METROLOGICAL ANALYSIS OF SMART HEAT METERS

L.Celenza[1], M.Dell'Isola[1], R.D'Alessio[1], G.Ficco[1], P.Vigo[2] and A.Viola[2]

[1]Università di Cassino e del Lazio Meridionale, Via G.Di Biasio, 43 03043 Cassino (FR) Italy
[2]Palmer, Parco Scientifico e Tecnologico del Lazio Meridionale, Via Casilina 03013 Ferentino
Corresponding author: ficco@unicas.it, phone +39(0776)2993666

Abstract

Nowadays heat meters only measure the consumptions of thermal energy and they normally do not allow remote transmission of measurement data for subsequent management purposes.

Furthermore, thermal energy measurements are normally performed without evaluating the real "quality" of the supplied thermal energy. On the other hand, the typical features of smart metering could allow to continuously transmit energy data, also interacting with supply and management issues.

In this paper, the authors present a brief critical analysis of the main issues of smart metering in thermal energy measurements both in a direct way using heat meters and in an indirect one using heat cost allocators to enhance energy savings of consumers.

The first results of some metrological tests aimed to evaluate the influence of common installation effects on commercial direct heat meters are also discussed.

1. Introduction

An energy "smart" meter is a device that measures, elaborates and transmitts the supplied energy (electrical, thermal, chemical) data in both domestic and industrial applications. Traditional meters only measures the total consumption and they do not always allow the remote transmission of measurement data for elaboration and management purposes.

Besides, a smart meter is a multifunctional meter that provides an abundance of useful information and management tools. It provides knowledge about the use of energy: how much, where, and when it was consumed and it facilitates effective energy saving. In addition smart meters allow data storage both locally and remotely by suitable data storage and transmission systems. Thanks to a wide variety of interfaces suitable for temperature and flow sensors and for other devices, a smart heat meter can provide an exact picture of energy consumptions and effective energy audits can be made in a short time.

Recent activities of the European Community clearly highlight the intention of pushing toward a wider and wider installation of smart meters in the whole energy scenario. The first reference to regulation and accounting thermal energy systems, even though indirect, can be found in 2002 in the Energy Performance of Buildings Directive [1]. This Directive in fact, indicates that the billing of the costs of heating, air-conditioning and hot water production based on actual consumption, could contribute to energy savings also in the residential sector. The directive also precises that inhabitants of buildings should be enabled to regulate their own heat consumptions. In the recent edition of the Energy Efficiency Directive [2], thermal energy measurements are considered an effective tool to improve energy efficiency and to promote energy savings. The Directive in fact introduces an important innovation in Europe, that is the requirement to install such devices by December 31, 2016 in condominiums and multi-purpose buildings. Also for this reason, smart meters are considered technological innovations indispensible for reaching the goal of the Energy-Climate Package (20/20/20 Package).

From a metrological point of view, thermal energy measurement is certainly one of the most tricky, both for the need to combine multiple measurements and for the difficulty of granting the correct measurement traceability in the traditional forms.

On the other hand, the measurement of energy consumptions by means of heat cost allocators is useful only to get a more reliable sharing of the costs among the users. Thus, heat cost allocators could be useful in a smart metering architecture for billing and management issues.

2. Thermal energy measurement

Thermal energy consumptions can be measured both in a direct way [3] by means of complete heat meters and in an indirect one by means of the so-called heat cost allocators.

2.1 Heat meters

Heat meters measure thermal energy by combining the volume flowrate of the heat conveying liquid leaving and entering a closed heat exchange circuit with the enthalpy difference between the inlet and outlet section of the circuit itself. Furthermore, in an heat exchange circuit in which the heat conveying fluid is normally at liquid state, the pressure difference between inlet and outlet section can be considered negligible. Thus, to get the enthalpy difference, it will be sufficient to measure the inlet and outlet temperatures and to know the thermal and physical

properties of the heat liquid at those temperatures (see fig.1 and equation 1).
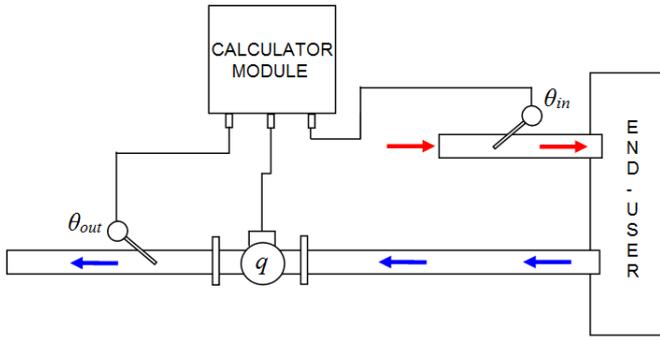

