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THE INRIM THERMAL ENERGY STANDARD

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Abstract – In 2009, INRIM opened a research activity to plan the design and the realization of an innovative Thermal Energy Standard. The paper presents the main features of the new national standard and the innovative measurement approach adopted in order to faithfully simulate the real operating conditions of direct heat meters. An overview of the measurement procedure and the first experimental results for assessing the metrological performances of the thermal energy standard are given.

Keywords: Thermal energy measurement, heat meter.

1. INTRODUCTION

For a provider or operator of heating systems, the measurement of the thermal energy consumed by the end-user is a task of fundamental importance in the process of production-distribution-sales. Its correctness is a sensitive issue that involves the vendor-client relationship and that, in the wake of the European directive MID EC2004/22 [1], must be faced by the major European countries.

The spread of District Heating systems and the need for an accurate and precise assessment of the effective thermal energy consumed by the end-user, have represented the main driving forces towards the technological innovation in the field, the development of smart management, monitoring and control systems and the setting up of a national metrology network able to ensure the traceability for the measured quantities and the validation of the measuring instruments.

The INRIM participation to the Call for Project of the 7th Framework Program SME 2012 has allowed to start a research activity supporting the development of the Italian Standard for Thermal Energy Measurement.

The paper deals with the development of a new standard characterized by a new approach to the thermal energy measurement and presents the first experimental results used to assess the metrological performances of the INRIM Thermal Energy Standard (T.E.S.).

2. WHY AN INNOVATIVE STANDARD

The European Standard EN 1434 [2] applies to heat meters, describing their measuring principle and technique and specifying the general requirements for this kind of thermal energy measurement devices; moreover, part nr. 6 is devoted to the description of the installation, commissioning, operational monitoring and maintenance of heat meters. The typical installation layout and working condition for such a measuring instrument is represented in Fig. 1.

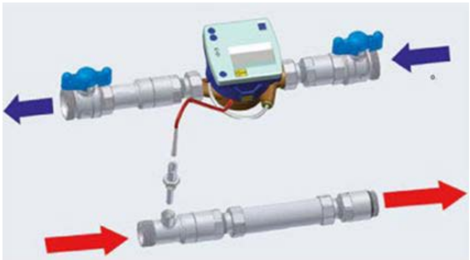

Fig. 1. Scheme of thermal energy measurement by EN 1434

Therefore, the quantity of heat released or absorbed by a fluid flow rate is given by the time integration of the product between the mass flow rate ($\dot{m}$) and the specific enthalpy difference of the heat conveying fluid (Δh) between the inlet and outlet sections of its control volume (1).

$$Q = \int_0^t \dot{m}\Delta h dt \tag{1}$$

Using water as system heat conveying liquid, then thermodynamic properties (density and specific enthalpy) should be calculated according to the Equation of State given by the International Association for the Properties of Water and Steam (IAPWS), using the International Temperature Scale of 1990 (ITS-90); in particular, the relation known as the Industrial Formulation for the Thermodynamic Properties of Water and Steam (IAPWS-IF 97) is recommended [3]. Such a form for the Equation of State of water (2) is explicit in the dimensionless Gibbs Free Energy (γ), which is expressed as function of the reduced temperature (τ) and pressure (π); the other water properties can be calculated by the application of the thermodynamic relations.

$$\gamma(\pi,\tau) = \sum_{i=1}^{34} n_i (7{,}1-\pi)^{I_i}(\tau - 1{,}222)^{J_i} \tag{2}$$

The measurement standards for thermal energy belong to NMIs or to accredited laboratories and shall ensure the metrological traceability for the quantity "enthalpy flow" of single-phase liquid water, defining the operating flow rate and temperature ranges.

The national standards for thermal energy measurement allow calibrating heat meters and verifying their compliancy to the European directive MID EC2004/22. In most of the NMIs heat meters are calibrated by installing:

- the flow meter and the lower temperature sensor sub-assemblies in a dedicated measurement section of the water flow rate standard;
- the higher temperature sensor in a conventional thermostatic bath.

An example of this kind of measurement system is shown in Fig. 2.

