Review of in situ methods for assessing the thermal transmittance of walls

Abstract

Reducing the energy requirements of buildings is essential in order to address anthropogenic global warming. Among the various factors affecting the energy requirements of buildings, the thermal transmittance of the walls is critical in understanding heat loss. It is therefore necessary to assess the thermal transmittances carefully in order to develop effective means of energy conservation. Although various theoretical methods and methods using in situ measurements are available for this purpose, the correct use of such methods depends on many factors. In a detailed review of more than 150 publications (scientific papers, congress reports, books, and other documents), the best-developed methods in use by researchers and professionals are analysed. These methods involve theoretical estimation, heat-flow meters including a simple hot-box heat-flow meter, thermometric methods, and quantitative infrared thermography. This review is intended to be a useful resource for researchers and professionals in that it covers the fundamental theoretical background, the equipment and material required for in situ measurements, the criteria for installing the equipment, the errors caused by metrological and environmental aspects, data acquisition, data processing, and data analysis.

Keywords

Thermal transmittance (*U*-value); walls; theoretical estimation method; heat-flow-meter method (HFM); simple hot-box heat-flow meter method (SHB-HFM); thermometric method (THM); quantitative infrared thermography method (QIRT).

1. Introduction

Concerns about environmental degradation and anthropogenic global warming have increased over the past few decades. The European Union recently set a goal of decreasing greenhouse gas emissions by 80% compared with 1990 emissions by the year 2050 [1]. To achieve this, the building sector needs to decrease its greenhouse gas emissions by 90% [1]. The energy demands of existing buildings are important components of the total energy consumption [2–4]. Heating constitutes the main energy use in buildings, and generates 40% of their total greenhouse gas emissions [5–7].

The thermal properties of the envelope of a building strongly affect its annual energy requirement [8–10]. More energy is lost through the walls than through other parts of the envelope [11–13] because the walls have the largest surface area in contact with the exterior environment [14]. The thermal transmittances of the walls are the most important thermophysical properties affecting the energy performance of a building [15,16] because they control heat losses to and gains from the exterior environment, and the energy requirements of the heating, ventilation, and air conditioning system [17–19]. Thermal transmittance (also called the overall heat transfer coefficient or *U*-value, in units $W/(m^2·K)$) is the heat flow rate at steady state divided by the area of the wall and by the difference in temperature between the two sides of it [20]. Applying energy conservation measures to improve the *U*-values of the walls of a building (i.e., to decrease the heat transfer rate between the interior and the exterior environments) is the most effective means of decreasing the energy requirements of a building [21].

It is imperative to determine the *U*-values of the walls of a building when performing an energy audit. However, *U*-values are usually overestimated [22], meaning the energy requirements of the building being assessed will also be overestimated [14,23]. Use of incorrect *U*-values may preclude interventions in a building with an inadequate energy performance [24,25] or cause unnecessary (and costly) energy conservation measures to be applied [26].

Thermal transmittance can be determined using various methods, and it is necessary to understand the requirements, advantages, and limitations of each. The determination of thermal transmittance has been discussed to some extent in previous reviews. Bagavathiappan et al. [27], Kylili et al. [28], and Lucchi [29] published reviews of infrared thermography applications in all engineering fields. However, these reviews were generic, so determination of *U*-values was not examined in sufficient detail, and other methods of assessing thermal transmittance were not discussed. Bagheri et al. [30] described the use of thermal networks to assess energy flux in buildings in which thermal transmittances had been determined. Sun et al. [31] reviewed experimental methods for determining variables (including the *U*-value) affecting the optical and thermal performances of windows, and Schiavoni et al. [32] reviewed the thermophysical properties of more than 30 insulating materials. However, in situ methods of determining the thermal transmittances of walls have not received the same attention. Many articles on the thermal transmittance of walls have recently been published, it therefore seems appropriate to undertake a critical review of published work on the determination of *U*-values for building envelopes. This information could be useful to practitioners performing energy audits and to researchers seeking up-to-date knowledge. This review is focused on methods of assessing the thermal transmittance of walls because, as mentioned above, the energy requirements of a building are affected by the walls more than they are by other parts of the building envelope [11–13,33–35].

The methods reviewed here were selected from many published methods, focusing particularly on those most widely used. These methods (see Fig. 1) are (i) the theoretical estimation method (ISO 6946 [36]), (ii) the heat-flow-meter method (HFM) (ISO 9869-1 [37]), (iii) the simple-hot-box HFM (SHB-HFM) [38,39], (iv) the thermometric method (THM) [40–43], and (v) quantitative infrared thermography (QIRT) [44–51].

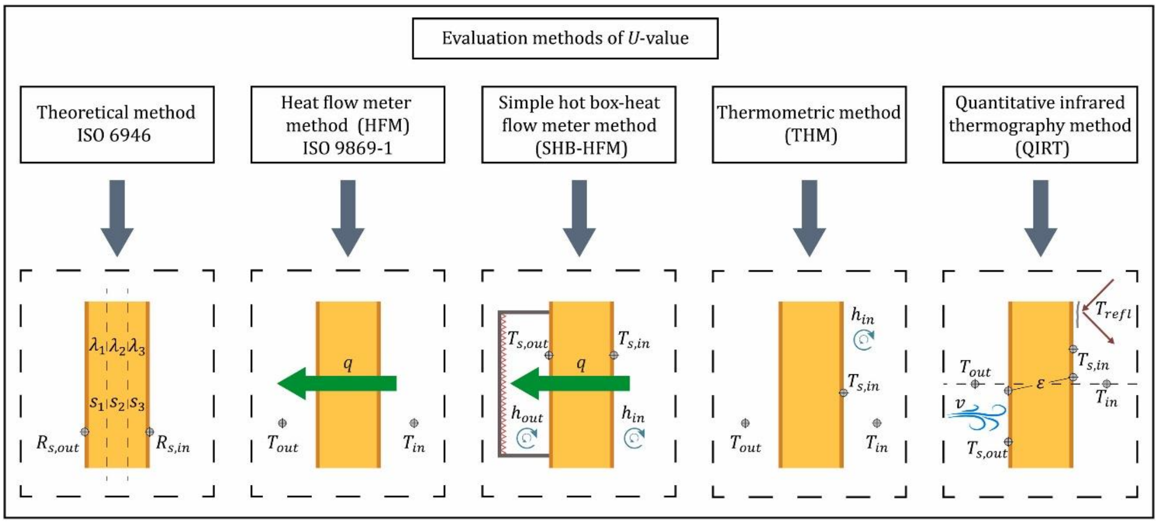

Fig. 1. Methods used to determine *U*-values

The general theory of estimation methods is reviewed in Section 2. The practical approaches are then analysed in Sections 3–6, paying attention to (i) theoretical aspects of each method, (ii) the equipment required to perform the required tests, (iii) metrological performance, (iv) test conditions, (v) data acquisition, and (vi) data analysis. Future research directions and the main contributions of this review are summarized in Sections 7 and 8, respectively.

2. Theoretical methods of estimating thermal transmittance

The ISO 6946 method [36] is used to estimate the thermal transmittance of a wall from the thickness and thermal conductivity of each layer and the thermal resistances of the internal and external surfaces of the wall. The *U*-value is calculated using the equation

$$U = \frac{1}{R_{s,out}+\sum_{i=1}^{n}\frac{s_i}{\lambda_i}+R_{s,in}}, \quad (1)$$

where s_i (m) and λ_i (W/(m·K)) are the thickness and thermal conductivity, respectively, of each wall layer, and $R_{s,out}$ and $R_{s,in}$ ((m^2·K)/W) are the thermal resistances of the external and internal surfaces, respectively. The resistances are determined using values suggested in the ISO 6946 method, derived from precise boundary conditions in terms of convective and radiative heat transfer. A typical wall has an $R_{s,in}$ of 0.13 and an $R_{s,out}$ of 0.04.

This method is widely used (see Table 1), its main advantage being that it gives a *U*-value using a simple calculation without requiring physical testing. The method is therefore widely used during the design phase. The method is also used in various countries as evidence that national energy efficiency standards have been met [52]. However, there is a high degree of uncertainty in a *U*-value calculated using this method, because in most cases the wall composition and thermal conductivities of the layers are unknown [53]. The composition of a wall can be determined in several ways, such as (i) endoscopic analysis [53–55]; (ii) using reliable technical information (e.g., building project documents) or databases for the building indicating the numbers, types, and characteristics of the wall layers [56]; and (iii) making estimates based on analogous buildings or professional experience [53,56]. Destructive and non-destructive techniques can of course be applied to determine the composition of a wall. Least reliable are estimates based on analogous buildings or professional experience because the thicknesses and thermophysical properties of the different layers cannot be accurately estimated [53,57]. The most effective techniques are endoscopy and the use of technical documents because these techniques yield less uncertain estimates of the numbers and properties of wall layers. Endoscopic analysis allows other characteristics (e.g., the moisture content [58]) to be assessed, but performing such measurements could damage the wall, so are not common.