Figure 1 – Measurement scheme of an heat meter

In heat meters, a calculator module elaborates measurement data by means of equation (1).

$$H = \int_{t_1}^{t_2} q\, \rho(\vartheta)\, c_p(\vartheta)\, \Delta\vartheta\, dt = \int_{t_1}^{t_2} q\, K\, \Delta\vartheta\, dt \qquad (1)$$

where:
- H is the thermal energy supplied, J;
- q is the volumetric flowrate of the heat conveying liquid, m^3 h^{-1};
- $\rho(\vartheta)$ is the density of the heat conveying liquid, kg m^{-3};
- c_P is the specific heat at constant pressure of the heat conveying liquid, kJ kg^{-1} K^{-1};
- $\Delta\vartheta$ is the temperature difference between the inlet and outlet section of the system, K;
- K is the thermal coefficient, J m^{-3} K^{-1};
- t is the time, s.

The calculator continuously elaborates the volumetric flowrate q and the temperature difference $\Delta\vartheta$ data by using a thermal coefficient $K(\vartheta_{in}, \vartheta_{out}) = \overline{\rho}(\vartheta_{out}) \cdot \overline{c}_p(\vartheta_{in}, \vartheta_{out})$, that is a function of the average density ρ and of the heat value c_p of the heat conveying liquid.

Finally, from equation (2) obtained by applying the uncertainty propagation law [4], it is evident that in some operative conditions (*e.g.* small $\Delta\vartheta$, low flowrates, impurities in the heat conveying liquid) the relative uncertainty of heat consumptions may become critical.

$$\frac{u_Q}{Q} \cong \sqrt{\frac{u_k}{K}^2 + \frac{u_V}{V}^2 + \frac{u_{\Delta\vartheta}}{\Delta\vartheta}^2} \qquad (2)$$

2.2. Heat cost allocators

Heat cost allocators are commonly used to measure thermal energy in an indirect way. These devices do not allow effective "true" measurement of thermal energy but only the sharing of heat consumptions among users as a share of the total heat consumption of a building. It is therefore always necessary to get a measurement of the total energy delivered by means of a direct heat meter mounted at the inlet and outlet section of the whole building or dedicated to a part of it (e.g. a column).

Heat cost allocators, in fact, are mounted on each radiator present in the single unit and they register the temperature (specifically the difference between the temperature of the radiator surface and the ambient one).

Then, the heat cost allocators calculate heat consumptions units according to equation (3).

$$U_{A,i} = \sum_{i=1}^{N} \left(RF_i \int_t \left(\vartheta_{s,i} - \vartheta_{ind,i} \right) dt \right) \qquad (3)$$

where:
- $U_{A,i}$ are the units consumed by the ith radiator, adimensional;
- RF_i is a rating factor depending on the ith radiator (shape, dimension, material) and on the thermal coupling of temperature sensors, adimensional;
- $\vartheta_{s,i}$ is the surface temperature of ith radiator, K;
- $\vartheta_{ind,i}$ is the indoor environmental temperature in the ith ambient in which the radiator is mounted, K;
- t is the time, s;
- N is the number of radiators in the same unit.

Therefore, heat measurements data are strongly influenced by the correctness of the single installation and from the exact knowledge of the characteristics of the plant and of the radiators.

