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Design of a Calibration System for Heat Flux Meters

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Abstract Accurate heat flux measurements are needed to gain a better knowledge of the thermal performance of buildings and to evaluate the heat exchange among various parts of a building envelope. Heat flux meters (HFMs) are commonly used both in laboratory applications and *in situ* for measuring one-dimensional heat fluxes and, thus, estimating the thermal transmittance of material samples and existing buildings components. Building applications often requires heat flux measurements below $100\,\mathrm{W \cdot m^{-2}}$. However, a standard reference system generating such a low heat flux is available only in a few national metrology institutes (NMIs). In this work, a numerical study aimed at designing an HFM calibration apparatus operating in the heat flux range from $5\,\mathrm{W \cdot m^{-2}}$ to $100\,\mathrm{W \cdot m^{-2}}$ is presented. Predictions about the metrological performance of such a calibration system were estimated by numerical modeling exploiting a commercial FEM code (COMSOL®). On the basis of the modeling results, an engineered design of such an apparatus was developed and discussed in detail. The system was designed for two different purposes: (i) for measuring the thermal conductivity of insulators and (ii) for calibrating an HFM with an absolute method (i.e., by measuring the applied power from the heater and its active cross section) or by a relative method (i.e., by measuring the temperature drop across a reference material of known thickness and thermal conductivity). The numerical investigations show that in order to minimize the uncertainty of the generated heat flux, a fine temperature control on the thermal guard is needed. The predicted standard uncertainty is within 2 % at $10\,\mathrm{W \cdot m^{-2}}$ and within 0.5 % at $100\,\mathrm{W \cdot m^{-2}}$.

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1 Introduction

Improvements in the energy efficiency of buildings are called upon by European directives, such as the 2002/91/CE, which sets the maximum values of energy needs and thermal transmittance of building envelope components. *In situ* measurements of envelope components are needed for: (i) estimating the thermal transmittance of existing buildings in order to perform the energy certification and (ii) validating the energy performance design of new buildings. When the design data about existing buildings are not available, it can be necessary to perform invasive tests to detect stratigraphy and materials properties. Alternatively, the thermal transmittance can be measured *in situ*, according to ISO 9869, by means of an heat flux meter (HFM). Since measurement conditions are usually not stationary while the thermal conductance has to be obtained in steady-state conditions, long measurement runs are required to perform accurate *in situ* estimations.

HFMs provide an indirect measurement of heat fluxes through a wall (or a material specimen) by means of a one-dimensional heat flux sensor (HFS) and several temperature sensors (thermocouple or thermoresistance) which provide an estimate of the temperature gradient across the building component under investigation. The wall thermal conductance (or transmittance) is then evaluated by post-processing the acquired data. An HFS is basically made of a thin plate of an insulating material sandwiched in a thermopile (i.e., a connection in series of many differential thermocouples) which gives the temperature difference across the plate itself. When an heat flux crosses the HFS, the insulating material offers a known thermal resistance and, as a consequence, a temperature gradient builds up. The temperature difference across the plate is proportional to the heat flux and to the plate thickness and inversely proportional to its thermal conductivity.

Even though in the last few years, several studies have been conducted to investigate the metrological performance of HFMs and the associated calibration procedures [1–3], the devices employed in building applications are often uncalibrated and, consequently, the measurement traceability cannot be guaranteed. This poor practice is probably due both to the intrinsic technical complexity of the measurement chain and to a lack of suitable reference standards even at the NMI level. In addition, available international standards and guidelines are mainly concerned with the operative measurement techniques in the laboratory and in the field, while HFM calibration facilities are not described in detail [4–6].

Two HFM calibration methods, aimed at getting the relation between the thermopile signal output and the applied heat flux, are commonly used. The first involves the use of a one-sided guarded hot plate (GHP), where a uniform flux is generated between two plates held at different temperatures. The HFM under calibration is positioned in the intermediate zone. The applied heat flux is calculated from the temperature drop across a reference specimen of known thickness and thermal conductivity [2,7–10]. In the second method, the applied heat flux is calculated with a null detection technique using a two-sided GHP apparatus. The GHP intermediate heater is adjusted until the heat flux through the null HFS is zeroed. In this way, the applied heat flux to the HFS under calibration can be directly calculated from the electric power applied to the heater and its active cross-section [1].

