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AN INNOVATIVE METHOD FOR THE THERMAL CONDUCTANCE MEASUREMENT OF WINDOWS

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ABSTRACT

One of the most important contributions to the energy requirements in buildings is due to heat transfer through the window surfaces. Therefore, several efforts were made in order to obtain new window frames and glass assemblies with low thermal heat transfer characteristics. To this point of view, it is also necessary to reach accurate measurements of the above-mentioned parameters.

In this paper, the authors show an innovative measurement method based on radiative and conductive heat transfer which performs window thermal conductance measurements with annexed uncertainty budget evaluation.

In the design of the experimental apparatus the authors used a 3D finite volume software whose results were useful for the system optimisation and characterisation.

INTRODUCTION

The European Community, in accordance with the Kyoto protocol, promotes actions in the sustainable building sector with the intent to: i) reduce carbon dioxide emissions, ii) minimise waste and iii) prevent indoor pollution.

To this viewpoint the Energy Performance of Building (EPBD) (Directive 2002/91/CE of 16/12/2002 [1]) promotes the improvement of energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.

This Directive introduces requirements as regards: i) the general structure of a methodology to calculate the integrated energy performance of buildings; ii) the application of minimum requirements on the energy performance of new buildings and of large existing buildings that are subject to major renovation; iii) energy certification of buildings; and iv) regular inspection of boilers and of air-conditioning systems in buildings and in addition an assessment of heating installation in which the boilers are more than 15 years old.

The EPBD was assimilated by Italian law by means of the legislative degree n. 192 of 19/08/2005 [2] and its added integration [3].

In particular, as regards the minimum requirements for the energy performance of buildings, very severe limits are imposed to the thermal transmittance of building envelopes whose windows have a predominant role.

In order to evaluate the thermal transmittance of windows two different approaches can be used: i) a simplified method [4] and ii) a measurement one [5].

The simplified model in [4] rarely gives low uncertainty values for complex geometry estimated parameters whereas the measurement method reported in [5] presents several disadvantages as the measurement procedure complexity and the uncertainty evaluation.

In the present paper, in particular, the authors introduce an innovative measurement methodology which leads to the determination of the window thermal conductance, getting the measurement independent on the thermal convective coefficients and avoiding all the complex procedure reported in [5], by conjugating the use of radiative heat transfer and the vacuum technology.

NOMENCLATURE

C	[W/(m^{2}K)]	Thermal conductance
d	[m]	Minimum distance between aluminium plate and window face
F	[-]	View factor
k	[W/mK]	Thermal conductivity
L	[m]	Length
$\dot{q}$	[W/m^2]	Heat flow
T	[K]	Temperature
u	[-]	Uncertainty
x	[-]	Physical quantity

Special characters

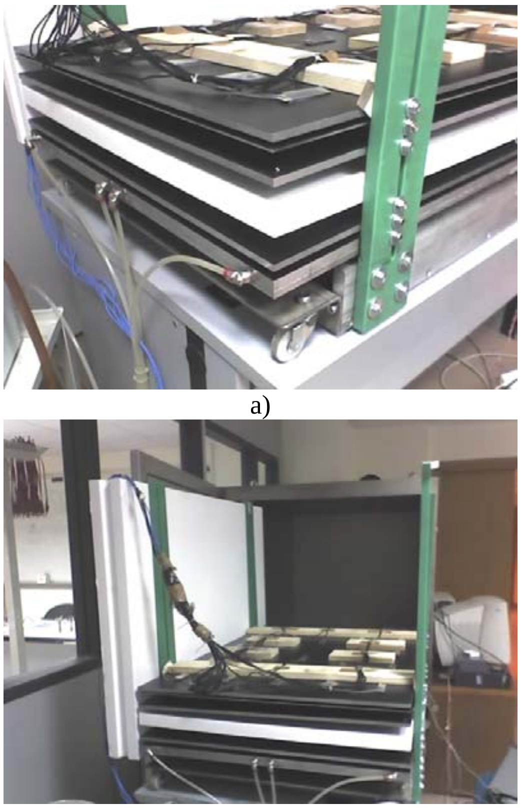
ε	[-]	Thermal emissivity
σ	[W/(m^{2}K^4)]	Stefan-Boltzman's costant

