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(Article begins on next page)

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The INRiM thermo-hydraulic mock-up for thermal energy measurement devices: design, construction and metrological characterization

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Abstract

At the National Institute of Metrological Research (INRiM), the first European thermo-hydraulic simulator (mock-up) for testing both traditional and innovative thermal energy measurement devices and heat cost allocators has been recently built up, in the context of the EU Seventh Framework Programme FP7-SME-2012. The INRiM mock-up is an automatically reconfigurable thermo-hydraulic circuit equipped with a sufficient number of sensors aimed at measuring all the physical quantities involved in direct heat metering. It allows simulating typical central heating systems with several types of water radiators as heat exchangers and characterized by different distribution circuit topologies. The paper describes the INRiM thermo-hydraulic mock-up, highlighting its design features and metrological capabilities and discussing the first measurement results.

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Keywords: Thermal energy measurement; direct heat meters; heat cost allocators; energy saving; central heating systems

1. Introduction

Measuring and allocating accurately the thermal energy consumptions on existing apartment blocks is not so trivial, in particular, for those central heating systems characterized by outdated hydraulic distribution topologies, which do not allow to perform a single flow rate and temperature difference measurement for each flat.

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Nowadays, direct heat meters represent the most accurate devices for measuring thermal energy consumptions, since they allow detecting directly the physical quantities involved in the assessment of the enthalpy flow of a single-phase heat conveying fluid. On the other hand, indirect heat meters or heat cost allocators can be easily suited to almost every kind of central heating system, but they are often based on rough assumptions for both the mean temperature of the fluid inside the radiator and heat transfer conditions, which may lead to inaccurate measurements.

All these measuring devices must be compliant with the requirements pointed out by the European Directive MID 2004/22/EC [1], in order to ensure a fair billing of the thermal energy consumptions. Moreover, the satisfaction of these metrological requirements allows the operators or end-users to choose rationally the best cost effective solutions in the framework of energy saving.

An experimental thermo-hydraulic circuit, which simulates a typical central heating system with water radiators as heat exchangers, has been recently built up at INRiM in order to test the functionality and the accuracy of both conventional and innovative heat metering and cost allocation devices, in experimental conditions as close as possible to the working ones.

2. Design and construction of the experimental thermo-hydraulic circuit

A fully-instrumented and hydraulically-reconfigurable central heating system simulator has been designed and built up at INRiM in order to test the measurement capabilities of conventional and innovative heat metering devices, in a set of heat transfer conditions that are representative of the ones experienced in real applications (i.e. residential heating by means of water radiators). The design configuration consists of 40 radiators of different sizes and materials (20 aluminum, 14 steel and 6 cast iron radiators), deployed on the mock-up vertical walls in aligned arrangement; namely, the vertical walls are subdivided into 4 floors, in order to simulate 8 living units with 5 radiators each, by shelves of about 0.8 m depth, which prevent the mutual thermal interaction between adjacent water radiators. The thermo-hydraulic circuit is automatically reconfigurable, by the actuation of 180 motorized valves, in order to simulate different water distribution network topologies (vertical columns or horizontal loops). The following figure shows an overview of the thermo-hydraulic circuit of the central heating system simulator, which has been installed into a 300 m^3 hangar at INRiM.

Fig. 1. Overview of the thermo-hydraulic circuit of the central heating system simulator

A conventional natural gas condensation boiler (thermal power modulation of the burner ranging from about 10 kW to 50 kW) and a centrifugal pump with electronic speed control are used for ensuring, respectively, the desired water supply temperature and flow rate to the thermo-hydraulic distribution circuit. An adequate air exchange rate is ensured by a mechanical ventilation system (maximum air extraction of about 5200 m^3/h).

The mock-up enables the comparison between accurate direct measurements of the thermal energy exchanged by different kinds of water radiators and the measurements provided by any conventional or innovative heat metering or cost allocation device. Along this line, each water radiator is equipped with its own electromagnetic flow meter (8 mm internal diameter) and its pair of platinum resistance thermometers (Pt100 directly immersed in the water flow) for inlet and outlet water temperature measurements (Fig. 2). The overall number of sensors installed at the central heating system simulator is equal to 332 and comprehends 60 electromagnetic flow meters, 212 platinum resistance thermometers and 60 differential pressure transducers.

