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Thermal transmittance measurements with the hot box method: Calibration, experimental procedures, and uncertainty analyses of three different approaches

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ABSTRACT

A large amount of heat loss through building envelopes takes place via inhomogeneous components such as windows, doors, and thermal bridges. This loss can be approximated by measuring in lab the actual thermal transmittance of these components with the use of a hot box. The calibration and experimental procedures can be performed, taking into account three standards for calibrating hot boxes: the European EN ISO 8990; the American ASTM C1363-05; and the Russian GOST 26602.1-99. An experimental setup for testing the accuracy of these standards has recently been created at the University of Perugia; after a measurement campaign for the validation of the test rig, the differences of the approaches were evaluated. Results showed that although the EN ISO 8990 and ASTM C1363-05 are similar in terms of procedures definition, methodology of thermal transmittance calculation, and level of uncertainty, the GOST 26602.1-99 differs from the others since it adds individual measurements of the thermal characteristics of each sample component. The analysis highlighted that the ideal procedure should include the Russian method to define the thermal behavior of each component under analysis, with a contemporary validation of the global results to be performed with one of the other two approaches.

1. Introduction

Buildings energy consumption accounts for a 20–40% of total energy use in developed countries and is above industry and transport figures in the European Union and the United States of America [1,2]. For this reason, recent legislation, such as the EU Directive 2010/31 [3] on energy efficiency in buildings, has tried to raise minimum energy efficiency standards, for both the single components and the entire building.

The envelope of a building plays a fundamental role in its energy balance. Therefore, the thermal properties evaluation of each component requires a high level of accuracy. For homogeneous materials or multilayer modules whose geometry and thermophysical properties lead to one-dimensional heat flux, the thermal transmittance results are easy to calculate. Simply use the single layers' thermal conductivities [4] obtained from manufacturers or measured through simple test rigs, for example, the guarded hot plate [5].

When components cannot be treated as homogeneous (such as when the structure is made of different materials, or when the heat transfer is two- or three-dimensional), different approaches are needed to accurately evaluate the thermal resistance of the elements. Numerical evaluations can represent an answer [6,7], but these methods need to be integrated by experimental validations.

For many years, hot box facilities have been used for thermal testing of inhomogeneous components, even if they have been applied with different standards throughout the world. Each hot box configuration consists of two closed rooms kept at constant, individual temperatures: the environmental chamber which is cold; and a metering chamber which is warm. The two rooms are divided by the specimen under test or by a panel where the specimen is installed. The evaluation of the heat flux between the two rooms is the definition of the specimen's overall thermal resistance, and also includes the air film resistances on both the cold and warm side.

At the Department of Industrial Engineering of the University of Perugia, a hot box apparatus has been designed, built, and calibrated according to three different standards: the European EN ISO 8990 [8]; the American ASTM C1363-05 [9]; and the Russian GOST 26602.1-99 [10]. Using information from a literature review, the three approaches were compared, focusing on the differences of calibration and measurement procedures, and evaluating the uncertainties of each method.

2. Overview of hot boxes applications

Today, hot boxes are reliable instruments for various types of measurements. However, their history dates to the first attempts of Mumaw [11], who in the early 70s used this device to test large and highly thermal resistant wall sections. Soon after, the potential benefit of this apparatus in the field of inhomogeneous materials

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Nomenclature

A	area (m^2)
F	fraction (–)
h	heat exchange surface coefficient ($W/m^2\,K$)
K	coefficient ($W/m^2\,K^{1.25}$)
L	length (m)
P	confidence level (%)
Q	specific heat flow (W)
q	specific heat flow per area unit (W/m^2)
R	thermal resistance ($m^2\,K/W$)
T	temperature (K, °C)
U	thermal transmittance ($W/m^2\,K$)
x	generic variable in the uncertainty measures (various)

Greek symbols

Δ	difference
λ	thermal conductivity (W/m K)
σ	standard deviation (various)
ν	degree of freedom (–)

Subscripts

a	air
ASTM	ASTM Standard
av	average
b	baffle
bor	border of the support panel where the specimen is installed
c	convective
calc	calculated
cold	cold chamber
e	external
edge	specimen perimeter
f	fan
fl	flanking loss
GOST	GOST Standard
hot	hot chamber
hcw	hot chamber walls
i	internal
ISO	ISO Standard
in	input
k	number of generic variables in the uncertainty measures
out	external ambient
S	specimen
s	surface
ST	standardized
sp	support panel
t	Student-*t*
tot	total

testing drew the attention of those investigating window systems. Klems [12] created the general guidelines for hot box construction, also proposing a procedure for the evaluation of the thermal losses through the hot (metering) chamber. In particular, he underlined the idea that heat transfer through the box walls must be defined with a high level of accuracy (even if they are well insulated). For this purpose, he introduced a calibration protocol to measure heat dispersions. The analysis on fenestration systems can also be extended to auxiliary components. Fang [13] studied the influence of high-reflectivity venetian blinds' characteristics in a hot box setup, suggesting an empirical correction factor for the window *U*-value.

Another popular application of this measurement system is in research on building materials. Adam and Jones [14] analyzed stabilised soil blocks (widely used as raw material in The Sudan), defining the thermal properties as a function of dry density and moisture content. Wakili and Tanner [15] compared the results of numerical analysis on porous clay bricks with the effective performance of the hot box, showing that the grade of mortar penetration into the void of bricks could change significantly the masonry thermal resistance. Gao et al. [16] focused their investigation on heat loss estimations for hollow blocks. Extending the analysis to dynamic conditions, they developed a simplified numerical tool that takes into account the multidimensional pattern of the thermal field. They conducted the validation through a hot box apparatus, setting a "linear step" excitation of air temperature. The hot box capability to perform unsteady conditions analyses is also testified by the work of Burch et al. [17], who derived empirical Transfer Function Coefficients of a multilayer masonry wall by an experimental campaign based on the generation of a slow ramp excitation in the climatic chamber.

