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Validation of quantitative IR thermography for estimating the U-value by a hot box apparatus

I Nardi, D Paoletti, D Ambrosini, T de Rubeis and S Sfarra

DIIIE, University of L'Aquila, Piazzale Pontieri, 1 Monteluco di Roio, I 67100, L'Aquila, Italy

E-mail: iole.nardi@graduate.univaq.it

Abstract. Energy saving plays a key role in the reduction of energy consumption and carbon emission, and therefore it is essential for reaching the goal of the 20-20-2020 policy.
In particular, buildings are responsible of about 30% of the total amount of Europe energy consumption; the increase of their energy efficiency with the reduction of the thermal transmittance of the envelope is a point of strength with the actions and strategies of the policy makers.
Currently, the study of energy performance of buildings is based on international standards, in particular the Italian one allows to calculate the U-value according the ISO 6946 or by in-situ measurements, using a heat flow meter (HFM), following recommendations provided in ISO 9869.
In the last few years, a new technique, based on Infrared Thermography (IRT) (also referred to as Infrared Thermovision Technique – ITT), has been proposed for in situ determination of the thermal transmittance of opaque building elements. Some case studies have been reported.
This method has already been applied on existing buildings, providing reliable results, but also revealing some weaknesses.
In order to overcome such weak points and to assess a systematic procedure for the application of IRT, a validation of the method has been performed in a monitored environment.
Infrared camera, the heat flow meter sensors and a nearby meteorological station have been used for thermal transmittance measurement. Comparison between the U-values measured in a hot box with IRT as well as values calculated following international standards and HFM results has been effected.
Results give a good description of the advantages, as well as of the open problems, of IR Thermography for estimating the U-value.
Further studies will help to refine the technique, and to identify the best operative conditions.

1.Introduction

Today's in Eu Countries total buildings energy consumptions are 30-40% of the final energy and the demand is raising in the residential sector. Some recent European directives encourage policy actions to reduce the energy need for heating and cooling by 20% by 2020 and 80% in 2050 compared to 1990 levels in order to mitigate the environmental impacts of the built environment. It appears very important to underline that the knowledge of the thermal behaviour of the building envelope is an essential component of the strategies of the policy makers. Among the thermal parameters, the thermal transmittance (U-value $W/m^2{\cdot}K$) is very important, since it is used to define the total energy consumption and to determine the optimal thermal comfort of occupants.
The thermal transmittance is a measure of how well an envelope resists to heat transfer and its knowledge is essential for retrofitting and energy saving measures.
Nowadays the U evaluation is based on international standards, in particular it is possible to calculate the design value with ISO 6946 [1] or by in situ measurements, using a flow meter following recommendations foreseen in ISO 9869 [2].
The real energy performance of an envelope can be accurately estimated only for well-characterized systems; in particular the U-value depends on the materials, their age, thickness, density, thermal mass.

For this reason significant inaccuracies in these parameters may be great source of uncertainty: especially in historic buildings in some conditions the actual wall U-value does not always agree with the design value, therefore it is necessary to measure and analyze in situ the U-value.
Currently, for in situ measurements the heat flux method is used. The U value is determined by measuring the temperatures on the surfaces of the wall and the heat flux through it, determined by a sufficient temperature gradient between indoor and outdoor. At least 72 h of measurements are necessary to evaluate the transmittance, and the progressive average method is commonly used to process data.
Several authors [3-9] have demonstrated that some errors are due to non-accurate measurements of surface temperatures, location, number and type of sensors and probes, thermal bridges, shielding or variation of temperature gradient; it is clear, however, that measurement is less precise if the temperature gradient is low.
Many studies have been effectuated for increasing the measurement accuracy, for example Cesaratto *et al* [4] found that the location of sensors causes an error up to 46% related to theoretical value.
Recently an alternative approach has been proposed, the quantitative infrared thermography (namely IRT) for in situ measurements of thermal transmittance, and different studies have been performed [10-17]
This method can be applied in a quasi-steady state condition and may be considered rapid and non-destructive.
However despite the IR inspection seems to be an easy task, it is not free from error; in fact, the neglecting of some factors of influence can lead to erroneous evaluation of the object under analysis.
Such factors can be characterized as procedural (camera calibration, focus, placement), technical or environmental factors.
A validation of the method is proposed in a controlled environment.
In fact, in this new method the most sensitive variables proved are the exact measure of the reflected apparent temperature, the wall surface temperature, and the emissivity of the surface of the envelope.
Today a detailed study on the influence of the several environmental variables on the determination of the U-transmittance with quantitative IR thermography compared with HFM method and theoretical value in a controlled environment is missing.
The aim of this work is to validate the use of IRT for measuring the U-value of a test wall with well-known characteristics in an environment with controlled parameters for comparison with HFM method. A hot-box has been employed to perform such test.
Results are compared and the possible causes of differences between them are also analyzed.