Both methods have advantages and disadvantages. Influence quantities which affect the calibration accuracy are, among others: (i) the operating temperature, (ii) the thickness of the reference specimen, (iii) the overall thermal conductance of the layer between the hot and cold plates, (iv) the contact resistance at the various interfaces, and (v) the uniformity of the heat flux. Critical aspects which need a careful investigation in an HFM calibration are the dependences of the calibration curve from the temperature gradient across it and from the average temperature in the measuring section. The design of an adequate calibration apparatus should be able to vary, independently, such parameters.

The design of a novel standard system for HFM calibration is presented in the paper. A thorough numerical investigation of the system was carried out in order to evaluate its metrological performance and the potential application as a calibration standard. The aim of this work was to validate the design of such a calibration apparatus which is currently under construction.

2 Design of the Calibration System for HFMs

The main features of the HFM calibration system are presented in Fig. 1. The sketch also highlights the computational domain employed in the numerical simulation which, as shown, presents an axial symmetry. Compared to the GHP system commonly used in the thermal-conductivity measuring procedure described in [7] and [9], the system has an additional thermal guard in order to prevent heat dispersion in the upper section "Cc" (see Fig. 1), thus ensuring that the heat flux generated by the main heater flows through the measuring section "Oo." Furthermore, a coaxial thermal guard and a thick insulation material are used to get a one-dimensional heat flux through the device under calibration. The working temperature of the HFM can be varied by acting on the plate "QOPR," whose temperature is controlled by a fluid-flow cooling system. A stack of up to three Pyrex glass plates with a certified thermal-conductivity coefficient (BCR-039) is inserted between the hot plate "Ee" and the measuring section "Oo" to estimate the heat flux from the temperature drop across the sections "Ee" and "Mm."

The design of the apparatus was flexible enough to be used in different applications: (i) for measuring the thermal conductivity of insulating materials by generation of a known heat flux and (ii) for calibrating HFMs with an absolute method (i.e., by measuring the power generated by the main heater) or with a relative method (i.e., by measuring the temperature drop across the Pyrex reference material) [11,12].

The metrological performance of the calibration system was preliminarily checked by a numerical investigation employing a commercial Finite Element Code (COMSOL®), with a computational grid made of 15 221 nodes and 30 078 triangular elements, chosen on the basis of a grid sensitivity analysis. The boundary conditions employed in the simulation are: (i) uniform temperature at the sections "OP" and "CD", (ii) zero heat flux through the lower side "QR" and the upper side "Cc", and (iii) axial symmetry.

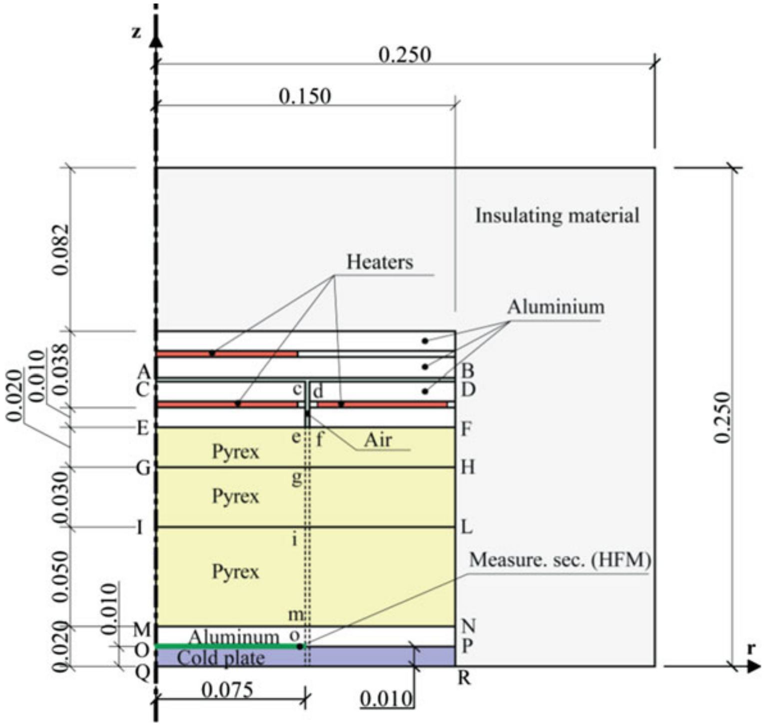

Fig. 1 Sketch and computational domain used for the numerical design of the calibration apparatus. All dimensions are in m

The numerical investigations were carried out at three different average heat flux values: $100\,\mathrm{W \cdot m^{-2}}$, $50\,\mathrm{W \cdot m^{-2}}$, and $10\,\mathrm{W \cdot m^{-2}}$. The results presented here were obtained by iteratively adjusting the side and upper guard power in order to obtain a mean temperature difference across the air gaps "ABCD" and "cdef" equal to or less than 0.1 mK.

