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COMPARATIVE ANALYSIS OF DIFFERENT METHODS TO EVALUATE THE THERMAL CONDUCTIVITY OF HOMOGENOUS MATERIALS

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ABSTRACT

Thermal conductivity of materials for structural elements and thermal insulation represents a fundamental parameter in the assessment of the energy need of buildings. In this paper, two different systems for thermal conductivity measurement are compared, based respectively on the calibrated hot box and on the guarded hot plate methods. The study is specifically aimed at assessing the range of thermal transmittance where the hot box system is suitable and verifying the strengths and the weaknesses of the system.

The comparison between measurements on specimens with different thermal conductivity and thickness showed that the two methods are substantially equivalent in the considered range of thermal conductivity, but are not completely interchangeable. In particular, the measurement campaign confirmed the expectation that the hot box system gives more accurate results with low thermal resistance samples.

INTRODUCTION

The correct evaluation of thermal conductivity is often object of debate as it represents a fundamental parameter in fields such as the assessment of the energy need of buildings. In this paper, two different measurement systems are compared, based on the calibrated hot box and the guarded hot plate methods. The hot box setup is mainly used for thermal measurements on large and inhomogeneous specimens, but it is also suitable for uniform materials like those usually tested thanks to the guarded hot plate facility. The study is aimed at assessing the range of thermal transmittance where the hot box system is more reliable and identifying the weaknesses and the strengths of the system. The comparative analysis between the two test methods was performed by testing three different materials, with different thermal conductivities.

Keywords: thermal conductivity, thermal transmittance, measurement, calibrated hot box, guarded hot plate.

MEASUREMENT METHODS

Calibrated hot box

The calibrated hot box apparatus of the Department of Industrial Engineering of the University of Perugia was built following the recommendations of the Standard ISO 8990 [1], as well as tips gathered from a literature review. The results of previous measurement campaigns performed on masonry specimens by a heat flow meter apparatus [2], available at the laboratories of the University of Perugia, were also taken into account.

In this hot box apparatus, the thermal transmittance of the specimen is obtained from the heat rate needed to maintain the hot chamber at a fixed temperature, once the temperature of the cold chamber is fixed and steady-state conditions are achieved. The strict requirements on temperature control and the need of limiting the chamber volume oriented the choice of the heating system towards an original solution: self-regulating electric heating cables positioned on the wall opposite to the specimen under test, in the hot chamber. The cold side is cooled by a chiller placed completely outside the cold chamber, except for the internal water-air heat exchanger. The control and monitoring system is connected to a data acquisition system that permits to visualize and store the measured data, as well as to select the rate of data storage. Measurements are performed with an accuracy that meets the requirements of the supplementary criteria of ISO 8990. It is also possible to acquire thermographic images and determine the thermal field on the specimen surface. An exploded view of the entire setup is shown in fig. 1, while the components installed in the apparatus are sketched in fig. 2.

The hot box apparatus was expressly designed to measure the thermal transmittance of windows [3] but it can also be used to evaluate the thermal conductivity of homogeneous materials, using the same calibration procedure.

The hot box needs a series of calibration measurements in order to evaluate the heat losses different from the flux transmitted through the specimen, such as metering chamber losses, heat transfer through the surround panel and all flanking losses [4].