2. Guarded Hot Box description

The importance of a hot box stands in its capability to analyze and investigate the thermal transmittance of homogeneous and big samples of walls, glazing, ceilings or floors or thermal bridges [18], in a quite simple way: two rooms, a hot and cold one, are kept at a desired temperature, while a specimen (object of the study) separates them. By measuring the power provided to the hot chamber to keep it at a constant temperature, and knowing the imposed temperatures on the two sides, it is possible to obtain the thermal transmittance.
Starting from this concept, several hot box designs have been developed and realized all over the world, and different guidelines have been emanated through the years, varying from a country to another. A comprehensive overview of them is described in [19].
The hox box employed at the Department of Industrial Engineering and Information and Economics (DIIIE) of the University of L'Aquila to perform tests is built according to the UNI EN ISO 8990 [20] and it is a Guarded Hot Box (GHB). This means that the hot chamber is composed by a smaller chamber, called *metering chamber* or *metering* box, whose task is to further confine the heat of the hot chamber, and to host sensors and probes, and by a guard chamber. It is well known in literature that the measure errors are reduced while increasing the perimeter of the metering box that, according to UNI EN ISO 8990, should measure at least 100x100 cm.
To further minimize the heat loss through the lateral sides of the sample, there could be a *tempering ring* that helps to strengthen the hypothesis of mono-dimensional heat flow through the specimen.
Figure 1, rearranged from the abovementioned norm, helps to understand how the fluxes are scattered in a GHB.

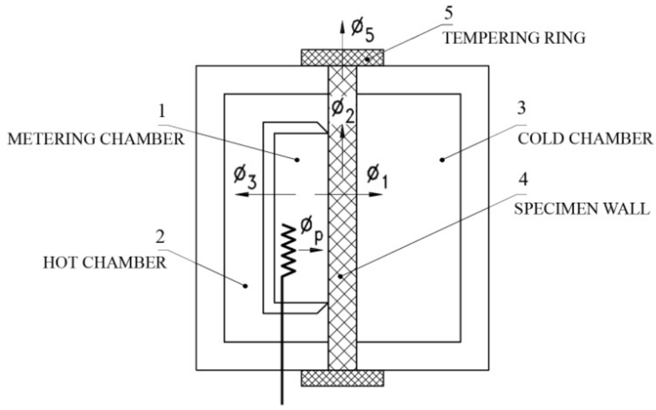

Figure 1. Heat fluxes in a guarded hot box.

Standing on figure 1, the heat flux Φ_1 through the sample equals the thermal power Φ_p inlet minus the flanking flux Φ_2 (that might exit the apparatus through the tempering ring causing a flux Φ_5) minus the heat flux Φ_3 through the walls of the metering box, i.e.:

$$\Phi_1 = \Phi_p - \Phi_2 - \Phi_3 \quad (1)$$

Therefore, it is possible to know the flux that interests the specimen by subtracting from the power Φ_p (that is required from the heating devices to keep constant the hot chamber temperature, and which can be easily measured) the power lost by the apparatus itself, that is through the specimen (causing a bidimensional flux) and through the envelope of the metering chamber. Of course, it is important to minimize as much as possible Φ_2 and Φ_3, and to measure these “unbalances”, for an appropriate evaluation of the flux through the wall.

