applicable standards [7], a TEM is either complete (i.e. which does not have separable sub-assemblies, being a single indivisible unit) or combined (i.e. with separable sub-assemblies as flow sensor, a temperature sensors pair, a calculator) or hybrid (the so-called compact) which for the purpose of type approval and verification, can be treated as a combined instrument but, after verification, its sub-assemblies shall be treated as inseparable.

Initial verification of TEMs is performed according harmonized standard EN 1434-5 [14] at "*rated operating conditions*" in the whole measuring range of the EU-type certification (i.e. Module B) in terms of fluid temperatures and temperature difference, flow-rate, heat output, working pressure and nominal pressure). At each verification point the percentage error e_{MUT} is calculated through the following equation:

$$e_{MUT} = \frac{x_{MUT} - x_{ref}}{x_{ref}} \times 100 \qquad (2)$$

where x_{MUT} is the value indicated by the meter, sub-assembly or combination of sub-assemblies under test; x_{ref} is the reference value indicated by the master meter. Verification is passed if the measured errors are within the corresponding maximum permissible error (MPE). As a general principle of legal metrology, MPEs in subsequent verification are generally higher (or almost equal) than those in the initial one. In Italy, the national authority has established that MPEs in subsequent verification are double the corresponding ones in initial verification and EU-type certification (i.e. those established by Annex VI of the MID). In Figure 1 the MPE in subsequent verification for a flow sensor as a part of a TEM is reported.

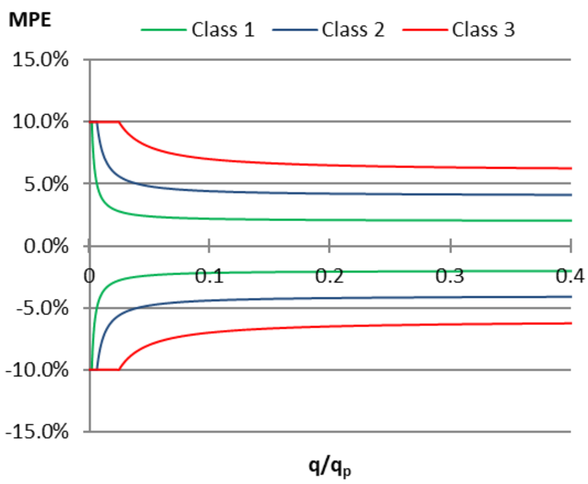

Figure 1: Maximum permissible errors in initial verification for the flow sensor as a part of thermal energy meter

2.1 The experimental campaign

The authors specifically designed an experimental campaign aimed at evaluating the metrological criticalities of TEM verification both in the laboratory and on the field. The experiments were designed aiming at testing the following possible verification combinations, that is: i) complete meter (output in energy); ii) separate sub-assemblies (flow sensor and temperature sensor pair); iii) combination of sub-assemblies (calculator with temperature sensor pair and simulated flow pulses).

The meter under test (MUT) is made up of separate sub-assemblies (see Figure 2):

- magnetic flow sensor, MI-004 approved class 1, q_i=4 m³/h, q_p=100 m³/h, q_s=125 m³/h, resolution R=1 dm³;
- temperature sensor pair manufacturer Jumo, model PT500, MI-004 approved, $\Delta\vartheta_{min}$ =3 °C, $\Delta\vartheta_{max}$ =180 °C, ϑ_{min} = 0 °C, ϑ_{max} =180 °C, resolution R=0.01 °C;
- calculator, MI-004 approved, $\Delta\vartheta_{min}$ =2 K, $\Delta\vartheta_{max}$ =110 K, ϑ_{min} = 0 °C, ϑ_{max} =150 °C, resolution R=10 kWh.

a) b)

Figure 2: The meter under test: a) flow-sensor, b) temperature sensors pair

Tests in the laboratory were performed at HEMINA, a division of ISOIL Group, which is an accredited laboratory for liquid volumes and flow in the range between 0.020 and 1000 m³/h and pipe diameters ranging DN3 to DN 250. The test facility is made up of six independent calibration lines, each performing the static gravimetric method. A calibrated reference master meter is also present in each line allowing the application of the volumetric method also. The expanded calibration uncertainty is within 0.16% and 0.20% respectively for the gravimetric and volumetric method, including the contribution of the best available device assumed equal to 0.10%. In Figure 3 a picture of the test bench is reported.

Figure 3: The flow Calibration plant at Hemina Laboratory

Aiming at simulating the on-site verification, the METRON Division of ISOIL Industria has performed a test campaign on the same test bench at Hemina Laboratory using the procedure and reference systems and auxiliary devices normally used on the field and, in particular:

- US clamp-on flow sensor, accuracy within 3.0% (see Figure 4);
- calculator;
- temperature sensors pair Pt1000, calibration uncertainty (k=2) equal to 0.08 °C;
- n.2 thermostatic baths, with uniformity and stability within 0.1°C;
- US thickness meter, calibration uncertainty (k=2) equal to 0.06 mm;

Figure 4: The flow Ultrasonic clamp-on flow-meter

3. Results and Discussion

In the following the results of the experimental runs have been presented and discussed, together with the analysis of the outcome of the verification process.

