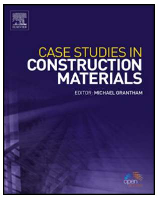
Case Studies in Construction Materials 1 (2014) 53–59

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm



Case Study

Evaluating in situ thermal transmittance of green buildings masonries—A case study

Francesco Asdrubali *, Francesco D'Alessandro, Giorgio Baldinelli, Francesco Bianchi

University of Perugia, Department of Engineering, Via G. Duranti 65, 06125 Perugia, Italy

ARTICLE INFO

Article history:
Received 20 December 2013
Received in revised form 14 April 2014
Accepted 14 April 2014
Available online 19 April 2014

Keywords:
Masonry
Green buildings
U-value
Heat flux measurements
Infrared thermography
Performance gap

ABSTRACT

The determination of the thermal properties of a building envelope is fundamental for the correct design of energy efficient constructions. Opaque walls can be easily modeled as parallel and homogeneous layers, being characterized by a monodimensional thermal flux which allows to evaluate the thermal transmittance with analytical models. These procedures are well established and they lead to reliable results; however, it is important to verify the actual performance with in situ thermal transmittance measurements. This analysis is more important when the wall performance is high, being closely linked to economic assessments.

The paper presents the results of a measurement campaign of in situ thermal transmittance, performed in some buildings in the Umbria Region (Italy), designed implementing bio-architecture solutions. The analyzed walls were previously monitored with thermographic surveys in order to assess the correct application of the sensors. Results of the investigation show that in situ thermal transmittance measurements and theoretical calculated *U*-value are not in perfect agreement. The mismatch becomes important for monolithic structures such as walls made of thermal blocks without insulating layers.

1. Introduction

Thermal insulation in buildings is a key factor to achieve the thermal comfort of the occupants and the reduction of heat losses, so diminishing the energy requirement for heating and cooling. The main ways of heat transfer, conduction, radiation and convection, can be reduced through appropriate construction techniques and materials selection.

The growing attention to energy savings in the building sector has led to more and more performing walls characterized by very low values of thermal transmittance. This parameter describes the insulating capacity of a wall; it depends on its global layout and on the characteristics of the single layers. The thermal properties of multilayer walls can be deduced from the declared data of heat transmission of the single layers given by the manufacturers (ISO, 2007). Such declarations, issued on the basis of current regulations, report values obtained by laboratory measurements (ISO, 1991, 1994a; Asdrubali et al., 2010; Asdrubali and Baldinelli, 2011) or numerical simulations (ECSS, 2012). The values of thermal conductivity for highly insulating layers are generally well established and often supported by experimental evidences; on the contrary, the situation is less defined for other components of the vertical walls such as bricks and tiles, whose thermal properties can be

---

[*] Corresponding author. Tel.: +39 0755853716; fax: +39 0755853697.
E-mail addresses: francesco.asdrubali@unipg.it (F. Asdrubali), dalessandro.unipg@ciriaf.it (F. D'Alessandro), giorgio.baldinelli@unipg.it (G. Baldinelli), bianchi.unipg@ciriaf.it (F. Bianchi).

http://dx.doi.org/10.1016/j.cscm.2014.04.004

evaluated only through complex analyses (Kus et al., 2013; Morales et al., 2011). Therefore, in situ thermal transmittance measurements become strategic to evaluate the correctness of masonry installation and to determine its behavior during the use of the building. This phase is definitely the most energy consuming of the entire life cycle of a building (around 80%), as shown in (Asdrubali et al., 2013a).

The paper presents the results of some in situ thermal transmittance measurements performed on selected buildings, located in central Italy. The buildings construction was partially funded by the Umbria Region, through various tenders, in order to diffuse good practices of energy efficient buildings. The study is part of a wider monitoring activity involving construction site inspections, energy-environmental assessments (monitoring of actual energy consumption and proper operation of the plants) and field measurements of hygrothermal, acoustic and lighting parameters (Asdrubali et al., 2013b). The buildings were built between 2007 and 2008 and monitored between 2010 and 2013.