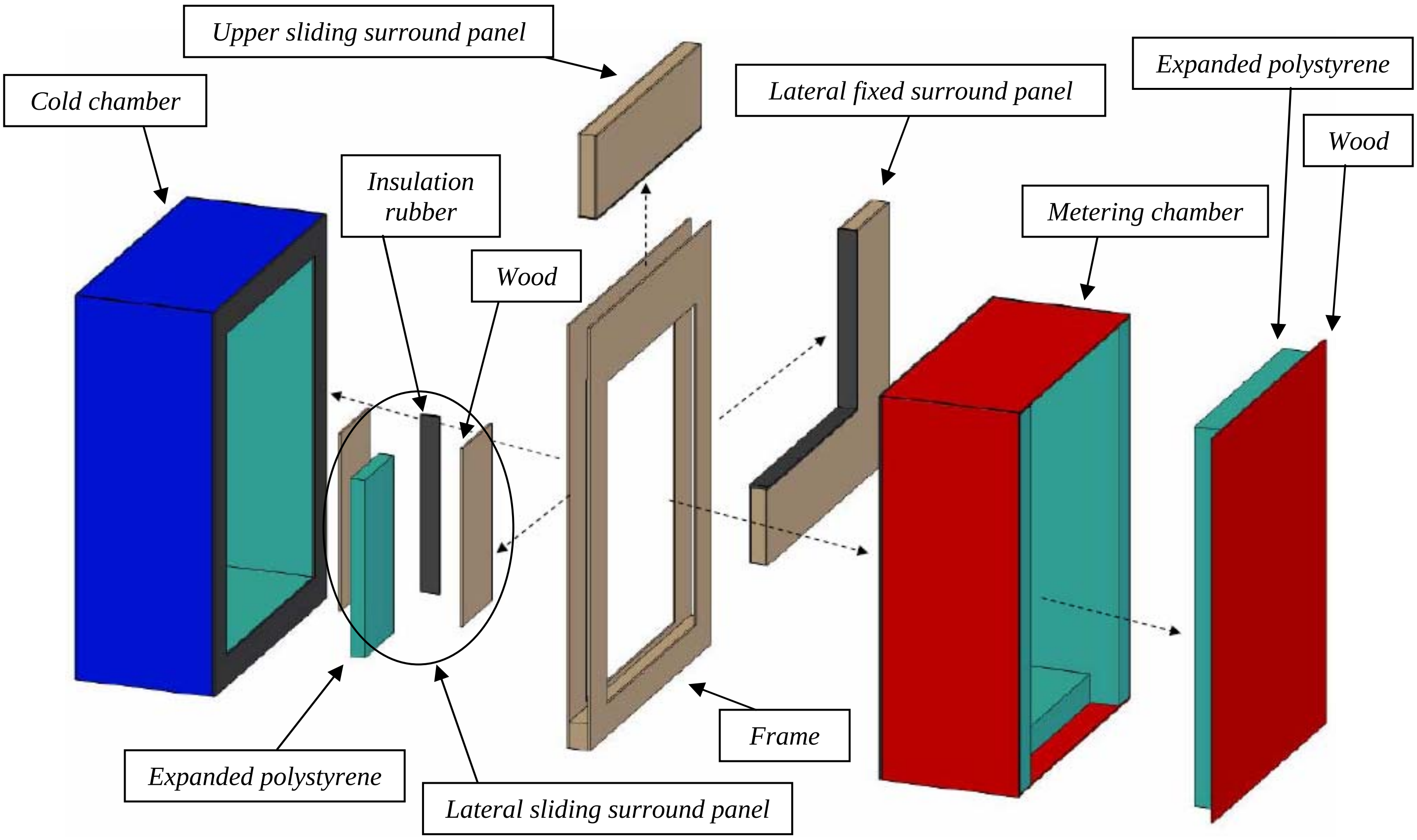

Figure 1. Exploded view of the hot box apparatus.

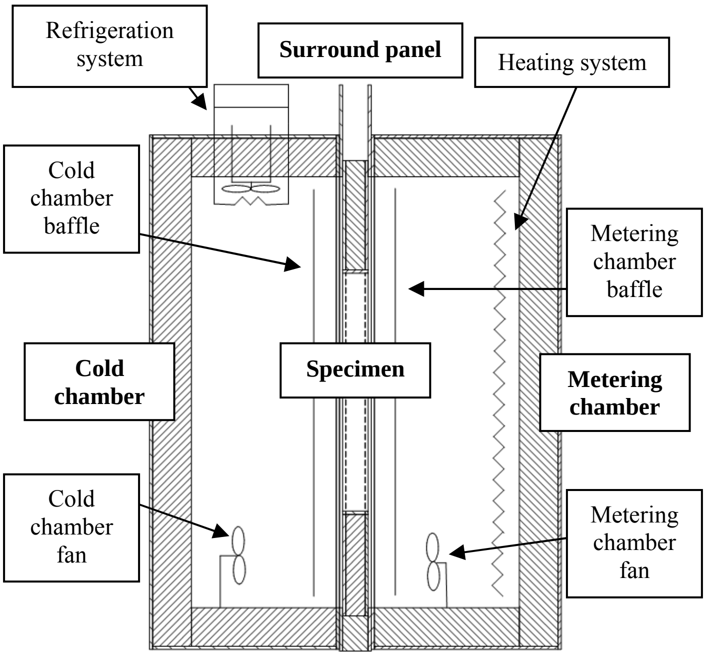

Figure 2. Sketch of the hot box apparatus.