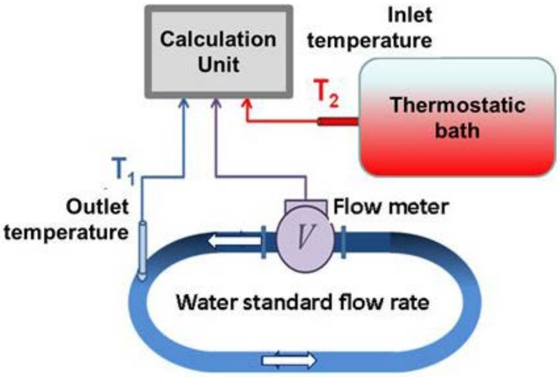

Fig. 2. Typical measurement system for Thermal Energy

The INRIM measurement system allows calibrating the complete heat meters with all their sub-assemblies simultaneously exposed to experimental conditions very close to the operating ones; namely, the two temperature sensors are tested inside independent pipe water flows, able to reproduce a large set of possible thermodynamic conditions as can be found at the inlet and outlet flow sections of a generic heat exchanger. Fig. 3 shows a sketch of the operating principle of the INRIM T.E.S.

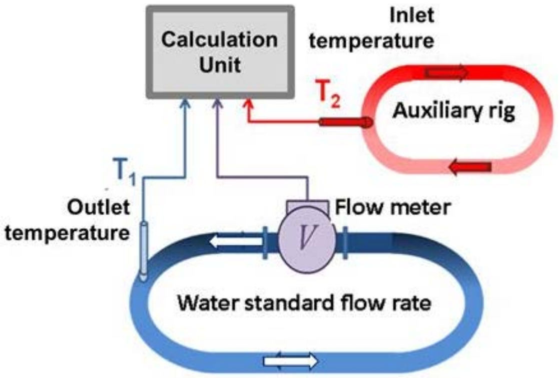

Fig. 3. Sketch of the “two-flows configuration” of the INRIM Thermal Energy standard

The calibration of both the temperature sensors in water forced flows inside pipes could also allow reproducing the desired fluid bulk temperatures, that are the actual temperatures at which the thermodynamic properties of the fluid should be evaluated, at different and accurately generated temperature profiles. Moreover, since the aim of the flow meter and the downstream temperature sensor, installed at the outlet section of a heat exchanger very close to each other, is to measure the fluid flow rate and temperature locally, the mutual influence between these two neighbouring measuring instruments should be investigated.

3. THE INRIM THERMAL ENERGY STANDARD

The INRIM T.E.S. operates in the temperature range from 18 °C up to 90 °C and volumetric flow rate range from 0,2 l/s to10 l/s, that means a maximum measured thermal power of about 3 MW.

The measurement system consists of two separate hydraulic circuits: the first coincides with the primary flow rate standard [4], where the flow meter under test and the lower temperature sensor are installed and the second is an auxiliary rig, where the higher temperature sensor can be immersed in a forced water flow.

In Fig. 4a, an overview of the INRIM Thermal Energy laboratory is given. Fig. 4b shows the temperature reference sensors on the primary flow rate standard.

a

b

Fig. 4 (a) View of the INRIM Thermal Energy Standard; (b) Sensors for reference temperature measurement at the primary flow rate standard

3.1. The high temperature auxiliary rig

In order to calibrate both the temperature sensors of heat meters in forced water flows inside pipes, a separate high temperature auxiliary rig has been built up (Fig. 5). It works independently and simultaneously with the primary flow rate standard, at different temperature and pressure levels, ranging from 15 °C to 120 °C and between 1 bar and 3 bar.

Fig. 5. The high temperature auxiliary rig of the INRIM Thermal Energy Standard

It is a 15 l capacity thermo-hydraulic circuit, mainly consisting of a circulation pump, an expansion vessel, a heat exchanger and a measurement branch to fit the thermometer under test (Fig. 6). The heat exchanger is immersed in an oil thermostatic bath, which ensures to set up the desired temperature level and guarantees a long term stability lower than 10 mK.

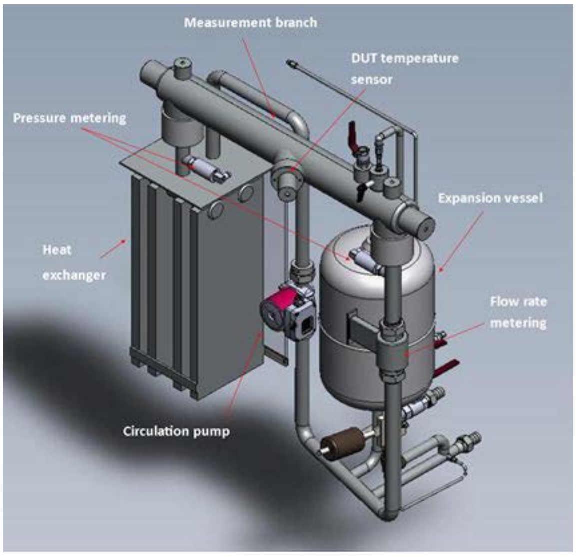

Fig. 6. Functional scheme of the thermo-hydraulic circuit of the high temperature auxiliary rig