2. Methodology for in situ thermal transmittance measurements

The thermal transmittance of opaque walls is the main parameter to assess building efficiency during the heating season, while during the warm period other parameters (above all mass and heat capacity) have to be taken into account because of the dynamic behavior of the structure. Generally, this parameter is measured by laboratory tests with steady-state conditions on the surfaces of the wall in compliance with EN 1934 (ECS, 1998). During the test, the temperatures of the two wall surfaces have to be kept as constant as possible in order to avoid fluctuations, generating consequently a stable and adequate flux through the sample. The hot box apparatus allows to create these conditions and the measurement results can be compared with the outputs of numerical simulations, as shown in (Wakili and Tanner, 2003). Although the laboratory assessment is a robust methodology that allows standard comparisons between different opaque structures, it is still useful to evaluate the thermal transmittance of walls in real conditions, viz. on existing buildings. Different techniques can be employed to measure in situ thermal transmittance such as, for instance, thermographic surveys (Albatici and Tonelli, 2010; Fokaides and Kalogirou, 2011); however, the common in situ methodology is the one that uses thermal flux sensors (Peng and Wu, 2008; Desogus et al., 2011), described in the present paper.

Measurements of in situ thermal transmittance have to be performed according to the Standard ISO 9869 (ISO, 1994b), which gives the measurement methodologies, the equipment to be used and the data processing procedures, considering the variability of the measured phenomenon. The measure consists in the acquisition of the values of heat flux density passing through the sample and of the (surface or air) temperature values of the measurement area defined in the internal and external sides. At least one heat flux sensor and two temperature probes on each side of the system under test are required; temperature probes are usually installed on the surface of the sample in order to obtain the conductance value of the masonry.

A thermographic analysis is performed to properly install the sensors, hence avoiding singularities (such as thermal bridges or other defects) that could bring to incorrect results (Asdrubali et al., 2012).

Furthermore, the wall should not be irradiated by sunlight during the measurement; if this is not possible, a proper protective screen should be employed. The occurrence of a variable regime, mainly due to external conditions, requires a long measurement time period, in order to consider the transient effects related to energy absorption and release.

Measurements reported in the present paper were carried out with a wireless instrumentation and processed using the progressive average procedure: the acquisition time is three days if the indoor temperature is stable, otherwise, the time interval must be extended to seven days.

In order to take into account of the above mentioned transient effects, the values of heat flux density and temperature averaged on an adequately long time period must be used in the calculation of the thermal resistance R in place of the instantaneous values (Eq. (1)):

$$R = \frac{\int_0^t [T_{si}(t) - T_{se}(t)]dt}{\int_0^t q(t)dt} \tag{1}$$

where $T_{si}(t)$ is the function of indoor surface temperature vs. time; $T_{se}(t)$ is the function of outdoor surface temperature vs. time; $q(t)$ is the function of heat flux passing through the unit area of the sample vs. time.

Once the experimental data measured at finite and equal time intervals are collected, Eq. (1) is discretized by calculating the ratio between the sum of the differences of surface temperatures and the sum of the heat flux per unit area, acquired for the considered period (Eq. (2)):

$$R = \frac{\sum_{j=1}^{n} (T_{sij} - T_{sej})}{\sum_{j=1}^{n} q_j} \tag{2}$$

where T_{sij} is the indoor surface temperature at jth instant; T_{sej} is the outdoor surface temperature at jth instant; q_j is the heat flux passing through the unit area of the sample at jth instant.

The thermal conductance Λ in non-steady state can be calculated in the same way using Eq. (3):