3. Smart metering of thermal energy

In modern buildings, central heating/cooling plants are now more and more encouraged despite the local ones, since they are more easily maintainable and expected to present higher thermal efficiency and to be less polluting. In such scenario, a possible effective smart metering architecture in heating/cooling applications could foresee the following schemes: i) a direct heat meter installed at the inlet and outlet section of each unit in a "ring" configuration (see fig.2a) and ii) a direct heat meter installed at the basis of a column linked with an heat allocator for each level of the building (see fig.2b).
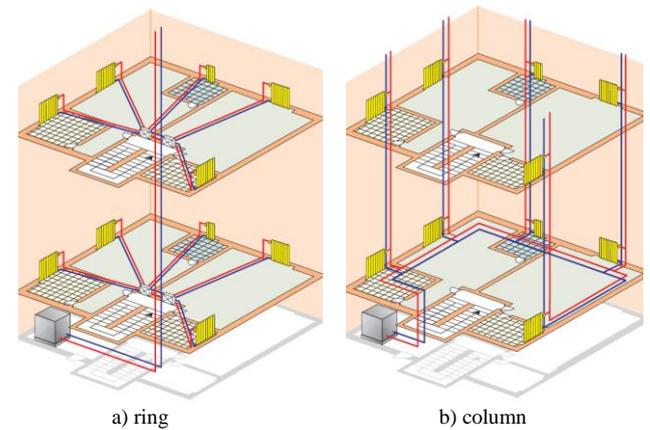

a) ring   b) column

Figure 2 – Central heating/cooling configurations

This latter configuration could be useful also for energy requalifications of old existing buildings and could provide to group devices with same characteristics (i.e. exposure, type of radiator, installation conditions, ...) for an higher effectiveness, both for metering/accounting purpose and management issues.

On the other hand, the main limit regarding full application of smart meter technologies, not only for thermal energy measurements, derives by the lack of both standardization and interoperability between different devices: meters, concentrators, management software.

Thus, in a smart heat meter, the calculator could be interfaced with a central unit to automatically acquire the

data coming from other units (i.e. other heat meters or heat cost allocators) and climatic one. In addition to the traditional billing, the transmission and elaboration of these data could allow the consumer to get a proper management of the heating/cooling plant together with a real time energetic diagnosis of the whole building unit.

Furthermore, smart heat meters could allow the following general issues:

– the monitoring and optimization of users consumptions and indoor supply systems (boilers, stoves, air conditioners);
– the detection of possible anomalous behaviours in the plant and/or the disconnection of some devices in order to avoid faults;
– the detection of hazardous conditions (fumes, gas, water/heat leaks, fire) allowing the remote interruption of electrical energy, gas and heat by using suitable warning and alarm systems;
– the detection of intrusion, providing general alarm systems;
– the definition of a pricing policy based on the real "quality" of the delivered heat;
– the integration with other smart meters (electricity, gas and water) and heat cost allocators;
– a real time operational rating and energetic diagnosis of the plant and/or of the building unit.

On the metrological hand, a smart heat meter could allow to consider adequate correction coefficients both for calibration and for installation effects especially on the flow sensor (i.e. presence of swirl, obstructions, elbows) and on the temperature sensors pair (i.e. immersion depth and radiative contributions of the pipe).

Finally, an heat smart meter could also take into account the real quality of thermal energy supplied to the unit (i.e. the energy at ϑ_{in}) and the one returned (i.e. the energy at ϑ_{out}). Thermal energy consumptions, in fact, could be characterized not only by the measured quantity but also by the quality, as an example by considering the temperature at which the energy is delivered. Thus, an exergetic balance could be useful to this aim.

4. Installation effects influence

On the technical field, the 2004/22/CE directive (named MID, the Measuring Instruments Directive) [5] generally fixes the rules for the approval and initial verification of heat meters (see annex MI-004) in terms of essential requirements and maximum permissible errors (MPEs). For technical specification about the metrological performance, the MID refers to the corresponding national standards implementing the European harmonized standard (or OIML recommendations). For heat meters, these standard are EN 1434 [6] and OIML R75 [7] series. On the other hand, heat cost allocators are not regulated by MID and only EN 834 [8] technical standard is available.

The metrological relevance of introducing proper correction coefficients due to installation effects have been demonstrated by some first experimental tests conducted at LAMI, the industrial measurement laboratory of the University of Cassino, on two MID approved commercial heat meters.