Table 1
Summary of studies of the theoretical method for estimating thermal transmittance

Subject	Comment	References
Application of the method to case studies and/or comparison with experimental methods such as HFM and QIRT.	Applications of the theoretical method to various case studies. Studies in which the theoretical method is used to assess the results obtained using experimental methods are included.	
Influence of environmental factors and limitations of the method.	Studies of the limitations of the method and/or studies of the effects of environmental factors on the thermophysical properties of the materials.	
Method development.	Studies of proposed and applied new techniques for obtaining results using the method and of estimating the uncertainties involved.	

In most building material databases, the thermal conductivity of a material can vary between a minimum and a maximum depending on the density of the material [53]. This characteristic is typical of insulating materials. The limits for such materials can give different thermal transmittances (the thermal resistance of the insulating material has the strongest effect on the result of Eq. (1)). The method developed by Ficco et al. [53] can be used in such cases, in which an average is obtained of the maximum values ($U_{i,max}$) and minimum values ($U_{i,min}$) associated with the wall according to the thermal conductivity limits for each layer (see Eq. (2)).

$$U = \frac{U_{i,max} + U_{i,min}}{2} \tag{2}$$

Ficco et al. [53] thus developed a method for estimating the uncertainties involved in the ISO 6946 method caused by the contributions of the thicknesses and the thermal conductivities of the layers. A rectangular distribution with a maximum limit $\lambda_{i,max}$ and a minimum limit $\lambda_{i,min}$ is used for the thermal conductivity, so the uncertainty can be estimated using Eq. (3). Thermal conductivity is estimated to have a relative uncertainty of 3% when the layers are characterized by endoscopy. A contribution related to the thickness of each layer is considered because of the possible differences between expected and actual values and because of the accuracy of the instrument used (e.g., Vernier calipers).

$$u(\lambda_i) = \frac{\lambda_{i,max} - \lambda_{i,min}}{\sqrt{12}} \tag{3}$$

Determining the configuration of a wall is challenging if it is not possible to acquire technical information on the composition of the wall or to use an endoscopy device, meaning that it may not be possible to use the theoretical method [25]. The most difficult characteristics of a wall to identify are [53,58,65,66] (i) the stratigraphy of the façade; (ii) heterogeneities; (iii) the presence of moisture; (iv) ageing of the materials and deterioration of the thermal properties; and (v) the difference between the actual and estimated thermal conductivities caused by environmental conditions. The actual and estimated thermal conductivities may be different because the thermal conductivity may vary with changes in temperature and environmental moisture content [72,73,75,77]. Fixed environmental values are therefore used to calculate the thermal characteristics of materials in most databases, as specified in the standard ISO 10456 [78]. However, such calculations imply that variations in thermal conductivity caused by climatic variations are not considered. Pérez-Bella et al. [67–69] established a simplified procedure for applying ISO 10456 using conductivity correction factors (*CCF*s) for the external environmental conditions for each provincial capital in Spain. A *CCF* can be used to simplify the application of ISO 10456 by combining conversion factors for temperature and moisture, as shown in Eq. (4), and then applying the *CCF* to the thermal conductivity of the material of interest using Eq. (5), i.e., using the *CCF* to modify the *U*-value determined using Eq. (1).

$$CCF = F_{Tcorrection} \cdot F_{Mcorrection} \tag{4}$$

$$\lambda_{CCF} = \lambda \cdot CCF \tag{5}$$

In Eqs. (4) and (5), the *CCF* (dimensionless) was defined by Pérez-Bella et al. [67], $F_{Tcorrection}$ (dimensionless) is the temperature correction factor, $F_{Mcorrection}$ (dimensionless) is the moisture correction factor, and λ_{CCF} ((m^2·K)/W) is the thermal conductivity of the material corrected using the *CCF*.

This method has also been used to validate experimental data because of a data interpretation criterion in ISO 9869-1 (see Eq. (6)). Section 7.3 of ISO 9869-1 includes a statement specifying that results are representative if the experimental and theoretical values are <20% different as long as the theoretical value is accurate. The difference can be >30% if the thermophysical properties of a wall are not known [25,61,70,71], but such differences can be caused by other factors such as thermal bridges, heterogeneities in the wall, material ageing, or moisture [58,65,66,74,76]. These factors are particularly likely to affect historical buildings. In studies of historical masonry and stone buildings, Lucchi [58,66] found that thermal transmittances estimated using the ISO 6946 method were higher than those determined using measurement methods. In situ methods can therefore be used to decrease the errors associated with theoretical estimates. However, the theoretical method provides representative results as long as the number of layers and their properties are determined carefully and the wall is in a reasonable state (i.e., without thermal bridges or excess moisture).

$$\sigma = \frac{U_{9869-1} - U_{6946}}{U_{6946}} \tag{6}$$

In Eq. (6), U_{9869-1} (W/(m²·K)) is the thermal transmittance determined using HFM as described in ISO 9869-1 [37] and U_{6946} (W/(m²·K)) is the thermal transmittance determined using the ISO 6946 method [36]. Although HFM is specified, measurements can be made using other methods such as THM [41,42] or QIRT [48,51].

3. HFM

3.1. Theory and equipment

HFM is currently the only experimental method that has been standardized, and it is described in ISO 9869-1 [37]. HFM has been used more than any other method to study *U*-values in recent years (see Table 2). The thermal transmittance of a wall is determined by measuring the heat flux through the wall and the temperatures of the environments either side of it. It is a non-destructive method, and its disadvantages are the requirement to access the building, limitations on where probes can be mounted (because of furniture, for example), and the possible influence of the occupants of the building on the measurements [38,61]. Performing the measurements requires [37] (i) a heat flux plate consisting of a transducer with temperature sensors, which generates an electrical signal related to the heat flux through the wall; (ii) two high-precision air temperature probes (giving maximum errors of ±0.2 °C), such as thermocouples or thermistors [64]; and (iii) a data logger to connect to the probes and store the data. Some dynamic analysis methods require both the internal and external surface temperatures of the wall to be measured to allow convective and radiative heat transfers between the wall surfaces and air to be excluded. The equipment should be calibrated just before use, but it is difficult to obtain accredited calibration services for heat flux plates [79]. Other equipment can be used during a test, e.g., a weather station to monitor environmental conditions (wind speed and environmental moisture content) or an infrared camera to make a qualitative assessment using ASTM C1060 [80] or ISO 6781 [81] to ensure that the heat flux plate is mounted correctly [53,61]. Such optional equipment can be used to ensure that the test is conducted under appropriate environmental conditions and that the wall is in an appropriate state of repair.

Table 2
Summary of research on the heat-flow-meter method (HFM)

Subject	Comment	References
Application of HFM in different case studies.	Studies of the practical application of HFM to various case studies, e.g., unoccupied and historical buildings.	
Metrological and operational limitations.	Studies of metrological limitations on using the probes (particularly the heat flux plate) and how probes may affect the thermal behaviour of the wall being investigated.	
Influences of environmental factors.	Studies of the effects of environmental factors (e.g., thermal gradient or wind speed) on the results.	
Data processing and analysis.	Proposed and applied data analysis methods for steady-state and dynamic HFM.	

The main criteria for siting the probes (see Fig. 2) are (i) the heat flux plate should be mounted at a height of 1.5 m above xxx [46] and generally between windows and corners to avoid the effects of thermal bridges [14,70,89]; (ii) the heat flux plate should be mounted at least 1.3 m from heating equipment (e.g., fan coils or radiators) to avoid incorrect measurements [86]; (iii) the heat flux plate is sometimes coated with a thin layer of silicon grease to ensure adequate contact with the wall, and sometimes a thin PVC film is placed on the wall to avoid staining it [63,101,106]; (iv) Peng and Wu [19] recommended that the heat flux plate should be plastered or embedded in the surface to avoid incorrect measurements; and (v) indoor and outdoor air temperature probes should be mounted 30–40 cm (horizontally) from the wall to avoid convective effects [40,41,43]. The temperature inside a building generally varies between floor and ceiling [40], therefore equipment to measure air temperature should be mounted a maximum of 20 cm from the other probes [41]. An auxiliary structure can be used to mount the external probe at the recommended distance [55].