The possibility of testing full-scale samples allows for the investigation of particular components of building envelopes, such as the cavity between two walls as analyzed by Aviram et al. [18], or the Wakili et al. experiments [19] on the thermal behaviour of a balcony board. The applications of hot box setups can also be extended to horizontal components. Elmahdy and Haddad [20], for example, modified the classic positioning of the specimen to evaluate the thermal transmission of skylights and sloped glazing in correspondence to various inclinations. Finally, it is worth mentioning the particular use of the hot box that was proposed in the Bondi and Stefanizzi research [21], where the structure, with minor adjustments, is used to evaluate the moisture transfer resistance (as opposed to simple heat transfer), of hollow bricks.

3. Design criteria and heat balance of hot boxes

The guidelines for hot boxes design criteria of EN ISO 8990 [8] and ASTM C1363-05 [9] follow the same basic concept. The sample is positioned between two rooms which are maintained at different temperatures in steady-state conditions. The thermal resistance of the specimen is obtained by measuring the power required to keep the hot chamber at constant temperature. The GOST 26602.1-99 [10] uses two methods. The first is similar to the other two standards, but the second method makes use of rooms at different temperatures in stationary conditions. The insulating properties of the specimen must be evaluated through the measurement of heat flows and temperature differences between the hot and cold sides. The insulating properties must also be evaluated at different points of the sample surface which are representative of an area with homogeneous properties (Fig. 1). The critical point of this procedure consists of defining the specimen parts where constant thermal features could be assumed, and also where the measurement is not influenced by heat transfers different from those crossing the sample, once the steady-state conditions are guaranteed. The other methodologies, on the contrary, do not have to deal with the problems linked to specimen complexity. However, particular attention must be paid to the fact that the heat flows from the metering chamber do not follow the path of the specimen. These approaches leave the possibility of choosing two main types of construction: the guarded hot box (Fig. 2a) and the calibrated hot box (Fig. 2b). The first is built with a guard chamber that contains the metering box. Since the two volumes are kept at the same temperature, correction for heat loss via walls is not necessary. The second construction does not have a guard chamber (a quality that permits the testing of larger samples), but the entire apparatus is located in a surrounding ambient whose temperature is known, but gener-

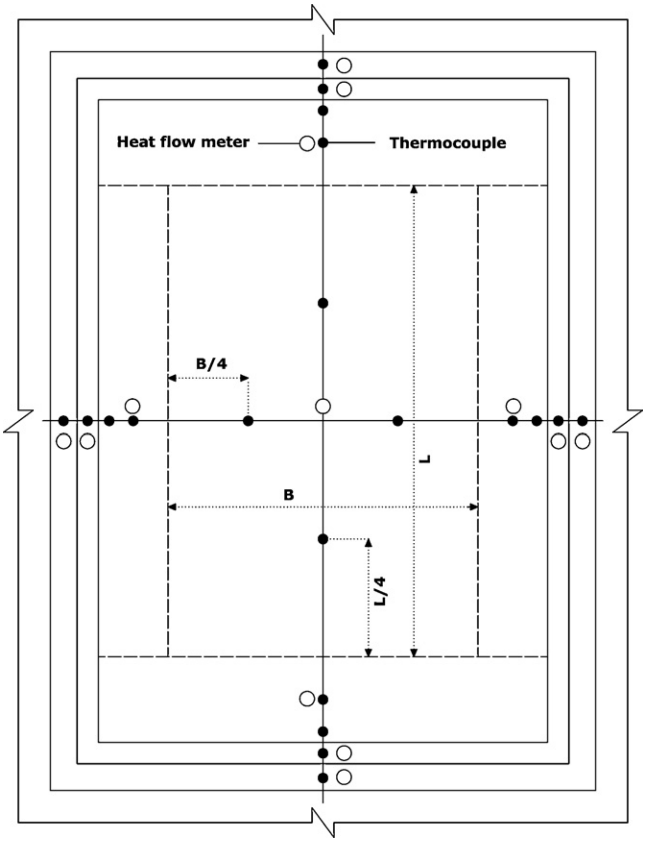

Fig. 1. Example of a specimen (window) surface division and sensors'positioning, according to the Russian Standard GOST 26602.1-99.

ally different from the metering chamber. In the United Kingdom, a third type of setup is used. The wall and edge guarded hot box, which is between the calibrated and guarded design in style [22], eliminates the guard chamber by keeping the temperature of the outside surface of the metering box the same as inside the metering box, by the use of a wall plate heater system.

In the present work, the comparison between the different approaches is performed with a calibrated hot box, designed and produced at the Department of Industrial Engineering of the University of Perugia. During the tests, the steady state conditions are reached and then, the responses of heat flow meters and thermocouples mounted on the specimen are registered for the evaluations of GOST 26602.1-99 (method of the heat flow and temperature measurements, since the calibrated hot box method is not provided by this standard), according to the equation that gives the total thermal transmittance as a function of the thermal properties of the p single homogeneous zones:

$$U_{ST} = \left(\frac{1}{h_{ST,i}} + \frac{A_S}{\sum_{p=1}^{m} A_p q_p / (T_{p,s,e} - T_{p,s,i})} + \frac{1}{h_{ST,e}} \right)^{-1} \tag{1}$$

Referring, on the other hand, to the EN ISO 8990 and ASTM C1363-05, the following heat balance has to be verified (Fig. 2b):

$$Q_S = Q_{in} + Q_f - Q_{hcw} - Q_{sp} - Q_{sp,fl,cold} - Q_{sp,fl,out} - Q_{S,fl} \tag{2}$$

where Q_S, is the heat flow through the specimen; Q_{in}, is the heat flow given to the metering chamber to maintain the steady-state conditions; Q_f, is the heat released by the fan; Q_{hcw}, is the heat flow transferred from the hot chamber to the external ambient by the box walls; Q_{sp}, is the heat flow that crosses the support panel; $Q_{sp,fl,cold}$, is the heat flow from the metering chamber to the cold chamber due to the flanking losses of the support panel; $Q_{sp,fl,out}$, is the heat flow from the metering chamber to the external ambient due to the flanking losses of the support panel; $Q_{S,fl}$, is the heat flow due to the flanking losses of the specimen.