The aim of the tests was to verify the influence of flow disturbers installed upstream to the flowmeter (turbine and ultrasonic) in terms of metrological performance decay.

The tests have been performed by means of an heat meter gravimetric test bench whose main components are: i) a 1000 liters tank with electrical heaters to get a water test temperature ranging from 15 to 90°C; ii) a flowrate regulation system; iii) a straight pipe lenght for the installation of one device under test (DUT) per time.

The volume flowed in the DUT has been compared with the mass of the liquid conveyed into a 600 L and a 60 L tanks and measured by 2 precision scales (with a 10 g and 1 g division, respectively) on which the tanks are installed. The bench works in a range from 0.01 up to 20.0 m^3 h^{-1} and for nominal diameters from DN15 to DN40. Figure 4 shows a scheme of the bench and the test layout during the tests performed.
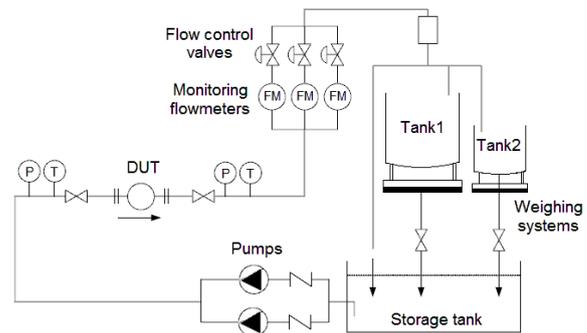

Figure 4a – Heat meters gravimetric test bench scheme

Figure 4b – Heat meters test layout at LAMI

The test bench has been previously calibrated with the facilities of LAMI (accredited laboratory n.105 by Accredia) and its expanded uncertainty have been estimated (with a coverage factor of 2 corresponding to a coverage probability of 95 %) to be about 0.15% at the lower flowrates whereas at higher flowrates it is expected to be about 0.05-0.10%.

In compliance with the MID, an heat meter is either a complete instrument (i.e. a direct heat meter) or a combined instrument consisting of three sub-assemblies: i) flow sensor, ii) temperature sensor pair, and iii) calculator. For each sub-assembly a characteristic MPE is fixed. Thus, the resulting MPE is the sum of three MPEs (flow sensor, temperature sensor pair, and calculator).

The expanded uncertainties shall either: i) not exceed 1/5 of the maximum permissible errors of the heat meter or the subassemblies, or ii) be subtracted from the

maximum permissible errors of the heat meter or the subassemblies to obtain a new MPE.

As an example, in equation (3) and in fig.3 the MPE for a Class 2 MID heat meter (with $\Delta\vartheta_{min}$=3°C , q_p=1.5 m³ h⁻¹ and $\Delta\vartheta$=20°C) is reported.

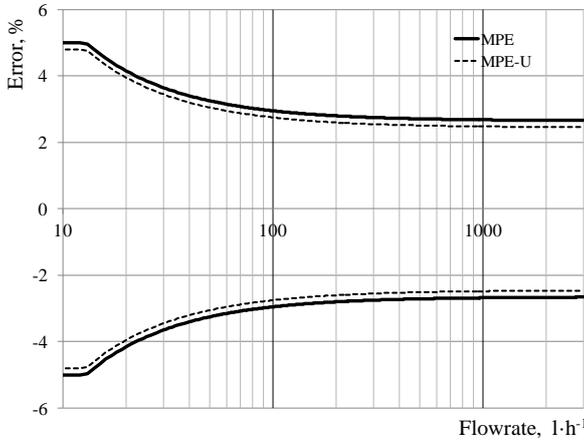$$MPE_{cl.2} = \pm\left(3 + 0.02\frac{q_p}{q} + 4\frac{\Delta\vartheta_{min}}{\Delta\vartheta}\right) \qquad (3)$$

