

Laboratory and in-situ non-destructive methods to evaluate the thermal transmittance and behaviour of walls, windows, and construction elements with innovative materials: a review

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Abstract

The experimental characterization of the overall thermal transmittance of homogeneous, moderately- and non-homogeneous walls, windows, and construction elements with innovative materials is very important to predict their thermal performance. It is also important to evaluate if the standard calculation methods to estimate the U -value of new and existing walls can be applied to more complex configurations, since the correct estimation of this value is a critical requirement when performing building energy simulations or energy audit. This paper provides a survey on the main methods to measure the thermal transmittance and thermal behaviour of construction elements, considering laboratory conditions and *in-situ* non-destructive measurements. Five methods are described: the heat flow meter (HFM); the guarded hot plate (GHP); the hot box (HB), considering the guarded HB (GHB) and the calibrated HB (CHB); and the infrared thermography (IRT). Then, previous studies dedicated to the assessment of the thermal performance of different heavy- and light-weight walls are discussed. Particular attention is devoted to the measurement of the U -value of non-homogeneous walls, including the effect of thermal bridging caused by steel framing or mortar joints, and the presence of PCMs or new insulation materials in the configuration of the walls.

Keywords: *Thermal transmittance; U-value; heat flow meter; guarded hot plate; guarded hot box; calibrated hot box; infrared thermography.*

Highlights:

- Review on the main methods to measure the U -value of non-homogeneous walls.
- Methods: heat flow meter, guarded hot plate, guarded and calibrated hot box, infrared thermography.
- Standards framework and discussion of the main advantages and drawbacks of each method.
- Description of methodologies and working principles of laboratory and *in-situ* measurements.
- Measurement of the thermal transmittance of different heavy- and light-weight walls.

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1. Introduction

The thermal transmittance (U -value) of the building envelope plays a key role in the overall thermal performance of a building, in both the thermal comfort and the energy savings throughout its operational phase. In fact, as suggested by Sassine [1], evaluating how much heat is lost through the building envelope is a vital requirement for building energy simulation and audit, and it is also needed to support decision making during design, construction and refurbishment.

During the design phase, the thermal transmittance of the elements must be correctly estimated and optimized taking into account the climate conditions, the construction typology, and the final use of the building. In this context, the level of insulation is one of the main features that influence the U -value of the opaque elements [2], and it plays a critical role in energy saving by reducing the rate of heat transfer through the building envelope [3]. In literature, it is suggested that the level of insulation should be increased in colder climates to reduce the energy demand for heating, and reduced in warmer climates (while the ventilation and free cooling strategies should be improved) to reduce the energy demand for cooling [4]. The estimation of the overall thermal transmittance of building envelope components is also crucial when performing the building energy simulation, in order to optimize the design and the configuration of the construction elements and to reduce the energy demand for air-conditioning during the operational phase. This is usually carried out by considering the opaque element in terms of its different successive layers, and taking into account the

thickness and the thermal conductivity of each layer. In a very simple approach, the U -value can then be calculated by finding the reciprocal of the sum of the thermal resistance of each layer of the construction element. The internal and external surface resistances (fixed values are typically considered) should also be added. As stated by Evangelisti *et al.* [5], the external convective heat transfer coefficient is typically related to the wind velocity, wind direction and surface roughness. However, this layer-by-layer approach does not account for thermal bridges caused by metal framing crossing insulation layers in lightweight steel-framed (LSF) construction or mortar joints in heavyweight walls, air gaps around insulation and cavities with air movements, moisture contents, and so on. Moreover, as stated by Lucchi [6], the calculation of the U -value of construction elements composed by plane, parallel and uniform layers, in which the heat flow is unidirectional, is more theoretical than real. There is a number of standards that cover calculation methods to estimate the thermal transmittance of different construction elements, including some of the features listed above (*e.g.*, refs. [7][8][9][10][11][12][13][14]). However, the overall thermal transmittance of some non-homogeneous opaque elements cannot be calculated using these standards.

The development of new laboratory experiments and innovative non-destructive *in-situ* methods to measure the U -value of non-homogeneous walls has been a subject of great interest during the last years. On one hand, the results of these experimental methods are crucial for the validation of numerical or analytical models to determine the U -value of more complex configurations, and to support new standard procedures. On the other hand, the development of new non-destructive *in-situ* measurements to determine the overall thermal transmittance of existing walls is very important for energy audit, or retrofitting actions. In fact, as suggested by Sassine [1], when dealing with existing buildings, it is more complicated to perform the thermal characterization of the construction elements, since the properties of materials are usually unknown, components have often been degraded over time, and the experiments should be simple, fast, and non-destructive. Most of the methodologies described in the literature concern measurements of samples in laboratory conditions with well-known environmental conditions, geometries, configurations and materials. Therefore, there is a lack of reliable methodologies for *in-situ* measurement of the U -value of existing walls in real buildings, particularly for existing LSF walls. As stated by Gori *et al.* [15], the right evaluation of the thermophysical properties of building elements based on *in-situ* measurements can enable their performance to be assessed for qualitative assurance and correct decision in policy making, building design, construction and refurbishment.

This paper aims to provide a survey on the main methodologies used to measure the overall thermal transmittance and thermal behaviour of homogeneous elements, moderately-

homogeneous and non-homogeneous walls, windows, and construction elements with innovative materials, such as aerogel, phase change materials (PCMs) and vacuum insulation panels (VIPs). Homogeneous elements are typically made of one material or an assembly of materials with uniform thermal properties. However, construction elements traditionally used in buildings are not homogeneous, and they are composed by several assembled components. A non-homogeneous wall is defined as a construction assembly composed of parts that are not of the same kind (such as structural members crossing insulation layers, piping, electrical outlets, construction defects such as insulation voids, etc.) and materials with significantly different thermophysical properties. Therefore, the evaluation of the overall thermal performance of the wall as a whole can become very challenging since the thermal resistance of the different parts of the wall can be very different from each other. A moderately-homogeneous wall can be composed of several materials with diverse thermal properties, but considered as a quasi-homogeneous wall made of a material with equivalent thermophysical properties. This is typically the case of heavy masonry walls. In the first part of the paper five established methods are discussed: (i) the heat flow meter (HFM); (ii) the guarded hot plate (GHP); the hot box (HB) – considering (iii) the guarded HB (GHB) and (iv) the calibrated HB (CHB), and at last, (v) the infrared thermography (IRT). In the second part of the paper, some studies that used these methods are discussed, and other *in-situ* experiments are presented. Particular attention is devoted to the measurement of the overall thermal transmittance of LSF walls, by including the effects of thermal bridges caused by steel framing components and the presence of PCMs in the configuration of the walls. The *in-situ* thermal characterization of existing walls is also discussed in this part of the paper. In many studies, several methods are considered together in order to perform comparative analyses between results obtained by different experimental methodologies and to compare experimental measurements with standard and analytical procedures.

2. Main methods for the thermal characterization of building elements

2.1. Heat flow meter (HFM)

The HFM method is the most widely used technique for determining the thermal transmittance of a building element. According to greenTEG [16], this method is also the only procedure that provides reliable quantitative information about a building envelope. It consists in establishing a temperature difference between the two surfaces of the element and analyzing the heat flux across the specimen (from the "hot" to the "cold" side). Indeed, ISO

9869-1 [17] describes the measurement of the environmental temperature of both "hot" and "cold" sides for the U -value determination. For achieving good results, the wall must not have any significant lateral heat flux, *i.e.*, there must be a representative unidirectional heat flow. The predominant heat transfer mechanism in this method is conduction. Convection and radiation effects (boundary conditions) can be simplified, taken together and treated as an ambient temperature, which should be adequately measured. The HFM method can be applied in laboratory controlled environmental conditions or in *in-situ* measurements. Table 1 summarizes the main advantages and drawbacks of the HFM method. The ASTM standards cover most issues related to the HFM method. The ISO standards are more general, although they contain all the necessary information for the application of this method. Table 2 summarizes the main standards that prescribe the essential procedures that should be considered, matching the contents of the ASTM and ISO standards.

Table 1 – HFM method: advantages and drawbacks.

Advantages	Drawbacks
<ul style="list-style-type: none"> - Non-invasive method [18]; - The higher the temperature gradient, the more reliable the results are [18]; - Internationally recognized and most widely used [19]; - Lightweight and easy to carry equipment [20]; - Can be used in controlled laboratory conditions or in <i>in-situ</i> measurements [17]. 	<ul style="list-style-type: none"> - The measurement is local (does not consider the entire surface of the element) [21]; - Time-consuming method that requires direct contact [17]; - Long measuring time (more than 3 days) [17]; - Completely adapted only for homogenous walls [17][22]; - Lightweight construction elements and the presence of multi-layered air spaces lead to questionable results [23]; - Highly dependent on the calibration and error of the equipment, outdoor and indoor thermal environment, thermal bridges, humidity and partial adhesion of sensors [21][23][24][25]; - The degree of precision depends on temperature variations within the space and differences between air and radiant temperatures [25]; - Dependent on the accuracy of the data logging system [17]; - Difficulties in dealing with internal heat sources, <i>e.g.</i>, walls with internal pipes inside which hot/cold water flows[18]; - It is relatively expensive and it leaves marks and damages surface of the building element [26].

For measuring the U -value of walls, the HFM method requires heat flux meters, thermocouples, and data acquisition systems. Figure 1 shows a sketch of a HFM laboratory apparatus, and an example of an instrumented wall. According to ISO 9869-1 [17], the data collected by the heat flux meter and the temperature sensors shall be recorded continuously or at fixed intervals over a period of full days. It should be pointed out that this standard was developed for *in-situ* measurement-cycles of 24 hours under outdoor environmental

conditions. The maximum period between two records and the minimum duration of the test depends on the nature of the element (*e.g.*, heavy- or light-weight construction, the insulation position, etc.), the indoor and outdoor temperatures (mean temperature and temperature fluctuations, before and during measurements) and the method used for the data analysis. The minimum duration for the measurements is 72 hours, if the temperature is kept stable around the heat flux meter; otherwise, the test may have to last over 7 days. The duration of experiments shall be determined by applying criteria to the values obtained during the test. According to the ASTM C1155-95 [22], the data of each sensor should be monitored at least every 5 minutes. With this, the average values of temperature and heat flow must be calculated and recorded in intervals of 60 minutes or less. The experiment should last three or more multiples of 24 h (24 h is a dominant temperature cycle). However, since temperatures on both sides are controlled (if/when in laboratory), the test duration must be adapted considering the temperature stability.

Table 2 - Main standards in the field of the HFM method.

ASTM	ISO
Principles for the use of the method and calculation of thermal properties	
- ASTM C1155-95 (2013) [22], “ <i>Standard practice for determining thermal resistance of building envelope components from the in-situ data</i> ”.	- ISO 9869-1:2014 [17], “ <i>Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance - Part 1: Heat flow meter method</i> ”.
- ASTM C1046-95 (2013) [27], “ <i>Standard practice for in-situ measurement of heat flux and temperature on building envelope components</i> ”.	
Steady-state thermal properties	
- ASTM C518-17 (2017) [28], “ <i>Standard test method for steady-state thermal transmission properties by means of the heat flow meter apparatus</i> ”.	- ISO 8301:1991 [29], “ <i>Thermal insulation - Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus</i> ”.
Thermal transmittance in glass	
	- ISO 10293:1997 [30], “ <i>Glass in building - Determination of steady-state U values (thermal transmittance) of multiple glazing - Heat flow meter method</i> ”.
Thermal storage properties in phase change materials and products	
- ASTM C1784-14 (2014) [31], “ <i>Standard test method for using a heat flow meter apparatus for measuring thermal storage properties of phase change materials and products</i> ”.	
Thermal transmission properties of vacuum insulation panels	
- ASTM C1667-15 (2015) [32], “ <i>Standard test method for using heat flow meter apparatus to measure the centre-of-panel thermal transmission properties of vacuum insulation panels</i> ”.	

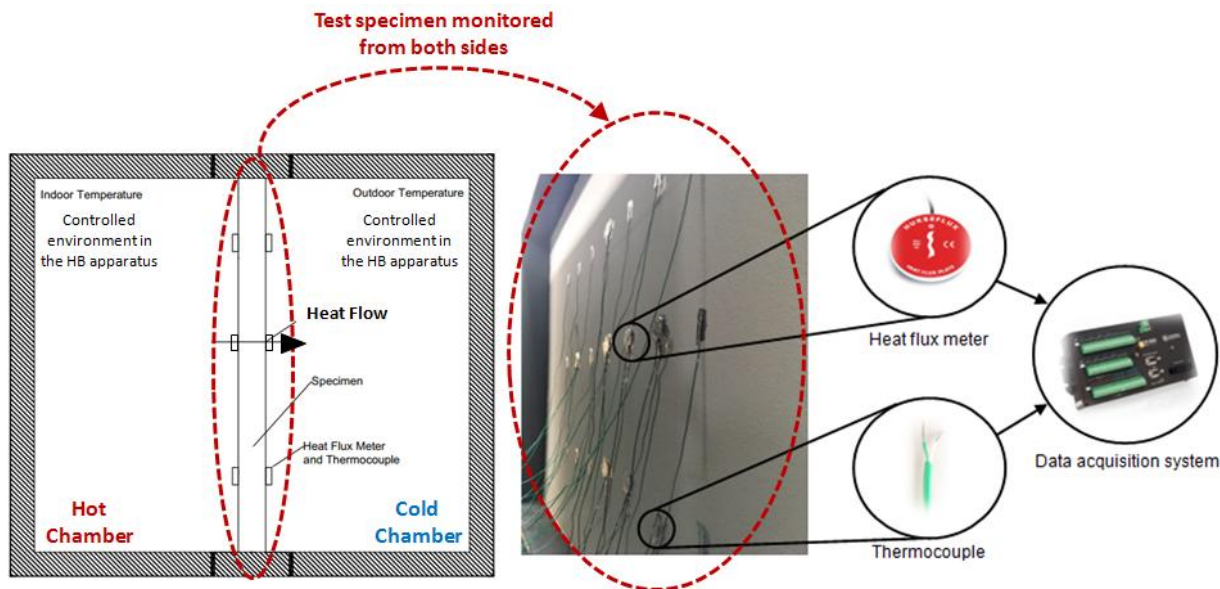


Figure 1 - Instrumented outer surface of an LSF wall (test sample): sketch of the application of the HFM method in a laboratory controlled environment.