Figure 2 depicts the numerical results concerning the temperature distribution in the apparatus for an average heat flux of $10\,\mathrm{W \cdot m^{-2}}$ (on the left) and $100\,\mathrm{W \cdot m^{-2}}$ (on the right). The pictures show how the heat flux through the Pyrex glass and the measuring section "Oo" is one-dimensional.

In Fig. 3, the vertical heat flux at $10\,\mathrm{W \cdot m^{-2}}$ and $100\,\mathrm{W \cdot m^{-2}}$ and its distribution as a function of the radial position at sections "Gg," "Mm," and "Oo" are reported; the maximum deviation from a uniformity flux condition is always less than 0.2 % and 0.75 % at the measuring sections of HFM and Pyrex glass, respectively.

The numerically estimated relative standard uncertainty was evaluated for all the operating conditions, assuming a rectangular distribution for the temperature profile as a consequence of the heat flux non uniformity in the lateral section "NF." It amounted to approximately 0.15 %. To verify the effectiveness of the lateral insulation, the system performance was studied as a function of the thermal conductivity of insulation materials. It was found that the uncertainty contribution approximately doubles when the

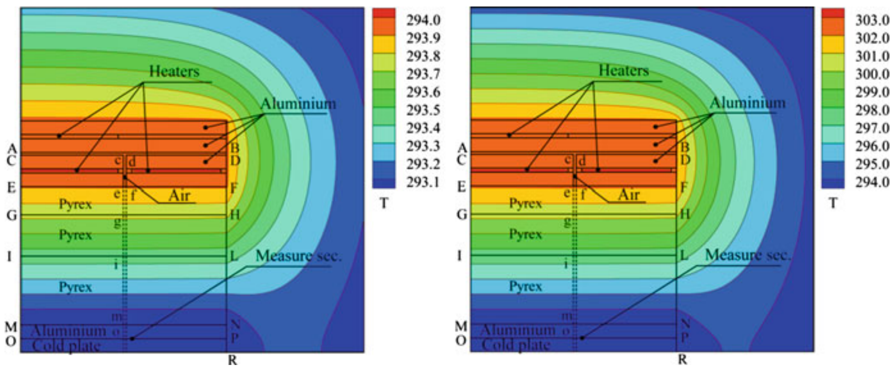

Fig. 2 Temperature distribution (in K) in the system, with a heat flux equal to $10\,\mathrm{W \cdot m^{-2}}$ (*on the left*) and $100\,\mathrm{W \cdot m^{-2}}$ (*on the right*)

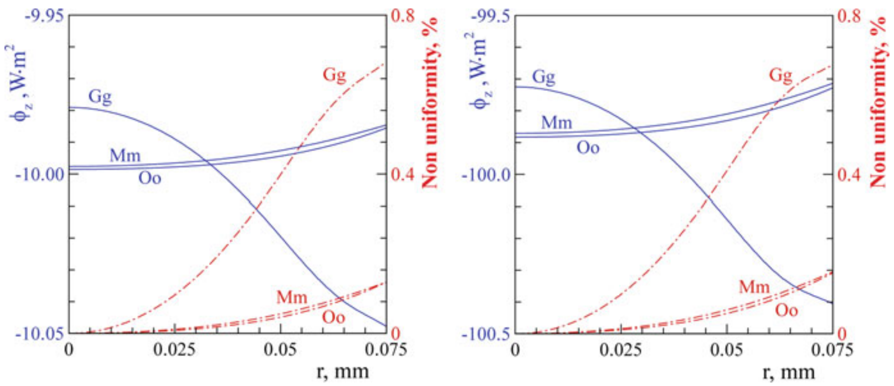

Fig. 3 Vertical heat flux and its profile as a function of the radial position at sections "Gg" and "Mm" of the Pyrex glass and "Oo" (measuring section of the HFM) for nominal heat fluxes equal to $10\,\mathrm{W \cdot m^{-2}}$ (*on the left*) and $100\,\mathrm{W \cdot m^{-2}}$ (*on the right*)

thermal conductance of the insulation increases by 50 %, whereas it can be practically considered constant when its thermal conductivity decreases by 50 % (Fig. 3).