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{sij} - T_{sej})} \tag{3}$$

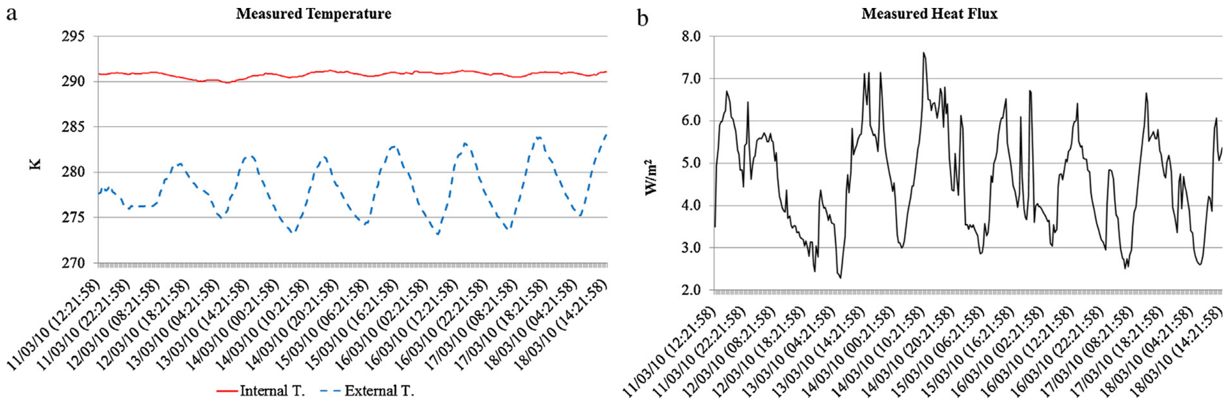


Fig. 1. Measured temperatures on the wall surfaces (a) and heat flux transmitted through the wall (b).

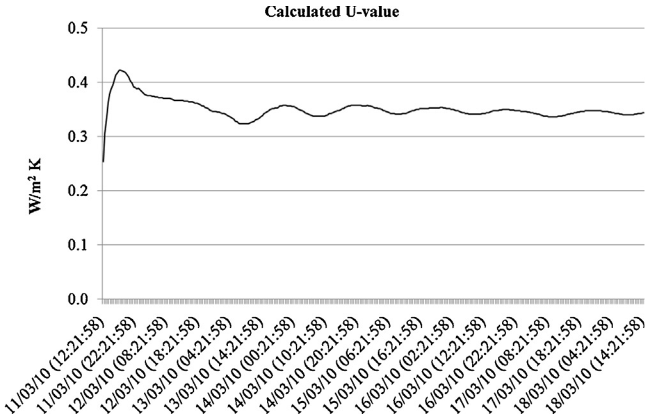


Fig. 2. Trend of the thermal transmittance of the wall.

Finally the thermal transmittance U is obtained by introducing the internal and external liminar coefficients h_i and h_e (Eq. (4)):

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{\Lambda} + \frac{1}{h_e}} \tag{4}$$

Figs. 1 and 2 show an example of in situ thermal transmittance measurements conducted in one of the buildings selected as case studies. The main feature of these measurements is the unsteady-state of external temperatures trend due to the night-day alternation, while the internal temperature remains quite constant around 18 °C (Fig. 1a). The trend of the heat flux (Fig. 1b) is strongly linked to the temperature difference between internal and external conditions; the delay of thermal flux reaches his maximum value of the day (sensor installed on the internal side) some hours later than the temperature difference peak between internal and external conditions. The examined wall is exposed toward the north-east direction and it is not directly hit by solar radiation; in this specific case, the theoretical thermal transmittance of the wall results equal 0.39 W/m^2 K, while the measured thermal transmittance is equal 0.44 W/m^2 K (Fig. 2).

The measurement uncertainty is reduced if the temperature of the internal surface is kept as constant as possible and if the temperature difference between the internal and the external surface is higher than 10 °C (Trethowen, 1986).

The trend of the transmittance value tends to stabilize around the final result of the measurement, which is still affected by errors and uncertainties due to the measurement instrumentation and weather conditions such as temperature, wind and solar irradiation, variations that cannot be controlled during the acquisition period; in general, the uncertainty of in situ thermal transmittance measurements ranges from 14 to 28% (ISO, 1994b).

3. Description of the tested walls

The buildings selected as case studies are located in Umbria Region in central Italy and are designed using principles of bio-architecture. The examined buildings present peculiar features, such as sunspaces (over 50% of the investigated situations), sustainable insulation materials (wood in one third of the cases), and solar shadings (about 50% of the cases). All

Table 1
Stratigraphy and description of the six case studies.