To evaluate the U -value in steady-state conditions, ISO 9869-1 [17] proposes the simple *average method*. The *average method* is very used because, in spite of leading to a longer test duration, it makes the calculation process simpler. In addition, it considers that the heat transfer process does not achieve a steady-state (which is what really happens), taking into account the variation over time of the heat flux and of the ambient temperatures. The *average method* indicated in this standard also proposes an alternative methodology for data correction, considering the effects of thermal storage (applicable to constructive elements with high thermal inertia).

The ASTM C1155-95 [22] indicates the *sum of least squares method* (rather complex method) and the *summation technique* (similar to the *average method*), requiring a significant difference between surface temperatures for fast convergence (the surface temperatures are required for the thermal resistance measurement). Since the procedure does not consider thermal storage, the method is sensitive to a gradual increase or decrease of temperature differences.

For evaluation of the U -value in a dynamic state, the ISO 9869-1 [17] presents another method with varying temperature and heat flow, to obtain the steady-state properties of a building element. The implementation of the *dynamic method* requires: (i) measuring the density of the heat flow rate and the temperatures at the indoor and outdoor surfaces, taken at several time intervals; (ii) computing the derivative of the indoor and outdoor surface temperatures; (iii) selecting the time intervals; (iv) computing the exponential functions of time constants; (v) forming the heat flow matrix; (vi) estimating heat flow vectors; (vii)

estimating total square deviation, and (viii) considering that the best time constant set is the one giving the smallest square deviation, which will provide the best estimate of the heat flow vector that allows in turn to estimate the thermal conductance.

The *average* and the *summation* methods are similar to each other and they can be considered the most widely used methods due to their simplicity and rapid achievement of results. However, the accuracy of the results can be strongly influenced by the measuring conditions. On the other hand, as stated by Atsonios *et al.* [33], the *dynamic* and the *sum of the least squares* methods are more likely to provide reliable results regardless of the measuring conditions. Nevertheless, they are less commonly used because of their complexity (*e.g.*, they require the use of complex algorithms and computational tools).

Atsonios *et al.* [33] carried out a comparative assessment of the four standardized methods described in ISO 9869 and ASTM C1155 for the *in-situ* measurement of the thermal resistance of three different walls (drywall, rubble and brick walls): the *average*, the *summation*, the *dynamic* and two different approaches of the *sum of the least squares* method (*SLS_HF* and *SLS_TIN* methods). Since the main limitations of the standardized methods are the duration of the measuring period and the dependence of the results accuracy on the measuring conditions, the authors evaluated the measuring period required for the experiments and the variability of the results of each method. They concluded that the *average* and the *summation* methods require a higher temperature difference between indoor and outdoor conditions to achieve reliable *R*-values in a short measuring period. Therefore, these methods should not be used when the temperature difference between the hot and the cold surfaces of the wall is too low. This conclusion is in agreement with the results provided by Desogus *et al.* [20] in a study to evaluate the use of the *average* method for different measuring conditions (with a temperature difference of 10 °C and 7° C). As pointed out by these authors, the reliability of this method depends on the temperatures difference between the two environments separated by the building envelope, and the smaller the temperature difference the less precise the results obtained. On the other hand, Atsonios *et al.* [33] concluded that for the *dynamic* and *SLS_TIN* methods, the results appear to be independent of the measuring conditions. However, the results are significantly affected by the direction of the heat flow, and present low variability (up to 6%) only if the heat flow direction is kept stable during the measurements. Regarding the *SLS_HF* method, it is not affected by the measuring conditions, providing fast and reliable results at all cases [33].

Gaspar *et al.* [34] and Deconinch and Roels [35] carried out comparative studies on the use of the *average* and *dynamic* methods based on different measuring conditions. They concluded that in case of low difference of hot-to-cold surface temperatures of the wall, only

the *dynamic* method leads to reliable results. Flanders *et al.* [36] compared the *summation* and the *sum of least squares* methods to estimate the *R*-value of construction elements of different buildings under winter *in-situ* conditions (high internal and external temperature difference). The results suggested that the latter method provides slightly lower *R*-values than the former, and that both methods can be used for temperature regimes encountered and for construction with the range of thermal mass and insulation levels evaluated. For these authors, each method has its intrinsic advantages: the *summation* technique is simpler (against its recognized random error), and the *sum of least squares* provides more information about the *R*-value sensitivity to temperature and better statistical report (against the complexity of the technique).

More methods for the *U*-value measurement based on the HFM approach can be found in literature, such as the RC networks [37] and the system identification tools [38].

2.2. Guarded hot plate (GHP)

The GHP method is suitable for determining the thermal conductivity in steady-state conditions, of materials or construction elements. While the HFM method can be applied to large-scale specimens (*e.g.*, full-size walls), the GHP methods are used for middle-scale or small specimens. Table 3 shows the main advantages and disadvantages of this method. The GHP apparatus is usually composed by two cold plates and a heated (measuring) plate bordered by a guard heating system (guard ring), as shown in Figure 2. An electric system heats the hot plate up, and a group of coolers or liquid-cooled heat sinks cools the cold plates down [39].

Table 3 – GHP method: advantages and drawbacks.

Advantages	Drawbacks
<ul style="list-style-type: none"> - Use of various elements and materials [40]; - High accuracy [41]; - Allows the control of the heat flux through the material [41]; - Simplicity of design and reduced cost [42]; - Most accurate technique for determining the thermal conductivity [43]. 	<ul style="list-style-type: none"> - Long measuring time [41]; - Limited to low conductivity materials [41]; - Test on relatively small-scale samples (such as 300 × 300 mm [39]).

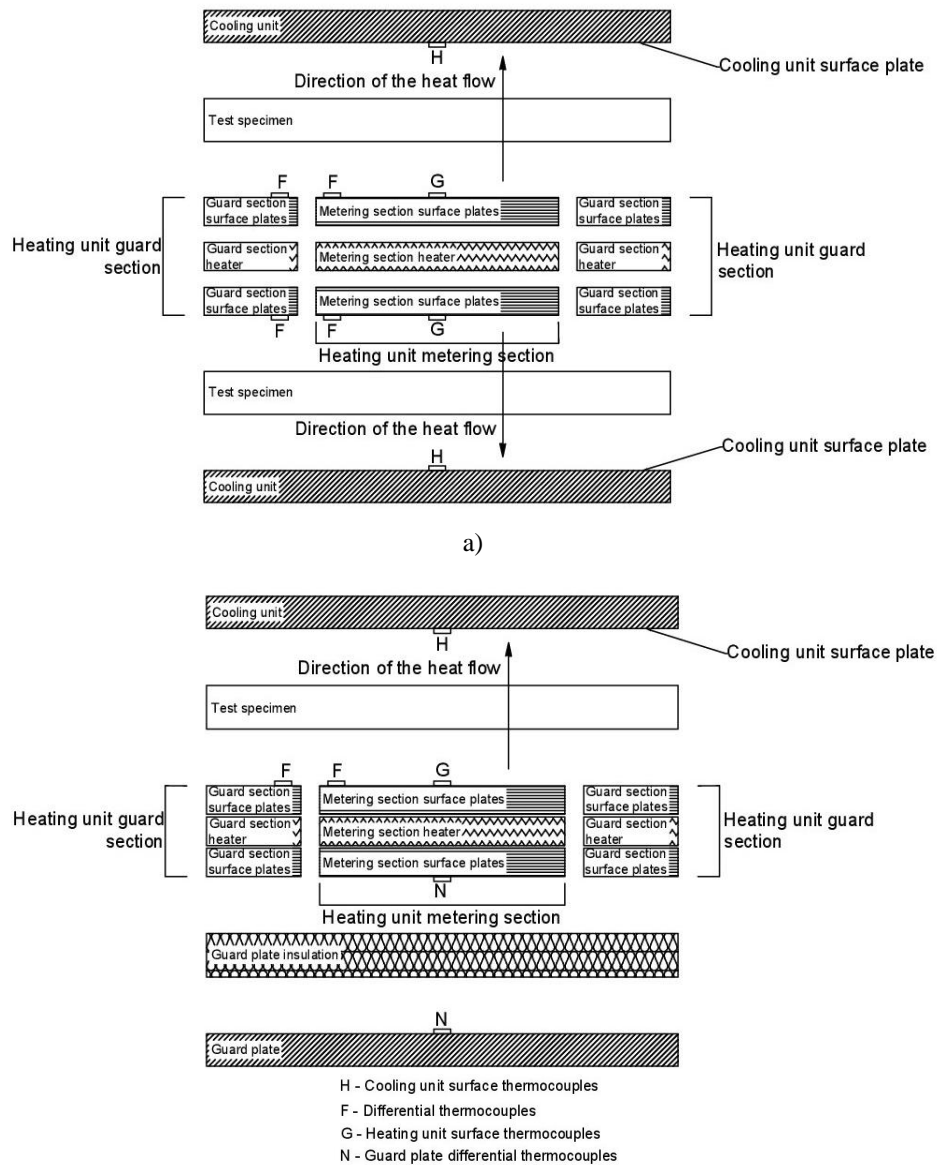


Figure 2 - Sketch of the functioning of the GHP apparatus: a) two-specimen apparatus, b) single-specimen apparatus. Adapted from ref. [44].

The operating principle of this method is very similar to that described for the HFM method. The heat flux is applied from the hot plate to the cold plate(s) in a direction perpendicular to the sample(s) surfaces, and the apparent thermal conductivity of the sample(s) is determined from the heat flux estimated after the heat input, the temperature difference measured between the plates and the thickness of the sample(s). In ideal conditions, the plates are in perfect contact with the sample, and the unidirectional heat flux is constant in time, while the border sector heated in a controlled way (so that its temperature equals that of the measuring heated plate) acts as an insulating guard, thus ensuring an adiabatic border [45]. Indeed, as remarked by Zarr [46], the GHP method establishes one-dimensional heat flow through the specimens by reducing undesired lateral heat flows to

negligible and controlled proportions. Table 4 presents the main standards in the field of the GHP method.

Table 4 - Main standards in the field of the GHP method.

ASTM	ISO
Principles for the use of the method and calculation of thermal properties	
- ASTM C177-13 (2013) [40], “ <i>Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus</i> ”.	- ISO 8302:1991 [44], “ <i>Thermal insulation – Determination of steady-state thermal resistance and related properties – Guarded hot plate apparatus</i> ”.
Steady-state thermal properties in glass	
	- ISO 10291:1994 [47], “ <i>Glass in building – Determination of steady-state U values (thermal transmittance) of multiple glazing – Guarded hot plate method</i> ”.

To ensure the reliability of the results and the correct implementation of the method for steady-state conditions it is necessary to assume some considerations. Salmon [43] says that the plates of the appliance should be identical in geometry and material and as flat as possible, must have high emissivity surfaces and should be made of highly conductive material so that there is an excellent uniformity of temperature. Temperatures in the guard ring and measuring zone should be as similar as possible, and the width of the shield should be at least 0.25 times the width of the measurement area and not less than the thickness of the sample to ensure unidirectional flow. Moreover, there must be a good thermal contact between the thermocouples and the plates. These plates should be placed parallel to the surfaces in an isothermal region to limit the flow of heat along them and minimize the error in the measured temperature. Finally, ASTM C177-13 [40] indicates that the measurement should run for at least four 30 minutes intervals or four longer system time constants. With this method, it is possible to obtain the U -value of the element or material, indirectly. To do this, the equations given in ISO 6946 [8] should be considered. This standard provides a methodology for calculating the thermal resistance and thermal transmittance of building components and some building elements (consisting of thermally homogeneous layers), based on the appropriate design thermal conductivities or design thermal resistances of the materials and products. It also provides an approximate method that can be used for elements containing inhomogeneous layers. However, cases where insulation is bridged by metal are considered outside of the scope of this standard.

Labudová and Vozárová [48] studied the thermophysical properties of a material in the GHP apparatus, in a dynamic state. A mathematical formulation was adapted to calculate the temperature variation in the hot plate sensor, which is determined by measuring the voltage

change through the source. It depends on the electric current of heating, the initial resistance of the hot plate and a temperature coefficient of the nickel resistivity (flat heat source). It was concluded that perfect thermal contact between the source of the plate and the sample is hardly guaranteed, and that the thermal contact resistance can cause a possible thermal barrier between the sample and the heat sink, which leads to significant errors. Heat losses from the side surfaces of the sample(s) cannot be neglected, and during the initial seconds of the test, there is an influence of the thermal inertia of the heat exchanger and of the thermal contact resistance between plate and sample(s).