The measuring zone, where under test thermometers are calibrated, is a 15 cm straight pipe branch (DN25); it is an open control volume with a single inlet and outlet section, where a constant water flow rate enters at constant temperature and pressure. The measurement branch is thermally insulated by an evacuated coaxial pipe, in order to ensure high temperature stability and uniformity. Fig. 7a and Fig. 7b show, respectively, the detail of the temperature measurement branch of the auxiliary rig and its functional scheme. The reference temperature of the measuring zone is obtained as the arithmetic mean of the temperatures given by two Pt100 thermometers, placed at the inlet and outlet sections of the measurement branch. An axial uniformity at the milli-Kelvin level is achieved.

a

b

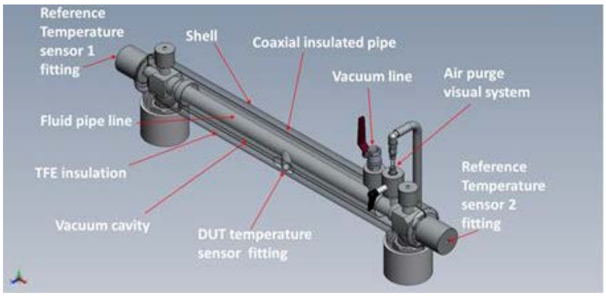

Fig. 7 (a). Detail view and (b) functional scheme of the temperature measurement branch of the auxiliary rig

By means of the electronic speed control of the circulation pump, the high temperature auxiliary rig ensures to achieve similar specific mass flow rates at the temperature sensor under test, as the ones which the other under test thermometer on the primary flow rate standard is exposed to.

A numerical analysis of temperature and velocity distributions in the measuring zone was carried out by means of Computational Thermal Fluid Dynamic simulation (Fig. 8 and Fig. 9). The results are supported by experimental data.

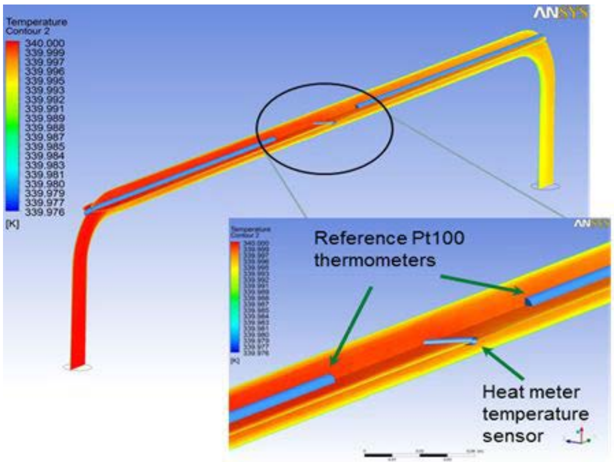

Fig. 8. Expected temperature distribution in the measuring zone by Computational Thermal Fluid Dynamic analysis

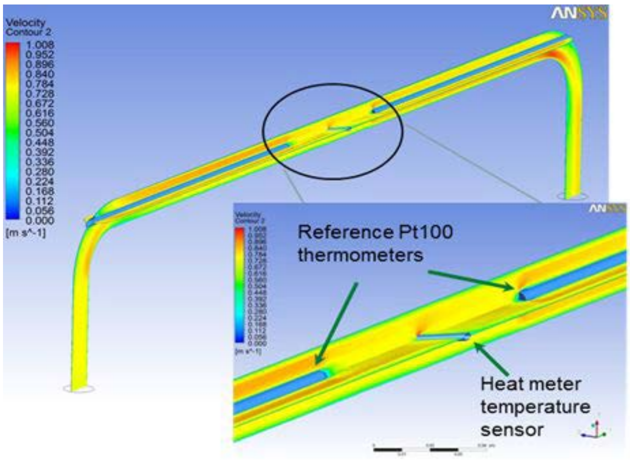

Fig. 9. Expected velocity distribution in the measuring zone by Computational Thermal Fluid Dynamic analysis

4. MEASUREMENT METHOD

The static weighing method with a flying start and stop, applied at the gravimetric facility of the INRIM primary flow rate standard, can be exploited also for the reference thermal energy measurement, instead of using a reference heat meter assembly, whose components were separately calibrated against the corresponding primary standards. Such a choice is endorsed, for instance, by the consideration that if a reference heat meter assembly is used, then it would be possible to have correlations between reference and under test measurements, so that systematic errors cannot be detected [5].