Once Q_S is obtained, the simple division for the specimen area, A_S, and the difference between the temperatures of each side of the system, ΔT, gives the specimen thermal transmittance.

The evaluation of each addendum in Eq. (2) deserves a detailed analysis to highlight the different approaches between the two standards.

As far as the assessment of Q_{hcw}, no detailed mention is reported in the ISO 8990, while the ASTM C1363-05 defines in Annex A3 an analytical method to estimate the metering box wall loss, and a more precise calibration procedure in Annex A2 and Annex A6. Following these procedures, once the hot and cold chambers temperatures are fixed, it is possible to obtain the combined values of Q_{hcw}, $Q_{S,fl}$ and $Q_{sp,fl,out}$ in correspondence to a range of environmental temperatures. Wires, electric feeding, and other discontinuities may cause energy transfer due to infiltrations [23], therefore, particular attention has to be paid in the construction phase. As for $Q_{S,fl}$, the EN ISO standard for hot box measurements in fenestration systems [24] gives tabulated values in Annex B as a function of the window's geometric properties and the support panel's thermal conductivity. The EN ISO 8990 and ASTM C1363-05 overlap as far as the evaluation of the fan input Q_f, both indicating that the heat equivalent to the shaft power has to be considered. Regarding the evaluation of the heat flow through the support panel Q_{sp}, the American Standard indicates the evaluation of the conductance by a separate measure (for

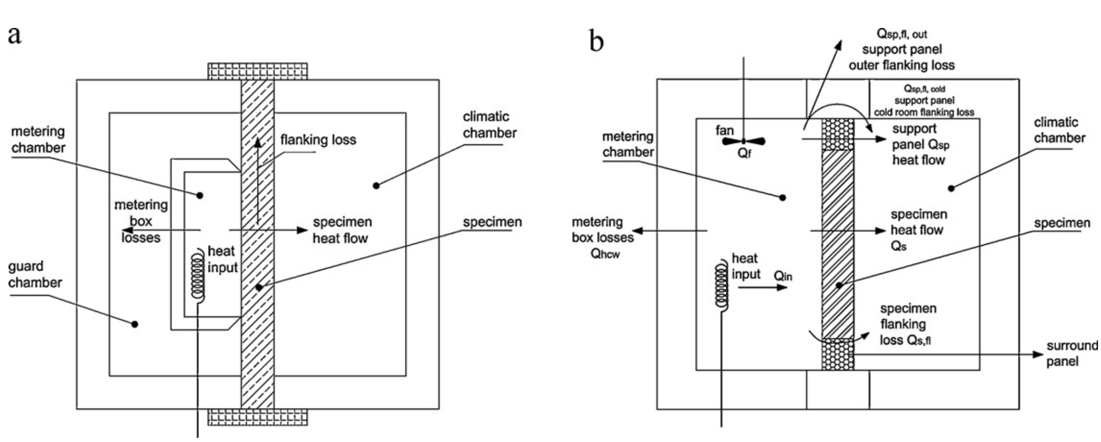

Fig. 2. Scheme of the guarded hot box (a) and the calibrated hot box (b).

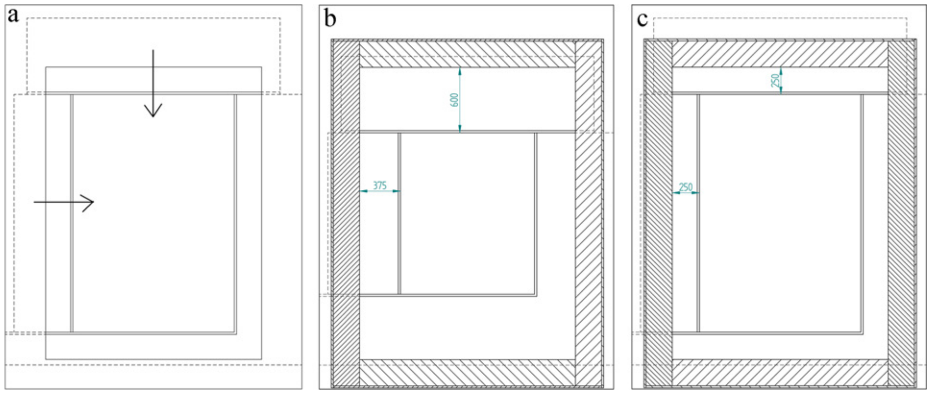

Fig. 3. Support panel of the hot box, lengths in mm. (a) Movable parts; (b) panel set-up for windows testing; (c) panel set-up for doors testing.

example, guarded hot plate), and obtaining the heat exchange of each test by a group of surface temperature sensors, positioned on both sides of the panel. EN ISO 12567-1 [24], instead, introduces Calibration Transfer Standards (CTS) with known thermal properties, and with the aim of executing a series of calibration measurements where Q_{sp} and $Q_{sp,fl,cold}$ are unknown. The CTS is made of expanded polystyrene, 0.020 m thick and covered on the external surfaces by two sheets of tempered float glass, 4 mm thick.

Once the level of heat flowing through the specimen is determined, the attention is turned to the surface resistances, both on the cold and hot sides. In GOST 26602.1-99, measurements give results independent of the adduction coefficients. Therefore, the standardized transmittance is calculated by the simple addition of the standardized external and internal liminar coefficients ($h_{ST,GOST,i}$ = 8.0 W/m^2 K and $h_{ST,GOST,e}$ = 23.0 W/m^2).

In the other two standards, each test provides a transmittance linked to the liminar coefficients of the single case. It is therefore necessary to evaluate the contribution of the test surface resistances, to be substituted by the standardized ones: $h_{ST,ISO,i}$ = 7.7 W/m^2 K and $h_{ST,ISO,e}$ = 25.0 W/m^2 K for the EN ISO 12567-1; $h_{ST,ASTM,i}$ = 7.7 W/m^2 K and $h_{ST,ASTM,e}$ = 30.0 W/m^2 K for the ASTM C1199-09 dedicated to hot box measurements in fenestration systems [25].