Thomas and Zarr [49] presented a mathematical model to measure the thermal conductivity of insulation materials in a GHP apparatus. The main steps of the study were: (i) to describe and confirm the incremental control algorithm and to determine satisfactory gain configurations using a mathematical model that simulates tests in seconds (not in days); (ii) to create and validate a model that responds by heating rates in the various components and interactions with their environments; (iii) simulating performance and dynamic control with the model and determining the configurations of the controllers. The determination of the temperature response is necessary to know the thermal storage capacities and the conductance values for all heat flow paths. With this, and by applying first-order differential equations governed by the energy balance, the dynamic system can be computed.

2.3. Hot box (HB)

The basis of the HB method is the measurement, at steady-state conditions, of the heat flux through the building components and the corresponding temperature differences across it. This method can be applied for the thermal characterization of homogeneous or non-homogeneous specimens and building structures or composite assemblies (*e.g.*, walls with windows, doors, etc.). There are two types of HB apparatus: the Guarded HB (GHB) and the Calibrated HB (CHB). Both methods are suitable for vertical and horizontal specimens (such as walls, ceilings and floors). The apparatus can be sufficiently large to study full-scale components. Figures 3 and 4 show, respectively, a sketch and a photographic view of the GHB apparatus. It consists of three main objects: the guard box, the metering box, and the cold box. The test specimen is placed between the guard/metering box and the cold box. A sketch of the CHB apparatus is shown in Figure 5. It consists of two main objects: the metering box and the cold box. The test specimen is placed between the metering box and the cold box.

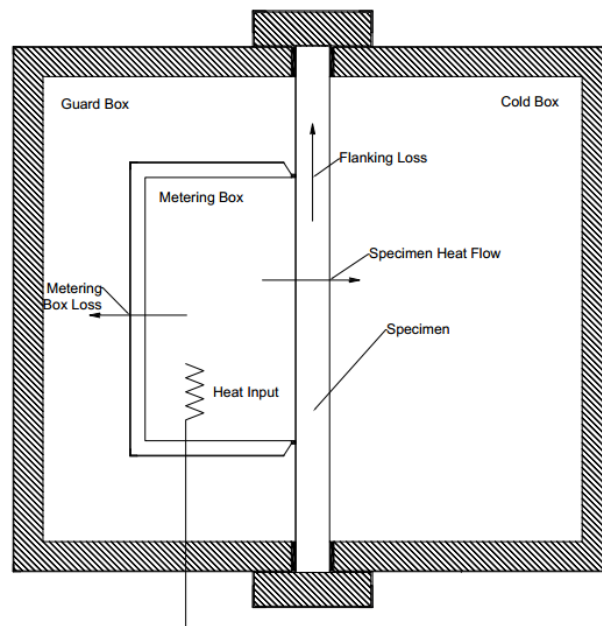


Figure 3 – Schematic of a typical GHB apparatus. Adapted from ref. [50].

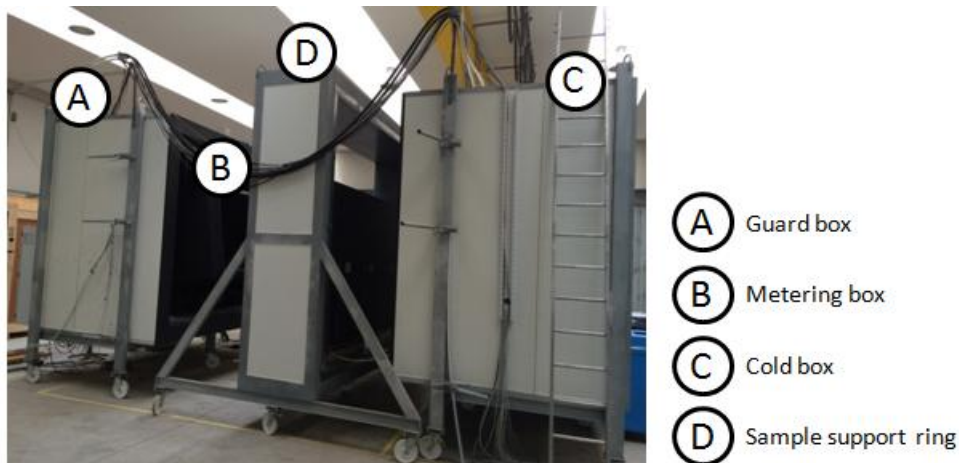


Figure 4 – GHB apparatus installed at the Department of Civil Engineering of the University of Coimbra.

The GHB and the CHB apparatus differ from the mode in which the metering box is surrounded. The first one is the self-masking, which has a controlled "guard" chamber surrounding the metering chamber. The second configuration is the masked hot box. In this configuration, the guarded chamber is the surrounding ambient. The CHB surrounding ambient needs to be a temperature-controlled space, which does not necessarily need to be at the same air temperature as that inside the metering box. In the GHB method, the temperatures in the boxes are controlled in such a way that, as far as possible, the temperatures in the guard and in the metering boxes are the same. This is fundamental to ensure that the total heat supplied to the metering box passes through the test element in a perpendicular direction to its faces. In the CHB method, the heat flow that passes through the

sample is determined from the total power supplied to the measuring box, correcting for losses or gains through the metering box walls and the flanking loss to the cold box occurring around the perimeter of the sample. These corrections are performed through calibration measurements, carried out prior to the test, using specimens of known thermal properties. Table 5 shows the main advantages and disadvantages of the HB method. Table 6 presents the main standards that contain all the necessary procedures in the field of the HB method.

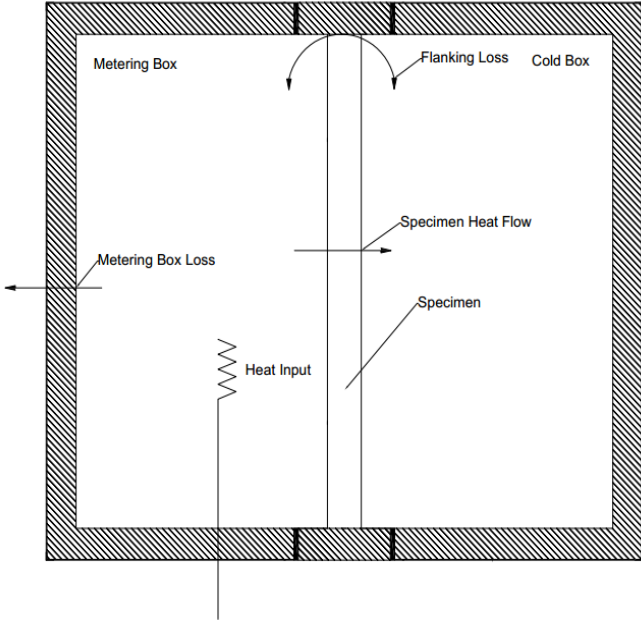


Figure 5 – Schematic of a typical CHB apparatus.

The HB apparatus requires a set of verifications, which must be carried out to establish its adequate operation and accuracy [51]. Tests are performed by simulating end-use application, taking into account the effect of testing conditions. For this purpose, interior (hot chamber) and exterior temperatures (cold chamber), and air velocity must be reproduced. The ISO 8990 [52] suggests a difference of at least 20 °C between chambers. The time required to reach stability for steady-state measurements depends on the apparatus. The ISO 8990 [52] requires measurements for *R*- and *U*-values from two successive measuring periods of at least 3 hours after the equipment has reached the stability or near-stability. For specimens with a high thermal resistance, the test period must be extended. The HB apparatus can also perform dynamic tests to compute the thermal performance of a wall specimen. Burch *et al.* [53] proposed a dynamic test method for determining transfer function coefficients for a wall specimen using a CHB. The dynamic method predicted with good agreement the diurnal performance of a masonry wall specimen, as determined empirically. To carry out the dynamic tests it is necessary to know the response of the measuring equipment to temperature changes. The dynamic test is made by modifying the exterior air temperature, usually

changing the cold box temperature in a sinusoidal cycle amplitude in a time interval within the capacity of the dynamic response of the equipment.

Table 5 – HB method: advantages and drawbacks.

Advantages	Drawbacks
Hot Box (HB)	
<ul style="list-style-type: none"> - The HB methodology is an accurate and reliable method for obtaining thermal resistance values on large-scale systems [54][55]; - Can test homogeneous or non-homogeneous specimens [56]; - The inside surface conductances provided by the box are similar to those that occur in practice under natural convection conditions, and realistic outside surface conductances can be provided in the cold room [57]; - The possibility of measurements under both winter and summer outdoor temperatures without removing the sample [58]; - HB large scale better simulates real phenomena, because the small-scale test does not adequately simulate the thermal performance when the specimen is under natural convection [59]. 	<ul style="list-style-type: none"> - Very expensive equipment [60]; - Long measuring time [52]; - Regular periodic calibration [61]; - Does not give the distribution of surface temperatures for locations of strong thermal bridges [62]; - Requires an operator very specialized in the equipment and thermal phenomena [56].
Guarded Hot Box (GHB)	
<ul style="list-style-type: none"> - Does not need to have a calibration factor for the flanking loss of the metering box, due to the existence of the guard box [52]; - More simple to calibrate than the CHB [52]. 	<ul style="list-style-type: none"> - The measuring area is limited to the size of the metering box [52]; - More challenging to analyze inhomogeneous specimens due to the size of the metering box [52].
Calibrated Hot Box (CHB)	
<ul style="list-style-type: none"> - CHB apparatus is simpler in design and operation than the GHB [51]; - Allows testing of larger specimens [52]. 	<ul style="list-style-type: none"> - Flanking loss between the metering chamber and the climatic chamber through the specimen frame [63]; - The laboratory temperature must be controlled to avoid corrections in the calibration factor [51].

Table 6 - Main standards in the field of HB method.

ASTM	ISO
Determination of thermal properties	
<ul style="list-style-type: none"> - ASTM C1363-11 (2011) [56], “<i>Standard test method for thermal performance of building materials and envelope assemblies by means of a hot box apparatus</i>”. 	<ul style="list-style-type: none"> - ISO 8990:1994 [52], “<i>Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box</i>”.
Determination of thermal transmittance of windows and doors	
<ul style="list-style-type: none"> - ASTM C1199-14 (2014) [64], “<i>Standard test method for measuring the steady-state thermal transmittance of fenestration systems using hot box methods</i>”. 	<ul style="list-style-type: none"> - ISO 12567-1:2010 [65], “<i>Thermal performance of windows and doors – Determination of thermal transmittance by the hot-box method - Part 1: Complete windows and doors</i>”. - ISO 12567-2:2005 [66], “<i>Thermal performance of windows and doors – Determination of thermal transmittance by the hot-box method - Part 2: Roof windows and other projecting windows</i>”.

The GHB apparatus was used in several studies to evaluate the U -value of different construction elements, for instance in refs. [67][68][69][70][71]. Brown and Stephenson [69] presented one of the first methodologies for measuring the dynamic heat transfer characteristics of a full-scale homogeneous specimen using the GHB. The calibration process was developed from first principles and supported by testing a specimen whose thermal characteristics were determined from measurements of material properties. The suggested methodology consisted of a series of measurements of the response of the test specimen, and facility, to sinusoidal variations of exterior temperature and internal power. An additional study of Brown and Stephenson [70] presented a development of the previous methodology, for measuring the dynamic heat transfer characteristics of full-scale non-homogeneous specimens. The study shows that the dynamic response of a wall system is quite sensitive to the magnitude of the interior and exterior surface convection coefficients. Geola *et al.* [71] designed and constructed a GHB facility to investigate the overall heat transfer coefficient of different greenhouse cladding materials – polyethylene plastic films with or without thermal screens.

In a recent paper, Buratti *et al.* [72] proposed a new method – the so-called *small hot-box* apparatus – to evaluate the thermal properties of small specimens (0.3×0.3 m). Different samples with known thermal properties were analyzed (polystyrol, foam polyurethane, polystyrene, wood, plasterboard, and cement insulating blocks). Following these authors, the proposed method can be a possible alternative system to be used instead of the conventional GHP apparatus. Modi *et al.* [73] also proposed a *mini-scale hot-box* apparatus to evaluate the thermal performance of an insulation building block.

2.4. Infrared thermography (IRT)

In literature, IRT technique can be divided into qualitative and quantitative IRT. The former is considered many times as support for HFM measurements. Quantitative IRT can be used for assessing the U -value of construction elements.

Over the last years, the use of IRT technique has increased in building energy audit. In a recent paper, Lucchi [74] presents a critical review on the use of this technique, describing: (i) the main passive and active approaches, (ii) well-established and emerging techniques, (iii) general procedures, (iv) types of infrared (IR) cameras, (v) technical issues, (vi) main limitations of the IRT and potential sources of errors, (vii) main advantages of the technology, and (viii) future trends in the use of IRT for energy audit. The author also pointed out the potential of IRT for: (i) thermal characterization of buildings, (ii) detection of thermal bridging, insulation level, air leakage and moisture, and (iii) assessment of thermal comfort.

Balaras and Argiriou [75] also pointed out that the use of IRT is a valuable tool for building diagnostics. It can be used for inspecting and performing non-destructive testing of building elements in order to detect where and how energy is leaking from the envelope of the building, to evaluate operation conditions of HVAC systems, and to identify problems with electrical and mechanical installations. Taylor *et al.* [76] added that IRT can be used as a qualitative tool during the different stages of the construction process to improve the final thermal performance of the building envelope.