Figure 3 – MPE for a MID approved class 2 heat meter

The applied flow disturbers simulating installation effect were a 90° obstruction and a clockwise swirl generator (see Fig.5) EN 14154-3 compliant [9]. The flow disturbers have been installed upstream to the meter in a typical heating configuration (i.e ϑ_{in}=90°C and ϑ_{out}=70°C) at flowrate ranging from q_i (lower limit) and q_s (upper limit).
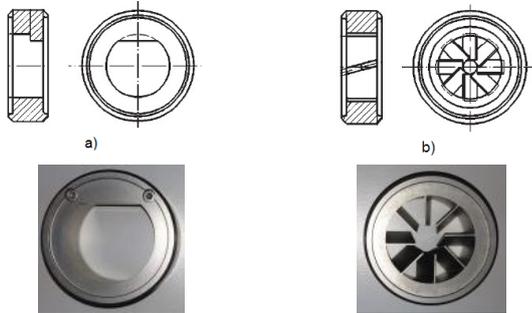

Figure 5 – 90° obstruction (left) and clockwise swirl generator (right) flow disturbances

The results of the tests are reported in table 1 and show that the ultrasonic MID class 2 heat meter (whose main technical data are DN15, q_i=0.03 m³ h⁻¹ , q_p=1.50 m³ h⁻¹, q_s=3.00 m³ h⁻¹, ϑ_{min}=2°C, ϑ_{max}=95°C, $\Delta\vartheta_{min}$=3°C, $\Delta\vartheta_{max}$=90°C) seems to be not particularly influenced by the flow disturbances. In fact, both at minimum and nominal flowrates no particular decay has been measured (see table 1 and figure 5). Only at q_s= 3.00 m³ h⁻¹ the error of the meter with a clockwise swirl slightly exceeded the MPE. This is probably due to the vortices formation downstream to the measuring section of the meter, which generate ultrasonic emissions that influence the measure.

Table 1 – Results of the performance test for a Class 2 Ultrasonic Heat Meter

| Test set up	q [m³h⁻¹]	Actual Error [%]	MPE [±%]	Result
no flow disturber, ϑ_m=90°C, ϑ_r=70°C	q_s=3.00	0.45	±2.66	pass
	q_2=1.10	0.60	±2.68	pass
	q_3=0.30	0.38	±2.75	pass
	q_4=0.09	0.25	±2.97	pass
	q_i=0.03	-2.20	±3.65	pass
clockwise swirl ϑ_m=90°C, ϑ_r=70°C	**q_s=3.00**	**3.46**	**±2.66**	**fail**
	q_2=1.10	0.04	±2.68	pass
	q_3=0.30	0.38	±2.75	pass
	q_4=0.09	-0.78	±2.97	pass
	q_i=0.03	-3.42	±3.65	pass
90° obstruction ϑ_m=90°C, ϑ_r=70°C	q_s=3.00	-1.11	±2.66	pass
	q_2=1.10	-0.05	±2.68	pass
	q_3=0.30	-0.44	±2.75	pass
	q_4=0.09	0.32	±2.97	pass
	q_i=0.03	1.27	±3.65	pass
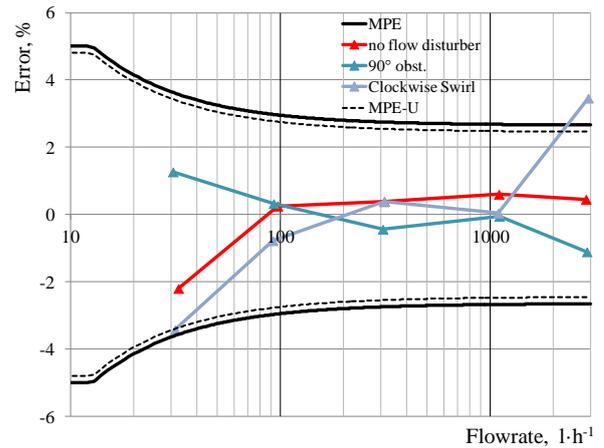
Figure 5 – Errors of the flow disturbance test on an MID Class 2 Heat Meter (ultrasonic)

On the other hand, the MID class 3 turbine heat meter (whose main technical data are DN15, q_i=0.06 m³ h⁻¹ , q_p=1.50 m³ h⁻¹, q_s=3.00 m³ h⁻¹, ϑ_{min}=1°C, ϑ_{max}=130°C, $\Delta\vartheta_{min}$=3°C, $\Delta\vartheta_{max}$=100°C) presents a significant decay of the metrological performance, especially: i) at low flowrates (q_s=60 m³ h⁻¹ and q_4 =160 m³ h⁻¹) with a 90° flow obstruction (see table 2 and fig. 6) and ii) at q_3=0.42 m³ h⁻¹ with the clockwise swirl generator where an error of about 3 times the MPE has been measured.