Subscripts

p	Aluminium plate
w	Window
up	Upper measurement system
down	Lower measurement system

EXPERIMENTAL APPARATUS

The experimental apparatus, reported in Fig. 1, is conceptually similar to the one reported in [6].



a)

b)

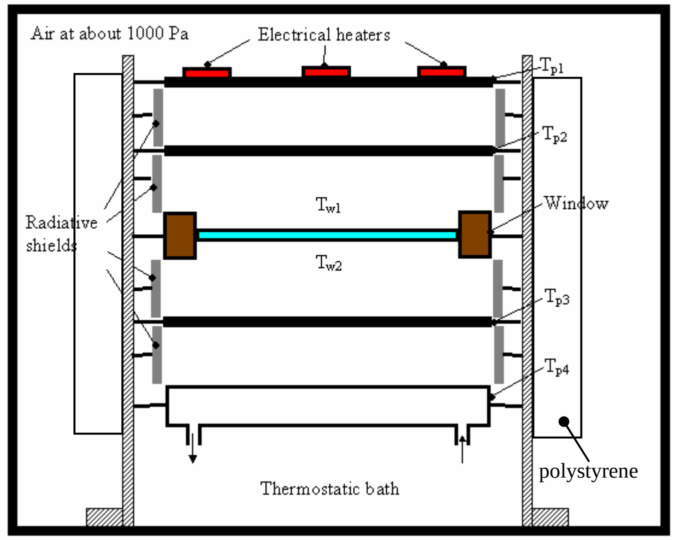
Figure 1 Experimental apparatus

The apparatus measures the window thermal conductance on the base of one-dimensional steady state comparative method.

Energy is supplied at the top of the apparatus by means of electrical resistances and it is withdrawn using a water cooling system at the bottom (Fig. 2).

In particular, by using aluminium plates and radiative shields, two radiative heat flow meter were obtained.

The dimensions of the vacuum chamber (1500 x 1000 x 1000 mm^3) and of the aluminium plates (1250 x 750 mm^2) are wide enough to allow the measure of the thermal conductance of several window configurations, also on the basis of geometrical and thermal symmetries.



c)

Figure 2 Schematic representation of the experimental apparatus

The measurement principle can be easily obtained through a thermal radiative and conductive heat transfer between the different aluminium plates ($p_{1\text{-}4}$) and the upper and lower face of the window ($w_{1,2}$). The authors point out that convection is negligible because of the low air pressure in the measurement chamber and the use of radiative shields avoids radiative "leakages" along the boundaries. Moreover, in order to reduce thermal bridge contributions due to the supports, the measurement apparatus was bounded with a 10 cm thick polystyrene.

In particular, by neglecting the cross-sectional area variation:

Thermal balance between facing plates p_i and p_j

$$\dot{q}_{p_i-p_j} = \left| \frac{k_{a,p_i-p_j}}{L_{p_i-p_j}} \cdot \left(T_{p_i} - T_{p_j}\right) + \frac{\sigma \cdot \left(T_{p_i}^4 - T_{p_j}^4\right)}{\frac{1-\varepsilon_{p_i}}{\varepsilon_{p_j}} + \frac{1-\varepsilon_{p_j}}{\varepsilon_{p_j}} + \frac{1}{F_{p_i-p_j}}} \right| \quad (1)$$

Thermal balance between plate p and window face w

$$\dot{q}_{p-w} = \left| \frac{k_{a,p-w}}{L_{p-w}} \cdot \left(T_p - T_w\right) + \frac{\sigma \cdot \left(T_p^4 - T_w^4\right)}{\frac{1-\varepsilon_p}{\varepsilon_p} + \frac{1-\varepsilon_w}{\varepsilon_w} + \frac{1}{F_{p-w}}} \right| \quad (2)$$

The view factors $F_{p_1-p_2}$, $F_{p_2-w_1}$, $F_{w_2-p_3}$ and $F_{p_1-p_2}$ are evaluated in accordance with [7].