The liminar coefficients for the measurements conducted according to the EN ISO 12567-1 are obtained by a calibration curve generated during the preliminary tests with two expanded polystyrene panels (CTS): one 0.060 m thick and the second 0.020 m thick, both covered on the external surfaces by two sheets of tempered float glass, 0.004 m thick. The only parameter necessary to obtain the total surface resistance of the specimen is the heat flow density. The ASTM C1199-09 [25] proposes for the calibration a single CTS, similar to the ones of EN ISO 12567-1 but only 0.013 m thick, and defining a different calculation procedure of the liminar coefficients. The liminar coefficients could also be evaluated in [25] through the area weighting method that implies the measure of the average surface temperature for both the hot and cold side of the test specimen. The thermocouples must be positioned in a way similar to the one proposed by GOST 26602.1-99, with the aim of covering isothermal areas [26].

The main differences among the three standards are therefore described. There are also some other minor variations: the minimum number of thermocouples to be installed on the various surfaces involved in heat exchange; different values of the temperature of the chambers; the conditions for considering uniform temperature inside the chambers; the relative humidity in the metering chamber (only the American Standard imposes a value lower than 15%, to prevent frost formation); the suggested specimen size; and the definition of steady state conditions.

4. The hot box setup

4.1. Description

The design of the hot box produced at the Department of Industrial Engineering of the University of Perugia was inspired by the need to test samples of standard dimensions. Annex E of the standard EN 14351-1 [27] reports a table with a list of all technical standards concerning the testing of fastenings (doors and windows). Among these, the dimensions of the samples for thermal properties evaluation are defined in [24]. For windows whose overall surface is lower than 2.3 m^2, the sample dimensions are equal to 1.230 m × 1.480 m following what is stated in [27] (ASTM E1423-06 [26] and GOST 26602.1-99 [10] indicates 1.200 m × 1.500 m). Whereas windows whose overall surface is bigger than 2.3 m^2, the sample dimensions are 1.480 m × 2.180 m. The overall surface includes the projected area of the window, including the frame. These dimensions obviously influence the design of the whole apparatus and in particular the dimensions of the panel which hosts the sample (support panel). The minimum distance between the sample and the edge of the panel is, according to the standard, 0.200 m, and the minimum thickness of the panel is 0.100 m.

The support panel was designed to be flexible and able to host standard samples of both doors and windows. It is mainly made of a rigid frame of four parts, which are movable thanks to some pistons (Fig. 3a). It is also possible to substitute the four parts of the support panel which, as previously mentioned, allows for the possibility to host alternatively a window (Fig. 3b) or a door (Fig. 3c). Thanks to the pistons, it is possible to adjust samples whose dimensions are slightly different from the standard ones and to seal the whole panel.

The support panel is a sandwich structure composed of two panels of wood (0.019 m each) with a middle layer of expanded polystyrene (0.240 m). The support panel divides the two rooms of the hot-box apparatus, the metering and climatic chamber. The two rooms have the same dimensions: 2.700 m high; 2.000 m long; and 0.900 m wide. The height and length were determined by the dimensions of the support panel. The width was determined as the result of a compromise of the needs to create a uniform climate in both rooms and have enough space to host all the instrumentations and probes. The walls of both rooms are made of the same materials of the support panel. The thermal conductivity λ of the expanded polystyrene is 0.034 W/m K, and the thermal transmittance of the walls is 0.134 W/m^2 K.

During the tests, the individual temperatures inside the two rooms are kept constant thanks to a heating system for the hot room and a cooling system for the cold room. The heating system is made of a 50 m long, S-shaped, heating wire disposed inside the hot room (Fig. 4), a few centimetres from the wider vertical wall. The

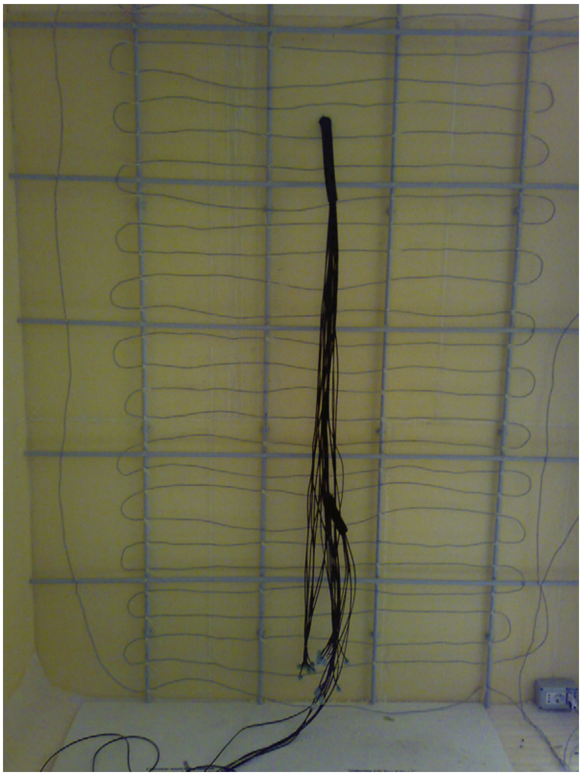

Fig. 4. Heating wire in the metering chamber.

heating power of the wire is 50 W. Due to a PID control system, the wire can switch on and off automatically. It is possible to maintain the internal temperature of the hot room at 20 °C, with a tolerance lower than 0.2 °C.