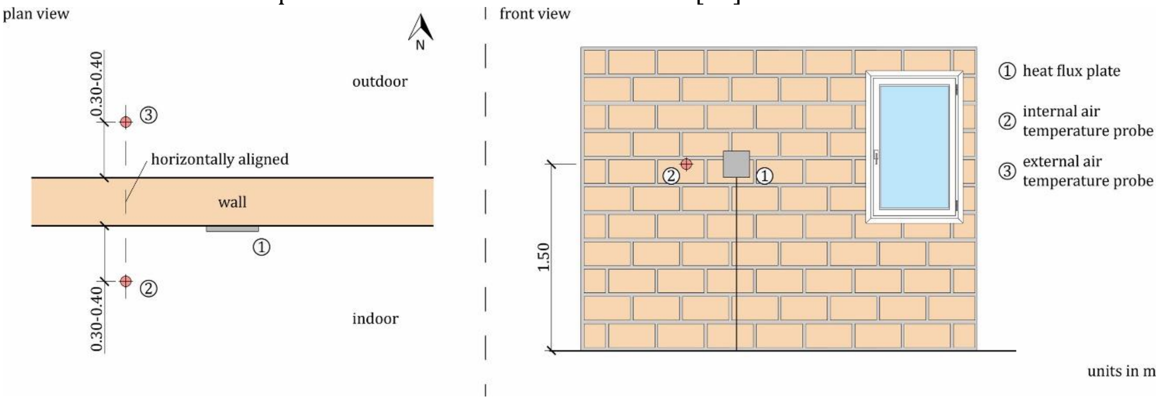

Fig. 2. Criteria for installing the probes used to make measurements for use in the heat-flow-meter method

3.2. Metrological performance, test conditions, and data acquisition

Despite widespread use, HFM has been found to suffer from metrological and operational problems. One of the most important is the effect of the heat flux plate on the thermal behaviour of the wall. Cesaratto et al. [83], Desogus et al. [54], and Trethowen [88] found that the plate can disturb the heat flux and consequently affect the measurements. Peng and Wu [19] found that the heat flux plate was the main contributor to errors in the determined *U*-values. Cucumo et al. [84] found that the siting of the heat flux plate strongly influences the thermal behaviour of the wall. Later, Cucumo et al. [85] found that the heat flux plate could change the thermal flux by up to 30%. Meng et al. [87] found that the error in the overall heat transfer coefficient caused by the location of the plate could be up to 26%. It is important to note that the bigger the heat flux plate, the smaller the error associated with the location of the plate [87]. Ficco et al. [53] published a detailed list of the contributors to uncertainty, quantified the errors, and suggested measures to decrease the uncertainty. Some of the contributors were (i) poor contact between the plate and wall, which can contribute 2%–5% and can be solved by applying silicon grease, and (ii) the flux is not one-dimensional, which can contribute 1%–5% and can be prevented using qualitative assessment methods using infrared thermography or repeated tests in different positions.

A strong temperature gradient is required to give representative results. Desogus et al. [54] found that a temperature difference of 10 °C between the exterior and interior gave an uncertainty of 10% and that the uncertainty decreased as the thermal differential increased. Others, such as Albatici and Tonelli [45], Ficco et al. [53], and Gori and Elwell [93], confirmed that a strong thermal gradient is required to give results with a low degree of uncertainty. However, it is difficult to ensure a strong thermal gradient, especially for walls with low *U*-values requiring temperature differences of >19 °C [64], which is difficult to achieve in a warm climate. A stable temperature difference is required during a test to negate the influence of varying thermal gradient. Genova and Fatta [92] found that, in the Mediterranean climate, tests performed in summer gave less reliable results than tests performed in winter because of heat flux inversions and variations in the thermal gradient. The limitations of HFM in warm climates, which make it difficult to achieve a high thermal gradient, should be studied further. The effects of other factors (e.g., wind) have also been studied. Wang et al. [94] investigated the effect of wind speed on thermal transmittance measurements and found that high wind speed strongly affects the heat flux, errors >1.6% being found for wind speeds >1 m/s. Rain, snow, and humidity also strongly affect the *U*-value. The thermal conductivity of water is higher than the thermal conductivities of common building materials, thus water can modify the thermal behaviour of a wall [65]. The presence of moisture can change the thermal transmittance value by up to 71% relative to the value for the wall under normal conditions [65,120]. It is also important to consider the influence of the orientation of a wall on the overall heat transfer coefficient. Ahmad et al. [90] found that walls facing south, east, and west had higher heat fluxes than walls facing north, and that the orientation of a wall can affect the heat flux by 37.3% or more. The use of heating systems (and their operating cycles) while tests are being performed also needs to be considered. It is common practice to ensure a high thermal gradient by using the heating system in the building of interest. The operating cycle of a heating system causes the interior surface temperature of the wall and therefore the heat flux through the wall to vary, and strongly affects the convective heat flux [91]. Tests should therefore be performed when (i) the difference between the interior and exterior temperatures is >10 °C; (ii) no rain or snow is falling and the humidity is low; (iii) the wind speed is 0–1 m/s; (iv) controlled use of the heating system can give a strong thermal gradient; and (v) the equipment and probes are mounted on a north-facing part of the wall.

There is some disagreement about the optimum duration of a test using this method. ISO 9869-1 indicates that the test duration should depend on the type of the wall being analysed in that a measurement should last 3–7 d for a wall with a high thermal mass but should be performed at night for a wall with a low thermal mass, to avoid the effects of direct solar radiation on the measurements. The test duration should be long for a wall with a high thermal mass but the conditions must remain steady [82] because the mean temperature difference between the wall surfaces and heat flux inversions affect the test duration [59]. Studies have been performed using analysis times of 72 h [53], 1 week [45,57,90], and even 2 or more weeks [22,61]. Al-Sanea et al. [99] made measurements over a whole year to obtain mean values for different seasons with the aim of more fully characterizing the energy performance of the building than could be achieved using a shorter measurement period. The test duration is therefore an important factor and varies depending on the consistency of the conditions during the measurement or the data analysis method used (see Section 3.3 for further information). The need for a long sampling period is one of the main limitations of HFM compared with other methods. A shorter measurement time can be achieved using the excitation pulse method [121], as described in ISO 9869-1 and based on the response factor theory developed by Mitalas and Stephenson [122]. This method allows measurements with errors <2% to be obtained in 1.5 h, although more studies are required to validate the method. Shorter test durations can also be achieved using other methods, such as QIRT (see Section 6).

Readings have been acquired during measurements over various intervals, and studies have been performed using intervals of 5 min [25,54], 15 min [45,53], 30 min [53], 60 min [53], and 90 min [53]. However, very short or very long sampling intervals are not advisable because a short interval will give a large dataset (making data processing difficult), and long intervals may mean that important information is not collected.

3.3. Data analysis

Operational and metrological factors affect the validity of the measurements, although the type of data analysis to be performed also needs to be considered. Cesaratto and Carli [102] stated that the accuracy of a measurement can be improved by deliberately filtering the data to include only those measurements made when the thermal gradient is strong. The filtering process can be used to select observations made when (i) the difference between the interior and exterior temperatures was >10 °C; (ii) no rain fell; (iii) the wind speed was 0–1 m/s; and (iv) the operating cycle of the heating system started and stopped. Wind and rain effects can continue for 2–6 h after the rainfall stops [51], so these observations can be rejected.

Data processing methods strongly affect the results, and may cause variations of up to 20% in a dataset [91,102]. There are two main types of data analysis procedure, steady-state and dynamic methods. Different software tools are available for different data analysis procedures. Standard software can be used to process and analyse the data, but dynamic methods can be performed using specific software, such as CTSM [111], LORD [107], and MRQT [119].

3.3.1. Steady-state methods

Steady-state methods involve measuring the heat flux as well as the internal and external air temperatures. Two methods have previously been used, the average method (Eq. (7)) and the average method with storage effect correction (Eq. (8)). Eq. (7) does not require prior knowledge of the wall, but Eq. (8) requires knowledge of the thermophysical properties of the materials.

The average method relies on the assumption that using mean instantaneous heat flow measurements and mean differences between the internal and external air temperatures attenuate the oscillations, giving a steady-state thermal transmittance value (Eq. (7)). This steady-state method has been used more often than others.

$$U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n}\left(T_{in,j} - T_{out,j}\right)} \tag{7}$$

In Eq. (7), q_j (W/m^2) is the heat flux through the wall at time j and $T_{in,j}$ and $T_{out,j}$ (K) are the indoor and outdoor air temperatures, respectively, at time *j*.