The IRT is a technique widely used in building construction because it allows the measurement of surface characteristics involving all possible heat transfer phenomena [77]. The basic principle of IRT is that all objects emit thermal radiation, which depends on their temperature and emissivity. Emissivity comes from the relation between the energy emitted by the surface of an object and the energy of a black body (the ideal, perfect emitter). IRT allows to capture and analyze the IR radiation from an object, with or without illumination. Still, since the amount of radiation emitted by an object increases with (the fourth power of) the surface temperature, IRT allows perceiving the spatial temperature distribution. Table 7 summarizes the main advantages and disadvantages of this technique.

The IR cameras capture the radiation emitted by the surface converting it into electrical signals, and then creating an image with the distribution of the surface temperatures of the bodies, by applying the Stefan-Boltzmann law [78]. Although the image shows an approximation of the temperature at which the object is operating, the camera is actually using various data sources based on the areas surrounding the object to determine that value instead of detecting the actual temperature [79]. Figure 6 presents an example of the application of this technique in the inspection of buildings (note that the heat flux through the wall is the result of thermal stimulation by artificial sources – a hot chamber). Figures 6a and 6b show, respectively, a digital photograph and an IRT image with the temperature distribution of the outer surface of an LSF wall with an external thermal insulation composite system (ETICS). By analyzing the IRT image, it is possible to identify the location of the plastic wall plugs of the ETICS system. In fact, as suggested by O'Grady *et al.* [80], the IRT can be very helpful to define the correct locations for HFM sensors, since these sensors must be located in a place without any inhomogeneities or defects that may lead to incorrect results of the overall U -value of the construction element. Other authors have used IRT as a qualitative tool to select the right place for the location of HFM sensors, such as Asdrubali *et al.* [81], Evangelisti *et al.* [82] and Asdrubali *et al.* [83].

Table 7 – IRT method: advantages and drawbacks.

Advantages	Drawbacks
<ul style="list-style-type: none"> - Non-destructive method [84]; - Large number of applications [77]; - It can be used as support to justify the choice of the measurement zones [85]; - Requires no direct contact with the element and can be used over long distances [74][86]; - Lightweight and easy to carry equipment [86]; - Allows to evaluate extensive areas in a short period, and in real time [79]; - Allows to determine the overall transmittance of an envelope in a short time especially in comparison with HFM method [87]; - It is not a punctual measurement (it considers all the surfaces of the element) [88]; - It is able to detect several pathologies of the element [79]; - The IRT camera may calibrates automatically. 	<ul style="list-style-type: none"> - Very high price for the equipment [89]; - Qualified person to analyze the results [89] and to operate the IR camera; - Highly dependent on climatic conditions [86]; - Pollution and smokes with high emissivity may influence the results [75]; - Misreading information is taken by the camera when temperatures have very close range [79].

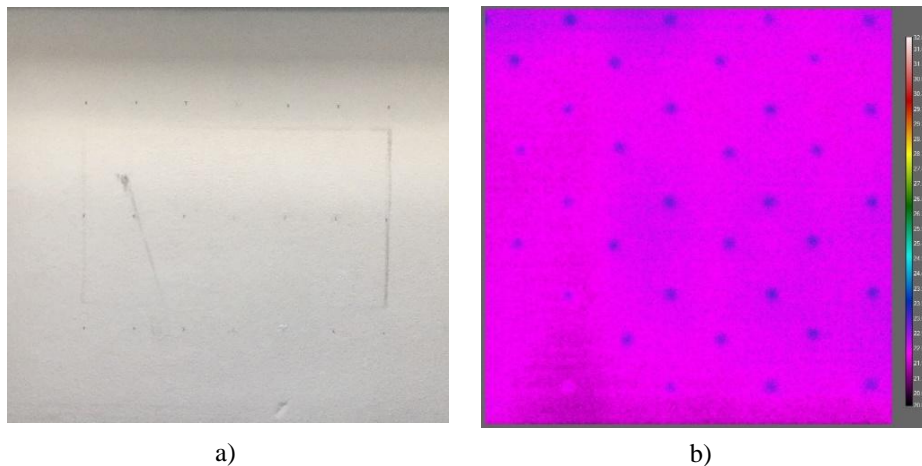


Figure 6 – Outer surface of a LSF wall with ETICS: a) digital photograph; b) IRT image.

Table 8 presents the primary standards that contain the necessary procedures that should be considered, to render a correct use of the IRT methodology, matching the contents of the ASTM and ISO standards. It should be remarked that a new standard, ISO 9869-2 [90], is under development concerning the *in-situ* measurement of the thermal transmittance of frame structures by means of the IRT technique.

Table 8 – Main standards in the field of IRT technique.

ASTM	ISO
Principles for the use of the method and calculation of thermal properties	
	- ISO/FDIS 9869-2 [90] (under development), “ <i>Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance - Part 2: Infrared method for frame structure dwelling</i> ”.
Detecting thermal irregularities in building envelopes	
- ASTM C1060-11a (2015) [91], “ <i>Standard practice for thermographic inspection of insulation for installations in envelope cavities of frame buildings</i> ”.	- ISO 6781:1983 [92], “ <i>Thermal insulation - Qualitative detection of thermal irregularities in building envelopes - Infrared method</i> ”.
Non-destructive testing terminology	
- ASTM E1316-17a (2017) [93], “ <i>Standard terminology for non-destructive examinations</i> ”.	- ISO 10878:2013 [94], “ <i>Non-destructive testing - Infrared thermography – Vocabulary</i> ”.
General principles	
	- ISO 10880:2017 [95], “ <i>Non-destructive testing - Infrared thermographic testing - General principles</i> ”.
Determination of the minimum resolvable and detectable temperature differences	
- ASTM E1213-14 (2014) [96], “ <i>Standard practice for minimum resolvable temperature difference for thermal imaging systems</i> ”.	
- ASTM E1311-14 (2014) [97], “ <i>Standard practice for minimum detectable temperature difference for thermal imaging systems</i> ”.	
System and equipment components and their characteristics	
	- ISO 18251-1:2017 [98], “ <i>Non-destructive testing - Infrared thermography - Part 1: Characteristics of system and equipment</i> ”.
Procedures for measuring and compensating for reflected temperature and emissivity	
- ASTM E1862-14 (2014) [99], “ <i>Standard practice for measuring and compensating for reflected temperature using infrared imaging radiometers</i> ”.	
- ASTM E1933-14 (2014) [100], “ <i>Standard practice for measuring and compensating for emissivity using infrared imaging radiometers</i> ”.	

Albatici and Tonelli [101] proposed an alternative methodology for the *in-situ* estimation of the U -value of opaque construction elements by means of IR thermovision. The authors stated that the proposed methodology can only be used during winter. Because of the difference between the estimated and the theoretical U -values, the authors suggested further research on several case studies to establish an average correlation between the results of the measurements and the theoretical values obtained from technical standards. To provide a robust procedure for the use of quantitative thermography and to validate this *in-situ* methodology, Albatici *et al.* [102] performed a parametric study on the thermal performance of different light- and heavy-weight walls for over three years. The authors defined some parameters of significance for the results accuracy, evaluated the influence of weather

conditions on the results, and provided a comparison between values achieved through IR thermovision, international standards approach and HFM method. The methodology provides good results for heavyweight construction, while further studies are needed for lightweight and super-insulated walls. In fact, the U -values measured for heavyweight walls showed absolute deviations of 8-20% and 10-18%, compared to the ones given by the HFM method and the standards approach, respectively. Nardi *et al.* [103] tested the previous methodology in a controlled environment provided by the GHB apparatus. The U -value of a large heavyweight sample-wall was determined by means of IRT, HFM method, and standards-based calculation. The IRT results show good agreement with the results of the other two approaches. Particularly, the difference between the results obtained from the IRT and the HFM methods was about 3.2-12.9%. Tejedor *et al.* [104] proposed a method for determining *in-situ* U -values using quantitative IRT with a deviation of 1-2% for single-leaf walls and 3-4% for multi-leaf walls. This method takes 2-3 hours, which is a great advantage in comparison to the typical 72 hours required for the execution of the HFM method in steady-state conditions. O'Grady *et al.* [105] evaluated the application of the quantitative IRT technique to evaluate the heat lost via multiple thermal bridges and windows. The methodology was validated against experimental measurements carried out in a HB device. Bianchi *et al.* [106] also proposed an IRT quantitative methodology to assess building envelope thermal losses due to thermal bridges, and Asdrubali *et al.* [78] proposed a methodology to perform a quantitative analysis of some sorts of thermal bridges through simple thermographic surveys and subsequent analytical processing. The IRT was also used by Ascione *et al.* [107] as part of an experimental apparatus to evaluate thermal bridging effects under dynamic conditions. In fact, the evaluation of the multidimensional and dynamic aspects of thermal bridges is very challenging and it should not be neglected when performing dynamic simulations using building energy simulation programs [108].

In another study, Nardi *et al.* [87] performed *in-situ* measurements based on the HFM and IRT methodologies to evaluate the thermal performance of three different walls (historical stone masonry, heavyweight wall made of hollow brick and concrete blocks, and lightweight wall made of cement-wood brick insulated by the interior) in real environment conditions. The results showed good agreement between the U -value obtained from the HFM and IRT methods for the heavyweight walls (up to 2.56%). For the lightweight wall, a discrepancy of about 47.62% was recorded.

Fokaides *et al.* [77] used IRT to estimate the overall thermal transmittance of different building envelope elements (wall, roof, glazing) in five dwellings within two seasons, during August 2009 and February 2010. According to these authors, the U -value can be determined

by using Eq. (1), where: ε_v is the wall spectral emissivity; σ is the Stefan–Boltzmann constant [$\text{W}/\text{m}^2\text{K}^4$]; $T_{s,out}$ is the outer surface temperature [K]; T_{out} is the outdoor ambient temperature [K]; v is the wind speed [m/s]; and T_{int} is the indoor ambient temperature [K].

$$U = \frac{\varepsilon_v \sigma (T_{s,out}^4 - T_{out}^4) + 3.8054v(T_{s,out} - T_{out})}{T_{int} - T_{out}} \quad (1)$$

All parameters can be measured using the same IRT camera to minimize systematic measurement errors (except for v , which must be measured by means of an anemometer). The value of emissivity must be measured because it depends not only on the surface materials, but also on actual surface conditions that suffer from pollution, moisture, etc.. The measurement of the ε -value can be achieved by two methods: comparison with a reference material (*e.g.*, special adhesive tapes with known emissivity) or direct measurement of the reflected brightness of the material. The absolute percentage deviations between the theoretical prediction and the measured U -values using IRT were found to be at an acceptable level, in the range of 10-20%.

Aversa *et al.* [109] proposed an innovative experimental procedure to investigate the thermal dynamic behavior of two prototype walls (an empty wall and a hemp fiber-filled wall) in terms of decrement factor and time lag. For the correct implementation of the method, it is necessary to ensure: (i) thermal stimulation by means of a heat source, focused in the centre of the wall of the prototype; (ii) conditioning of the test room over the duration of the test to ensure a constant indoor temperature; (iii) application of a periodic square wave signal for three cycles – for this purpose, lamps were turned on for 4 hours and turned off for another 4 hours (the total duration of the wall stimulation was 24 hours); (iv) simultaneous acquisition on the two wall surfaces, through two infrared cameras; (v) analysis of the thermographic data. The results were compared with those obtained with a numerical simulation and standard procedures. Comparing the experimental and the numerical simulation results, some minor differences were found, demonstrating a best result for the simulation with respect to measurements (lower decrement factor and higher time lag). On the other hand, very different results were obtained using EN ISO 13786, with respect to those obtained with experimental and numerical approaches. Output parameters of the new procedure are the same of standard one, but they were obtained with a different set-up. All the results related to the three approaches showed an improving in the thermal dynamic behavior of the fiber-filled wall, with respect to the empty one (lower decrement factor and higher time lag).

3. Evaluation of the thermal performance of different types of construction elements

3.1. Heavyweight construction

3.1.1. *In-situ* measurements

The *in-situ* measurement of the overall thermal transmittance of heavyweight walls has been investigated by several researchers to support energy audit and to characterize the thermal performance of existing walls. Heavyweight construction uses heavy materials such as reinforced concrete, concrete masonry, stone or brick. The development of *in-situ* surveys for characterizing the main thermophysical properties of materials and construction elements is also very important for the development of multidisciplinary approaches to assess the overall thermal performance of existing buildings [110]. As suggested by Rye and Scott [111], the U -value of existing walls is typically overestimated (up to 77%) by software-based calculation, underestimating the thermal performance of the walls. This inaccurate estimation of the thermal properties of the construction elements can impact the prediction of the energy demand for air conditioning of real buildings [112]. As reported by Byrne *et al.* [113], the incorrect estimation of the thermal resistance of existing building envelopes can also compromise the estimation of the impact of energy saving strategies and retrofitting actions. The most used non-destructive methodologies for the *in-situ* assessment of the thermal performance of existing heavyweight walls are the HFM method and the IRT technique.