Case 1	
Plaster	1.5 cm
Thermal block $\lambda_{eq.}$=0.220 W/m K	15 cm
Thermal insulation λ=0.037 W/m K	6 cm
Mortar	1 cm
Thermal block $\lambda_{eq.}$=0.220 W/m K	12 cm
Total thickness: 37 cm	
Calculated transmittance: 0.33 W/m^2 K	
Case 2	
Plaster	1.5 cm
Thermal block $\lambda_{eq.}$=0.220 W/m K	12 cm
Air gap	2 cm
Thermal insulation λ=0.033 W/m K	6 cm
Mortar	1 cm
Thermal block $\lambda_{eq.}$=0.143 W/m K	18 cm
Total thickness: 42 cm	
Calculated transmittance: 0.23 W/m^2 K	
Case 3	
Plaster	1.5 cm
Thermal block $\lambda_{eq.}$ = 0.255 W/m K	25 cm
Thermal insulation λ = 0.033 W/m K	6 cm
Air gap	3 cm
Thermal block $\lambda_{eq.}$ = 0.238 W/m K	12 cm
Total thickness: 49 cm	
Calculated transmittance: 0.27 W/m^2 K	
Case 4	
Plaster	2 cm
Thermal block $\lambda_{eq.}$ = 0.260 W/m K	25 cm
Air gap	4 cm
Thermal insulation λ = 0.033 W/m K	6 cm
Mortar	1 cm
Face brick	12 cm
Total thickness: 50 cm	
Calculated transmittance: 0.30 W/m^2 K	
Case 5	
Plaster	1.5 cm
Thermal block $\lambda_{eq.}$ = 0.178 W/m K	25 cm
Thermal insulation λ = 0.033 W/m K	6 cm
Air gap	2 cm
Face brick $\lambda_{eq.}$ = 0.358 W/m K	12 cm
Total thickness: 46.5 cm	
Calculated transmittance: 0.25 W/m^2 K	
Case 6	
Thermal plaster λ = 0.083 W/m K	3 cm
Thermal block λ = 0.151 W/m K	38 cm
Plaster λ = 0.34 W/m K	4 cm
Total thickness: 45 cm	
Calculated transmittance: 0.32 W/m^2 K	

buildings are provided with under-floor heating systems, seven of them are provided with rain water recovery systems. Most of buildings are integrated with PV modules and/or solar collectors, some of them are also equipped with geothermal heat pumps; more information on the buildings can be found in Asdrubali et al. (2013b).

Six walls of the aforementioned buildings were selected as case studies for the current research. The stratigraphy (from the internal surface to the external one) and the thermal transmittance calculated according to ISO 6946 of the six analyzed walls are reported in Table 1. Moreover, the values of thermal conductivity and equivalent conductivity of the individual layers declared by the manufacturer for each case studied are also reported. When data for a specific layer were not available, the thermal properties proposed by the Italian reference standard were used (UNI, 1994).

The calculated thermal transmittance for the six walls ranges from 0.23 W/m^2 K of case 2 to 0.33 W/m^2 K of case 1, demonstrating the medium-high thermal performance of the walls. The thermal transmittance values are lower than the limits established by the Italian Government at the time of construction (in 2006 the limits of thermal transmittance for

Fig. 3. Installation of the sensors on a tested wall: (a) inner surface of the wall; (b) outer surface of the wall; (c) acquisition system.

Table 2
Calculated and measured thermal transmittance values.

	Calculated thermal transmittance W/m^2 K	Measured thermal transmittance W/m^2 K	Difference measured – calculated %
Case 1	0.33	0.39	+15
Case 2	0.23	0.22	−14
Case 3	0.27	0.34	+21
Case 4	0.30	0.37	+19
Case 5	0.25	0.34	+26
Case 6	0.32	0.56	+43

vertical opaque structures for climatic zones D and E[1] were respectively 0.50 W/m^2 K and 0.46 W/m^2 K) and are in line with the limits valid at time of the present paper writing (after 2010 the limits for climatic zones D and E are respectively 0.30 W/m^2 K and 0.28 W/m^2 K).

The first five cases are double walls with an insulating layer 6 cm thick.