The GHB used to perform our tests, and depicted in figure 2, allows to study specimen whose net sizes can be larger than 180 x 180 cm (sizes of the metering box) and up to 300 x 300 cm (sizes of the chambers). Thanks to mobile metal supports, it is possible to move separately the two chambers and the specimen, and to clamp it to the chambers; moreover, the metering chamber moves on a rail: at the end of the run, the seal of the chamber is perfectly adherent to the specimen.

The wall of the metering box and of the two chambers are made of galvanized steel sheet (thickness 0.1 cm) filled with 10 cm of expanded polyurethane.

Inside the chambers, groups of electric resistances (er), each one of 1000 W, provide the thermal power; near them, fans (f) are mounted to allow air circulation and forced convection, while grid fans (gf) split and direct the air flow.

The voltage regulator that controls the electric resistances, and all the devices needed to set the parameters in the chambers, are mounted on the sides of the chambers themselves (sw1 and sw2), as the reciprocating water-cooled compression refrigerating unit, that cools through copper pipes the cold chamber (cc).

Figure 3 represents the overall view of the hot box when it is joined to the specimen with its support.

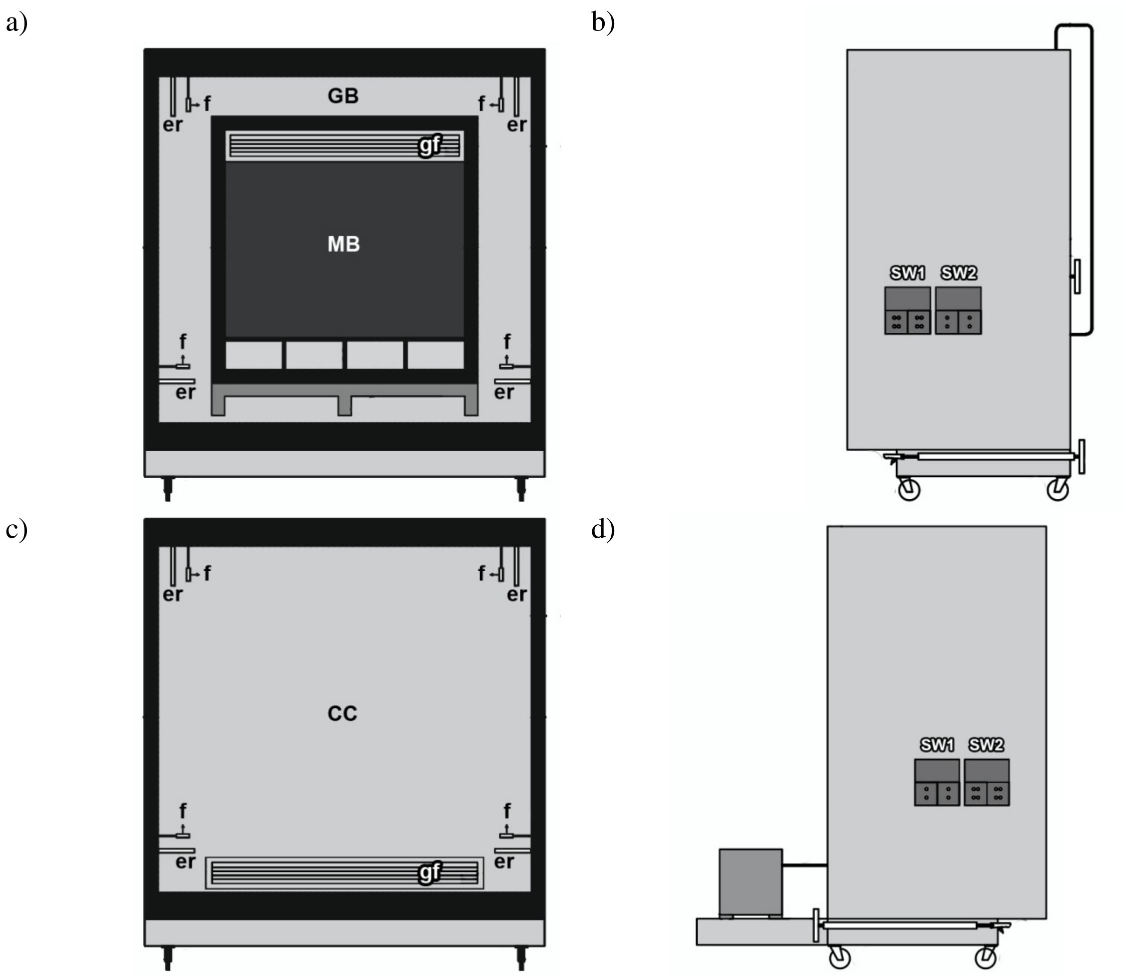