The temperatures $T_{p_{1-4}}$ of the four isothermal plates were measured through miniaturised Pt100 resistance thermometers inserted in 2 mm holes at the centre of each 1 cm thick plate. These resistance temperature detectors were calibrated using a thermostatic bath at the Laboratory for Industrial Measurements (LAMI) at the University of Cassino. The bath is characterized by a stability of 0.005°C and an uniformity of 0.02°C and a Pt25 transfer standard (with an uncertainty equal to 0.014°C) directly traceable to the National primary standards. The calibration curves were obtained on the basis of 7 calibration points in the range 0 to 80 °C using the generalized least squares technique [8]. The combined standard uncertainty was equal to 0.08°C in the above mentioned temperature range. The acquisition data system, interfaced by means of a RS-232C connector to a personal computer, allows a scan interval equal to 1 minute.

As regards thermal emissivity, all the surfaces of the window are covered by a paint of known thermal emissivity (the same paint used for the isothermal aluminium plates), measured by means of a S40 Flyr® infrared camera, also to avoid radiative phenomena in glass.

Therefore:

$$\varepsilon_{p_1} = \varepsilon_{p_2} = \varepsilon_{p_3} = \varepsilon_{p_4} = \varepsilon_{w_1} = \varepsilon_{w_2} = \varepsilon \tag{3}$$

Because of heat flow continuity, the temperatures T_{w_1} and T_{w_2} can be obtained from eqs. (1)-(2).

The thermal conductivity of the air between the plates and the windows was taken at the mean temperature value. In particular its dependence upon temperature is [9]:

$$\begin{aligned} k_a \big/ \left(W \cdot m^{-1} \cdot K^{-1}\right) &= \text{-1.8939E-12} \cdot (T/K)^4 + \\ &+ \text{2.6357E-09} \cdot (T/K)^3 \text{-1.4176E-06} \cdot (T/K)^2 + \\ &+ \text{4.1761E-04} \cdot (T/K) \text{-2.7388E-02} \end{aligned} \tag{4}$$

and:

$$\begin{aligned} k_{a,p_i-p_j} &= k_a\left(T = \frac{T_{p_i} + T_{p_j}}{2}\right) \\ k_{a,p-w} &= k_a\left(T = \frac{T_p + T_w}{2}\right) \end{aligned} \tag{5}$$

The standard relative uncertainty of air thermal conductivity is equal to 5%.

Once the two window temperatures T_{w_1} and T_{w_2} were evaluated, two thermal balances across the window can be applied:

$$\dot{q}_{p_1-p_2} = C_{up} \cdot \left(T_{w_1} - T_{w_2}\right) \tag{6}$$

and

$$\dot{q}_{p_3-p_4} = C_{down} \cdot \left(T_{w_1} - T_{w_2}\right) \tag{7}$$

The thermal conductance values measured through the upper parallel plates, C_{up}, and the lower ones, C_{down}, may differ since thermal leakages may occur.

Hence, a mean value can be taken:

$$C = \frac{C_{up} + C_{down}}{2} \tag{8}$$

EXPERIMENTAL UNCERTAINTIES OF THE APPARATUS

The estimation of the measured thermal conductance depends on different parameters as reported in eqs. (1)-(2). The corresponding standard uncertainty, $u(C)$, is evaluated by considering the standard uncertainties of the input quantities, $(\partial C/\partial x_i) \cdot u(x_i)$, where $(\partial C/\partial x_i)$ are the sensitivity coefficients of each parameter or physical quantity x_i [10].

In particular:

$$\begin{aligned} u^2(C_\alpha) &= \left(\frac{\partial C_\alpha}{\partial T_\beta}\right)^2 \cdot u^2(T_\beta) + \left(\frac{\partial C_\alpha}{\partial T_\gamma}\right)^2 \cdot u^2(T_\gamma) + \\ &+ \left(\frac{\partial C_\alpha}{\partial k_{a,\beta-\gamma}}\right)^2 \cdot u^2(k_{a,\beta-\gamma}) + \\ &+ \left(\frac{\partial C_\alpha}{\partial k_{a,\gamma-\delta}}\right)^2 \cdot u^2(k_{a,\gamma-\delta}) + \\ &+ \left(\frac{\partial C_\alpha}{\partial L_{\beta-\gamma}}\right)^2 \cdot u^2(L_{\beta-\gamma}) + \\ &+ \left(\frac{\partial C_\alpha}{\partial L_{\gamma-\delta}}\right)^2 \cdot u^2(L_{\gamma-\delta}) + \left(\frac{\partial C_\alpha}{\partial \varepsilon}\right)^2 \cdot u^2(\varepsilon) + \\ &+ \left(\frac{\partial C_\alpha}{\partial F_{\beta-\gamma}}\right)^2 \cdot u^2(F_{\beta-\gamma}) + \left(\frac{\partial C_\alpha}{\partial F_{\gamma-\delta}}\right)^2 \cdot u^2(F_{\gamma-\delta}) \end{aligned} \tag{9}$$

where $(\alpha, \beta, \gamma, \delta)$ are equal to (up, p_1, p_2, w_1) and $(down, p_3, p_4, w_2)$ alternatively.