A modified version of Eq. (7) is proposed in ISO 9869-1, and this takes the heat storage effect into consideration [37]. ISO 9869-1 requires Eq. (8) to be used if the thermal resistance value determined at the end of the test differs by >5% from the value measured 24 h before or from the value determined in the first period, as INT(2xD_T/3), where INT is the integer part and D_T is the total test duration in days.

$$U = \frac{\sum_{j=1}^{n} q_j - \frac{(F_{in}\delta T_{in} + F_{out}\delta T_{out})}{\Delta t}}{\sum_{j=1}^{n}(T_{in,j} - T_{out,j})} \tag{8}$$

In Eq. (8), F_{in} (J/(m^2·K)) is the total internal thermal mass factor, δT_{in} (K) is the difference between the mean internal air temperature in the 24 h before the measurement and the mean internal air temperature in the first 24 h of the test, F_{out} (J/(m^2·K)) is the total external thermal mass factor, δT_{out} (K) is the difference between the mean external air temperature in the 24 h before the measurement and the mean external air temperature in the first 24 h of the test, and Δt (s) is the time interval between the measurements. Determining the thermal mass factors for the wall requires previous knowledge of the thermal properties of the layers (Eqs. (9) and (10)), but ISO 9869-1 contains a procedure to use if these properties are not known.

$$F_{in} = \sum_{k=1}^{N} C_k \left[\frac{R_{out,k}}{R} + \frac{{R_k}^2}{3R^2} - \frac{R_{in,k}R_{out,k}}{R^2}\right] \tag{9}$$

$$F_{out} = \sum_{k=1}^{N} C_k \left[\frac{R_k}{R}\left\{\frac{1}{6} + \frac{R_{in,k} + R_{out,k}}{3R}\right\} + \frac{R_{in,k}R_{out,k}}{R^2}\right] \tag{10}$$

In Eqs. (9) and (10), $R_{out,k}$ ((m^2·K)/W) is the sum of the external thermal resistances from the k+1th layer to the outdoor air, $R_{in,k}$ ((m^2·K)/W) is the sum of the internal thermal resistances from the k−1th layer to the indoor air, C_k (J/(m^2·K)) is the thermal capacity of layer k, R_k ((m^2·K)/W) is the thermal resistance of layer k, and R ((m^2·K)/W) is the thermal resistance of the wall.

In general, Eqs. (7) and (8) give very similar results [62,104], but taking the heat storage effect into account can decrease the time it takes to perform the test. However, applying the steady-state method requires prior knowledge of the thermophysical properties of the wall, limiting the practical use of the method. Eq. (7) has been found to give a deviation of 10% 8 d after the start of the test, but the same deviation can be achieved 3 or 4 d after the start using Eq. (8) [104]. It is easy to use the steady-state method, but it is difficult to achieve stable steady-state conditions over time, meaning that it is often better to analyse the data using a dynamic method.

3.3.2. Dynamic methods

Roulet et al. [118] proposed one of the first dynamic methods, which took thermal variations into account using a heat equation [95,96,112]. This method was included in Annex B of ISO 9869-1 [37]. The building element is represented in the model by its thermal conductance and several time constants. These unknown parameters are obtained using an identification technique with the measured heat flow rate and temperature densities, and solving a set of linear equations that can be written in the matrix form

$$\vec{q} = (X)\vec{Z}, \tag{11}$$

where $\vec{q}$ is a vector whose M components are the last M heat flow density data q_j (with M being greater than the number of unknown parameters N), (X) is a rectangular matrix with M rows and N columns, and $\vec{Z}$ is a vector of N unknown parameter components, the first component of which is the U-value. The set of equations gives an estimated vector $\vec{Z}$ (see Eq. (12)). It is important to note that the time constants are also unknown. The aim of the procedure is to identify the best estimate for the constants using an iterative procedure, although the results may not converge, meaning that the result may have to be rejected [118].

$$\vec{Z} = [(X)^T(X)]^{-1}(X)'q \tag{12}$$

In Eq. (12), $(X)^T$ is the transpose of matrix (X).

A similar but simplified version of the Roulet et al. method [118] was developed by Anderlind [97,98]. In this method, oscillations in the transient part, including variations in the heat flow measurements caused by temperature variations, are taken into consideration so that the stationary behaviour of the wall can be isolated. Heat flow through the wall therefore has three elements (see Eq. (13)), one for the stationary behaviour of the heat flow measurements, and the second and third parts describe dynamic instantaneous fluctuations in heat flow caused by changes in surface temperature on each side of the wall.

$$q_j = \sum_{j=1}^{n}\left(\frac{1}{R'}\left(T_{s,in,j} - T_{s,out,j}\right) + \sum_{l=j=p}^{j-1} A_l\left(T_{s,in,l+1} - T_{s,in,l}\right) + \sum_{l=j=p}^{j-1} B_l\left(T_{s,out,l+1} - T_{s,out}\right)\right) \tag{13}$$

In Eq. (13), $T_{s,in,j}$ (K) is the internal surface temperature of the wall at time *j*, $T_{s,out,j}$ (K) is the external surface temperature of the wall at time *j*, *p* is the number of historical data points used to fit the model, *l* is the time at the beginning of the period considered, and R', A_l, and B_l are the regression coefficients. When using this method, the time required to adjust the model must be determined. Deconinck and Roels [104] state that the adjustment time should be 5/6 of the period measured and that 3 d should be the maximum analysis time.

Dynamic models based on a statistical autoregressive approach have found favour in recent years [109,115–117]. Such models involve a black box that can be used to estimate the thermal resistance of a wall with a standard deviation indicating the accuracy of the result. The model is based on adjusting the heat flux using temperatures measured at a certain time and using previously measured heat flow and temperature. The expression for determining heat flow at time *j* is

$$Q(B)q_j = \omega_{s,in}(B)T_{s,in,j} + \omega_{s,out}(B)T_{s,out,j} + e_j,$$
$$\text{with } Q(B)q_j = 1 + Q_1B^1 + \ldots + Q_{nq}B^{nq},$$
$$\omega_{s,in}(B) = \omega_{s,in,0} + \omega_{s,in,1}B^1 + \ldots + \omega_{s,in,nin}B^{nin}, \quad (14)$$
$$\text{and}$$
$$\omega_{s,out}(B) = \omega_{s,out,0} + \omega_{s,out,1}B^1 + \ldots + \omega_{s,out,nout}B^{nin},$$

where B is the back shift operator, $Q(B)$ is the input polynomial, e_j is the simulation error, $\omega_{s,in,nin}(B)$ and $\omega_{s,out,nout}(B)$ are the output polynomials (nin and $nout$ indicating the input order), and nq is the output polynomial order. The polynomial orders and sampling time should be appropriate for characterizing thermal transmittance [104].

A fourth type of dynamic analysis is used by the stochastic grey-box model. Unlike statistical autoregressive models, this type of model can characterize a wall from known physical attributes, leading to physical interpretation. Unlike the other models mentioned, grey-box models can describe complex phenomena and data structures [113]. Heat transfer through a wall is described as a set of continuous stochastic differential equations formulated using the states considered. Grey-box models have been used in many studies [100,103,108,110,114], the exact model depending on the states used in the particular study. Each model describes heat flow dependent on temperature and thermal resistance and capacity of the wall of interest.

A different grey-box model was recently proposed by Biddulph et al. [101]. In this model, a lumped thermal mass model is used to characterize a wall to allow the relationships between the parameters to be inferred through Bayesian analysis. The model has four thermal parameters: (i) the per unit area thermal resistance between the internal air and the thermal mass (R_1); (ii) the per unit area thermal resistance between the thermal mass and the external air (R_2); (iii) the thermal capacity of the wall (C); and (iv) the temperature of the thermal mass at the beginning of the test ($T_{mass,initial}$). This set of parameters allows the measured heat flux to be reproduced better than can be achieved using other models. The heat flux at time *j* through the wall from the internal air to the thermal mass is calculated using the steady-state heat flow equation

$$q_j = \frac{T_{in,j} - T_{mass,j}}{R_1}, \quad (15)$$

where $T_{mass,j}$ (K) is the temperature of the thermal mass at time *j*. $T_{mass,j}$ is initially $T_{mass,initial}$, and at the next time (*j+1*) the heat flow balance forward-difference equation shown in Eq. (16) is used.

$$T_{mass,j+1} = \frac{\frac{T_{in,j+1}}{R_1} + \frac{T_{out,j+1}}{R_2} + C\frac{T_{mass,j}}{\tau}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{C}{\tau}} \quad (16)$$

In Eq. (16), τ (s) is the interval between each timepoint in the dataset. Biddulph et al. recently developed a grey-box model that better estimates the parameters for the two thermal masses than was achieved in the previous model [106].