The effects of the temperature control on the side and upper thermal guards—by considering an average temperature difference across the air gap approximately equal to 10^{-2} K—were investigated. The results highlighted that the worst metrological performance was obtained in correspondence to the lower heat fluxes. It should be noted that any temperature change in the upper thermal guard affects the heat flux more than that in the side guard. It was found that, in the worst condition, a temperature variation of 10^{-2} K in the upper thermal guard caused a nonuniformity of the heat flux of about 0.41 %.

A summary of the numerical investigation results at nominal heat fluxes of $10\,\mathrm{W \cdot m^{-2}}$ and $100\,\mathrm{W \cdot m^{-2}}$ is reported in Table 1, showing the predicted performance in terms of the combined relative standard uncertainty.

Table 1 Numerically estimated performances, assuming a mean temperature difference across the side air gap equal to 10^{-2} K

Nominal heat flux ($W \cdot m^{-2}$)	10	100
Heat flux calculated at section "Oo" ($W \cdot m^{-2}$)	9.468	99.30
Maximum deviation from uniformity	0.44 %	0.19 %
Relative standard uncertainty		
Nonuniformity of the heat flux	0.13 %	0.05 %
Stability of the generated heat flux	0.15 %	0.20 %
Lateral heat flux losses	1.54 %	0.20 %

3 Engineered Design of the Calibration Apparatus

On the basis of the numerical investigation, a preliminary design of the HFM calibration apparatus was carried out. With respect to the numerically investigated configuration, several changes have been incorporated to the engineered setup in order to improve overall operation.

The Fig. 4 shows a scheme of the calibration apparatus designed. As its mass calibration apparatus is approximately 120 kg, to make easily accessible the HFM measurement zone and reduce the installation time before a calibration, it was decided to turn the system upside down. Because of that, the air gap which decouples the heaters was replaced by a solid insulator. The system also rests on three legs of insulating material to further minimize heat losses. The plate stack was also enclosed in a coaxial ring of rigid insulation of MicroTherm® which acted as a guide for the plates and was further insulated by several layers of soft insulation. The aluminum plates provided to homogenize the heat flux were made slightly thicker than those set in the simulation in order to accommodate flat heaters and control sensors. A passive coaxial guard ring made of borosilicate glass was added to minimize heat radial dispersion around the reference Pyrex plates in order to use the full calibration surface where an HFS is allocated. In this way, the calibration area is a circle of 300 mm in diameter. The Pyrex glass stack was made of three plates having different thickness, i.e., 20 mm, 30 mm, and 50 mm, which can be used alone or combined to widen the heat flux range. To minimize the distortion of heat flux lines, an HFS under calibration is always matched to a complementary plate of similar material which covers the whole calibration surface. The temperature control and homogeneity of the brass cold plate was achieved by milling several channels in the plate, sealing them with a lid and connecting the resulting fluid circuit to an external temperature bath.

A number of critical temperatures were identified and kept under control during the system operation; they are as follows:

i. The temperature difference between upper guard and main heaters, which was detected by two Pt-100 PRTs placed near the heaters. This parameter is managed by a PID controller acting on the guard heater to null the difference and, consequently, the upward heat flux;
ii. the temperature of the main heater, which is detected by a Pt-100 sensor connected to a PID to control the heat flux set point;

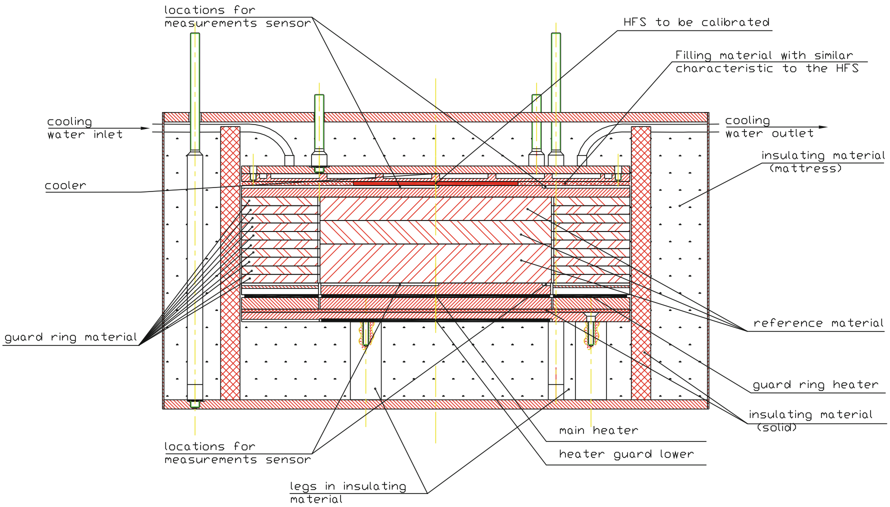

Fig. 4 Layout and main components of the engineered design of the HFM calibration apparatus

iii. the temperature difference between main and guard ring heaters. It is detected by eight type-J differential thermocouples evenly distributed on the annular interface between the heaters. The differential emf signal is sent to a PID to null the difference and, thus, the heat loss in the radial direction.