The procedure used herein allows calculating the thermal energy associated with a weighed amount of water that has virtually passed through a temperature difference, as settled by the high temperature auxiliary rig and the temperature control loop of the primary flow rate standard.

Once flow rate and temperature conditions are stably realized in the two separate hydraulic circuits, a sufficient amount of water is weighed and temperatures and pressures at the measuring sections of both the hydraulic circuits are recorded during the weighing time. It's worth to notice that the mass of water to be weighed or the weighing time must be decided according to the resolution of the measuring instruments.

The measurement model for the reference thermal energy calculation comes from conservation of energy and reads:

$$Q = M\overline{\Delta h} \quad (3)$$

where M is the mass of water and $\overline{\Delta h}$ is the average specific enthalpy difference between the two thermodynamic states realized, respectively, in the high temperature auxiliary rig and in the primary flow rate standard.

Traceability for the density of water is established by periodical analysis of water probes.

The implementation of the reference formulations for clean water properties (IAPWS-IF 97) in the measuring calculation unit leads to a negligible systematic offset, because of the level of purification of the water used at the thermal energy standard.

Since the validation of heat meters must be performed even at small temperature differences (down to 3 K), as indicated by the European directive MID EC2004/22, the attainment of a good stability in temperature measurement is essential. Such a goal can be reached by means of the use of fine temperature control loops for both the hydraulic circuits of the primary flow rate standard and the high temperature auxiliary rig.

Fig. 10 shows a typical reference temperature evolution, as measured at the auxiliary rig. A measurement stability lower than 0.01 K can be achieved.

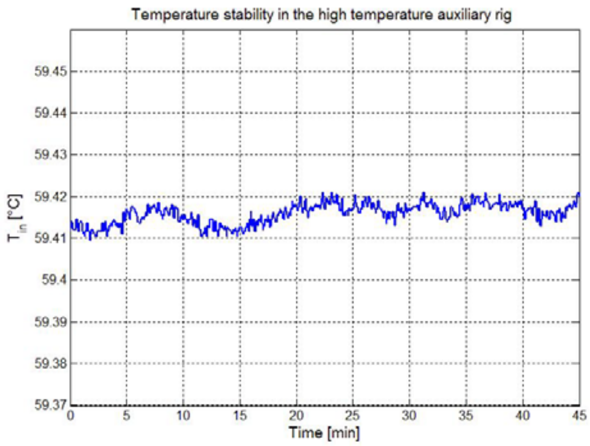

Fig. 10. Temperature stability in the high temperature auxiliary rig

The performance of the temperature control loop of the primary flow rate standard are worse than the ones of the auxiliary rig; the period of the temperature oscillation mainly depends on the water flow rate and has been observed to range between 3 and 5 minutes, while the amplitude on long time recording is lower than 0,1 K.

In order to improve the stability and the repeatability of thermal energy measurement, the weighing periods can be automatically synchronized with the water temperature evolutions in the two hydraulic circuits; in such a way, a very stable and repeatable temperature measurement is ensured in both the hydraulic circuits.

Heat meters can be calibrated by comparison with such a reference measurement for thermal energy; if the flow meter sub-assembly of a heat meter under test is of volumetric type, as for the most of commercially available heat meters, then the reference measurement of the volume that passed through the under test meter should be obtained from the weighed mass and the fluid density at the flow meter location. Thus, the measurement model becomes:

$$Q = M\frac{\overline{\rho_{out}}}{\overline{\rho_{dut}}}\overline{\Delta h} \quad (4)$$

where $\overline{\rho_{dut}}$ is the mean density of water at the location of the flow meter under test and $\overline{\rho_{out}}$ the mean density of water at the location of the lower temperature sensor.

When a heat meter with energy and volume pulse outputs must be calibrated, as a whole assembly in operating conditions close to the actual ones, the deviation of the meter under test is calculated as follows. Once the weighing time is selected, according to the resolution of the meter under test, and flow rate and temperatures are stably realized in both the hydraulic circuits, the flow is diverted into the weighing tank and the signal conveyed to the reference time counter is used to trigger the first pulse of the meter under test. When the weighing time is reached, the diverter switches back to the closed loop and the end-time signal is used to trigger the last pulse of the meter under test. In such a way reference and under test measurements take place simultaneously and the relative deviation can be calculated.