Finally

$$u^2(C) = \frac{u^2(C_{up}) + u^2(C_{down})}{4} \tag{10}$$

NUMERICAL SIMULATION OF THE EXPERIMENTAL APPARATUS

The final design of the experimental apparatus required a simulation process that was carried out by using the Finite Volumes commercial software FLUENT 6.1®. Both convection, thermal conduction and radiation are simulated and, in particular, the last one was simulated through the Discrete Ordinate Model (DOM) [11].

Moreover, the authors used in the simulation a typical window schematised in Figure 3, with a thermal conductance equal to $5.47\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ evaluated by a numerical simulation of the heat transfer through the window once its temperatures of the two surfaces were imposed (only conductive problem).

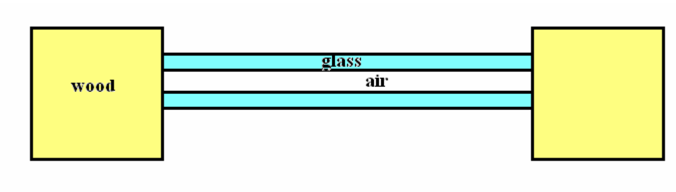


Figure 3 Scheme of the window used in the numerical simulation

The stationary temperature distribution in the chamber and across the window is reported in Figure 4.

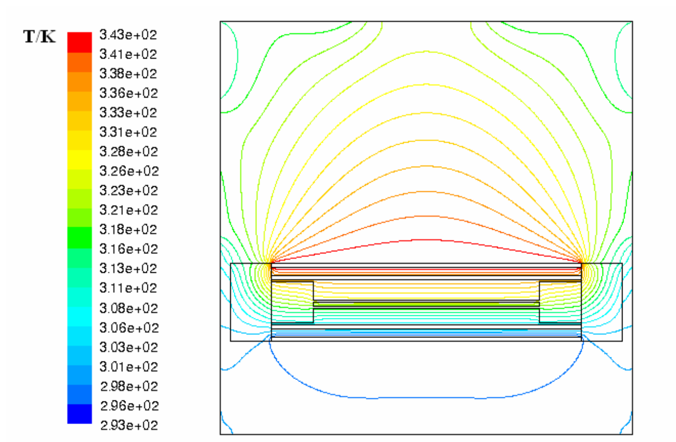


Figure 4 Numerical temperature distribution in stationary conditions

The thermal leakages are equal to about 7% respect to $\dot{q}_{p_1-p_2}$.

The authors also estimated the uncertainty budget on the basis of the numerical results. The obtained numerical results and the corresponding uncertainty propagations are reported in Table 1 and 2. It must be pointed out that the uncertainties of the parameters are typical values that can be obtained during experimental measurements in laboratory, and, moreover, the *d* parameter is the minimum distance between the window surface and the corresponding plate and it is necessary for the evaluation of the view factors in the case of non planes surfaces against plane ones.

Table 1 Numerical determination of window thermal conductance.

Parameter *x*	$u(x)$
ε =0.95	0.01
T_{p1} =343 K	0.60 K
T_{p2} =334.99 K	0.15 K
T_{p3} =303.42 K	0.15 K
T_{p4} =293.K	0.15 K
$L_{p_1-p_2}$ =2.0E-02 m	2.0E-03 m
$L_{p_3-p_4}$ =2.0E-02 m	2.0E-03 m
$L_{p_2-w_1}$ =3.4E-02 m	1.1E-01 m
$L_{w_2-p_3}$ =2.6E-02 m	8.3E-02 m
k_{a,p_1-p_2} =2.89E-02 W/(m K)	1.45E-03 W/(m K)
k_{a,p_3-p_4} =2.60E-02 W/(m K)	1.30E-03 W/(m K)
k_{a,p_2-w_1} =2.83E-02 W/(m K)	1.42E-03 W/(m K)
k_{a,w_2-p_3} =2.68E-02 W/(m K)	1.35E-03 W/(m K)
$d_{p_2-w_1}$ =5.0E-03 m	1.0E-03 m
$d_{w_2-p_3}$ =5.0E-03 m	1.0E-03 m
$C = 5.58 \dfrac{\mathrm{W}}{\mathrm{m^2 K}}$	