These dynamic methods offer considerable advantages over steady-state methods, being quicker than steady-state methods [62,101,104] and giving smaller deviations from theoretical values [105]. A method developed by Anderlind [97,98] was more accurate than the statistical autoregressive model and grey-box models over short periods of time [104], although the statistical autoregressive model and grey-box models are more accurate over longer periods. Tests performed in spring and summer can give representative results using these models, but the errors are larger than at other times of year because of the accumulation of systematic errors [101]. For such cases, grey-box models yield better results because they are less sensitive than other models to temperature variations [104].

The large number of methods made available in recent years mean that studies are required to identify the limitations of dynamic methods.

4. SHB-HFM

4.1. Theory and equipment

The difficulty of ensuring a thermal gradient >10 °C while performing measurements using HFM led to the recent development of a new method combining the advantages of hot-box methods [123] with HFM. Hot-box methods are laboratory tests characterized by a controlled temperature of the environment, and are thus not limited by climate conditions and have low measurement errors [124]. However, hot-box methods cannot be used to determine the overall heat transfer coefficient for an existing building. Several studies have therefore been performed with the aim of developing in situ hot-box methods (see Table 3). The hot-box method and HFM were combined by several research groups [125–127], and the model developed is called the temperature-control-box (TCB) HFM. This method involves mounting a hot box on the internal surface of a wall to control the internal air temperature (chosen to suit the season). The box heats the internal air in winter and cools it in summer. Meng et al. [38,39] recently developed the SHB-HFM, which is simpler than the TCB-HFM, the main difference being that in the SHB-HFM the thermal gradient is achieved only by heating and the simple hot box is always placed on the warmest surface. The simple hot box is mounted on the internal side of the wall in winter and the external side of the wall in summer. The TCB-HFM requires an air-conditioning unit but the SHB-HFM does not, meaning that the simple hot box is cheaper than a standard hot box. The SHB-HFM also uses relatively little electricity because the volume being warmed (i.e., the interior of the box) is small compared with a whole room. External environmental conditions affect SHB-HFM less than HFM, but SHB-HFM requires access to the building of interest and the installation of equipment in the same way as in HFM (see section 3.1).

Table 3
Summary of studies of the simple hot-box heat-flow meter (SHB-HFM)

Subject	Comment	References
SHB-HFM design.	Studies of the SHB-HFM design.	
SHB-HFM application.	Studies of the practical application of the SHB-HFM in case studies.	
Metrological and operational limitations.	Analyses of the metrological limitations related to the use of probes (heat flux plate and thermocouples).	

The items required to perform the SHB-HFM are [38,39]: (i) a simple hot box; (ii) three heat flux plates; (iii) a temperature probe; (iv) nine surface temperature probes; and (v) a data logger. The optimal dimensions of the simple hot box (L_{min}) were determined from multiple linear regression analyses of numerical simulations using L_{min} as the dependent variable and the thickness and thermal conductivity of the wall as the independent variables (see Eq. (17)) [39]. A box made of 15 mm wooden composite board and a 25 mm rubber sponge plate (λ=0.034 W/(m·K)) is used. The electrical heating equipment is installed on the vertical internal side of the wall. The heat flux plate and temperature probes have the same technical characteristics as the heat flux plate and temperature probes used in HFM (see section 3.1). An infrared camera can also be used to assess the wall before using SHB-HFM.

$$L_{min} = 3.0 s_{wall} + 0.2 \lambda_{eq} \tag{17}$$

In Eq. (17), s_{wall} (m) is the thickness and λ_{eq} (W/(m·K)) is the equivalent thermal conductivity of the wall.

It is important to note that results have only been published for tests carried out in summer [38]. The requirements for installing the equipment and probes in summer are that (see Fig. 3): (i) the simple hot box should be installed on an auxiliary structure at a height above the floor that can be varied and on a part of the wall without thermal bridges, and material should be placed between the simple hot box and the wall to make the seal tight and decrease internal air temperature fluctuations; (ii) the thermocouple to measure the internal air temperature should be placed in the middle of the simple hot box; (iii) three thermocouples to measure the external surface temperature should be mounted on the wall 15 cm apart and 30 cm from the sides of the box; (iv) three heat flux plates should be placed on the internal surface of the wall (within the simple hot box) 5 cm apart; and (v) surface temperature sensors should be placed symmetrically each side of the heat flux plates (an unspecified distance apart). Other criteria used for HFM (e.g., applying a thin layer of silicon grease) can be considered.

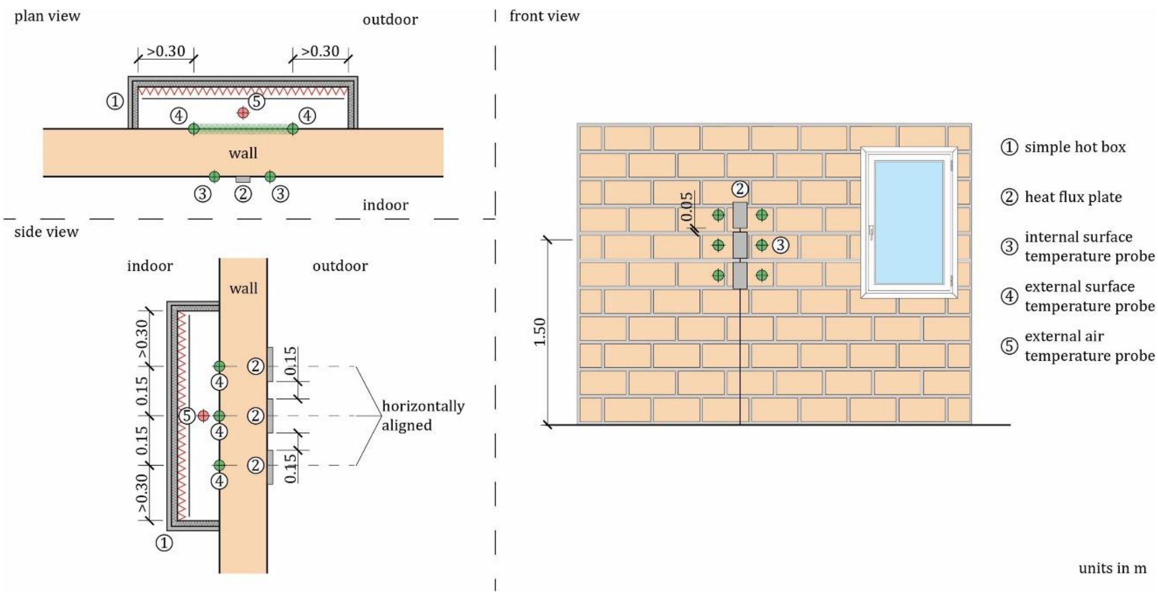

Fig. 3. Criteria for placing the measurement probes for the simple-hot-box heat-flow-meter method

The method is limited by the fact that an auxiliary structure is required when the box is placed on the exterior of a wall, so it will only be possible to place the box against a ground floor wall. The method therefore cannot be used on buildings with a ground floor façade different from the façades on the other floors.

4.2. Metrological performance, test conditions, and data acquisition

The configuration of the test model can ensure stable conditions during a measurement. The temperature increases for the first 24 h (the period allowed for heating the box interior), then the measured variables are stable with only slight variations [38]. Variability can be decreased by 7% by increasing the thermal gradient from 10 to 30 °C [39]. The optimal temperature difference during a test is >20 °C [39], which is quite difficult to achieve using other methods (e.g., HFM), meaning the ability to achieve this is one of the main advantages of SHB-HFM.

Errors associated with siting the heat flux plate can affect this method [53,84,85,87]. Surface temperature sensors should not be mounted on mortar joints or in areas near such joints [87] because the errors associated with the locations of the sensors can reach 6%. It is unlikely the sensors will be mounted on mortar joints because such joints are usually narrow, but care should be taken due to the large errors that can result. Thermography can ensure the probes are sited in suitable places to avoid introducing these errors (see Fig. 4) [41,87]. In previous tests [38], it was found that the error associated with placing the sensors 15 cm from their ideal locations was between −8.14% and −9.60%. Computer simulations indicated that the difference between the estimated and expected values was −5% if the heat flux plate was mounted on the internal surface but 3.7% if the heat flux plate was mounted on the external surface [38]. There are optimal box dimensions, as mentioned above (Eq. (17)), because the dimensions of the box strongly affect the validity of the results: a small box does not provide an adequate heat transfer area [38,39]. These results come from studies in summer and for certain wall types. Tests should also be performed using other wall types and in different seasons (e.g., winter) to investigate further the benefits and limitations of the method. It is important to study the limitations of the method when the interior and the exterior surfaces alternate in terms of which is warmer (typical for daily thermal oscillations in warm regions).