The cold room is equipped with an air-cooled compression refrigerator, placed on top of the rooms. The refrigerator's evaporator is made of copper pipes and aluminum cooling fins, and is equipped with a fan and thermostatic valve, cooling directly the air inside the room. The operating temperatures of the cold room vary from −10 to +10 °C. For this reason, the cold room is also equipped with a heating wire in order to return to desired temperature if

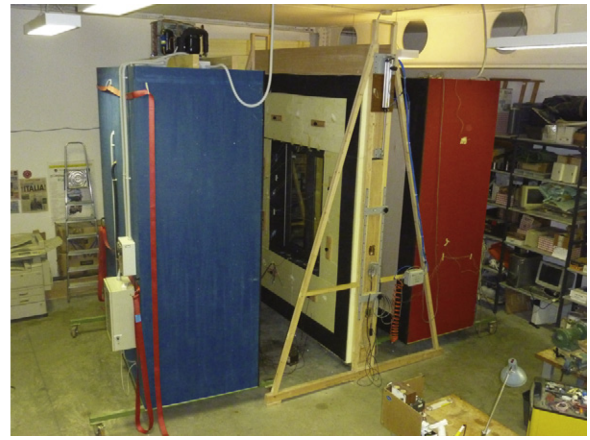

Fig. 5. General view of the hot box apparatus.

the room becomes too cold. A picture with a general view of the apparatus is shown in Fig. 5, while an enlarged view is sketched in Fig. 6.

4.2. Instrumentation and data acquisition

The choice of sensors (type, number, position) was inspired by the three standards analyzed.

For temperature measurements, T-thermocouples made of a junction copper (+) and constantan (−) were selected. The temperature range is from −200 °C to +400 °C, the sensitivity is 48.2 μV/°C. 142 thermocouples were installed inside the hot and cold chambers, while 69 differential thermocouples were needed to assess the temperature differences between the metering chamber and the external ambient.

The American and the European Standards indicate that the heat flux through the specimen has to be measured indirectly by the evaluation of the heat flux released by the resistances, in order to keep the temperature of the hot chamber constant. Therefore, an energy meter measures the electricity consumption (J) and, dividing this value by the time, the heat flux per time unit is obtained.

On the other hand, since the Russian standard recommends the use of heat flow meters, one for each thermally homogeneous

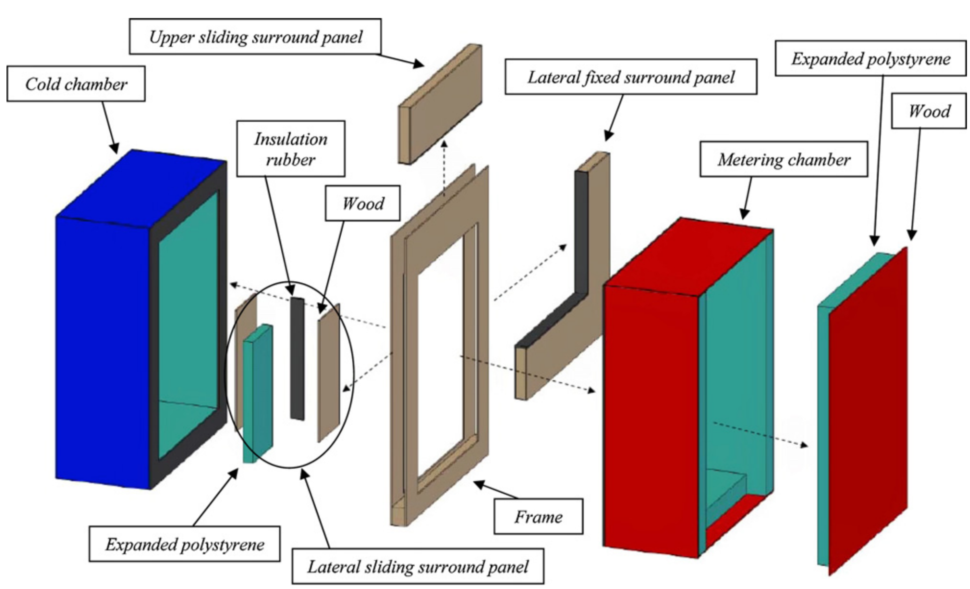

Fig. 6. Exploded view of the hot box apparatus.

Table 1
Test matrix for the characterization of the hot box according to EN ISO 8990 and ASTM C 1363-05.

	T_{hot} (°C)	T_{cold} (°C)	Fan	Specimen	Output	Standard
1	$T_{out}+2.5$	$T_{out}+2.5$	OFF	Support panel	$(Q_{hcw}+Q_{sp,fl,out})(T_{out}-T_{hot})$	ASTM + ISO
2	$T_{out}+5.0$	$T_{out}+5.0$	OFF	Support panel	$(Q_{hcw}+Q_{sp,fl,out})(T_{out}-T_{hot})$	ASTM + ISO
3	$T_{out}+10.0$	$T_{out}+10.0$	OFF	Support panel	$(Q_{hcw}+Q_{sp,fl,out})(T_{out}-T_{hot})$	ASTM + ISO
4	20	0	ON	Polystyrene (0.02 m)	F_{ci}; F_{ce}; $R_{s,t}$	ISO
					h_i; h_e	ASTM
5	20	10	ON	Polystyrene (0.02 m)	F_{ci}; F_{ce}; $R_{s,t}$	ISO
6	20	−10	ON	Polystyrene (0.02 m)	F_{ci}; F_{ce}; $R_{s,t}$	ISO
7	20	0	ON	Polystyrene (0.06 m)	$(Q_{sp}+Q_{sp,fl,cold})(T_{hot}-T_{cold})$; F_{ci}; F_{ce}; $R_{s,t}$	ISO
					$Q_{s,fl}$	ASTM
8	20	10	ON	Polystyrene (0.06 m)	$(Q_{sp}+Q_{sp,fl,cold})(T_{hot}-T_{cold})$; F_{ci}; F_{ce}; $R_{s,t}$	ISO
9	20	−10	ON	Polystyrene (0.06 m)	$(Q_{sp}+Q_{sp,fl,cold})(T_{hot}-T_{cold})$; F_{ci}; F_{ce}; $R_{s,t}$	ISO

zone, a total of 12 heat flow sensors (passive thermopile type) were installed in the metering side of the hot box. Two air speed sensors (one for each chamber) complete the instrumentation.

All acquired data are transferred to a PC, with the option of selecting the time step of the acquisitions; it is also possible to visualize and save the acquired data.