In particular cases 1, 2 and 3 are characterized by thermal blocks plastered on both faces and cases 2 and 3 have also air gaps increasing their performance: in these three walls the variation in calculated thermal transmittance values is essentially due to the different performance declared by manufacturers and to the thicknesses of the different layers. It is worth noting that the worst performing wall, case 1, includes an insulating layer characterized by a conductivity value significantly higher than the one of other situations.

Cases 4 and 5 are very similar and they both present an exterior surface characterized by face bricks. The difference in calculated thermal transmittance (0.05 W/m^2 K) is mainly due to the different thermal blocks employed in the two walls.

Case 6 is a wall without insulation; nevertheless, the thermal performance is similar to those of the other walls thanks to the excellent values of the thermal conductivity of the blocks and plaster declared by the manufacturers.

4. Results of in situ thermal transmittance measurements

Measurements were performed following the procedures given by standards; each wall was monitored for at least seven days. Internal conditions were kept constant by the floor heating systems of the apartments.

Fig. 3 shows the RTD Pt1000 temperature probes (accuracy = $\pm(0.10 + 0.0017|T|)$°C) and the heat flux sensor (accuracy = ±5% at 20 °C) applied on the wall named Case 5, as well as the Optivelox wireless acquisition system.

A preliminary infrared survey was performed in order to place the probes far from thermal singularities.

Table 2 reports the measured values of the thermal transmittance (with uncertainties according to reference (ISO, 1994b)) together with the calculated ones; differences between measured and calculated values are also reported.

The results of the measurements performed on the first five cases studies are generally slightly higher than the corresponding calculated values of the thermal transmittance. As far as case 2, the measured transmittance is on the contrary slightly lower than the calculated one. The presence of insulation in these five case studies ensures a good thermal behavior of the wall. The insulating materials seem to have thermal properties similar to those declared by the manufacturers, as a

---

[1] The Italian territory is divided into six climatic zones from A (warmest) to F (coldest); the division takes into account of the daily temperatures in each area.

consequence, the measured thermal transmittance values of the analyzed walls ranges from 0.20 to 0.40 W/m^2 K, apart from uncertainty.

The good performance of Case 6 (without insulation) depends mainly on the thick thermal block with excellent declared thermal conductivity values, since there is not a layer with a thermal insulating material. In this case, the difference between the calculated and the measured transmittance values is definitely higher if compared with the other five case studies: an explanation of this mismatch could be due to an overestimation of thermal resistance declared by the manufacturer.

5. Conclusions

Thermal transmittance is the fundamental parameter to characterize the heat losses of building envelopes. It is commonly measured in controlled laboratory conditions or estimated by means of numerical simulation starting from the values of thermal conductivity of the single layers constituting the opaque structure.

Nevertheless, none of the two methodologies allows to examine the actual behavior of the built wall in real conditions during the use phase of the building: at this aim, in situ thermal transmittance measurements have to be performed.

Six perimeter walls of buildings built with green architecture techniques were investigated in the present research; the walls are characterized by excellent values of thermal transmittance. The buildings are located in central Italy and their construction was funded by the Umbria Region.

In situ thermal transmittance measurements of the six walls allowed the comparison of the values calculated from the thermal properties of the single materials given by manufacturers with the actual performance measured on the built walls. Measurements were performed in compliance with the Standard ISO 9869 using temperature probes and heat flux sensors; other methodologies based on infrared surveys are available from Literature, but they still require further improvements.

The performed comparisons seem to be congruent: similar values of thermal transmittance obtained from calculations and in situ measurements, for those walls including artificial insulating layers, were found; in particular, the measured values of thermal transmittance are always slightly higher than the calculated ones, with the exception of case 2. On the other hand, theoretical values seem to be definitely overestimated for the wall composed of a thick thermal block with low declared thermal conductivity.

A result of the present study is that the measured *U*-value is always higher than the calculated one, in accordance with previous researches (BRE, 2000).

Several factors can explain the differences between measured and calculated values, such as:

- the performance data declared by the producers of building materials are often overestimated due to marketing reasons;
- thermal performance of building elements and materials are measured in controlled laboratory conditions;
- the actual installation of the materials in real buildings can be not perfectly made;
- external conditions (rain, wind, etc.) can influence the measurements.