3.1 In Laboratory test

In Table 1 the results of the TEM as a whole measuring chain (i.e. complete/hybrid/combined) with output in energy units are depicted. In this test, the gravimetric method has been used for determining the errors of the flow sensors, whereas the temperature sensors pair has been tested immersed in a pair of thermostatic baths together with two reference temperature sensors of the laboratory.

The results of the tests performed on two separate sub-assemblies (i.e. flow sensor and temperature sensors pair) have been reported in Table 2 and Table 3. In particular, tests of the flow-sensor have been repeated both for gravimetric and volumetric methods.

As far as the verification of temperature sensors pair is concerned, according to [14], the measured resistance values of the MUT have been used in a system of three equations to calculate the three constants of the temperature/resistance equation of EN 60751. Thereby the characteristic curve for the temperature sensor is known and it is compared with the “ideal” curve using the standard constants of EN 60751. The error at any temperature is then obtained as a difference between the characteristic curve for each temperature sensor and the “ideal” one. As a final step, the worst-case error of the temperature sensor pair has been determined over the temperature range and over the temperature difference range specified for the sensors.

Finally, in Table 4 the results of the combination of sub-assemblies (i.e. calculator and temperature sensors pair, with simulated flow values) have been reported.

Measured errors for in laboratory tests at all verification points were well below the corresponding MPEs.

3.2 On-field test

Aiming at assessing the reliability of on-field verification of TEMs, specific tests on the MUT were conducted in the same test facility (see par. 2.1) used as a plant system and at the same verifications points, by using reference master meters and standards, auxiliary devices available at the METRON Division of ISOIL Industria.

The results of the on-field tests are reported in Table 5 and Table 6 for the complete meter (whole measuring chain, output in energy units) and for the flow-meter as a separate sub-assembly, respectively. From the analysis of the results, it can be pointed out that complete meter failed the verification at low flow-rate and high $\Delta\vartheta$, thus confirming the predictable criticality related to the use of US clamp-on as reference master meter. In this case, in fact, a measured error of the energy equal to 7.44% has been found, exceeding the corresponding MPE of 4.32%. As far as the test of the separate sub-assembly flow meter is concerned, the above described criticalities related to the flow-rate measurement have been clearly confirmed, since at both the verification points, measured errors (i.e. 2.78% and 4.22% at 30 and 80 m^3/h, respectively) were found well above the corresponding MPE, equal to about 2.0% in both cases.

From the analysis of Table 5 and Table 6, a negative outcome of the on-field verification is obtained and the meter failed the verification, unlike the corresponding outcome of the laboratory tests. From the analysis of the experimental data it can be pointed out the poor behaviour US clamp-on master meter, since the laboratory tests performed immediately before on the same test bench were absolutely normal (see Table 1 and Table 2).

As above mentioned, the clamp-on technique needs the pipe material and dimensions (diameter and thickness) to be accurately known [12]. In this case, it is very likely that the dimensional characteristics of the carbon steel pipe measured on-field (i.e., external diameter 89.8 mm, pipe thickness 4 mm, calculated internal diameter 81.8 mm) may be slightly different from the actual ones of the measuring plant. The authors, in fact, performed a more accurate measurement of these dimensions by dismantling the pipe from the measuring line. The dimensional characterization (performed with a calibrated caliper and a US thickness gauge) returned the following values (reported expanded uncertainties are calculated with k=2): i) external diameter (89.07±0.02) mm; ii) thickness (4.06±0.06) mm; iii) calculated internal diameter (80.95±0.12) mm. Assuming these latter as more accurate values, an overestimation equal to about 2% of the measured flow-rate is demonstrated, leading to the occurrence of significant errors and different outcomes. On the other hand, no significant criticality was found relating to the temperature sensors pair.

4. Conclusions

In this paper, the issue of subsequent verification of thermal energy meters has been investigated performing an experimental campaign at laboratory premise and in the field on a class 1 thermal energy meter. The obtained results show that:

- verification points are easy to reproduce in the laboratory and all the possible test combination (i.e. complete meter output in energy, flow/temperature signal simulated, separate sub-assembly and combination of sub-assemblies) are almost applicable;
- for the investigated class 1 meter measured errors for in laboratory tests at all verification points were well below the corresponding MPEs;
- several practical criticalities occurred in-field, in particular related to the flow-rate measurement, since the US clamp-on technique is particularly affected by the dimensional measurements accuracy (i.e. pipe diameter and thickness);
- despite all tests in the laboratory were positive, the outcome of the in-field verification was negative both in the case of the complete meter and of the separate flow-sensor, and this can be reasonably ascribed to the reliability of the US clamp-on technique in the field.