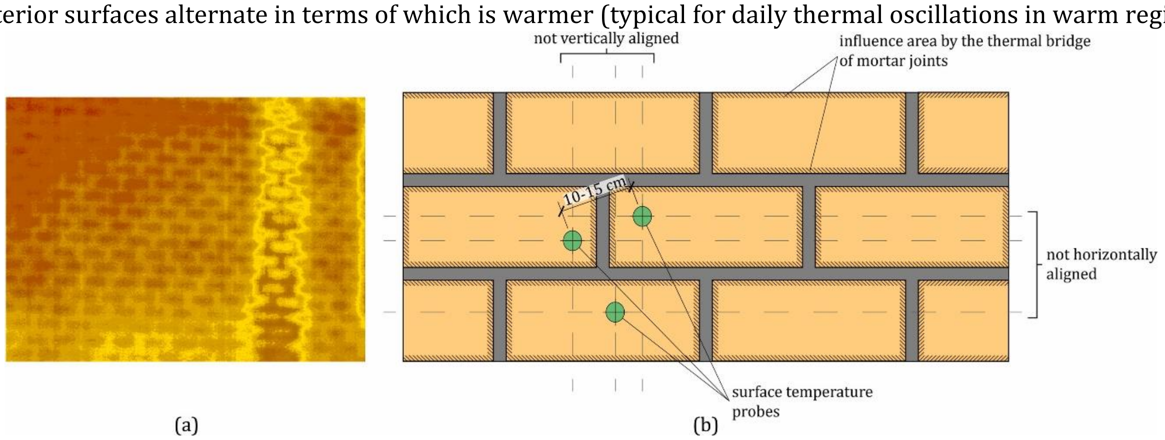

Fig. 4. (a) Thermogram of the internal surface of a wall with mortar joints between bricks and (b) criteria for mounting the surface temperature probes

A test should last at least 72 h, although the test period could be decreased if steady conditions can be guaranteed. The same factors affect data acquisition as for HFM. In a previous study using SHB-HFM [38], a sampling period of 2 min was used, but longer sampling periods can be used to make data processing more practical.

4.3. Data analysis

The proposed data analysis method is similar to the average method used for HFM (see Eq. (18)). The data filtering process has not been explained, but data from the first 24 h should be rejected because this is the temperature-stabilization period. The similarity of the method to HFM means that the same filtering conditions can be applied (see Section 3.3.).

$$U = \left(\frac{1}{h_{out}} + \frac{\sum_{j=1}^{n} \left(T_{s,in,j} - T_{s,out,j} \right)}{\sum_{j=1}^{n} q_j} + \frac{1}{h_{in}} \right)^{-1} \quad (18)$$

In Eq. (18), h_{out} (W/(m^2·K)) is the external heat transfer coefficient and h_{in} (W/(m^2·K)) is the internal heat transfer coefficient.

5. THM

5.1. Theory and equipment

THM, also called the air–surface temperature ratio method, is a non-destructive method which involves determining thermal transmittance by measuring the internal surface temperature of the wall and the temperatures of the environments divided by the wall. Eq. (19) was obtained from Eq. (7) for the average method for HFM using Newton's law of convective cooling. The main difference between THM and HFM is that the former does not require the heat flux through the wall to be measured.

$$U = \frac{h_{in}\left(T_{in} - T_{s,in} \right)}{T_{in} - T_{out}} \quad (19)$$

THM is widely used by professionals [41]. Specifications have only been provided by the manufacturers of equipment used to perform it [43], but THM has recently been used and validated in published studies (see Table 4).

Table 4
Summary of studies of the thermometric method (THM)

Subject	Comment	References
THM design.	Studies of THM design.	
THM application.	Studies of the practical application of THM in case studies.	
Metrological and operational limitations.	Analyses of the metrological limitations of using surface temperature probes.	
Effects of environmental factors.	Analyses of the effects of environmental factors on the results.	
Data processing and analysis.	Proposed and applied data analysis methods for THM.	

Performing THM requires [40–43]: (i) two temperature probes; (ii) three surface temperature probes; and (iii) a data logger. As for HFM, it is advisable to use a weather station to monitor climatological variables while THM is performed and to use an infrared camera to assess the envelope before performing THM.

The criteria for installing the equipment are: (i) three internal surface temperature probes should be adhered to the internal side of the wall (using a heat conductive adhesive) 1.5 m high, 10–15 cm apart [40,41,43], and 20 mm from any mortar joint between bricks (see Fig. 4) [87] (qualitative assessment by infrared thermography can be used to determine the locations of mortar joints and, if they cannot be identified, probes should be mounted not horizontally or vertically aligned [87]); and (ii) the air temperature sensors should be mounted as well aligned as possible 1.5 m high and 30–40 cm from the wall to avoid convective effects [40,41,43]. As for HFM, furniture and building occupant behaviour can affect the sites of the probes and the measurements made (see section 3.1).

5.2. Metrological performance, test conditions, and data acquisition

The main advantage of THM over HFM is that the former does not require a heat flux plate, so the measurement errors caused by the heat flux plate (described earlier for HFM) are excluded. THM therefore only has errors associated with the surface temperature probes (described for SHB-HFM above). In previous studies it was found that the test period should not affect the validity of the results [40,41] as long as there is a strong thermal gradient and conditions are stable [41]. As for HFM, the following factors should be considered when selecting a wall for analysis: (i) the wall should face north to avoid direct solar radiation affecting the measurement; (ii) the wall should not be exposed to other sources of radiation; (iii) the wall should be in an adequate state of repair (e.g., without cracks or flaws); and (iv) the wall should not contain thermal bridges.

The test duration should fulfil the same criteria as for HFM: (i) the test should be performed during the night for light walls and (ii) the test should be performed for 72–168 h for heavy walls. The test can be performed for a shorter period if stable conditions are guaranteed, and the mean deviation will be 2.63% from the value found over a longer period [42]. However, further studies are needed in different climates and for different types of walls to determine the optimum test durations under different conditions. Data acquisition intervals of 5 min [42], 15 min [41], and 30 min [40] have been used in previous studies. As mentioned in Sections 3.2 and 4.2, it is better to use time intervals neither too short nor too long to facilitate data processing and avoid loss of information.

5.3. Data analysis

Data processing and analysis are performed using data filtered in a very similar way to data in HFM, then Eq. (19) is applied to the subset generated. Unlike for HFM, no dynamic methods are currently available for performing the data analysis in a different way. The only discrepancy at the formulation level is associated with the way Eq. (19) is applied: Bienvenido-Huertas et al. [41] considered the measurement at each timepoint to be an independent measurement to which the filter was applied, giving the arithmetic mean of the filtered data, whereas Andújar Márquez et al. [40] and Kim et al. [42] applied Eq. (19) as a weighted sum of the observations obtained during the measurement period without specifying whether the data were filtered or not. To avoid negative values, Andújar Márquez et al. [40] used the absolute value of the denominator ($T_{in} - T_{out}$) to allow tests to be performed in winter or summer without giving negative results. Further studies are required to establish common criteria for applying the method.

Regarding the input variables, different values have been assigned to h_{in} in different studies. Bienvenido-Huertas et al. [41] and Kim et al. [42] used a value of 7.69 W/(m^2·K), calculated as the reciprocal of the thermal resistance of the internal surface ($R_{s,in}$) for horizontal fluxes in ISO 6946 [36], but Andújar Márquez et al. [40] used a value of 2.50 W/(m^2·K), also in ISO 6946, and other approximations of the convective coefficient could be used (e.g., 3.00 W/(m^2·K) from ISO 9869-1 [37]). Further studies should be performed to assess the convection correlation for this method.

6. QIRT

6.1. Theory and equipment

The difficulties involved in performing HFM have led to the development of methods to measure thermal transmittance by infrared thermography. Infrared thermography has traditionally been used to analyse building envelopes qualitatively [128]. Infrared thermography has many uses, such as (i) detecting thermal anomalies (e.g., materials with different thermal conductivities and the presence of moisture) [129,130], (ii) identifying thermal bridges [131,132], and (iii) detecting air infiltration [133,134]. However, infrared thermography has been used to determine *U*-values in the last decade. Such methods use infrared thermography to measure the surface temperature, emissivity, or reflected temperature, but infrared thermography can also be used to measure other variables such as the internal and external air temperatures [45]. These methods are non-destructive, rapid, and allow a wall to be analysed qualitatively. Infrared thermography tests can be performed more quickly than tests using other methods such as HFM and THM. Recent research has been focused on developing and analysing various methods (see Table 5), which can be divided into two categories, methods based on interior measurements and methods based on exterior measurements.