The calibration curves were obtained by testing two expanded polystyrene panels with same specimen dimensions (1.230 m x 1.480 m), a thick one (0.060 m) and a thin one (0.020 m); the thermal conductivity of the polystyrene (0.035 W/(m K)) was recovered by means of a different and independent test method. The heat flux transmitted through the hot chamber envelope was calculated from the thermal properties of the wall materials and the temperature measurements of a series of thermocouples on the inner and outer surfaces of the walls. The heat flow from the external environment to the metering chamber was calculated, apart from the contribution of thermal bridges, throughout the repetition of tests at different values of the laboratory temperature.

Thereafter, the effects of thermal bridges were evaluated in terms of linear thermal transmittance by means of a finite element model [5], starting from the chamber corners; the specific value obtained for the linear transmittance was 0.016 W/(m K).

A thermal bridge also exists near the specimen edge and is strictly dependant on the specimen thickness; for instance, the finite element analysis shows a value of 0.006 W/(m K) for a 60 mm thick specimen.

Another thermal bridge is represented by the junction for the surround panel (i.e. the panel supporting the specimen) and the envelopes of the hot and cold chambers, sketched in fig. 3. Its linear transmittance of 0.013 W/(m K) was obtained by finite element simulation, imposing an external temperature of 24°C and temperatures of 24°C in the (hot) metering chamber, 4°C in the cold chamber.

Once the peripheral losses are assessed, three further measurements are needed for each calibration panel, in correspondence of three different cold chamber temperatures, and maintaining the hot side at 20°C. The goal is to obtain a set of calibration curves: the surround panel thermal resistance as a function of the panel average temperature, the total surface thermal resistance and the convective fraction of the surface heat exchange as a function of the heat flux through the calibration panel.

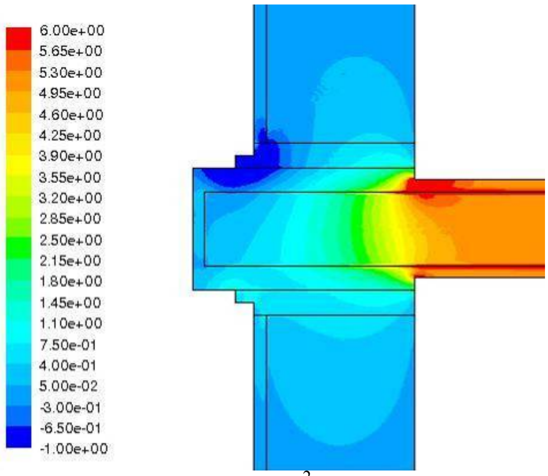

Figure 3. Hot box: heat flux (W/m^2) at the junction between the two chambers and the surround panel.

The results of the whole procedure are reported in figs. 4, 5, and 6. In case of homogenous material under test, the correction due to the surface resistance can be avoided if a set of thermocouples are mounted on the cold and hot surface of the specimen.

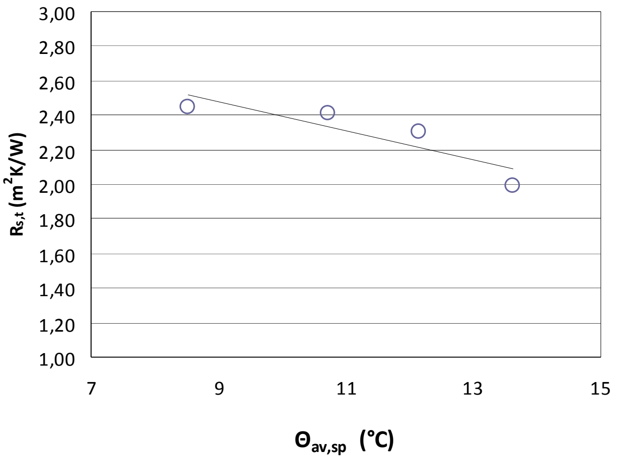

Figure 4. Calibration curves for the thermal resistance of the surround panel.

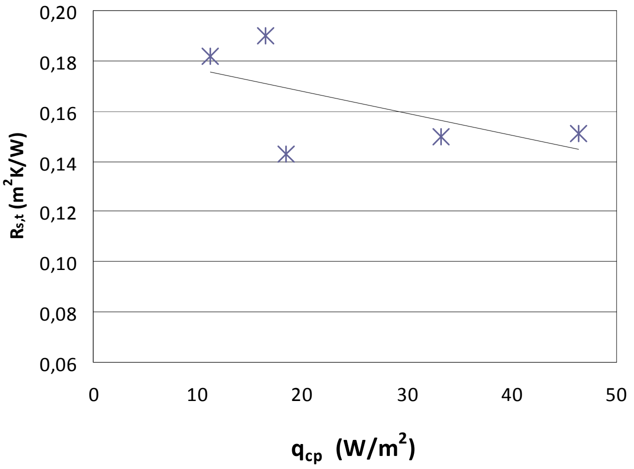

Figure 5. Calibration curves for the total surface resistance at the specimen surface.