5. EXPERIMENTAL RESULTS

The INRIM T.E.S. must allow calibrating heat meters, by testing the complete measuring assemblies, in those operating conditions which manufacturers, operators or end-users are interested to investigate. The test conditions are well defined by the European directive MID EC2004/22 and the European Standard EN 1434 and aim to reproduce the typical operating conditions that can be often found in real applications. The main criticalities in thermal energy measurement can be identified in:

- the measurement of flow rate in hot water, typically from 40 °C up to 90 °C;
- the measurement of small temperature differences between the inlet and outlet sections of the heat exchanger, namely down to 3 K.

The attainment of good metrological performances in such as critical as usual operating conditions is a key point for measurement traceability, because it can enable to detect systematic errors in a wide measurement range.

An extended program of measurement was carried out to have a complete evaluation of the metrological characteristics of the new INRIM T.E.S. and to check its calibration capabilities.

The tests were implemented taking into account, as main influencing factors, the water flow rate, the water temperature of the primary flow rate standard and the water temperature difference between the two separate hydraulic circuits; three levels for each factors have been investigated, as shown in Table 1.

Table 1. Measurement plan for the metrological characterization of the INRIM Thermal Energy Standard

Measurement plan	
Flow rate	1 l/s
	2 l/s
	3 l/s
Temperature of the primary flow rate standard	40 °C
	50 °C
	60 °C
Inlet-outlet temperature difference	3 K
	10 K
	30 K

Each measurement point of the test plan is defined by a flow rate, a temperature of the primary flow rate standard and a temperature difference; once these experimental conditions have been stably realized and the weighing time has been selected, the repetition of at least five successive weighings is performed. For each repetition, the corresponding reference thermal energy that virtually passed through the measurement sections at which a generic under test heat meter is located, is measured. Moreover, for each repetition, both the reference volume that passed the measuring section on the primary flow rate standard and the reference water temperature difference between the two hydraulic circuits are measured.

The repeatability of the reference measurements is calculated by the standard deviation of the five (or more) successive measurements, keeping constant the levels of the three influencing factors.

Fig. 11 shows the repeatability of reference thermal energy measurement obtained for the test plan. It can be noticed that the higher repeatability values obtained for temperature difference equal to 3 K and highlighted on the left top of Fig. 11, are due to the absence of synchronization between the weighing periods and the water temperature evolution in the primary flow rate standard. The effect of the fine temperature control loops, when small temperature differences (3 K) must be measured, is to improve thermal energy repeatability to values lower than 0,6%, similar to the values that can be obtained for higher temperature differences.

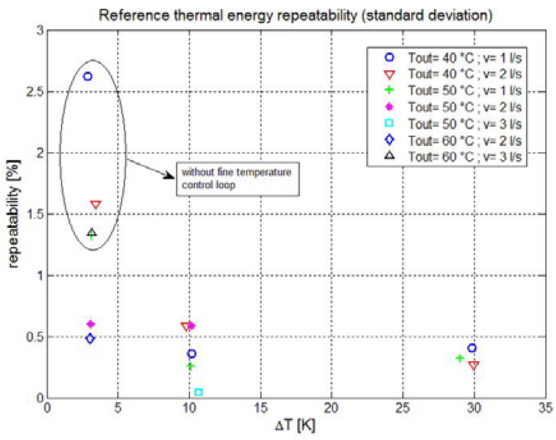

Fig. 11. Repeatability of reference thermal energy measurement

Fig. 12 and Fig. 13 show, respectively, the reference volume and temperature difference repeatability for the same measurement plan. It can be observed that the temperature difference measurement is characterized by a repeatability of more than one order of magnitude higher than the volume measurement and almost equal to thermal energy repeatability.