Table 1: Results of L#1 Test (Complete/Hybrid/Combined, output in energy)

MUT				*Reference*						e_{MUT} (%)	*MPE* (%)	*Outcome*
ϑ_{in} (°C)	ϑ_{out} (°C)	$\Delta\vartheta$ (°C)	E_{MUT} (kJ)	ϑ_{in} (°C)	ϑ_{out} (°C)	$\Delta\vartheta$ (°C)	q (m^3/h)	V (dm^3)	E_{Ref} (kJ)			
106.81	20.04	86.77	72367	106.67	20.03	86.64	4.40	199.71	72374	-0.01	4.29	Pass
35.03	20.04	14.99	31200	34.94	20.03	14.91	10.50	499.31	31061	0.45	5.62	Pass
23.37	20.05	3.32	43960	23.30	20.03	3.27	95.00	3169.70	43225	1.71	11.35	Pass

Table 2: Results of L#2 Test (separate sub-assembly, flow sensor)

Gravimetric method (U=0.16%, k=2)						
q (m^3/h)	V_{ref} (dm^3)	V_{MUT} (dm^3)	e_{MUT} (dm^3)	e_{MUT} (%)	MPE (%)	*Outcome*
4.40	199.92	199.85	-0.07	-0.04	2.01	Pass
10.51	500.33	499.65	-0.68	-0.14	2.01	Pass
94.99	3,159.53	3,155.00	-4.53	-0.14	2.00	Pass
Volumetric method with MM (U=0.20%, k=2)						
q (m^3/h)	V_{ref} (dm^3)	V_{MUT} (dm^3)	e_{MUT} (dm^3)	e_{MUT} (%)	MPE (%)	*Outcome*
4.41	199.79	200.08	0.28	0.14	2.01	Pass
10.51	501.02	500.40	-0.62	-0.12	2.01	Pass
95.00	3,168.43	3,167.54	-0.88	-0.03	2.00	Pass

Table 3: Results of L#3 Test (separate sub-assembly, temperature sensor pair)

ϑ_{in} (°C)	ϑ_{out} (°C)	$e_{\Delta\vartheta}$ (Ω)	$e_{\Delta\vartheta}$ (°C)	$\Delta\vartheta$ (°C)	$e_{\Delta\vartheta}$ (%)	*MPE* (%)	*Outcome*
97.98	0.00	0.25	-0.13	97.98	-0.13	1.18	Pass
180.00	112.49	-0.61	-0.31	67.51	-0.47	1.26	Pass
42.05	39.05	-0.01	0.01	3.00	0.25	7.00	Pass
180.00	177.00	-0.07	-0.04	3.00	-1.17	7.00	Pass

Table 4: Results of L#4 Test (Combination of sub-assemblies calculator and temp. sensors pair, output in energy, simulated flow signal)

MUT				*Reference*						e_{MUT} (%)	*MPE* (%)	*Outcome*
ϑ_{in} (°C)	ϑ_{out} (°C)	$\Delta\vartheta$ (°C)	E_{MUT} (kJ)	ϑ_{in} (°C)	ϑ_{out} (°C)	$\Delta\vartheta$ (°C)	q (m^3/h)	V (dm^3)	E_{Ref} (kJ)			
106.69	20.06	86.64	72489	106.57	20.06	86.52	4.40	200.00	72376	0.16	2.28	Pass
35.03	20.05	14.97	21867	34.94	20.05	14.89	10.50	350.00	21744	0.57	3.61	Pass
23.39	20.05	3.34	48865	23.31	20.05	3.25	95.00	3500.00	47534	2.80	9.38	Pass

Table 5: Results of F#1 Test (Complete/Hybrid/Combined, output in energy)

MUT					*Reference*						e_{MUT} (%)	*MPE* (%)	*Outcome*
ϑ_{in} (°C)	ϑ_{out} (°C)	$\Delta\vartheta$ (°C)	q (m^3/h)	E_{MUT} (MJ)	ϑ_{in} (°C)	ϑ_{out} (°C)	$\Delta\vartheta$ (°C)	q (m^3/h)	V_{ref} (dm^3)	E_{Ref} (MJ)			
99.64	20.01	79.58	4.34	361	99.83	20.06	79.77	4.05	1007	336	7.44	4.32	Fail
35.01	35.01	14.98	10.59	304	35.33	20.04	15.29	10.23	4671	298	2.01	5.61	Pass
23.37	19.99	3.27	94.94	787	23.37	20.10	3.27	89.94	54827	749	5.01	11.34	Pass

Table 6: Results of F#2 Test (Combined meter, flow sensor)

q (m^3/h)	V_{ref} (dm^3)	V_{MUT} (dm^3)	e_{MUT} (dm^3)	e_{MUT} (%)	MPE (%)	*Outcome*
30	5819	5981	162	2.78	2.07	Fail
80	15484	16137	653	4.22	2.03	Fail

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