Figure 2. Drawing of the guarded hot box: (a) hot chamber - inside view; (b) hot chamber - side view; (c) cold chamber – inside view; (d) cold chamber – side view.

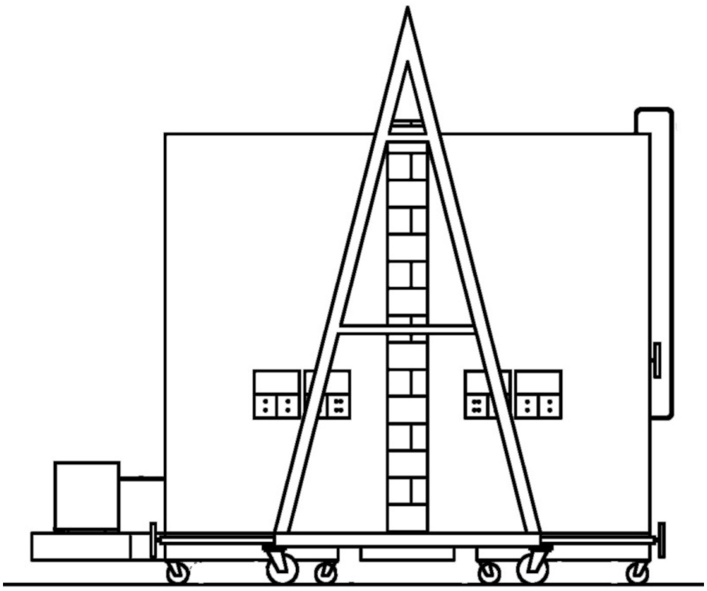

Figure 3. Overall view of the guarded hot box: (1) cold chamber, (2) hot chamber, (3) specimen and its support (4).

3. Equipment employed

In order to perform the tests, two air temperature probes have been employed to monitor the temperature inside each chamber. Also a heat flux meter has been employed, together with three surface temperature probes (two for the cold side, and one for the hot one) placed using a thermal compound.
Finally, an infrared camera has been used: the technical specifications of the equipment are listed in table 1.

Table 1. Technical specifications of the equipment used.

	Instrument	*Brand and type*	*Input*	*Measuring range*	*Resolution*	*Error (@25°C)*
1)	Fluxmeter	Hukseflux HFP01		-2000÷+2000 W/m^2	50 μV/W/m^{-2}	5% on 12 h of measurement
2)	Temperature probes	LSI Lastem EST124 - Pt100		-40 ÷ 80°C	0.01°C	0.15°C
3)	Data logger	LSI Lastem M-Log ELO008	*Potential difference*	-300 ÷ 1200 mV	40 μV	±100 μV
			Pt100	-50 ÷ 125°C	0.003°C	±0.05°C
4)	Temperature probe	Kimo HD100		-20 ÷ 70°C	0.1°C	±0.4% of reading ±0.3°C
5)	Infrared camera	FLIR ThermaCAM® S65 SH		-40 ÷ 1500 °C	0.05° C	± 2° C or ± 2%
				FOV	24° x 18° / 0.3 m	
				IFOV	1.3 mrad	
				Spectral range	7.5 -13 μm	
				Sensor	Focal plane array uncooled microbolometric; 320 x 240 pixels	