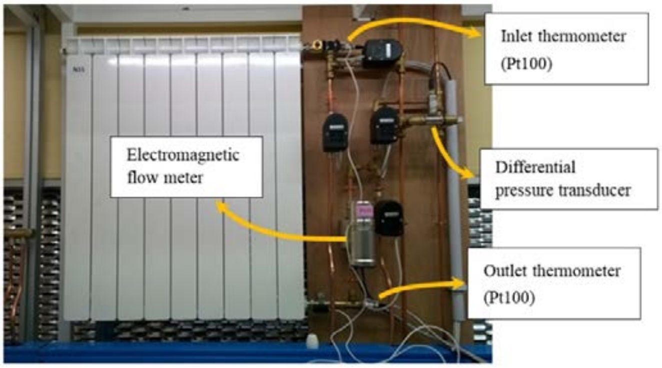

Fig. 2. Sensors for reference measurements at a water radiator

In order to assist the design phase and to preliminary verify the achievement of realistic heat transfer conditions inside the laboratory, the method of Computational Thermal Fluid Dynamics has been used for simulating several design configurations and working conditions of the mock-up [2,3]. The numerical simulations have shown that the selected installation layout of the water radiators on the walls of the laboratory (vertical alignment of the radiators with shelves for their confinement) and the ventilation system prevent the thermal interaction between adjacent radiators due to the buoyant ascending warm air fluxes and ensure the onset of typical heat transfer conditions at radiator surfaces (Fig. 3a). Moreover, the selected air ventilation system allows keeping the air temperature and the thermal stratification inside the laboratory at stable and acceptable levels and ensures heat metering tests to be performed with maximum indoor air temperature conditions not exceeding 28 °C (Fig. 3b).

a **b**

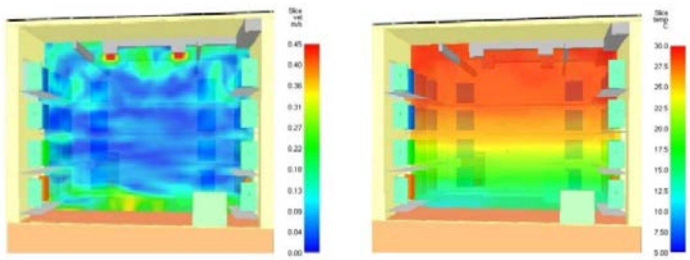

Fig. 3. (a) Computational thermal-fluid-dynamic simulation of the indoor air velocity field at the mock-up; (b) computational thermal-fluid-dynamic simulation of the indoor air temperature field at the mock-up

All the measurement signals are acquired and converted by a PLC, which also allows actuating the motorized valves for switching the hydraulic distribution modes and controlling the condensation boiler and the pump. The SCADA-HMI software Movicon™ enables to monitor and store the measurement data and to automatically control and regulate the operation of the thermo-hydraulic system. Furthermore, the SCADA enables the execution of the thermal energy calculation procedure for each water radiator (Radiator Calculation Unit), implementing the reference IAPWS formulations for the assessment of the thermodynamic properties of water [4,5] and the time integration of the calculated thermal power.

3. Reference heat metering and cost allocation in the central heating system simulator

In order to test the functionality and the effectiveness of heat metering and cost allocation devices, the reference measurements of the exchanged thermal energies coming out from the central heating system simulator must be characterized by high accuracy.

Each measuring instrument, with its corresponding measurement chain, was calibrated with INRiM reference standards. The following table summarizes the calibration uncertainties associated with electromagnetic flow meters, platinum resistance thermometers and differential pressure transducers installed at the mock-up.