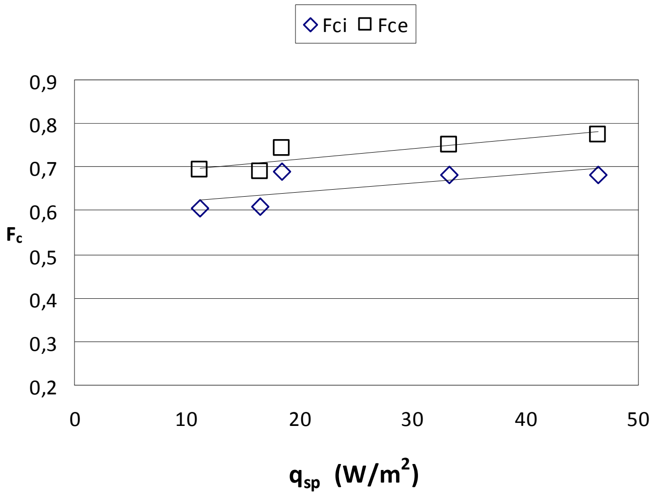

Figure 6. Calibration curves for the convective fraction of the total surface heat exchange at the hot (F_{ci}) and cold (F_{ce}) side.

The uncertainty was estimated by the law of propagation based on the root-sum square formula [6,7]. Since thermal conductivity λ is a function of n independent variables u_i, which are known with an uncertainty Δu_i, each one with the same confidence level (95%), the global uncertainty $\Delta\lambda$ can be written as follows:

$$\Delta\lambda = \sqrt{\sum_{i=1}^{n}\left[\frac{\partial\lambda(u_i)}{\partial u_i}\right]^2 \Delta u_i^{\,2}} \qquad (1)$$

Guarded hot plate

The guarded hot plate apparatus, available at the Energy Efficiency Laboratory (EELab) of the University of Modena and Reggio Emilia, was built according to the ASTM C-177 Standard [8]. This is similar and substantially equivalent, but not identical, to other measurement standards [9,10].

The apparatus requires testing simultaneously two samples in the form of a square slab with size 300 mm x 300 mm or bigger. An exploded sketch is shown in fig. 7.

The measurement process requires that a fixed heat rate is delivered by an electric heater sandwiched between the two samples. This produces a heat flow through the samples, towards two plates chilled by a liquid cooling system.

From the heat flow rate at steady state and the temperature measured at the hot and cold surfaces of the samples, it is possible to recover the thermal conductivity of the tested material.

The heater is split into a square element (the central heater), which is supplied with an assigned power rate, and a frame element (the guard heater), which is kept at the same temperature of the central element by a closed-loop control system. This is aimed at achieving a one-dimensional thermal field in the actual test section, corresponding to the central heater alone.

A couple of metal plates (the hot plates) are interposed between the heaters and each sample, matching the same square element/frame element scheme and hosting the hot side temperature sensors.

A couple of metal plates (the cold plates) is also interposed between each sample and the chilled plates, again matching the square element/frame element scheme and hosting the cold side temperature sensors. The temperature sensors and the power supply devices are all connected to a computerized data acquisition system.

The control software, managing either the data acquisition process or the closed-loop control of the guard heater, is built in the LabView programming environment.

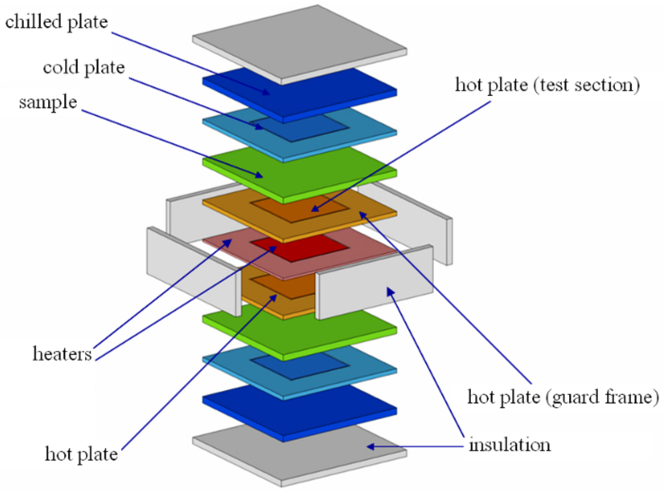

Figure 7. Sketch of the guarded hot plate apparatus.