4. InfraRed Technique (IRT)

In the last years, the efforts of different research groups aim to find the best way to measure the thermal transmittance using an infrared camera.
Therefore, different procedures have been proposed, and a recent work [21] compares them proposing a kind of sensitivity analysis.
According to that study, the methodology proposed by Albatici et al. is the most variable, but it is the only one that involves the use of an IR camera to evaluate all the quantities needed for the calculation of the thermal transmittance. Hence, in this work, we decided to use and validate that approach.
Assuming that ε_ν is the emissivity of the wall on the IR camera spectral range, v is the wind velocity, and T_{in} T_{out} and T_w are respectively the indoor environment, the outdoor environment temperature and the surface temperature of the element expressed in Kelvin, the thermal transmittance can be calculated as follows:

$$U = \frac{5.67\,\varepsilon_v \left[\left(\frac{T_w}{100} \right)^4 - \left(\frac{T_{out}}{100} \right)^4 \right] + 3.8054\,v\,(T_w - T_{out})}{(T_{in} - T_{out})} \quad (2)$$

The previous equation can be eased in the following expression in case of absence of ventilation:

$$U = \frac{5.67\,\varepsilon_v \left[\left(\frac{T_w}{100} \right)^4 - \left(\frac{T_{out}}{100} \right)^4 \right]}{(T_{in} - T_{out})} \quad (3)$$

Equation 2 derives from the heat balance of a wall, assuming a simplification of the Jurge's equation for the expression of the convective heat transferred.
The procedure explained by Albatici et al is easily managed. Using approximating black bodies, even with simple devices whose length is 5-6 times bigger than their opening, it is possible to calculate T_{in} and T_{out}. During our tests, we used a black PVC pipe. As an alternative, for the measure of the indoor temperature, Albatici et al propose to frame from the outside with an IR camera, the inside of the room during a quick opening of a window.
Then, T_w can be derived in a piece of wall, after setting in the IR camera the wall emissivity in the spectral range of the camera. The latter can be evaluated, once again, with the IR camera, using the procedure [22] or using a black tape [13] or using the procedure of [23].

5. Results and discussion

The validation of the IRT method has been performed comparing the U-value obtained by comparison with the results of the heat flow method and of theoretical calculation, on a specimen wall, by means of a guarded hot box.
The comparison is needed in order to assess the reliability of the IRT technique, and to stand out if there are limits to its applicability. Therefore, a hot box has been used to test this method at different temperature levels and different temperature gradients, aimed to simulate multiple boundary conditions of a building, since the strength of the IRT technique could consist in the possibility to quickly investigate buildings' envelope in a quite simple way, and therefore to ease the work of energy auditors.
Although in a recent work [21] the IRT technique has been applied to different small samples (0.5 x 0.5 m) of homogeneous material, the approach followed in this work has been chosen to replicate in-situ measurement conditions, of a bigger and multi-layered sample.
To proceed with the theoretical calculation, norm UNI EN ISO 6946:2008 has been followed, therefore the thickness and the conductivity (derived form of UNI 10351 [24]) of each layer of the wall have been collected.
Table 2 shows the data, listed from the inside to the outside.

Table 2. Stratigraphy of the sample.

	Material	Thickness [m]	Superficial mass [kg/m²]	Conductivity [W/m·K]
1	Plaster	0.003	4.2	0.70
2	Concrete blocks	0.20	183.0	0.62
3	Plaster	0.025	35.0	0.70
4	EPS (UNI 7819 (15 kg/m^3))	0.05	0.8	0.04
5	Plaster	0.003	4.2	0.70

The overall thermal transmittance calculated equals 0.56 W/m^2·K
In order to determine the U-value following ISO 9869:1994 [2], three thermoresistances and a flux meter have been employed on the specimen wall of the GHB. The acquisition rate of data by the data logger has

been 10 minutes. The two chambers simulated the indoor and outdoor environments: furthermore, different temperature gradients have been imposed in the GHB to simulate different boundary conditions.
The temperature gradients remained quite constant over the measurements campaigns, due to the set point imposed, unless the low-oscillating temperature in the cold chamber due to the repetitive on-offs of the chiller. It is possible to state, however, that steady-state conditions occurred during the measurement campaigns.
The results obtained, shown in table 3, confirm what already assessed in literature: the HFM method values depend on the temperature gradient. This raises a new issue: which of the three values obtained should be considered for the following evaluation. We decided to consider a mean value, of about 0.62 W/m^2·K.