Table 1. Expanded calibration uncertainties of the measuring instruments

Expanded calibration uncertainties (95% level of confidence)	
Electromagnetic flow meters – 8 mm internal diameter (radiator flow meters)	0,2% in the range 90 l/h ÷ 1800 l/h 0,2% ÷ 0,8% in the range 60 l/h ÷ 90 l/h
Electromagnetic flow meter – 20 mm internal diameter (overall flow meter)	0,2% in the range 500 l/h ÷ 11500 l/h
Temperature measurement chain	0,02% in the range 0 °C ÷ 90 °C
Differential pressure transducers	0,02% in the range 50 Pa ÷ 50000 Pa

The calibration uncertainties of the measuring instruments and the uncertainties associated with the Equation of State [6,7] (IAPWS-IF97), used for the estimation of the thermodynamic properties of water, propagate over the reference thermal power calculation model, which consists on the product between the mass flow rate and the specific enthalpy difference of the heat conveying fluid. An evaluation of the expected uncertainty propagation on the reference thermal power measurement, as function of mass flow rate and temperature difference between the inlet and outlet section of a heat exchanger, has been performed by means of the Monte Carlo method [8,9] (Fig. 4).

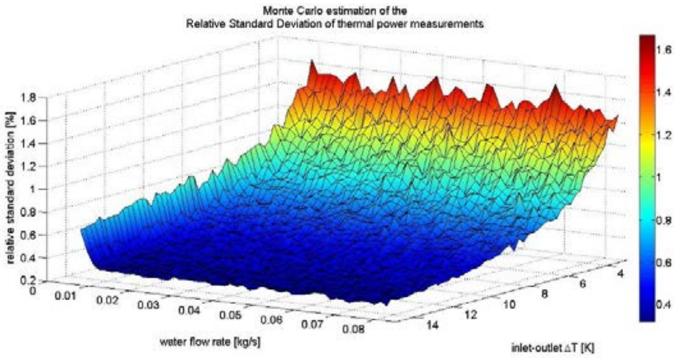

Fig. 4. Monte Carlo estimation of the relative standard deviation of the probability distributions associated with thermal power measurements

Many contributions, which influence the stability of the measured quantities, can be preliminary identified and corrected by a suitable design of the thermo-hydraulic circuit and the correct sizing of the main components, like the heater, the pump, the hydraulic separator and the expansion vessel. The main factors that affect the measurement stability are:

- the regulation field of the condensation boiler, as determined by the thermal power modulation of the burner;
- the working point of the centrifugal pump on its head loss-flow rate characteristic, as determined by the electronic control of its velocity and by the external characteristics of the hydraulic circuit;
- the topology of the thermo-hydraulic distribution network, as determined by the state of the motorized valves;
- the air exchange rate ensured by the forced ventilation system and the number and distribution layout of supply and exhaust vents;
- the presence of free, entrained and dissolved air in the hydraulic circuit of the central heating system simulator;
- the working pressure of the thermo-hydraulic circuit, as determined by the expansion vessel;
- the separation between the thermo-hydraulic distribution network and the smaller hydraulic circuit of the condensation boiler, ensured by the hydraulic separator.

The tests for evaluating the accuracy and the functionality of direct or indirect heat metering devices consist on the simulation of typical heat consumption profiles of central heating systems, where the water radiators forming the living units are managed in terms of open-close state of the corresponding valves, flow rate and water supply temperature, as well as in real applications. Every working condition and layout configuration of the thermo-hydraulic circuit, which is set during a functionality test, is monitored for a sufficiently long time period (at least 30 minutes) to reach steady flow rate and temperature conditions and to perform a statistically significant comparison between reference and under-test measurements for thermal energy and heat cost allocation. The following figure shows the stability of reference flow rate measurements (Fig. 5a) and inlet-outlet temperature difference measurements (Fig. 5b), as can be obtained for a specific water radiator; during the time periods characterized by stable temperature measurements, the inverse proportionality between relative standard deviation and mean value, for reference inlet-outlet temperature difference measurements, can be observed.