The apparatus also hosts two radiation screens (baffles) placed in both chambers between the heating/cooling source and the support panel. The standard requires that the emissivity of the screens has to be higher than 0.80. Poplar wood panels with a value of emissivity of around 0.90 were chosen. Two fans, one in each chamber, help to avoid thermal stratification.

4.3. Calibration

The complete characterization of the hot box apparatus was conducted following the test matrix reported in Table 1 The experiment was performed in accordance with the calibration requirements of the European and the American Standards. The first three tests allowed the definition of heat dispersion from the metering wall to the external environment. The linear regression equation obtained through this process is written as follows:

$$Q_{hcw} = 4.5349(T_{out} - T_{hot}) - 4.0153 \tag{3}$$

with a regression line coefficient of determination equal to 0.9959.

Once the peripheral losses are assessed, three further measurements for each calibration panel are needed according to [8], in correspondence to three different cold chamber temperatures, and maintaining the hot side at 20 °C. The goal is to obtain a set of calibration curves: the support 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.

The results of the procedures are reported in the calibration curves of Fig. 7. Through these measurements, the surface heat transfer coefficients and the specimen flanking losses as proposed in [9,25] are also evaluated.

4.4. Validation

To validate the experimental results obtained in the hot box apparatus, another test rig was used to measure the thermal conductivity of materials, based on the guarded hot plate method. The comparative analysis between the methods was performed by testing three different materials covering a relatively wide range of thermal conductivities and referring to the European Standards ISO 8990 [8] and 12567-1 [24].

The most conductive tested sample is a 0.015 m plasterboard panel, a material that is often used in the building sector within packages for vertical and horizontal internal partitioning. A 0.050 m panel of expanded polystyrene (EPS) with graphite was chosen as representative of the high thermal resistance materials that are commonly used for insulation of building elements. The 0.020 m plywood sample was tested because its expected value of thermal conductivity falls between the expected values of the two other materials under test. It is also worth noting that there has been an increased interest in wood as raw material in the building sector.

Table 2
Cross comparison of thermal conductivities for the analyzed samples.

Sample	Hot box W/(m K)	Hot plate W/(m K)	Literature W/(m K)
Plasterboard	0.245 ± 0.015	0.255 ± 0.005	0.250
Plywood	0.109 ± 0.008	0.114 ± 0.003	0.120
Polystyrene with graphite	0.032 ± 0.003	0.030 ± 0.002	0.031

The results of the measurement campaign are reported in Table 2, together with the uncertainty of each value (see next paragraph for the uncertainty estimation of the hot box measurements), and reference data obtained from the literature [28,29] or product data sheets [30].

Taking into account of the uncertainties, the values obtained with the two test rigs practically overlap and are close to data obtained from the literature. This procedure can therefore be considered an exhaustive validation of the reliability of the hot box apparatus.

5. Uncertainty

The uncertainty was estimated by the law of propagation based on the root-sum square formula [31,32]. Since the standardized thermal transmittance U_{ST} is a function of n independent variables x_k, which are known with an uncertainty Δx_k, each one with the same confidence level (95%), the global uncertainty ΔU_{ST} can be written as follows:

$$\Delta U_{ST} = \sqrt{\sum_{k=1}^{n} \left[\frac{\partial U_{ST}(x_k)}{\partial x_k}\right]^2 \Delta {x_k}^2} \tag{4}$$

The definition of the function $\Delta U_{ST}(x_k)$ for the European and American Standards has to take into account a large number of variables, including the results of the calibration process. In particular, for the EN ISO 12567-1, the thermal transmittance uncertainty depends on the following parameters:

$$\Delta U_{ST,ISO} = \Delta U_{ST,ISO}(Q_{in}, Q_f, T_{out}, T_{hot}, A_{sp}, T_{sp,i}, T_{sp,e}, R_{sp}, L_{edge}, T_{a,i}, T_{a,e}, A_S, F_{ci}, F_{ce}, T_{b,i}, T_{bor,i}, T_{b,e}, T_{bor,e}, R_{s,tot}) \tag{5}$$

while for the ASTM C1199-09:

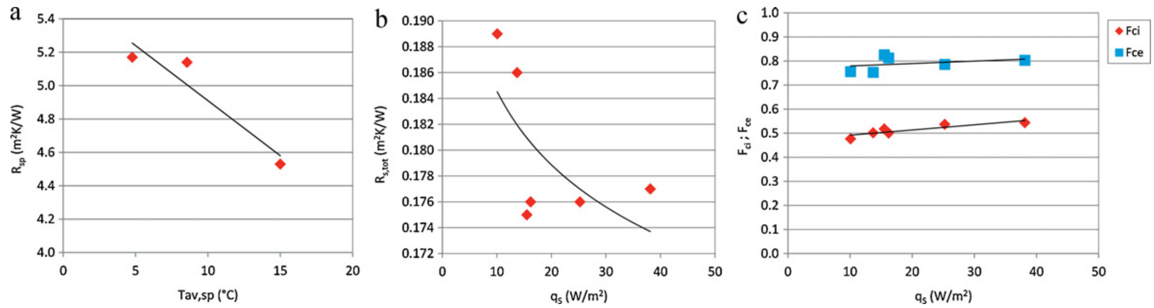

Fig. 7. Calibration curves. (a) Thermal resistance of the support panel; (b) total surface resistance at the specimen surface; (c) convective fraction of the total surface heat exchange at the hot (F_{ci}) and cold (F_{ce}) side.

$$\Delta U_{ST,ASTM} = \Delta U_{ST,ASTM}(Q_{in}, Q_f, T_{out}, T_{hot}, A_{sp}, T_{sp,i}, T_{sp,e}, R_{sp}, L_{edge}, T_{a,i}, T_{a,e}, A_s, T_{b,i}, T_{b,e}, K_{c,i}, K_{c,e}) \quad (6)$$

The uncertainties of factors obtained from instruments' measurements (thermocouples, heating wire power, etc.) have been extracted from manufacturers' data. As far as parameters derived from a calibration curve (e.g. the heat dispersion from the metering wall or the convective fraction of the total surface heat exchange), the uncertainty values are linked to the imperfect structure of the correlation formula chosen to describe the dependence. In this case, the calculated value x_{calc} with its precision interval is:

$$x = x_{calc} \pm t_{\nu,P}\sigma \quad (7)$$

where $t_{\nu,P}$ is the Student-t value of the ν's degree of freedom and P's confidence level (95%), σ is the standard deviation of the least square curve fit value.