Table 3. HFM Results.

Campaign	Mean heat flux [W/m^2]	Mean inside wall temperature [°C]	Mean outside wall temperature [°C]	U-Value [W/m^2·K]
1	10.85	19.79	3.15	0.59
2	6.5	20.45	11.64	0.66
3	10.1	28.55	13.45	0.60

Finally, the IRT technique has been employed, with a little variation of the method; in fact the measurements of temperatures cannot be performed without splitting the hot box.
Therefore, the two chambers of the hot box have been separated, but the specimen wall remained clamped to the hot chamber; the warehouse where the GHB is located has been assumed as the outdoor, and since there isn't forced convection, it has been possible to apply equation 3.
With this set up, it was possible to measure T_{out} by an approximating black body realized with a black PVC pipe internally finned with a closed end, and it was also possible to frame the wall with the IR camera to measure T_w. The last temperature needed, T_{in}, has been acquired with a temperature probe (the fourth of table 1). Data and results are shown in table 4.

Table 4. Results obtained with IRT technique.

Campaign	T_{in} [°C]	T_{out} [°C]	ΔT [°C]	T_{refl} [°C]	T_{wall} [°C]	U-Value [W/m^2·K]
1	32.20	11.30	20.90	11.88	13.48	0.51
2	32.50	12.27	20.23	12.75	14.68	0.59
3	24.60	12.27	12.33	12.57	13.59	0.53
4	23.30	12.24	11.06	13.26	13.98	0.78

Campaigns 1 and 2 differ in the outdoor temperature, which affects the reflected temperature and the U-value, that is increased of 15.7%.
Keeping constant the outdoor temperature and decreasing the indoor temperature of about 8°C (as in campaigns 2 and 3) the measured thermal transmittance decreases of 10.2%.
The wall temperature being similar (as in campaigns 1 and 3), and by varying the reflected temperature and the air temperature gradient, the thermal transmittances obtained are comparable.
The result obtained during the fourth campaign is much higher than the others, and it seems an outlier; in this test the air temperature gradient is the minimum and the reflected temperature is the maximum.
From table 4 it appears clear that even the IR techniques provides oscillating results, depending on the boundary conditions imposed. This drawback, typical of the IR method, has been already outlined in literature, even by applying other techniques [15, 21, 25, 26]; this weak point, however, is common to all methods that involve in-situ measurements, and the IRT technique is not an exception in this sense.
The mean U-value of the first three campaigns is 0.54 W/m^2·K, while the mean value between all the campaigns is 0.60 W/m^2·K; both these values have been considered in the following discussion.
Despite the variations already discussed, the IR thermography results show good agreement to the design value and to HFM method.
In table 5 the percentage differences between the results of the three methods are shown.

Table 5. Results and their percentage difference.

U [$Wm^{-2}K^{-1}$]			Percentage difference		
Design Value	HFM	IRT	Design-HFM	HFM-IRT	Design-IRT
0.56	0.62	0.60	10.71%	3.23%	7.14%
		0.54		12.90%	3.70%

The percentage differences between the methods range from 3.23% to 12.9%, according to which U- value from IRT is considered; however, these results can be considered acceptable, even though they are gathered in steady-state condition, never achieved in in-situ campaigns; furthermore, in real tests, errors in the estimation of variables like wind speed, mean reflected temperature or wall emissivity, or the wall exposure, can lead to mistaken results.
The reflected temperature in our tests didn’t vary significantly, since they were performed in a warehouse, but further experiments will be performed to assess the possible sensitivity to this parameter
The tests performed have confirmed that an optimum temperature difference between the inside and the outside must be almost 20°C, so it occurs a good thermal flux through the envelope, in order to reduce uncertainty in the measurements.
In conclusion, the main goal of our research is a validation of the IR method for quick in-situ determination of the energy performance of buildings, very important for planning energy refurbishment processes.
It is clear that a more extensive study is necessary, based on different walls typologies, and in order to assess the sensitivity to the above mentioned parameters.
Currently some improvements of the hot box are in progress: measurements will be performed with a fundamental logic based on software and hardware components, setting and control devices.

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