Several studies were dedicated to the assessment of the thermal performance of existing and historic building elements [6][111][114][115][116][117]. Lucchi [114] investigated the thermal transmittance of historical traditional stone masonries, characterized by different heritage values, historical ages and intended use. The experimental results, based on HFM measurements, were compared to the U -value of the walls calculated from standard procedures. The author explains that the most important challenges for the *in-situ* assessment of the thermal performance of existing stone walls are related to the correct definition of the wall morphology and thickness, the prediction of the thermal properties of stone elements and accounting for the existence of air voids and gaps. It was concluded that historical stone masonries have a better thermal performance than the one expected from the standard calculations. In another study, Lucchi [6] evaluated the overall thermal transmittance of historical brick masonries, providing a comparison between standard data, analytical calculation procedures and *in-situ* HFM measurements. The main goal of this study was to provide a guidance for energy audit, simulation, and labeling of historic buildings. The author concluded that standard and analytical procedures tend to overestimate the thermal

performance of historic brick masonries. Doran [118] also carried out *in-situ* measurements to determine the U -value of building elements and to evaluate how the experimental results can be compared with predicted performance, as calculated using the methods described in the relevant standards. The results showed that, in a number of cases, the measured U -values were greater than the U -values obtained by calculation. Moreover, the author pointed out that some existing calculation procedures used for regulatory purposes may often underestimate the true heat losses for walls, in some cases by more than 30%.

Meng *et al.* [119] evaluated the U -value of different non-homogeneous block walls (including mortar joints, insulation layers and cement plaster) using the HFM method. The authors concluded that the location of thermocouples and heat flow meters, the size, shape and angle of the heat flow meters can affect the accuracy of the results. For example, the results showed that the measurement errors can be up to 6% and 26% when thermocouples and heat flow meters are improperly placed, respectively. Other works have reported that the accuracy, error and uncertainty of the results achieved using the HFM method can be affected by practical issues (for example the measurement locations), and by temperature fluctuations and small temperature difference between the interior and exterior environments [20][112][120][121][122]; so the tests must be performed during the heating period (winter), to ensure the largest temperature difference. To overcome outdoor and indoor thermal environment limitation of the HFM method and to avoid the heavy equipment of the HB, Meng *et al.* [19] proposed a new simple HB - HFM method for *in-situ* measurements (Figure 7).

Sassine [1] believes that in addition to the experimental evaluation of the thermal resistance of an existing wall, the thermal capacitance of the wall must be quantified, as this is an important parameter for dynamic modeling. The author proposed a fast method for the *in-situ* thermal characterization of walls based on complex Fourier analysis to determine the thermal capacitance and the thermal conductivity of different elements, using the measured inner and outer surface temperatures of the walls and the outer heat flux. The method does not require any imposition of particular boundary conditions and it provides satisfactory and accurate results. The author believes that this method can serve energy audit purposes, as the main thermal properties of the walls can be determined without resorting to personal estimates and assumptions often leading to erroneous studies [1]. Another feature to have in mind when estimating the thermal transmittance on existing walls (when only air and surface temperatures probes are used) is the value of the convective heat transfer coefficients. These values are typically obtained by applying the correlations available in literature, or constant standard values, which can be insufficient for some cases. Evangelisti *et al.* [123] carried out

a study to assess the influence of different convective and radiative heat transfer coefficient expressions on the measurement of the thermal transmittance. The authors concluded that the accurate estimation of the convective heat transfer coefficients is crucial for the right quantification of the overall U -value of existing walls and that the standard values are not necessarily representative of real heat transfers between environment and walls.

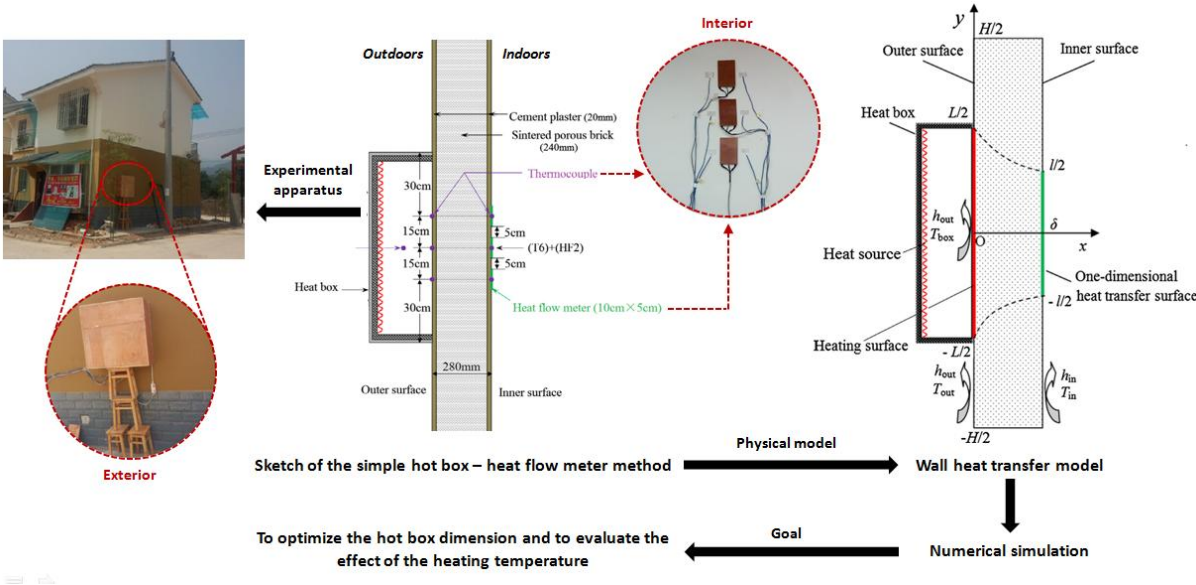


Figure 7 – Sketch of the simple HB - HFM method proposed by Meng *et al.* [19] for the *in-situ* measurement of walls thermal transmittance. Figure adapted from ref. [19].

Baldinelli [124] carried out an experimental study based on a single construction setup with a movable wall to define the stationary and dynamic thermal properties of low-e insulators installed on vertical hollow brick walls under real outdoor conditions (Figure 8). The fixed envelope of the parallelepiped setup was built with a high insulation level and the temperature inside the room was kept constant by an electrical heat pump. The tested walls were instrumented in accordance with the ISO 9869 requirements: two heat flow meters and nine thermocouples on the inner side and nine thermocouples on the outer side, all distributed over a central square of 0.5 m wide. As described by the author, the tested low-e material consists of two layers of bubble polyethylene and two layers of low-emissivity aluminum film, continuously thermowelded to have two faces made of low-e material [124]. Figure 8 summarizes the methodology proposed by the author. The steady-state results were compared to those obtained by using other methods such as the GHP, the HB method and the theoretical analysis, showing a good agreement among the different approaches. The dynamic results allowed to directly define the contribution of the low-e panel *in-situ*.

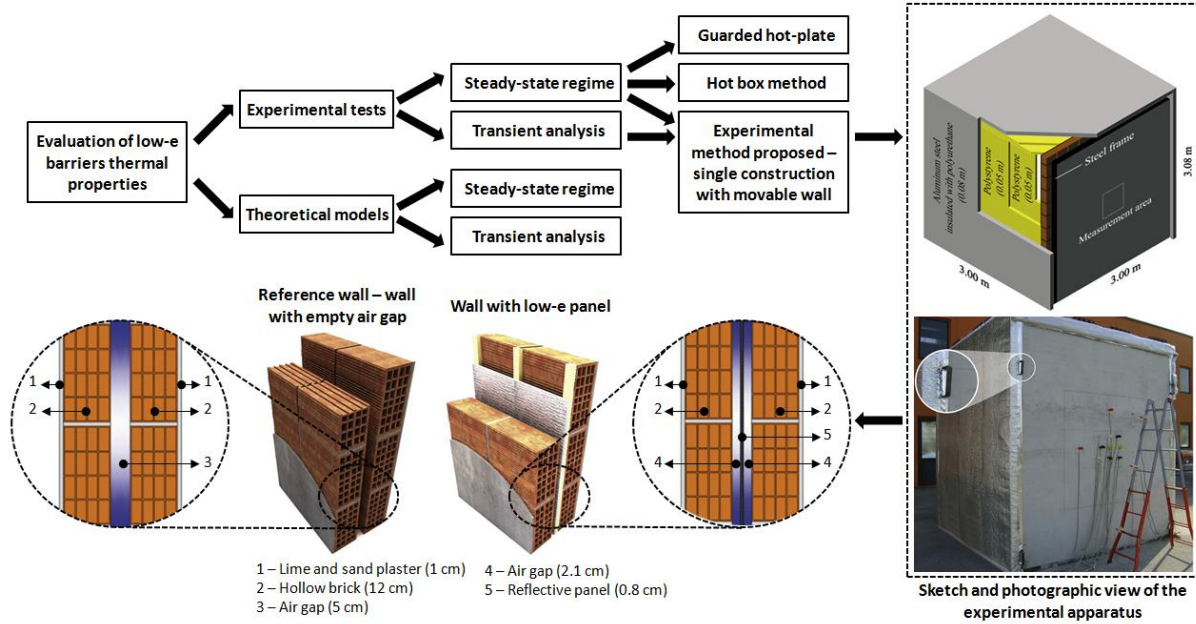


Figure 8 – Methodology proposed by Baldinelli [124] for the evaluation of the thermal properties of low-e barriers. Figure adapted from ref. [124].

Several studies have used IRT technique for the qualitative evaluation of existing walls [75][125] in order to assess their morphology [114], to find the presence of non-homogeneities, thermal bridges, and damage (such as decay, cracks, etc.) [126], for moisture detection and hygrothermal performance evaluation [127], to evaluate the thermal behavior of the building [128], to assess the impact of retrofitting actions [113], and to identify the best position for the placement of HFM sensors [82]. Kordatos *et al.* [129] have also used IRT to evaluate the degradation of murals in historic monuments. Moropoulou *et al.* [125] provided a review on the main non-destructive techniques, including IRT measurements, which can be used as tools for the thermal characterization of existing walls, allowing the protection of the built cultural heritage. Balaras and Argiriou [75] reviewed the use of IRT for building diagnostics with an emphasis on how it can be implemented to support office building audit following the TOBUS methodology [130]. Further studies have proposed *in-situ* methodologies for quantifying the overall thermal transmittance of building elements using IRT technique [77][101][126][131][132][133]. Some of these studies also show that IRT can support the HFM measurements concerning the qualitative analysis of the building elements.

3.1.2. Laboratory measurements

Measurements in controlled environmental laboratory conditions are typically used to provide reliable results for validating numerical approaches. They can also be used to validate *in-situ* methodologies to characterize the thermal performance of construction elements. The most

used methods in laboratory are based on the HB fundamentals. Many times, the tests in the HB are combined with HFM and IRT measurements.

Martín *et al.* [134] proposed a dynamic testing method inside a GHB apparatus to determine the response factors of a perforated clay blocks wall (Figure 9), without knowing the properties of the materials of the wall. The response factors approach is one of the methods to solve the Fourier equation based on the approximation of the loads, which main advantage is its simplicity. However, it may require a large number of factors to achieve accurate results. As shown in Figure 9, the authors started to carry out tests in steady-state regime to evaluate the thermal resistance and the thermal transmittance of the wall. Then, tests in dynamic regime were performed in the GHB apparatus to obtain the response factors of the wall. The method was then validated using a finite-volume simulation code. The results showed that the errors in the prediction of the U -value by adding the response factors are higher for the experiments (up to 9.5%) than for the numerical analysis (up to 0.5%). However, the results showed that the method can be a good approach, when the thermal properties of the different materials employed in the construction solution are not known *a priori*. The authors highlighted that the methodology was tested only for walls with low thermal resistance and medium inertia. Therefore, more tests should be performed to extend the methodology to other sorts of walls. In another study, Sala *et al.* [135] used the same GHB apparatus to perform static and dynamic tests for the thermal characterization of a L200 × H200 cm wall of three layers: a 1 cm-thick gypsum layer on the inner side, a hollow brick layer of 4 cm, and a 3 cm insulation layer on the outer side. A numerical study was also carried out to obtain the thermal performance of the wall in stationary and dynamic conditions. The main goal of these authors was to evaluate the error introduced by assuming an heterogeneous layer of the wall as an equivalent homogeneous layer. The results showed that the errors can be significant, even when the heterogeneities are not excessive. Finally, Martín *et al.* [136] used the GHB apparatus of the previous studies to evaluate the behavior of a reinforced concrete pillar thermal bridge in both steady-state and dynamic conditions. The authors remarked that there is a great uncertainty about the dynamic behavior of thermal bridges. In fact, this research gap was also pointed out by Ascione *et al.* [137]. In this context, O’Grady *et al.* [80] proposed a new non-invasive and easy-to-use IRT methodology for the *in-situ* assessment of the heat loss through a thermal bridge – a concrete column in a brick wall. The methodology was tested under laboratory steady-state conditions in a HB apparatus. More studies have used GHB measurements to evaluate the thermal performance of different construction elements, *e.g.*, block and brick cavity walls with variable aspect ratio of the cavity [138], and lime/cement stabilized hollow and plain earth blocks [139].