The function $\Delta U_{ST}(x_k)$ is more simple for the Russian Standard, depending only from the output of thermocouples, heat flow meters, and area dimensions of each p thermally homogeneous surface:

$$\Delta U_{ST,GOST} = \Delta U_{ST,GOST}(q_p, A_p, T_{p,i}, T_{p,e}) \quad (8)$$

6. Comparative analyses of the three methods for an aluminum framed window

The three standards have been compared through a measurement campaign conducted on a two shutter window with a thermally broken aluminum frame (lateral thickness equal to 0.050 m). The transparent surfaces are made of two glazed sheets of stratified glass divided by an air gap of 0.015 m. The internal glazing is composed by two layers of 0.003 m thick, sheets of float glass divided by a 0.37 mm film of polyvinyl butyral, while the external glazing is made of two layers of 0.004 m thick, sheets of float glass divided again by a 0.37 mm film of polyvinyl butyral. The internal face of the external glazing is covered by a low-emission coating, and the spacer is thin-walled stainless steel.

The hot box was equipped with all the sensors necessary to evaluate the thermal transmittance according to the European, American, and Russian Standard (Fig. 8). The GOST 26602.1-99 indicates that, after establishing steady state heat transfer, the validation of the choice of homogeneous zones on the sample has to be executed by measuring the density of heat flow and the temperature of the sample's inner surface. In case of substantial variation in temperature and density of heat flow within the zone (above 10%), it is necessary to adjust the location of the sensors. This procedure results in a time consuming process, made of numerous movements of the sensors and consequent long measurements (at least three hours) in steady-state conditions, until the homogenous areas are identified. Of course, the number of tests increases with specimen non-homogeneity. Even if the number of tests for finding these zones could be reduced with use of a numerical model, the aim would still be to define a first-attempt thermal field visualization, as close as possible to the real conditions.

Fig. 8. View of the sample with sensors installed, hot side.

As mentioned before, the three standards use different standardized surface heat transfer coefficients to define the standardized thermal transmittance U_{ST}. In creating a comparative analysis, the results are presented using a common value of $h_{ST,i}$ (7.69 W/m^2 K) and $h_{ST,e}$ (25.00 W/m^2 K), extracted from the EN ISO 12567-1. At the same time, the set point temperature of the metering and the weather chamber were fixed to the values indicated in the European Standard (20 °C and 0 °C respectively), even if the other Standards specify different levels, especially for the cold side (−17 °C for the ASTM E1423-06 and −20 °C for the GOST 26602.1-99).

In Fig. 9, the results of the test are sketched, together with the uncertainties of each method applied. It is evident that values of the standardized thermal transmittance show little differences, with a maximum deviation of 3% in terms of the expected value. The European and American Standards produced similar results, both in terms of absolute values and uncertainties. The slight difference

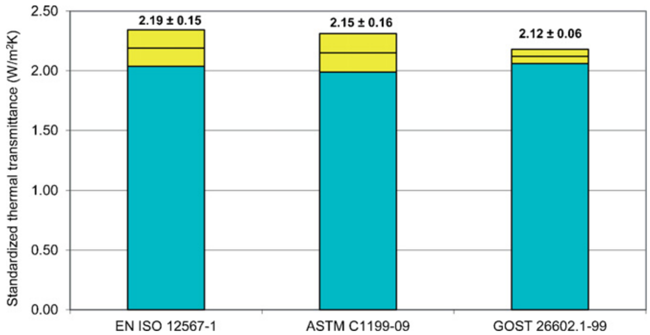

Fig. 9. Aluminum window standardized thermal transmittance and relative uncertainty for the three Standards analyzed.

is essentially due to the different evaluation methods of support panel thermal resistance.

As far as the GOST 26602.1-99, its short interval of uncertainty testifies a higher precision with respect to the other two standards if the homogenous zones are well defined. It also gives more detailed information about the local heat exchanges of the different part of the window, since it is possible to obtain the thermal insulation performance of the single components such as the central area of the glazing, the different components of the frame, or the thermal bridge in the glass edge area created by the spacer.

7. Conclusions

The experimental evaluation of inhomogeneous components thermal transmittance has been carried out through the hot box method, following three different standards. All the tests were executed in an apparatus designed and produced at the University of Perugia to meet all requirements of EN ISO 8990, ASTM C1363-05, and GOST 26602.1-99. The preliminary measurements underlined that a long and detailed calibration procedure is needed both for the European and American Standards, with the aim of properly defining the hot box characteristics. Data obtained from this process remained valid for all samples tested in the same apparatus. As far as the Russian Standard, no calibration is needed for the chambers, but each sample had to be deeply analyzed to define the thermally homogenous zones before proceeding to the actual measurement.

EN ISO 8990 and ASTM C1363-05 seem very similar in terms of procedures definition and methodology of heat exchange definition. Both treat the sample as a "black box" and calculate the total heat transfer that passes through the survey itself without considering (and being affected by), the different parts that constitute the component under test. The results obtained thanks to these two procedures are therefore very similar.

The GOST 26602.1-99, on the contrary, tries to individuate the thermal properties of each part of the sample, giving more information on the weaknesses and strengths of the various elements of the survey. However, it becomes time consuming, complicated, and difficult to be applied when the specimen is strongly inhomogeneous.