The temperature uncertainty takes into account calibration, uniformity and stability contributions and the uncertainty of $L_{p_2-w_1}$, $L_{w_2-p_3}$ is evaluated in accordance with a rectangular distribution taking into account the maximum and the minimum distance between plate and window.

The difference between the results obtained by the model, $5.58\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$, and the window value $5.47\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ is about 2%, while the obtained uncertainty is about 18%, and, consequently, a very good agreement is obtained.

As regards the uncertainty contributions, the most important ones are the uncertainty of T_{p1} and L_{w2-p3}, since T_{p1} uncertainty depends on a high stability uncertainty, whereas L_{w2-p3} has a high percentage uncertainty due to surface irregularity.

Table 2 Numerical determination of window thermal conductance uncertainty.

Parameter *x*	$\left[\frac{\partial C}{\partial x}\cdot u(x)\right]^2 \Big/ \frac{\mathrm{W}^2}{\mathrm{m}^4\mathrm{K}^2}$	$\frac{\left[\frac{\partial C}{\partial x}\cdot u(x)\right]^2}{u^2(C)}\cdot 100$
ε	3.6E-04	0.035
T_{p_1}	4.8E-01	47
T_{p_2}	6.6E-02	6.4
T_{p_3}	5.6E-02	5.4
T_{p_4}	2.1E-02	2.1
$L_{p_1-p_2}$	8.1E-03	0.79
$L_{p_3-p_4}$	1.1E-02	1.0
$L_{p_2-w_1}$	3.9E-02	3.8
$L_{w_2-p_3}$	3.2E-01	31
k_{a,p_1-p_2}	4.8E-03	0.47
k_{a,p_3-p_4}	9.9E-03	0.96
k_{a,p_2-w_1}	7.4E-04	0.072
k_{a,w_2-p_3}	5.2E-03	0.51
$d_{p_2-w_1}$	4.9E-05	0.0047
$d_{w_2-p_3}$	1.3E-04	0.013
$u(C)=1.01\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$		

To investigate the time required to reach stationary conditions, unsteady numerical simulations were carried out and the results are reported in Figure 4.

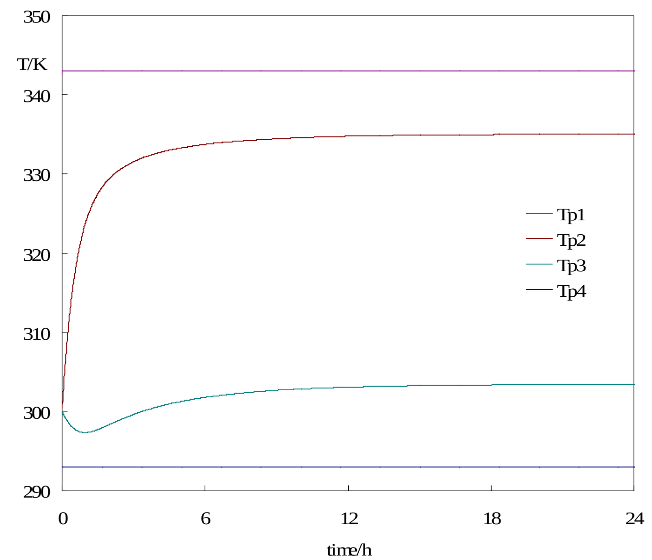


Figure 4 Numerical time evolution for temperature of aluminium plates

The steady temperature distribution is reached in about 11 hours (variations lower than 10^{-3} K for both $T_{p_1}-T_{p_2}$ and $T_{p_3}-T_{p_4}$).

This value is comparable to the time required for the measurement of the effective thermal conductivity through the experimental apparatus (conductivimeter) [6].