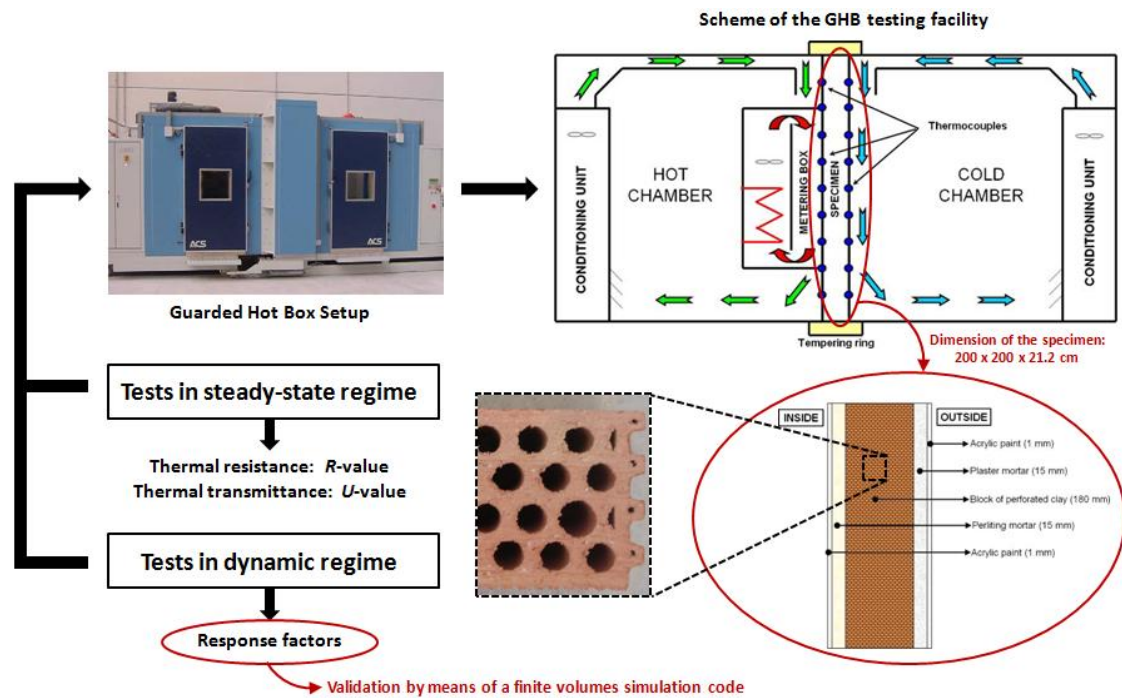


Figure 9 – Methodology proposed by Martín *et al.* [134] for the thermal characterization of low thermal resistance and medium inertia walls under steady-state and dynamic conditions using the GHB apparatus. Figure adapted from ref. [134].

Kus *et al.* [140] evaluated the hygrothermal performance of a pumice aggregate concrete hollow blocks wall (L120 × H240 × W19 cm) using a CHB apparatus. The authors concluded that the heterogeneous nature and the rough surface characteristics of the blocks, plus the wet construction type of block, are the most problematic features that make measurements and evaluation difficult. Özdeniz [141] investigated the hygrothermal behavior of new briquette (concrete block with pumice as aggregate) walls, both theoretically and experimentally. The proposed briquette wall employs the ventilated cavity wall principle. HB measurements were conducted on different assemblies of both newly-designed and regular briquette walls. The author concluded that the perlite filled pumice concrete briquette wall has the best performance, among the tested walls. As stated by Thorsell and Bomberg [142], hygrothermal models are very important to evaluate the effects of climate, moisture and air movement on the thermal performance of assemblies. However, in another study [143], the authors added that experimental tests are typically performed on dry materials, without considering the air and moisture movements, which can mishmash the results achieved from experimental and numerical models. In this context, the authors proposed an integrated methodology that combines CHB measurements and computer simulation to evaluate the thermal performance of different walls considering the features listed above [142][143].

Further studies to assess the thermal performance of hollow concrete blocks [144] and perforated porous clay bricks [145] walls were carried out, in which CHB measurements were used to validate numerical models. Jeong *et al.* [146] have also used CHB tests to evaluate the thermal transmittance of large-scale thermally-enhanced concrete specimens (L150 × H150 × W22 cm).

Donatelli *et al.* [147] developed an experimental procedure based on IRT measurements for the evaluation of the thermal transmittance of opaque construction elements. The main goal of this study was to provide an alternative solution to the HFM method in order to overcome some restrictions of the method, such as the long measuring periods, the dependence on weather conditions and the great difference between internal and external surface temperatures of the tested walls. The proposed IRT method was applied on two lab-made hollow brick based walls (L100 × H100 × W10 cm). The results showed discrepancies with theoretical U -values determined in accordance with the ISO 6946 standard procedure of about -3.5 to 2.9%. Nardi *et al.* [148] presented an up to date survey on quantitative IRT approaches for the assessment of the U -value of opaque construction elements. The authors have also carried out a quantitative IRT study to assess the validity of four different IRT methods by applying different operative conditions in a GHB controlled environment. The methods proposed by Madding [149], Fokaides and Kalogirou [77], Dall'O' *et al.* [150] and Albatici *et al.* [102] were compared in the study, considering a multilayered wall (L300 × H300 × W28 cm) built to reproduce a typical external envelope of the 1970s Italian building stock. The IRT based results were then compared with the ones obtained by HFM measurements and theoretical calculations. Simões *et al.* [151] also compared three different IRT methods to evaluate the U -value of four homogeneous building elements (medium-density fiberboard, extruded polystyrene, natural cork, and cement bonded particle board): the methods proposed by Fokaides and Kalogirou [77], Albaciti and Tonelli [101] and Vollmer and Möllmann [152]. According to this work, the method that provides the most reliable results is the one proposed by Fokaides and Kalogirou [77].

Ruuska *et al.* [153] carried out a study to determine the thermal conductivity and the specific heat capacity of two concrete types, and the specific heat capacity of 14 plasters, through the HFM method. The FOX 50 HFM (by LaserComp, Inc) that runs on WinTherm50 software was used for the measurements. It should be remarked that the specimen size of this particular apparatus is pretty small, from 50 to 61 mm in diameter and 0-25 mm thick [153]. The results achieved were in accordance with published values and theory, which shows that this HFM apparatus can be used to determine the specific heat capacity of inhomogeneous materials. The authors also recommended that the best way to measure the thermal

conductivity of inhomogeneous materials is to use both rubber sheets and thermocouples because it is a good way to eliminate errors caused by air caps and poor contact between the surfaces of the specimens and the apparatus's plates.

Manzan *et al.* [154][155] developed a combined experimental and numerical approach to evaluate the thermal performance of different interior-side insulation methodologies that can be used for the refurbishment of historical buildings. The authors concluded that the effect of structural elements employed to fix the insulation layers to existing walls must be considered when evaluating the thermal conductance of the wall, mainly when these elements are made of steel.

3.2. Lightweight construction - LSF assemblies

Generally speaking, LSF is a dry construction system consisting of three main types of materials that are used in walls and slabs: cold-formed steel studs for load bearing, interior and exterior sheathing panels and insulation materials. Soares *et al.* [156] provided an extensive review on this type of construction, pointing out the main features related with its energy efficiency and thermal performance. Regarding thermal behavior, LSF elements are typically classified according to the location of the thermal insulation layers as cold frame (the thermal insulation is placed inside the wall between the steel studs), hybrid (the thermal insulation is distributed between the external surface and the wall gap between steel studs), and warm frame construction (all thermal insulation is placed outside the steel framing on the external surface).

As suggested by Soares *et al.* [156], LSF construction can play an important role in the development of a more sustainable built environment as it shows great potential for recycling and reuse, lower water consumption, high architectural flexibility for retrofitting purposes, high seismic performance, easy prefabrication allowing modular construction, small weight, economy in transportation and handling, reduced disruption onsite and speed of construction. However, the high thermal conductivity of the metal structure can lead to significant thermal bridges, which can affect the thermal performance of LSF assemblies. Moreover, the steel skeleton crossing insulation layers make the prediction of the thermal performance of the LSF assemblies difficult during the design phase and during the dynamic simulation of the energy in buildings. In addition, the *in-situ* measurement of the overall thermal transmittance of LSF walls is very challenging due to the presence of non-homogeneous layers and thermal bridges. However, the *in-situ* characterization is very important for the post-evaluation of the thermal performance of LSF assemblies, and for energy audit. At this point, it should be reminded that the existing standardized methods described in standards ISO 9869-1 [17] and ASTM C1155

[22] for the *in-situ* measurement of the overall thermal transmittance of construction elements only concern homogeneous walls. In fact, a standardized method for the *in-situ* measurement of the U -value of existing LSF walls is still missing. Regarding laboratory conditions, the ISO 8990 [52] and the ASTM C1363 [56] can be used for the experimental assessment of the overall thermal transmittance of LSF walls using the HB apparatus. For the calculation of the overall thermal transmittance of construction elements, the ISO 6946 [8] is only applicable for construction elements with thermally homogeneous layers. In fact, this analytical method is not applicable for many LSF elements (other than full warm frame construction) in which insulation layers are bridged by metallic elements. In recent years, many studies have been carried out in the scope of the experimental calculation of the U -value of LSF walls in laboratory conditions combined with analytical and numerical simulations. Few studies were however devoted to the development of new *in-situ* measurements.

One of the first methods to determine the theoretical U -value of walls with cold-formed steel profiles was the ASHRAE *zone method* [157]. This method allows calculating the R -value of walls with cross-section high thermal conductivity elements (such as steel profiles). This methodology is a modification of the *parallel path method*, in which the wall is divided into several parallel paths with different thermal resistances. However, the ASHRAE *zone method* can only be applied to walls and slabs with metallic profiles assembled in one direction, and it cannot be applied in situations where steel profiles are perpendicular to each other. Based on the ASHRAE *zone method*, Kosny *et al.* [158] developed the *modified zone method* for metal stud walls with insulated cavities, which differs from the previous approach in the way that the zone of influence of the metal stud thermal bridging is estimated, leading to more reliable results. In the *modified zone method*, the zone width depends on the following three parameters: the ratio between the thermal resistivity of sheathing material and cavity insulation, the size (depth) of the stud, and the thickness of the sheathing material.

Gorgolewski [159] suggested a simplified method to estimate the theoretical U -value of cold and hybrid LSF assemblies. This method is an adaptation of the approach established in ISO 6946 [8] that includes various additional parameters (*e.g.*, flange width, stud spacing and depth) to account for the overall thermal behavior of the steel-framed element. As shown by the author, with this method, the mean error of prediction (compared with finite-element numerical modeling) is less than 3% with a maximum error of 8% for a range of 52 constructions assessed [159]. Additional details about this method can be found in ref. [160], including some examples regarding the calculation of U -values of hybrid and cold frame LSF assemblies. The methodology proposed by Gorgolewski [159] was used in several studies to estimate the thermal behavior of LSF assemblies, which is required to evaluate the overall

thermal behavior of LSF buildings [4][161]. For example, Soares *et al.* [161] proposed a multi-dimensional optimization model combining EnergyPlus and GenOpt tools for the annual optimization of the incorporation of PCM-drywalls in air-conditioned LSF residential buildings in different European climates. In another study, Rodrigues *et al.* [4] proposed an integrated energy performance-driven generative design methodology to foster modular LSF residential buildings in hot climates.

Many research works have been carried out to find some ways to reduce or avoid thermal bridges in LSF buildings, and to improve the thermal performance of LSF assemblies. In this context, the following design strategies can be listed according to refs. [156][162][163]: (i) keeping the facade geometry as simple as possible; (ii) avoiding interruption of the insulation layer and placing a continuous insulation layer on the external side of the steel framing; (iii) using materials with the lowest thermal conductivity possible where the interruption of the insulation layer is unavoidable; (iv) attaching the studs to the external insulation layer using fixings with low thermal conductivity; (v) attaching the insulation layers to the overall width, at the joints of building elements; (vi) installing doors and windows in contact with the insulation layer. Martins *et al.* [24] studied several strategies for the mitigation of thermal bridges and they presented the following guidelines: (i) introducing at least one-third of continuous thermal insulation; (ii) if the previous condition is verified, then some mitigation strategies could be very much reduced or even irrelevant (*e.g.*, male or female studs, thin rubber strips, fixing bolts instead of steel plate connections and slotted steel profiles); (iii) when selecting or designing thermal profiles, choose the ones with higher number of narrow slots since they are more efficient than the ones with larger slots; (iv) whenever possible, try to use two layers of perpendicular steel studs, avoiding trespassing the entire wall cross-section with two parallel steel profiles. Kosny and Christian [164] also showed that the use of continuous external thermal insulation is an efficient way to improve the thermal performance of LSF walls. Moreover, they showed that increasing the space between the steel profiles allows increasing the thermal resistance of the walls. Höglund and Burstrand [165] studied an efficient way to reduce the heat flux through the wall by increasing the heat flux path and decreasing the area of the steel profile (by inserting grooves in the profile web). A similar study was carried out by Blomberg and Claesson [166], who have also concluded that one of the most effective strategies to reduce heat flux is to use perforated steel profiles. The study showed that: (i) the thickness of a standard steel profile has to decrease sixfold to achieve the equivalent thermal properties of a metal profile with slots; (ii) the heat flux through a steel profile decreases as the number of slots increases.