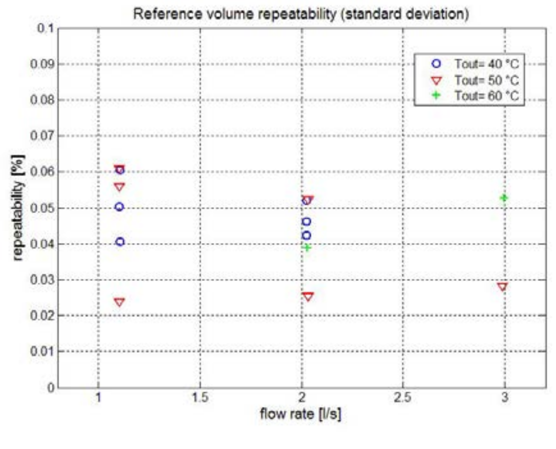

Fig. 12. Repeatability of reference volume measurement

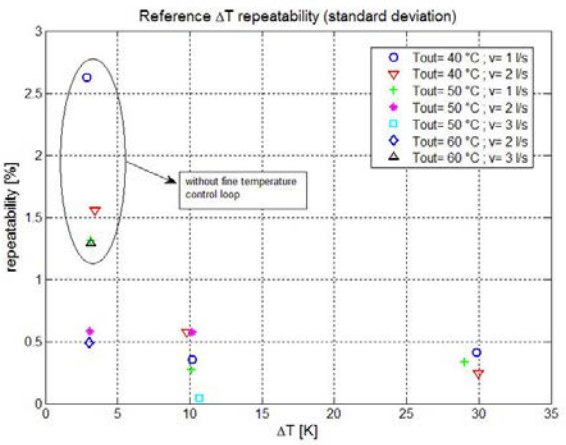

Fig. 13. Repeatability of reference temperature difference measurement

Along this line, concerning the validation of complete heat meters in actual operating conditions, the main efforts should be focused to as stable as possible temperature difference measurements in forced flow conditions. It's worth to notice that, in order to attain thermal energy repeatability lower than 0,6% (relative standard deviation) with water temperature differences of about 3 K, the repeatability of temperature measurement should be lower than 0,03%, that means, for instance, a standard deviation lower than 0,015 K at 50 °C.

Measurement stability can be determined for every point of the test plan, by taking the standard deviation of the reference thermal power measurements during the weighing periods; thermal power can be measured by using a reference flow meter installed in series with the measuring section on the primary flow rate standard.

Fig. 14 shows the stability of the quantity (q), calculated as follows:

$$q = \frac{\rho_{out}}{\rho_{dut}} \Delta h \qquad (5)$$

which has the dimension of a specific enthalpy difference.

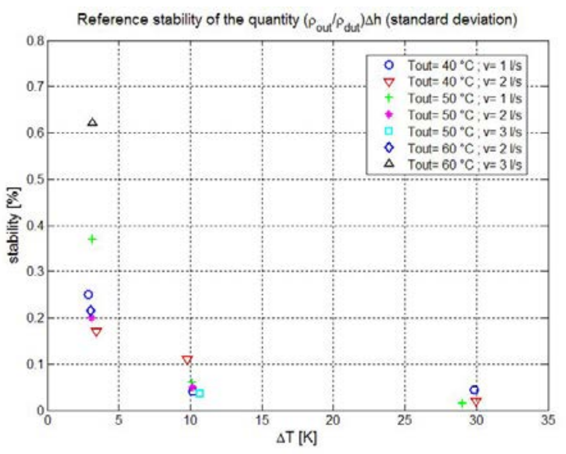

Fig. 14. Stability of the reference measurement of the quantity *q*

6. CONCLUSIONS

The INRIM Thermal Energy Standard has been recently developed in order to enable the validation of heat meters in experimental conditions close to the operating ones. The heat meter under test can be calibrated with all the sub-assemblies simultaneously exposed to actual operating conditions, that means both temperature sensors immersed in water forced flows at different temperature levels and the flow meter installed on the primary flow rate standard at the desired temperature level. Such a measurement system and approach could open the possibility to reproduce and investigate the effects of typical measurement conditions that can be found in real application, like, for instance, the presence of temperature profiles at the fluid inlet and outlet sections of a heat exchanger.

An extended program of measurements was carried out in order to characterize the metrological performances of the INRIM T.E.S. and to evaluate the repeatability of reference thermal energy measurement. The inlet-outlet temperature difference stability has been observed to be the main influencing factor.

The preliminary results pointed out that, in order to attain thermal energy repeatability lower than 0,6% (relative standard deviation) with water temperature differences of about 3 K, the repeatability of temperature measurement should be lower than 0,03%, that means, for instance, a standard deviation lower than 0,015 K at 50 °C. Such performances in temperature measurements are ensured by the automatic water temperature control systems currently implemented in the Thermal Energy Standard.

The results have indicated to further improve water temperature stability and water temperature control, in order to ensure traceability of thermal energy measurement in a as wide as possible set of temperature difference conditions. Concerning future works, particular efforts will be focused on the attainment of a repeatability on reference thermal energy measurement lower than 0,5% (relative standard deviation) even for small temperature differences (around 3 K) and lower than 0,3% for temperature difference higher than 10 K.

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