Table 2 – Results of the performance test for a Class 3 Turbine Heat Meter

| Test set up	q [m³h⁻¹]	Actual Error [%]	MPE [±%]	Result
no flow disturber, ϑ_{in}=90°C, ϑ_{out}=70°C	q_s=3.00	1.64	±3.68	pass
	q_2=1.10	2.06	±3.72	pass
	q_3=0.42	2.98	±3.83	pass
	q_4=0.16	3.00	±4.12	pass
	q_i=0.06	2.45	±4.90	pass
clockwise swirl ϑ_{in}=90°C, ϑ_{out}=70°C	q_s=3.00	0.13	±3.68	pass
	q_2=1.10	-3.28	±3.72	pass
	q_3=0.42	**15.04**	**±3.83**	**fail**
	q_4=0.16	1.08	±4.12	pass
	q_i=0.06	0.44	±4.90	pass
90° obstruction ϑ_{in}=90°C, ϑ_{out}=70°C	q_s=3.00	0.94	±3.68	pass
	q_2=1.10	0.53	±3.72	pass
	q_3=0.42	1.65	±3.83	pass
	q_4=0.16	**-4.87**	**±4.12**	**fail**
	q_i=0.06	**5.47**	**±4.90**	**fail**
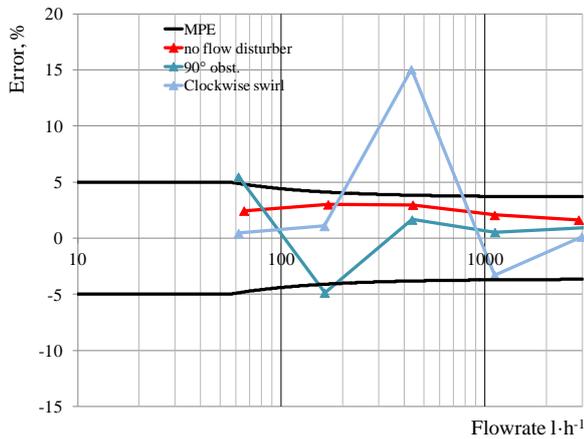
Figure 5 – Errors of the flow disturbance test
on a MID Class 3 Heat Meter (turbine)

5. Conclusions

Several benefits come from the introduction of smart metering in thermal energy metering, in particular in: i) accounting, billing, and end-user management; ii) correction of the errors; iii) optimization and control of energetic systems; iv) fault detection. Furthermore, the possible integration between direct heat meters and heat cost allocators could allow to get a more accurate and reliable sharing of energy costs among users.

The main limits of smart metering is nowadays represented by the lack of both standardization and interoperability between different devices: meters, concentrators, management software.

On the metrological point of view, smart metering could allow to electronically apply effective correction coefficients due to calibration and installation effects.

As an example, the authors experimentally demonstrated the decay of metrological performance of commercial MID approved complete heat meters in presence of common standardized flow disturbers. Such a decay of the metrological performance could be recovered by a smart heat meter by means of correction factors, specific for each flow disturber (i.e. for the local plant installation characteristics).

6. References

[1] Directive 2002/91/EC of the European Parliament and of the Council, of 16 December 2002 on the energy performance of buildings.

[2] Directive 2012/27/EU of European Parliament and of the council of 2012, on energy efficiency.

[3] UNI 10200:2005 Centralized heating systems Heating costs sharing

[4] ISO/IEC Guide 98-3:2008 Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement (GUM:1995).

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[6] EN 1434-4:2007, Heat meters - Part 4: Pattern approval tests.

[7] OIML R 75, Heat meter - Part 1 to part 3, International Organization of Legal Metrology.

[8] EN 834:1994, Heat cost allocators for the determination of the consumption of room heating radiators, Appliances with electrical energy supply.

[9] EN 14154-3:2005+A2:2011, Water Meters, Part 3: Test Methods and Equipment.