Zalewski *et al.* [167] proposed a 3D numerical method for the assessment of the effect of thermal bridges in prefabricated lightweight building walls with a steel framework. The numerical method was validated using experimental results carried out in a controlled laboratory environment as shown in Figure 10. In the first part of the study, the authors used IRT for the qualitative assessment of the thermal behavior of the sample, *i.e.*, to visualize thermal bridges. Then, surface temperature measurements with thermocouples were compared with those provided by IRT to evaluate the evolution of the outside surface temperature during the experiment. In the second part of the study the authors used local and non-destructive heat flux measurements to show the importance of thermal bridges in the thermal performance of the wall. At the end, the experimental results were used to validate the simulation model. Kosny *et al.* [158] used the CHB apparatus to measure the thermal performance of 23 steel-framed wall samples, considering a set of stud frame configurations, insulation sheathing and fiberglass batt insulations. The experimental results were compared to the R -value estimated using the *parallel path method*, the *isothermal planes method* and the ASHRAE *zone method*, showing that these methods do not fully account for the 3D effects created by steel framing, often underestimating the R -value of the walls when insulation sheathing is used. Mayer *et al.* [168] used the GHB apparatus to evaluate the thermal performance of different wall assemblies and to provide experimental results to validate a developed 3D finite-element analysis thermal modeling approach. Other studies that have highlighted the potential of the GHB apparatus to estimate the overall thermal transmittance of LSF assemblies can be found in literature, for instance, the works carried out by Soret *et al.* [169] and Amundarain [170]. The IRT method described by O'Grady *et al.* [80] can also be used for the U -value measurement of LSF walls.

In a recent paper, Atsonios *et al.* [171] have proposed two new methods for the *in-situ* measurement of the overall thermal transmittance of existing cold frame LSF walls, which take into account the effect of thermal bridging due to the metal structure: the *representative points method (RPM)* and the *weighted area method (WAM)*. The first method considers that the heat flow on specific points at the internal surface of the wall is always equal to the averaged heat flow of the whole surface. The *WAM* method is based on the *zone method* concept. According to the authors, the two methods comprise five general steps: (i) IRT of the internal surface of the wall; (ii) assessment of IR images to estimate the temperature profile; (iii) analysis of temperature profile according to each method; (iv) recording of outdoor/indoor air temperature and heat flux values at the locations which are indicated by each method; and (v) calculation of the overall thermal transmittance of the wall. The methods were numerically validated for both cold frame and hybrid LSF walls, and experimentally

validated on a well-known cold frame LSF wall. The numerical results showed that the methods can be applied to both typologies of LSF walls. Moreover, the results based on the *in-situ* measurements were in good agreement with the theoretical results obtained according to ISO 10211 [9].

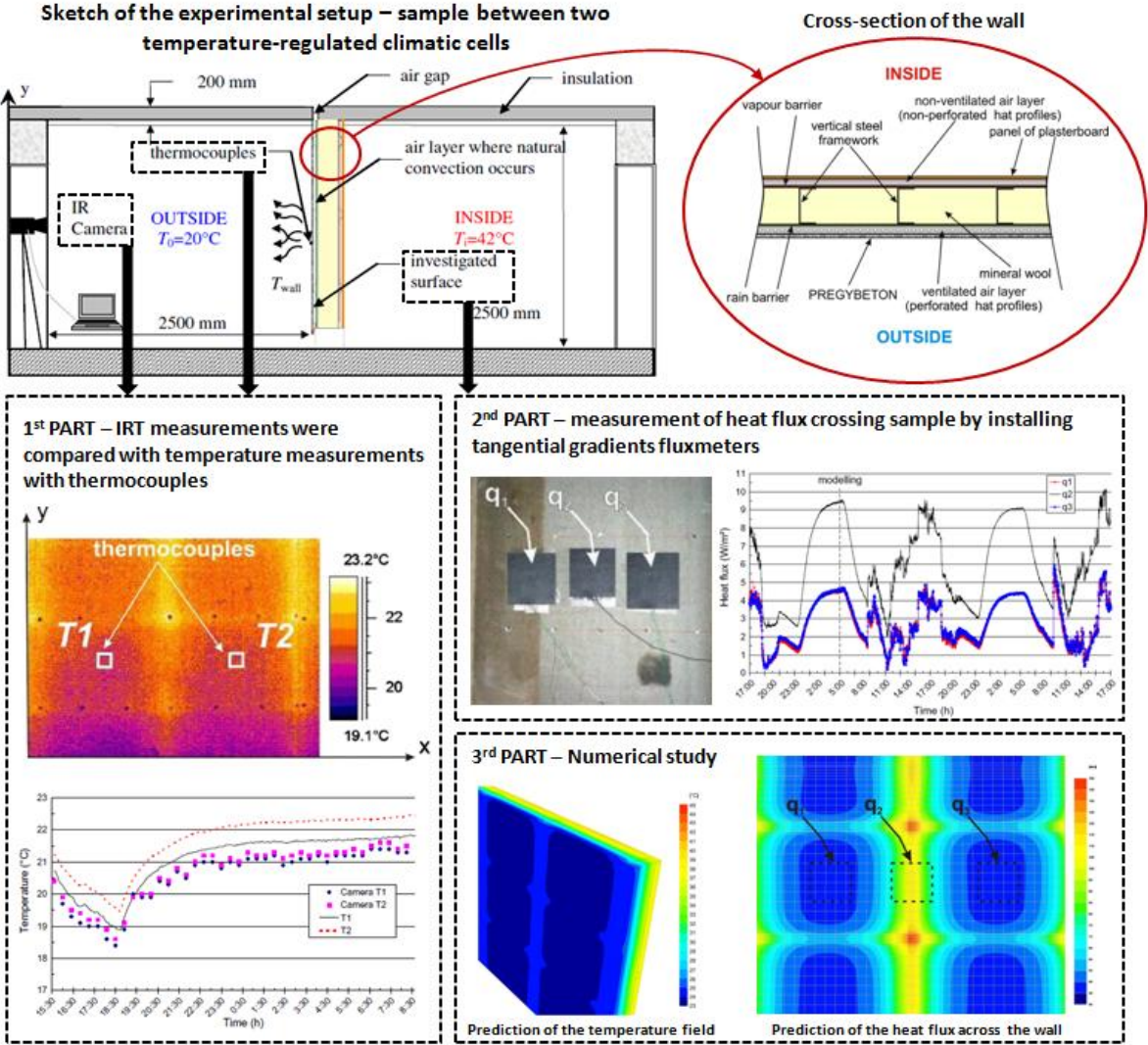


Figure 10 – Methodology proposed by Zalewski *et al.* [167] for the experimental and numerical characterization of thermal bridges in a prefabricated lightweight building wall with a steel framework. Figure adapted from ref. [167].

Yao *et al.* [172] carried out an experimental and numerical study to evaluate the thermal performance of a lightweight steel-bamboo wall. A testing room was built using this new LSF assembly and *in-situ* measurements were performed to determine the heat transfer coefficient, time lag and decrement factor of the wall. The behavior of two commonly used walls was taken for comparison purposes: a reinforced concrete wall and an aerated concrete blocks wall. The experimental apparatus was a combination of the HFM and HB methods, in

order to take advantage of the two methods and to overcome some of their drawbacks – the HFM should not be used in summer conditions; dynamic data analysis requires long-period measurements and complex calculations; the HB procedure is not suitable for in field measurements. Surface temperature sensors and heat flow meters were used to record internal and external surface temperatures and the average heat flux through the wall. These values were then used to estimate the U -value of the wall. The results showed that the steel-bamboo wall has a high thermal performance with an improvement of the U -value by up to 26.1-48.4% in comparison to the other two walls.

3.3. New or non-conventional insulation materials

The use of new and more efficient insulation materials can improve the thermal performance of construction elements, dealing with lower thicknesses of the insulation layers [156]. Aerogel insulation blankets may be seen as one of the most promising thermal insulation materials as they have a thermal conductivity 2 to 2.5 times lower than that of conventional mineral wool [173]. Lakatos [174] used different methods for the experimental evaluation of the thermal transmittance of walls with an opaque aerogel insulation layer. A Holometrix type HFM was used to measure the thermal conductivity of insulation materials with different thicknesses. Then, two different steady-state methods were used for measuring the thermal resistance of walls: the calibrated chamber method and heat flux measurements by Hukseflux apparatus. The authors have also used IRT to visualize the impact of adding aerogel. The results showed that by using a 0.013 m thick opaque aerogel insulation layer on a 0.25 m brick wall, the retardation time can be increased from 13 to 17 h. Wakili *et al.* [175] evaluated the potential of aerogel for retrofitting purposes. The authors carried out *in-situ* measurement of the U -value of a retrofitted stone wall of a building situated in the city of Zurich, Switzerland, dating from 1877. IRT was also performed during the cold weather period, when there was a large temperature difference between indoor and outdoor environments. The results showed that thin additional insulation layers can be added to the existing external wall to improve the overall thermal performance of the wall without changing the overall appearance of the building. Walker and Pavía [176] evaluated the *in-situ* thermal performance of seven internal insulation alternatives on a historic brick wall with a traditional lime plaster finish, using heat flux sensors for U -value measurement, thermal imaging survey and monitoring of internal wall temperature. The thermal insulation options evaluated were: aerogel, thermal paint, cork lime, hemp lime, calcium silicate board, timber fiber board and PIR board. The results showed that all these internal insulations can be used to reduce the U -value of the wall (between 34–61%) with the exception of a thermal paint which had no

effect. Aerogel also showed good potential for insulating historic structures as its thickness is almost half the other insulation materials, thus minimizing the adverse visual impact of insulating historic buildings.

Another promising insulation technology is the use of vacuum insulation panels (VIPs), which have a thermal resistance 5 to 8 times higher than other conventional insulation materials [177]. In the study conducted by Wakili *et al.* [178], the GHP method was used to determine the thermal conductivity at the centre-of-panel and the edge effect, *i.e.*, the linear thermal transmittance due to the thermal conductivity of the barrier envelope. The results showed that VIPs with a low perimeter-to-surface ratio have a lower effective thermal conductivity. Nussbaumer *et al.* [179] studied the behavior of a system of VIPs embedded in an expanded polystyrene foam forming insulation boards mounted on a concrete wall. The thermal transmittance measurements were carried out using a GHB apparatus and IRT was used as an inspecting tool to recognize damaged VIPs in winter conditions. Capozzoli *et al.* [180] evaluated the equivalent thermal conductivity of VIPs and their performance degradation caused by vacuum loss. The guarded heat flux meter apparatus was used for the experiments. Baldwin *et al.* [181] used a GHB apparatus to determine the effective thermal resistance of a wall assembly incorporating VIPs. The authors pointed out that this method allows a more accurate representation of all thermal bridges, including those between panels. Mandilaras *et al.* [182] carried out a comparative study of conventional and VIP based ETICS utilizing both experimental and theoretical/numerical techniques. A mockup two-storey LSF building located in Athens, Greece, was considered in the experiments. A drywall construction envelope based on a cavity wall system incorporating ETICS was also considered. Two types of ETICS were installed on the walls of the mockup: a conventional system using EPS as insulation material and a VIP system incorporating a composite insulation component consisting of two layers of mineral wool and one layer of VIP. The results showed that the thermal resistance of the VIP wall was 123% higher than the thermal resistance of the EPS wall. They also showed that there was a significant difference between the anticipated and the achieved thermal performance of the VIP ETICS as the *in-situ* measurements of thermal resistance were considerably lower than expected.

Some non-conventional insulation materials that show low environmental impact can also be found in literature. Mavromatidis *et al.* [183] experimentally evaluated the thermal behavior of two different multilayer fibrous insulations for building applications. A GHB apparatus was used to measure the heat transfer through the samples. Afterwards, the experimental results were used for numerical validation purposes. Ye *et al.* [184] have also used a GHB apparatus to measure the thermal resistance of sheep-wool insulation and wool-

hemp mixtures, both in the form of bonded insulation batts. Shea *et al.* [185] claimed that the presentation of robust data regarding the main thermal properties of straw bales are very important for the development of projects employing this natural fiber insulation material. The authors carried out an experimental study to evaluate the thermal performance of an innovative prefabricated natural plant fiber building system. The FOX 800 HFM was used to evaluate the thermal conductivity of straw bales of different densities. The thermal transmittance of a prefabricated straw-bale panel was also evaluated using a GHB apparatus. At the end, an IRT survey was undertaken on a prototype straw-bale house to identify thermal anomalies, thermal bridging, air infiltration and other weaknesses in the building fabric.

In a recent paper, Lee *et al.* [186] provided an overall survey on reflective thermal insulation systems with radiant barriers and reflective insulations. The authors stated that although many studies have been carried out on reflective insulation, there are still uncertainties in predicting the correct thermal resistance improvement due to the application of these materials. For these authors, the most commonly used method to measure the thermal resistance value is the GHB apparatus, which can simulate large-scale assemblies that are closer to real conditions. The HFM method can be used to test smaller specimens. Escudero *et al.* [187] carried out an experimental study to evaluate the thermal resistance of radiant barriers for building insulation. The HFM method was used to characterize the insulation layer itself, while the GHB was used to determine the total thermal resistance of a building component including a radiant barrier.