Table 5
Summary of studies of quantitative infrared thermography (QIRT)

Subject	Comment	References
Design of interior QIRT.	Studies of the design of QIRT based on interior measurements.	

Design of exterior QIRT.	Studies of the design of QIRT based on exterior measurements.
Application of QIRT.	Studies of the practical application of QIRT to case studies.
Metrological and operational limitations.	Analyses of the metrological limitations related to using different equipment.
Effects of environmental factors.	Analyses of the effects of environmental factors, such as the thermal gradient and wind speed, on the results.
Data processing and analysis.	Proposed and applied data analysis methods for QIRT.

In the first QIRT study in 2008, Madding [49] proposed that thermal transmittance could be calculated using the internal convective component and the radiative component expressed as the linear Stefan–Boltzmann law

$$U = \frac{4\varepsilon\sigma\left(\frac{T_{s,in}+T_{refl}}{2}\right)^3 (T_{s,in}-T_{refl}) + h_{in}(T_{s,in}-T_{in})}{T_{in}-T_{out}}, \quad (20)$$

where ε (dimensionless) is the wall emissivity, σ is the Stefan–Boltzmann constant ($5.67\cdot10^{-8}$ W/(m²·K⁴)), and T_{refl} (K) is the apparent reflected temperature.

A similar method was presented by Fokaides and Kalogirou [48] but using the third power of only the surface temperature rather than the third powers of the mean internal surface temperature and reflected temperature, giving the expression

$$U = \frac{4\varepsilon\sigma T_{s,in}{}^3 (T_{s,in}-T_{refl}) + h_{in}(T_{s,in}-T_{in})}{T_{in}-T_{out}}. \quad (21)$$

The convective coefficients used in Eqs. (20) and (21) were different in different studies. Eq. (20) has been used with Holman correlations [148] and Earle correlations [149], but Eq. (21) has been used with values taken from ISO 6946.

Both Eq. (20) and Eq. (21) were designed for measurements made on the interior of a wall. However, three methods for tests using measurements made on the exterior of a wall have been developed. One was developed by Albatici et al. [44–46] using the heat balance relationship for the outside of a wall. The external convective contribution was determined from the Jürges correlation, published by Watanabe ($5.8 + 3.8054v$) [150], but the equation was simplified by removing the constant from the linear regression to give

$$U = \frac{\varepsilon\sigma(T^4_{s,out}-T^4_{out}) + 3.8054v(T_{s,out}-T_{out})}{T_{in}-T_{out}}, \quad (22)$$

where v [m/s] is the local wind speed.

Dall'O' et al. [47] used a different thermal balance from Eq. (22) by considering equivalence between the convection heat flux exchanged with the exterior and the heat flux of the wall (see Eq. (23)) using h_{out} from the convective correlation published by Watanabe but without simplification, giving

$$U = \frac{(5.8+3.8054v)(T_{s,out}-T_{out})}{T_{in}-T_{out}}. \quad (23)$$

Tanner et al. [50] proposed a standardized QIRT using a constant h_{out} and applying the same thermal balance as that used by Dall'O' et al. [47], giving

$$U = \frac{8.7(T_{s,out}-T_{out})}{T_{in}-T_{out}}. \quad (24)$$

Tejedor et al. [51] recently proposed an approach using interior measurements based on the equivalence of the heat flux and convective and radiative fluxes. The main difference between this and the models of Eqs. (20) and (21) is that the convective coefficient used in the new approach is approximated using dimensionless numbers, giving

$$U = \frac{\varepsilon\sigma\left(T^4_{refl}-T^4_{s,in}\right) + \frac{k\left\{0.825+\frac{0.387Ra_L^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}\right\}^2}{L}(T_{in}-T_{s,in})}{T_{in}-T_{out}}, \quad (25)$$

where Ra_L (dimensionless) is the Rayleigh number, Pr (dimensionless) is the Prandtl number, k is the thermal conductivity of air (W/(m·K)), and L is the height of the wall (m).

There is no consensus on which theoretical approach should be adopted because the convection correlations used in different studies were established for particular test conditions, therefore each is specific to certain characteristics, such as the surface finish of the wall (soft or rough) and the wind direction (windwards or leewards).

Performing a QIRT requires an infrared camera with a focal plane array calibrated by an accredited calibration laboratory [141]. A hot-wire anemometer (a filament connected to an electrical circuit, to monitor variations in the electrical resistance of an air flux) is used to measure the wind speed near the wall [45,46]. The internal and external air temperatures can be measured using temperature probes [48,51] or via the procedure proposed by Albatici et al. [44–46], who considered the different elements of the wall as black bodies. In this method, (i) the external temperature can be measured using a cardboard box with a small hole [45] or a hosepipe [45,140] and (ii) the internal temperature can be measured by partly opening a window in the room being studied [45]. The reflected temperature can be measured from the mean temperature of a crumpled piece of aluminium foil with emissivity 1 fixed to the surface [151]. The emissivity can be determined using (i) adhesive tape of known emissivity provided by the manufacturer [152], (ii) a contact thermometer [152], or (iii) an ITT-emissometer (a soldering iron with the tip protected with ground graphite [153]).

The criteria for installing the equipment are (see Fig. 5): (i) the infrared camera should be placed 1.5 m from the wall at an angle between 15° and 50° to avoid the reflection of the technician affecting the measurement [28,51]; (ii) all the elements required (e.g., the infrared reflector) should be mounted 1.50 m above the floor [51]; and (iii) the hot-wire anemometer should be 0.1 m from the wall surface [46]. Unlike HFM, the procedure proposed by Albatici et al. [44–46] can be performed without entering the building using the black bodies described above. It is important to describe the requirements for mounting the external black body. A cardboard box with a small hole or the hosepipe should be placed 1.5 m high and near the wall, then the equipment should be left for 15–60 min in the exterior environment before a thermogram is acquired. Measurements of the hole in the external body and the window opening should be performed using an emissivity of 1.

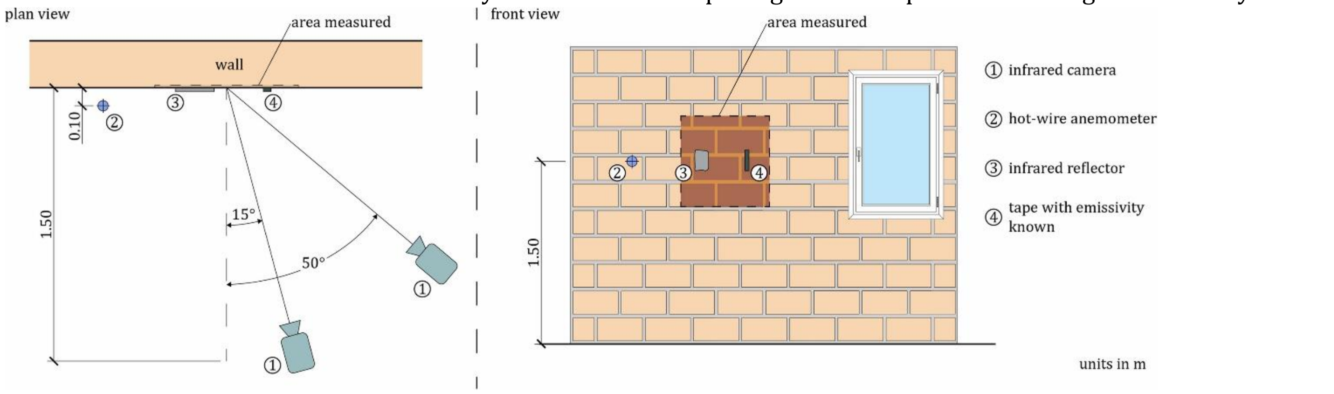

Fig. 5. Criteria for installing the equipment and probes for the quantitative infrared thermography method. The choice of probe and material will depend on the selected method. The exterior and interior are not distinguished in the figure.