VALIDATION OF THE MEASUREMENT TECNIQUE

In order to validate the proposed measurement method, the authors measured the thermal conductance of a polystyrene panel instead of a window, whose thermal conductivity was previously determined through the experimental apparatus, conductivimeter, reported in [6].

The experimental uncertainty propagations is reported in Table 3.

Table 3 Experimental determination of polystyrene thermal conductance uncertainty.

Parameter *x*	$u(x)$	$\frac{\left[\frac{\partial C}{\partial x}\cdot u(x)\right]^2}{u^2(C)}\cdot 100$
ε	0.01	1.5
T_{p_1}	0.58 K	80
T_{p_2}	0.15 K	7.9
T_{p_3}	0.15 K	4.4
T_{p_4}	0.15 K	2.6
$L_{p_1-p_2}$	2.5E-03 m	2.3
$L_{p_3-p_4}$	4.3E-04 m	0.39
$L_{p_2-w_1}$	1.3E-03 m	0.012
$L_{w_2-p_3}$	5.8E-04 m	0.0039
k_{a,p_1-p_2}	1.42E-03 W/(m K)	0.43
k_{a,p_3-p_4}	1.28E-03 W/(m K)	0.55
k_{a,p_2-w_1}	1.39E-03 W/(m K)	0.030
k_{a,w_2-p_3}	1.29E-03 W/(m K)	0.038
$C=0.98\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$ and $u(C)=0.05\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$		

As regards the uncertainty budget, the same conclusions may be given as for the numerical simulation. However, the authors intend to improve the measurement performances of the experimental apparatus by means of a more accurate regulation system of the electrical heaters, reaching at least half of the present uncertainty.

This is a very important result since the uncertainty of the distance between the plates and the window surface is negligible, and consequently complex windows profiles that require complex measurements of the mean distance between the window and the plates can be measured with good uncertainty results.

As regards the steady state, it is reached in about 13 hours (variations lower than 10^{-3} K for both $T_{p1} - T_{p2}$ and $T_{p3} - T_{p4}$), as reported in Figure 5.

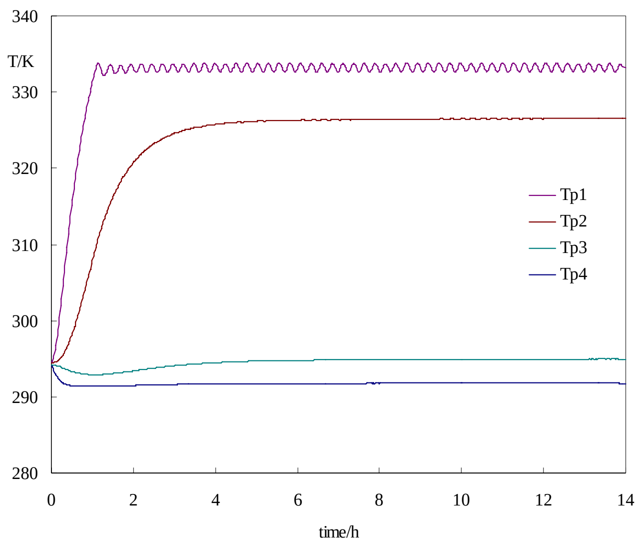


Figure 5 Experimental time evolution for temperature of aluminium plates

The corresponding values obtained from the conductivimeter are $C = 1.07\frac{\mathrm{W}}{\mathrm{m^2K}}$ and $u(C) = 0.05\frac{\mathrm{W}}{\mathrm{m^2K}}$, showing a perfect compatibility with the ones obtained from the present apparatus (difference of about 8%).

CONCLUSIONS

In the present paper the authors show an innovative measurement methodology for thermal conductance of windows. This methodology allows an accurate uncertainty evaluation and it does not require a complex procedure as the hot box method. Moreover, it gives directly the value of the thermal conductance and not the thermal transmittance, avoiding convective contribution.

The experimental results were compared to the ones obtained for a reference material, previously characterised by means of the experimental apparatus reported in [6], giving a very good agreement.

Moreover, the most important uncertainty contribution is given by the temperature of the hot plate, allowing an easy future improvement of the experimental apparatus by means of a more accurate temperature regulation system developed for this purpose.

ACKNOLEGMENTS

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