3.4. Window systems

Smith *et al.* [188] used a GHB apparatus to evaluate the thermal performance of secondary glazing as a retrofit alternative for single-glazed windows. The authors evaluated the thermal transmittance of four secondary glazing products: plastic film, magnetically attached plastic sheet, plain and low-e glass. The results showed that the thermal resistance of the windows with secondary glazing was 130 to 290% better than the R -value of the base window. Cox-Smith [189] has also proposed a method for measuring the thermal resistance of fenestration products such as windows and doors using a GHB apparatus. Appelfeld and Svendsen [190] carried out tests to determine the thermal transmittance of ventilated windows by using a GHB setup. Basak *et al.* [191] used a GHB facility to measure the overall heat transfer coefficient of different building material samples. The authors evaluated and compared the overall system performances for a fuzzy logic based temperature control scheme in the GHB using three types of test specimens: a single glazing, a double glazing and a plank of extruded polystyrene. It was concluded that the fuzzy logic based temperature strategy was capable of

controlling the temperature of the metering box as well as the guard box with the desired level of accuracy. Klems [192] used a CHB apparatus for measurements on prototype high-performance windows. A calorimetric HB facility proposed by Lechowska *et al.* [193] was used to measure the thermal transmittance of a multi-layer glazing with ultrathin internal glass partitions. Several authors have also used GHB facilities to measure the thermal performance of vacuum glazing systems [194][195][196].

3.5. PCM-enhanced elements

PCMs undergo melting and solidification at a nearly constant temperature, becoming very suitable for thermal management and thermal energy storage applications. As reviewed by Soares *et al.* [197], a huge number of studies have been developed to improve the thermal performance of building envelope solutions by including PCMs in their configurations. However, the prediction and measurement of the overall thermal transmittance of non-homogeneous assemblies incorporating PCMs is still very challenging. This is mainly caused by the intrinsic physics of these materials (namely the variation of the main thermophysical properties with temperature), and the non-linear nature of the phenomenon, *i.e.*, the presence of different stages during a complete phase change cycle – solid, liquid and mushy zone phases. The experimental methods to measure the U -value of construction elements are typically based on reaching steady-state conditions. Therefore, the overall thermal transmittance of construction elements with PCMs cannot be measured during phase change processes, as heat is absorbed or released by the PCM (the material acts like an "energy source" or an "energy sink"). It can only be measured somehow when the PCM is completely melted or solidified. At these stages, PCMs can be treated as "normal" materials, with known thermophysical properties. The development of experimental approaches and standard procedures to measure the overall thermal transmittance of real-scale PCM-enhanced elements in conditions similar to those experimented in real buildings is extremely challenging and it can be seen as a hot research area for the next decade.

As pointed out by Cabeza *et al.* [198], the appropriate characterization of the PCM itself is essential to foster the technology, but it is not always possible to carry it out with conventional equipment, mainly due to the size of the samples. In this context, the authors provided an extensive survey on the main unconventional experimental technologies available for the characterization of the main thermophysical properties of PCMs. Dutil *et al.* [199] have also highlighted the importance of the characterization of PCMs for model validation purposes. In addition, they stated that it is unclear whether the measurements of the thermophysical properties of PCMs done on small samples are representative of the

macroscopic thermal behavior of the final building application. Several studies have been carried out to evaluate the thermal performance of PCM-enhanced elements by considering different scales of the samples. For instance, a transient GHP method based on heat flux and temperature measurements was used by Lachheb *et al.* [200] for the experimental assessment of the thermal behavior of a plaster composite containing a microencapsulated PCM. Amaral *et al.* [201] evaluated the thermal conductivity of rigid polyurethane (RPU) foams, with and without PCMs, based on steady-state and transient methods (Figure 11). Three different approaches were used: the transient plane source approach (small-scale specimen), the guarded hot plate (middle-scale specimen), and the heat flux meter method in a HB setup (large-scale specimen). Shukla *et al.* [202] proposed a novel dynamic HFM apparatus to measure the dynamic thermal properties of a PCM impregnated gypsum board. The results were later compared to those obtained through differential scanning calorimeter (DSC) measurements. Kosny *et al.* [203] have also used a dynamic HFM apparatus for the thermal performance analysis of fiber insulations containing bio-based PCMs. Additionally, a HFM apparatus operating in dynamic mode was used by Mandilaras *et al.* [204] for the determination of the effective heat capacity of PCM-enhanced building components. Finally, Principi and Fioretti [205] carried out an experimental study based on the HFM method to evaluate the improvement of the thermal performance of hollow bricks through the insertion of a PCM inside the enclosures of the bricks. Silva *et al.* [206] and Vicente and Silva [207] have also experimentally evaluated the thermal behavior of PCM-enhanced brick masonry walls.

Few studies using the HB method for measuring the thermal performance of PCM-enhanced assemblies are found in literature. Indeed, further work has to be developed in the future to establish reliable dynamic methods to measure the overall thermal transmittance of non-homogeneous assemblies with PCMs. In literature, there is also a lack of reliable large-scale experimental results that can be used for validating numerical simulation approaches. Figure 12 shows a sketch of the methodology proposed by Cao *et al.* [208] to evaluate the impact of a PCM-enhanced wall on the indoor air and wall temperature using the GHB apparatus. The results showed that the inclusion of the PCM layer in the wall reduces the interior air and wall temperatures up to 2 °C in comparison to the wall without PCM.

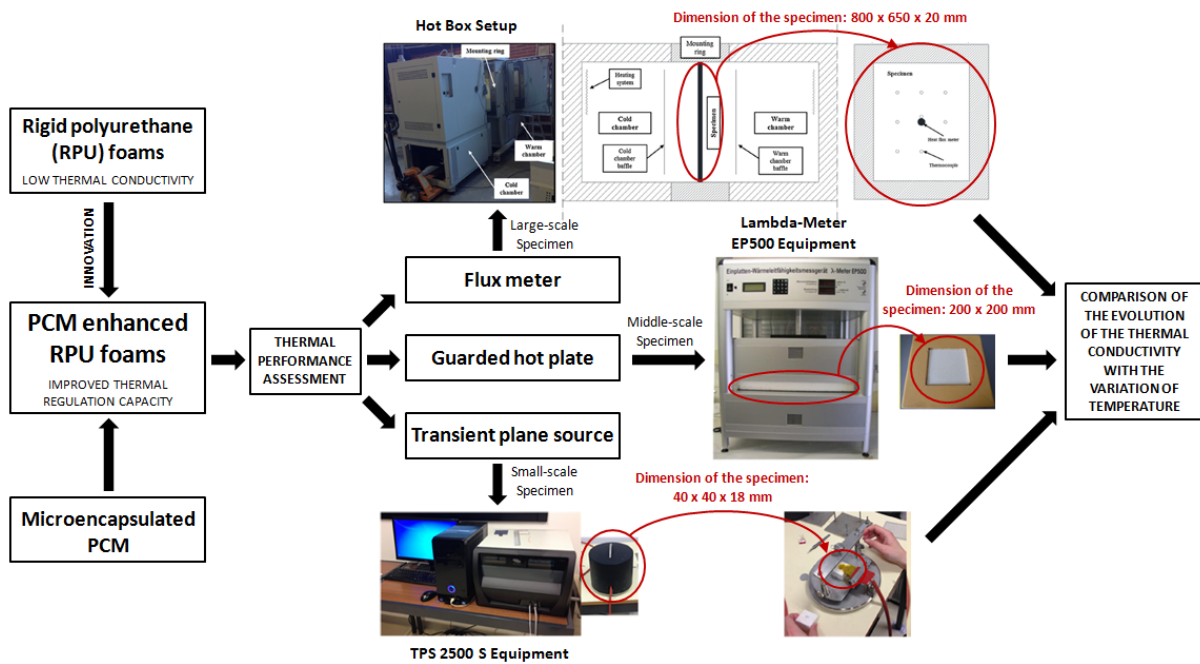


Figure 11 – Methodology proposed by Amaral *et al.* [201] for the experimental evaluation of the thermal conductivity of RPU foams with and without the incorporation of PCMs based on steady-state and transient methods. Figure adapted from ref. [201].

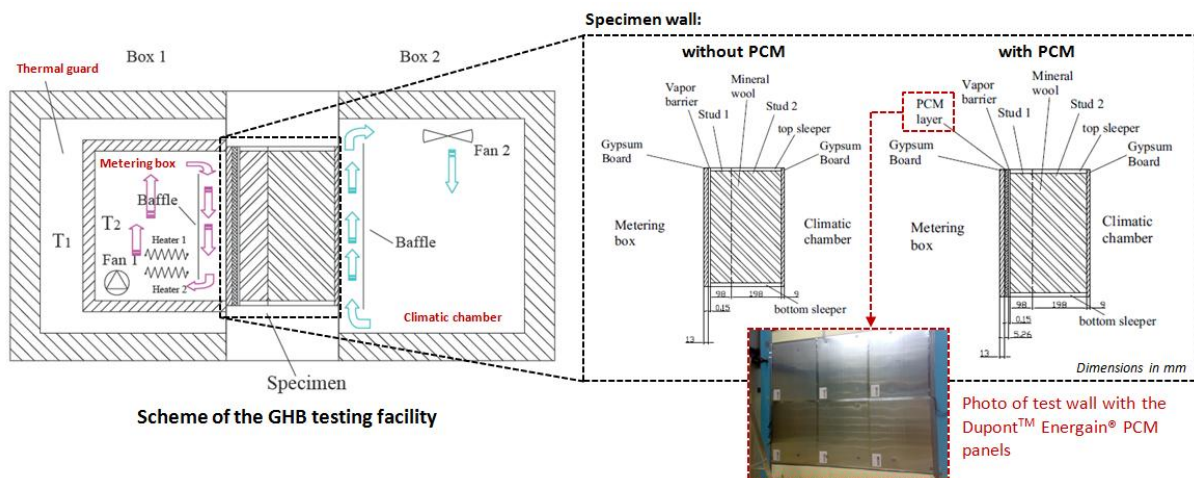


Figure 12 – Methodology proposed by Cao *et al.* [208] to evaluate the impact of a PCM-enhanced wall on the indoor air and wall temperature using the GHB apparatus. Figure adapted from ref. [208].

4. CONCLUSIONS

This paper provides an extensive survey on the main methods to measure the overall thermal transmittance and the thermal behavior of non-homogeneous and moderately-homogeneous walls, windows and construction elements with innovative materials, considering laboratory conditions and *in-situ* non-destructive measurements. The following established methods

were reviewed: the heat flow meter (HFM); the guarded hot plate (GHP); the hot box (HB), considering the guarded HB (GHB) and the calibrated HB (CHB); and the infrared thermography (IRT). In the first part of the paper, a standards-based framework was provided, and the main advantages and drawbacks of the listed methods were described. In the second part, previous studies dedicated to the assessment of the thermal performance of different construction elements (heavyweight construction systems, LSF assemblies, new insulation materials, window systems and PCM-enhanced elements) were discussed. The presented studies have used some of the methods listed above, individually or in combination with each other. In fact, in many studies, some methods were considered together in order to perform comparison analyses between results obtained by different experimental methodologies and to compare experimental measurements with standard and analytical procedures. The main conclusions of this review article are:

- The right estimation of the U -value of building elements can support decision making during design, construction, energy audit and refurbishment processes;
- The *in-situ* characterization of the U -value of construction elements using quantitative IRT is an active area of research, but further research is required to quantify the influence of several parameters on the thermal performance analysis, such as emissivity, surface heat transfer coefficients, air velocity, the presence of thermal bridges and materials with different thermophysical properties, etc., in a way that this technique can be used for all sorts of construction elements (*e.g.*, historic masonries, LSF elements, high-insulated walls, PCM-enhanced elements, etc.). Moreover, the majority of studies found in literature refers to homogeneous or moderately-homogeneous walls, and more research should be carried out to provide reliable methodologies that use quantitative IRT for the measurement of the thermal transmittance of non-homogeneous construction elements. In the meanwhile, qualitative IRT can support the HFM measurements concerning the qualitative assessment of the building elements.
- The *in-situ* measurement of the overall thermal transmittance of LSF walls, including the effect of thermal bridging due to metal structure, is very important for designers, engineers and energy audit. However, there is still a great uncertainty about the dynamic behavior of thermal bridges and further efforts should be devoted to develop new methodologies for the laboratory and *in-situ* measurement of the influence of thermal bridges in the overall thermal transmittance of building envelop elements. The

experimental approaches can then be used to provide reliable experimental results for numerical simulation validation purposes;

- More studies should be carried out for the development of new experimental approaches for the accurate estimation of the convective and radiative heat transfer components in thermal transmittance measurements, mainly when only air and surface temperature probes are used;
- More controlled experimental studies should be developed to evaluate the hygrothermal performance of building elements considering the effects of climate, moisture and air movement on the thermal performance of assemblies. The results of these studies can then be used for validating numerical approaches;
- The *in-situ* characterization of the overall thermal transmittance of historic masonries can provide important information for energy audit and for setting reliable databases on thermal performance of traditional masonries;
- The development of full-scale experimental apparatus to evaluate the overall thermal transmittance of new insulation materials is very important to foster new technologies and to provide reliable experimental results for numerical simulation validation purposes;
- The measurement of the overall U -value of non-homogeneous window systems is fundamental for labeling purposes and to understand the thermal behavior of these systems, providing important information for the dynamic simulation of energy in buildings, and to foster new technologies;
- The measurement of the overall thermal transmittance of non-homogeneous assemblies incorporating PCMs is very challenging due to the variation of the main thermophysical properties of PCMs with temperature and the non-linear nature of the phase-change processes. The development of experimental dynamic approaches and standard procedures to measure the overall thermal transmittance of real-scale PCM-enhanced elements in conditions similar to those experimented in real applications is extremely challenging and it can be seen as a hot research area for the next decade.

Acknowledgments

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