The three approaches were compared by the thermal transmittance evaluation of an aluminum framed window. The values obtained were very close, with a maximum difference of 3% in terms of the U_{ST} expected value. The lowest uncertainty ΔU_{ST} is linked to the Russian Standard, since, in this case, the sample is relatively homogeneous. On the other hand, the American and European Standards result with some uncertainty correlated to the calibration process, but the correspondent value could be considered independent from the specimen complexity.

An ideal procedure should include the GOST 26602.1-99 method to define the thermal behaviour of each part of the component under analysis, with a contemporary validation of the global results to be performed with one of the other two approaches (EN ISO 8990 or ASTM C1363-05).

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References

[1] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy and Buildings 40 (3) (2008) 394–398.
[2] F. Asdrubali, M. Bonaut, M. Battisti, M. Venegas:, Comparative study of energy regulations for buildings in Italy and Spain, Energy and Buildings 40 (2008) 1805–1825.
[3] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast).
[4] International Standard ISO 6946, Building components and building elements – Thermal resistance and thermal transmittance – Calculation method, 2007.
[5] American Society for Testing and Materials, ASTM C177-97: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus, West Conshohocken, PA, 1997.
[6] European Standard EN ISO 10077-2, Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Numerical method for frames, 2003.
[7] European Standard EN ISO 10211-1, Thermal bridges in building construction – Heat flows and surface temperatures – General calculation methods, 1995.
[8] European Standard EN ISO 8990, Thermal insulation – Determination of steady-state thermal transmission properties – Calibrated and guarded hot box, 1996.
[9] American Society for Testing and Materials, ASTM C1363-05: Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus, West Conshohocken, PA, 2005.
[10] Interstate Standard of Russian Federation GOST 26602.1-99, Windows and doors. Methods of determination of resistance of thermal transmission, 1999.
[11] J.R. Mumaw, Calibrated hot box: an effective means for measuring thermal conductance in large wall sections, in: American Society for Testing and Materials, ASTM STP 544, Heat transmission measurements in thermal insulations, West Conshohocken, PA, 1974, pp. 193–211.
[12] J.H. Klems, A calibrated hot box for testing window systems – Construction calibration and measurements on prototype high-performance windows, in: Proceedings of ASHRAE/DOE-ORNL Conference on Thermal Performance of the Exterior Envelopes of Buildings, Kissimmee (Florida), 1979, pp. 338–346.
[13] X.D. Fang, A study of the U-factor of the window with a high-reflectivity venetian blind, Solar Energy 68 (2) (2000) 207–214.
[14] E.A. Adam, P.J. Jones, Thermophysical properties of stabilised soil building blocks, Building and Environment 30 (2) (1995) 245–253.
[15] K.G. Wakili, C. Tanner, U-value of a dried wall made of perforated porous clay bricks hot box measurement versus numerical analysis, Energy and Buildings 35 (2003) 675–680.
[16] Y. Gao, J.J. Roux, C. Teodosiu, L.H. Zhao, Reduced linear state model of hollow blocks walls, validation using hot box measurements, Energy and Buildings 36 (2004) 1107–1115.
[17] D.M. Burch, R.R. Zarr, B.A. Licitra, Dynamic test method for determining transfer function coefficients for a wall specimen using a calibrated hot box, insulation materials, in: American Society for Testing and Materials, ASTM STP 1030, Testing and Applications, West Conshohocken, PA, 1990, pp. 345–361.
[18] D.P. Aviram, A.N. Fried, J.J. Roberts, Thermal properties of a variable cavity wall, Building and Environment 36 (9) (2001) 1057–1072.
[19] K.G. Wakili, H. Simmler, T. Frank, Experimental and numerical thermal analysis of a balcony board with integrated glass fibre reinforced polymer GFRP elements, Energy and Buildings 39 (2007) 76–81.
[20] A.H. Elmahdy, K. Haddad, Experimental procedure and uncertainty analysis of a guarded hot box method to determine the thermal transmission coefficient of skylights and sloped glazing, ASHRAE Transactions 106 (2) (2000) 601–613.
[21] P. Bondi, P. Stefanizzi, Hygro-thermal performance of hollow bricks and current standards, Energy and Buildings 33 (2001) 731–736.
[22] S.D. Gatland, W.P. Goss, R. Baumgardener, R. Williams, R.G. Millar, A wall and edge guarded hot box for fenestration testing, in: American Society for Testing and Materials, ASTM STP 1320, Insulation Materials: Testing and Applications, West Conshohocken, PA, 1997, pp. 46–58.

[23] R.R. Zarr, D.M. Burch, T.K. Faison, C.E. Arnold, M.E. O'Connell, Calibration of the NBS calibrated hot box, Journal of Testing and Evaluation 15 (3) (1997) 167–177.
[24] European Standard EN ISO 12567-1, Thermal performance of windows and doors – Determination of thermal transmittance by hot box method – Complete windows and doors, 2000.
[25] American Society for Testing and Materials, ASTM C1199-09: Standard Test Method for. Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods, West Conshohocken, PA, 2009.
[26] American Society for Testing and Materials, ASTM E1423-06: Standard Practice for Determining Steady State Thermal Transmittance of Fenestration Systems, West Conshohocken, PA, 2006.
[27] European Standard EN 14351-1:2006+A1, Windows and doors – Product standard, performance characteristics. Part 1. Windows and external pedestrian doorsets without resistance to fire and/or smoke leakage characteristics, 2010.
[28] European Standard EN ISO 10456, Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values, 2008.
[29] Italian Standard UNI 10351, Building materials. Thermal conductivities and vapour permeabilities, 1994.
[30] LAPE srl, Greypor® G 400. Available from: www.lape.it/pdf/st_greypor_g/Greypor%20G400.pdf (accessed 3.03.2010).
[31] European Standard ENV 13005, Guide to the expression of uncertainty in measurement, 1999.
[32] S. Yuan, G.A. Russel, W.P. Goss, Uncertainty analysis of a calibrated hot box, in: A.O. Desjarlais, R.R. Zarr (Eds.), American Society for Testing and Materials, vol. 4, ASTM STP 1426, Insulation Materials. Testing and Applications, West Conshohocken, PA, 2002, pp. 189–202.