6.2. Metrological performance, test conditions, and data acquisition

The method requires very specific environmental conditions. It is important for the conditions to be similar to steady state. Therefore, before a test is performed a stable heat transfer state should be achieved for 3 or 4 h [48] with a minimum difference of 10 °C between the interior and exterior temperatures [45,46,48,51] (the optimal thermal gradient should be 7–16 °C [138]). The external temperature should be <6 °C for at least 12 h before a test is performed. A small difference between the reflected or surface temperature and exterior temperature gives more accurate results than a large temperature difference [137]. It is difficult to achieve a strong thermal gradient in summer, so tests should ideally be performed in winter [48,51]. Other climatological parameters strongly affect QIRT tests. Lehmann et al. [143] found higher wall surface temperatures when there was no wind than when there was wind. Wind speeds <1m/s allow steady conditions to be guaranteed. Vijver et al. [145] found that wind combined with a clear sky and solar irradiation strongly affect QIRT test results. Tests should therefore ideally be performed 2 h before dawn [46] and when (i) the difference between the internal and external air temperatures is 7–16 °C, (ii) the wind speed is 0.1–1 m/s, (iii) no rain is falling, and (iv) the wall has not been exposed to direct radiation (to avoid thermal inertia effects).

The input variables strongly affect the validity of the results because these variables can cause atypical values to be found [46,136,140]. Deviations of 50% in wind speed, external air temperature, internal air temperature, and surface temperature have been found to give measurement errors of 9%, 5%, 50%, and 50%, respectively [46]. The surface temperature is affected by thermal bridges, which can cause measurement errors of up to 56% [139]. A 1 °C change in reflected temperature can cause errors of up to 100% in the *U*-value calculated using Eqs. (20) and (21) [48]. Emissivity only needs to be measured once because it will remain stable throughout a measurement because it is not affected by temperature changes [142,144]. The type of wall being analysed (simple or with several layers) will affect the results obtained using various methods [138].

The effects of the technical characteristics of the camera must also be considered when performing QIRT tests. Madding [49] assessed the effects of using noise equivalent temperature difference cameras with different resolutions on the uncertainties of the measurements, and recommended using the same camera to determine both the reflected and internal surface temperatures in an attempt to avoid systematic errors. The location of the anemometer will strongly affect Eqs. (22) and (23), therefore making simultaneous measurements in different places can reduce the error caused by variations in wind speed measurements [140].

Different QIRT tests can behave similarly when measurements are made in similar ways. Methods using interior measurements give almost the same results even though different equations are used, and the same is true for methods using external measurements [137]. In general, QIRT gives results more similar to the values given in ISO 6946 than HFM, the deviations from the given values being between 1.7%–154% for QIRT [47,48,135,137] and 5%–155.17% for HFM [45,135,137,139].

Instantaneous measurements can give non-representative results [146], therefore a test needs to last 2–3 h [51]. Increasing the test duration can decrease uncertainty in the results [147], and tests should be performed when it is cloudy to exclude the effects of solar irradiation. As for HFM, there is disagreement on the optimum interval between thermograms being acquired. Intervals of 1 min [51], 15 min [49], 20 min [48], and 30 min [137] have been used. At least ten instantaneous measurements should be made to allow the uncertainty to be properly estimated [141].

6.3. Data analysis

Data processing and analysis are simpler for QIRT than other methods such as HFM. Data processing is usually performed using commercial software for the camera model used [48,51]. It is essential to determine the optimum analysis area when analysing thermograms. Tejedor et al. [51] state that the optimal analysis area for a single-leaf wall is 104 px × 221 px and that the optimal analysis area for a multi-leaf wall is 146 px × 212 px. Constant wind speed variations over a short period mean that the mean wind speed should be used [47,137]. All the equations use instantaneous measurements, and the final result is the mean thermal transmittance for the whole measurement period [137].

7. Future research directions

Some aspects of thermal transmittance measurement methods have not yet been assessed or need to be assessed in greater detail. These aspects are: (i) using in situ methods in historical buildings; (ii) using the methods for types of wall not yet analysed (although the use of the methods to assess lightweight steel-framed walls is currently being studied [60]); (iii) using the methods in warm conditions; (iv) determining the convection correlation that best fits THM; (v) determining the optimum THM parameters, on which there is currently a divergence of opinion; (vi) developing a dynamic analysis procedure for THM; (vii) determining the convection correlations that best fit QIRT; and (viii) studying the effect of thermal storage on the different methods.

8. Conclusions

Improving the energy efficiencies of existing buildings to meet new sustainability objectives is an important challenge [1]. It is essential for the thermal transmittances of walls to be estimated properly, to allow effective energy conservation measures to be applied [21]. The variety of methods for determining overall heat transfer coefficients and a lack of a previous review of the methods available for determining U-values mean that an exhaustive review is required.

More than 150 publications (of various types) published in the last 50 years are reviewed here. First, the problems relating to energy use in buildings and environmental degradation caused by energy use in buildings are assessed. Heat loss through walls is found to be one of the main factors affecting energy use in buildings. The best-developed methods for assessing heat loss through walls are also assessed. These methods are: (i) the theoretical estimation method (ISO 6946 [36]); (ii) HFM (ISO 9869-1 [37]); (iii) SHB-HFM [38,39]; (iv) THM [40–43]; and (v) QIRT [44–51]. The theoretical basis, equipment and materials required, metrological and environmental aspects, equipment installation procedure, and data acquisition and processing criteria, are then described for each method.

As described earlier, each method offers advantages and limitations, which determine the method that should be applied in specific circumstances. The benefits and limitations of each method are summarized in Table 6. The theoretical estimation method is often used in energy audits because no tests are required (the main advantage of this method), because the composition of a wall can be assessed using various methods, such as [53–56] (i) endoscopy, (ii) using reliable technical documentation or databases describing the envelope of the building of interest, or (iii) using estimates based on analogous constructions. In situ measurements can give more representative values [25,38,40,45–47,51,61,71], but the use of such methods is affected by many factors, with environmental factors being the most important. In situ measurement methods require [45,46,48,51,53,65,94,120,143,145] (i) a high thermal gradient ($T_{in} - T_{out}$ >10 °C), (ii) a wind speed of 0–1 m/s, (iii) zero rainfall, and (iv) no solar radiation or other radiation sources to affect the wall of interest. Other factors, such as metrological errors and data analysis, are also assessed in this review.

Table 6
Benefits and limitations of the different methods

Method	Benefits	Limitations
Theoretical estimation method.	No tests are required. Simple calculation procedure. Non-destructive method if no endoscopies are performed.	High level of uncertainty because the stratigraphy and thermophysical properties of the wall are not known. Wall damage if endoscopies (a destructive method) are performed.
Heat-flow-meter method (HFM).	Standardized method in ISO 9869-1. Non-destructive. Well-developed for research studies. Results are easily represented. Different data analysis procedures are available: steady-state methods and dynamic methods.	Need access to the building interior. Furniture limits probe locations. Building occupier behaviour affects measurements. Metrological errors related to the heat flux plate. Demanding environmental requirements. More useful in cold regions, limited use in warm areas or summer. Long test duration, >2 weeks in some cases.
Simple-hot-box heat-flow-meter method (SHB-HFM).	Non-destructive. Guarantees constant and adequate thermal gradient during a test. Can be used in areas with warm climates or in summer. Building occupier behaviour does not affect measurements. Shorter test than HFM.	Need access to the building interior. Devices can only be used on the ground floor (use for higher floors would require an auxiliary structure, increasing the cost). Use in winter has not been studied. Metrological errors related to the heat flux plate. Metrological errors related to the surface temperature probes.
Thermometric method (THM).	Non-destructive. Widely used by professionals. Does not have metrological errors related to the heat flux plate. Can give representative results quickly.	Need access to the building interior. Metrological errors related to the surface temperature probes. Demanding environmental requirements. Dynamic data analysis techniques not available.
Quantitative infrared thermography methods (QIRTs).	Non-destructive. Two alternative methods (interior and exterior), giving numerous possibilities for performing experimental measurements. Test can be performed without access the building interior (only for external methods). Test is quick. *U*-value can be estimated after qualitative assessment of the wall.	Need access to the building interior (only for interior methods). Metrological errors related to the infrared camera. Metrological errors related to the anemometer (only for exterior methods). Demanding environmental requirements. More useful in cold areas, limited use in warm areas or summer.

In summary, the choice of method will depend on factors such as: (i) the equipment and materials available; (ii) the dominant environmental conditions in the study area; (iii) the time available to perform the test; (iv) access to the building; (v) the possibility of installing probes; and (vi) the availability of technical documentation or other information about the wall. This review of the methods currently available for determining thermal transmittance through walls and the characteristics, requirements, and limitations of the methods will be a useful source of information to researchers and professionals in this field.

Acknowledgements
The study was funded by the University of Seville through the “V Own Research Plan” scheme.

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