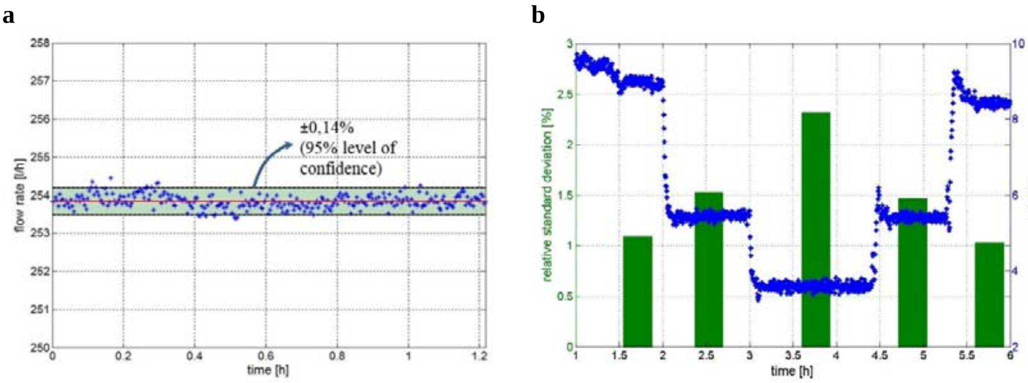

Fig. 5. (a) Stability of reference water flow rate measurements at a water radiator; (b) reference inlet-outlet temperature difference measurements at a water radiator and corresponding relative standard deviations during the time periods characterized by stable temperature measurements

4. Verification of the functionality and the accuracy of heat metering and cost allocation devices

In order to quantify the accuracy of heat metering or cost allocation devices, the results of the tests are given in terms of percentage differences between reference and under-test measurements (at least 5 comparisons for each test), with the corresponding uncertainties of the reference measurements. The latter are obtained by the Euclidean norm of the vector of the uncertainty contributions, whose main components are the thermal power measurement stabilities and the uncertainties resulting from the propagation of both calibration and equation of state uncertainties over the thermal power calculation model.

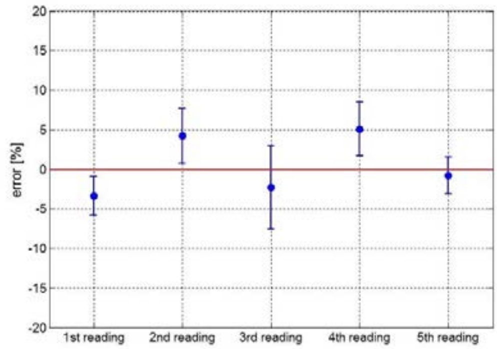

Fig. 6. Results of a typical functionality test for a thermal energy measurement device: percentage errors with respect to reference measurements and corresponding expanded uncertainty bars (95% confidence)

Fig. 6 shows an example of the results of a typical functionality test for a thermal energy measurement device, in terms of percentage errors with respect to reference measurements and corresponding expanded uncertainty bars (95% level of confidence). The higher uncertainty value of about 5% is related to the smaller value for temperature difference between the inlet and outlet sections of the water radiator, which, in this test case is about 3 K.

5. Conclusions

The INRiM thermo-hydraulic mock-up allows testing the accuracy and the functionality of heat metering and cost allocation devices in experimental conditions close to real ones. The possibility to simulate a wide set of heat consumption profiles, by automatically opening or closing the valves of the water radiators or by regulating the thermal output of the heater and the working regime of the pump, ensures to reproduce what typically happens during the operation of central heating systems. Moreover, the onset of thermal stratification inside the laboratory environment and the different convective-radiant heat transfer conditions which take place at radiator surfaces allow analyzing, at the same time, a significant set of values of exchanged thermal powers.

The expanded uncertainty values (95% level of confidence) associated with reference thermal energy measurements, obtained during the first tests carried out at the central heating system simulator, have been observed not to exceed 3% for temperature differences between the inlet and outlet sections of the heat exchangers ranging from 8 K to 15 K. For lower temperature differences, down to 3 K, the expanded uncertainties for reference thermal energy measurements increase up to about 5%.

The mock-up is adequate to verify heat metering and cost allocation devices, with a good level of accuracy, for a wide set of typical working conditions of central heating systems. Moreover, it can be used as accurate test rig for the development of innovative heat meters or heat cost allocation procedures.

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