A set of six calibrated sensors were used for measuring the actual plate temperatures and for calculating the applied heat flux. A pair of stainless-steel-sheathed PRTs was inserted in each plate at the measuring sections “Ee,” “Mm,” and Oo” with their sensing elements located at different radial positions in order to check for the temperature uniformity in real time (see Fig. 2).

During a calibration, the temperature of the main heater is set according to the heat flux set point, while the cold plate is held at constant temperature and the guard heaters are automatically controlled to minimize heat flux losses. The one-dimensional heat flux which flows through the HFS under calibration is then estimated from the reference material thickness and its certified thermal-conductivity coefficient. A HFS calibration would include several heat flux values repeated at different cold-plate temperatures in order to explore the whole response of a heat flux sensor.

Two similar HFM calibration apparatuses are under construction and testing at INRIM and at the University of Cassino. Future developments of the work will be the experimental validation of the numerical simulation which, once achieved, will help in a further optimization of the metrological performance of such calibration systems.

4 Conclusions

The results of a numerical investigation carried out to design a calibration apparatus for heat flux meters is presented in this work. The system was designed for two different purposes: (i) for measuring the thermal conductivity of insulators and (ii) for calibrating an HFM with an absolute method (i.e., by measuring the applied power from the heater and its active cross section) or by a relative method (i.e., by measuring the temperature drop across a reference material of known thickness and thermal conductivity).

The metrological performance of the designed calibration system was evaluated by numerical simulations with a Finite Element Code (COMSOL®). The results show that in order to minimize the uncertainty of the generated heat flux, a very fine temperature control on the side thermal guard is needed.

Following the numerical investigations, an engineered design of the calibration apparatus was developed and discussed in detail. Two calibration apparatuses are under construction to serve as primary- and secondary-level calibration standards. Once validated through experimental testing, the numerical model will help in further optimizing the calibration systems.

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References

1. F. Van der Graaf, in *Sensors*, vol. 4, ed. by W. Göpel, J. Hesse, J.N. Zemel (VCH, New York, 1989), pp. 295–322
2. R.L. Hauser, in *Building Applications of Heat Flux Transducers*, ed. by E. Bales, M. Bomberg, G.E. Courville (ASTM, West Conshohocken, Pennsylvania), pp. 172–183
3. S.N. Flanders, J. Building Phys. **18**, 28 (1994)
4. V. Murthy, B. Tsai, R. Saunders, in *Proceedings of ASME Heat Transfer Division*, vol. 3 (ASME, New York, 1997), pp. 159–164
5. J. Lackey, N. Normandin, R. Machand, M.K. Kurmaran, J. Building Phys. **18**, 128 (1994)
6. R.R. Zarr, V. Martinez-Fuentes, J.J. Filliben, B.P. Dougherty, J. Test. Eval. **29**, 293 (2001)
7. ASTM Standard C 177-85, *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus, Annual Book of ASTM Standards 20* (ASTM, West Conshohocken, Pennsylvania, 1993)
8. ISO 8301, *Thermal Insulation—Determination of Steady-State Thermal Resistance and Related Properties—Heat Flow Meter Apparatus* (ISO, Geneva, Switzerland, 1991)
9. ASTM Standard C 518-91, in *Annual Book of ASTM Standards 151* (ASTM, West Conshohocken, Pennsylvania, 1993)
10. ISO 8302, *Thermal Insulation—Determination of Steady-State Thermal Resistance and Related Properties—Guarded Hot Plate Apparatus* (ISO, Geneva, Switzerland, 1991)
11. M. Bomberg, K.R. Solvason, in ASTM STP 789, *Thermal Insulation, Materials and Systems for Energy Conservation in the '80s* (ASTM, West Conshohocken, Pennsylvania, 1983), p. 277
12. M. Bomberg, K.R. Solvason, in *Guarded Hot Plate and Heat Flow Meter Methodology* (ASTM, West Conshohocken, Pennsylvania, 1985), p. 140