The uncertainty is estimated by the law of propagation based on the root-sum square formula below [8] from the total uncertainties on heat flux, temperature difference between hot and cold plate, specimen area and thickness:

$$\Delta\lambda = \lambda \cdot \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta S}{S}\right)^2 + \left(\frac{\Delta L}{L}\right)^2} \tag{2}$$

The guarded hot plate apparatus was validated, with excellent results, by a blind-test comparison with an established apparatus available at DIENCA, University of Bologna, performed on a large set of samples.

SAMPLES AND RESULTS

The comparative analysis between the two test methods was performed by testing three different materials (fig. 8), covering a relatively wide range of thermal conductivities.

Figure 8. Pictures of the analyzed samples: plasterboard, plywood, and expanded polystyrene.

The most conductive tested sample is a 15 mm plasterboard panel, a material that is often used in the building sector within packages for vertical and horizontal internal partitioning.

A 50 mm panel of expanded polystyrene (EPS) with graphite was chosen as representative of the highly insulating materials that are commonly used for thermal insulation of building elements.

The 20 mm plywood sample was tested because its expected value of thermal conductivity lays between the ones of the other materials under test. Moreover, wood is knowing a raising interest as raw material in the building sector.

The results of the measurement campaign are reported in tab. 1, together with the uncertainty of each measure and reference data obtained from the literature [11,12] or product data sheets [13].

Table 1. Cross comparison of thermal conductivities for the analyzed samples.

Sample	*Hot box*	*Hot plate*	*Literature*
	W/(m K)	W/(m K)	W/(m K)
Plasterboard	0.245 ± 0.009	0.255 ± 0.005	0.250
Plywood	0.109 ± 0.005	0.114 ± 0.003	0.120
Polystyrene with graphite	0.032 ± 0.005	0.030 ± 0.002	0.031

As thermal conductivity of insulating materials such as expanded polystyrene is dependent on temperature, the conductivity values at the mean temperature of the specimen θ_m measured by the hot plate apparatus were corrected into the values at 10°C according to EN ISO 10456 [14]:

$$\lambda_{10°C} = \lambda \cdot \exp\left[0.003 \cdot \left(10°C - \theta_m\right)\right] \tag{3}$$

The results show that the thermal conductivity of samples with relatively high thermal resistance, such as the polystyrene panel (about 1.6 (m^2 K)/W) is better determined by the guarded hot plate method, both in terms of absolute values and relative uncertainty. Panels with medium and low thermal resistance, such as plywood (about 0.17 (m^2 K)/W) and plasterboard (about 0.06 (m^2 K/W), show similar accuracy level for the two methods.

CONCLUSIVE REMARKS

The thermal conductivity of homogenous materials can be evaluated with different methods. The comparison of measurements by a calibrated hot box apparatus with those by a guarded hot plate apparatus showed that the two methods are substantially equivalent in the considered range of thermal conductivity, but are not completely interchangeable.

Overall, the measurement campaign confirmed expectations that the hot box system under investigation gives more accurate results with low thermal resistance samples, while the guarded hot plate method is generally known to provide its best performance with high thermal resistance samples.

When the analysis is extended to highly conductive materials such as metals or rocks, the reliability of the hot plate is expected to be strongly affected by the (unknown) thermal resistance at the contact interfaces between samples and hot/cold plates, which may become of the same order of magnitude of the thermal resistance of the samples themselves. On the contrary, the accuracy of the hot box system is expected to improve with decreasing thermal resistance as uncertainties due to extraneous losses become less significant with respect to heat transferred through the specimen.

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NOMENCLATURE

Latin symbol	*Quantity*	*SI Unit*
A	Surface area	m^2
F	Fraction	-
L	Specimen thickness	m
q	Heat flux	W/m^2
R	Thermal resistance	$(m^2\ K)/W$
S	Specimen area	m^2
T	Temperature difference	K
u	Independent variable	-

Greek symbol	*Quantity*	*SI Unit*
$\Delta\lambda$	Uncertainty on thermal conductivity	W/(m K)
Δu	Uncertainty	-
θ	Temperature	°C
λ	Thermal conductivity	W/(m K)

Subscript	
10°C	Value at 10°C
av	Average
ci	Convective internal (hot side)
ce	Convective external (cold side)
cp	Calibration panel
m	Mean value
sp	Surround panel
s,t	Surface total

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