The gap between measured and calculated values of thermal transmittance does not particularly affect the design of the heating plants, because they are commonly oversized in order to take account of the pejorative effects of the installation process, thermal bridges, misuse of the heating system, etc.

On the contrary this gap becomes important when dealing with building certification schemes (such as LEED, BREEAM, etc.), that assign points on the basis of the calculated thermal transmittance of the building envelope: more points are obtained if low values of thermal transmittance are achieved. However, as shown in Table 2, calculated values are not perfectly representative of the actual behavior of the envelope, being often lower than the measured ones. So it could be worth introducing a monitoring survey during the exercise of the building in order to check if the calculated values declared in the building certification correspond to reality.

Therefore the in situ evaluation of the thermal transmittance becomes essential especially in high energy performing buildings, such as nearly zero energy buildings (Berardi, 2013), since an in situ thermal transmittance significantly higher than the declared one affects the actual performance of the building and may compromise its economic cost-benefit analysis.

Future work will include the execution of the in situ measurements in other buildings funded by Umbria Region within the same Program, in order to have a larger sample of walls; measurements will be carried out with more than one heat flux meter placed on the same wall and in different seasons.

Acknowledgement

The present study is part of wider activity funded by the Residential Buildings Policy Office, Umbria Region, Italy.

References

Albatici R, Tonelli AM. Infrared thermovision technique for the assessment of thermal transmittance value of opaque building elements on site. Energy Build 2010;42:2177–83.

Asdrubali F, Baldinelli G. Thermal transmittance measurements with the hot box method: calibration, experimental procedures, and uncertainty analyses of three different approaches. Energy Build 2011;43(7):1618–26.

Asdrubali F, Baldinelli G, Bianchi F, Libbra F, Muscio A. Comparative analysis of different methods to evaluate the thermal conductivity of homogenous materials. In: Proceedings of ASME – ATI – UIT 2010 Thermal and Environmental Issues in Energy System. Sorrento, Italy; 2010.

Asdrubali F, Baldinelli G, Bianchi F. A quantitative methodology to evaluate thermal bridges in buildings. Appl Energy 2012;97:365–73.

Asdrubali F, Baldassarri C, Fthenakis V. Life cycle analysis in the construction sector: guiding the optimization of conventional Italian buildings. Energy Build 2013a;64:73–89.

Asdrubali F, Buratti C, Cotana F, Baldinelli G, Goretti M, Moretti E, Baldassarri C, Belloni E, Bianchi F, Rotili A, Vergoni M, Palladino D, Bevilacqua D. Evaluation of green buildings overall performance through in situ monitoring and simulations. Energies 2013b;6:6525–47.

Berardi U. Clarifying the new interpretations of the concept of sustainable building. Sustain Cities Soc 2013;8:72–8.

Building Research Establishment. BRE Client Report No. 78132, Field investigations of the thermal performance of construction elements as built. 2000.

Desogus G, Mura S, Ricciu R. Comparing different approaches to in situ measurement of building components thermal resistance. Energy Build 2011;43:2613–20.

European Committee for Standardization. Standard EN 1934, Thermal performance of buildings: Determination of thermal resistance by hot box method using heat flow meter – Masonry. 1998.

European Committee for Standardization. Standard EN 1745, Masonry and masonry products: Methods for determining thermal properties. 2012.

Ente Nazionale Italiano di unificazione. Standard UNI 10351, Materiali da costruzione. Conduttività termica e permeabilità al vapore.Construction materials: Thermal conductivity and vapour permeability 1994.

Fokaides PA, Kalogirou SA. Application of infrared thermography for the determination of the overall heat transfer coefficient (U-value) in building envelopes. Appl Energy 2011;88:4358–65.

International Organization for Standardization. Standard ISO 8302, Thermal insulation: Determination of steady-state thermal resistance and related properties: Guarded hot plate apparatus. 1991.

International Organization for Standardization. Standard ISO 8990, Thermal insulation: Determination of steady-state thermal transmission properties: Calibrated and guarded hot box. 1994.

International Organization for Standardization. Standard ISO 9869, Thermal insulation: Building elements: In-situ measurement of thermal resistance and thermal transmittance. 1994.

International Organization for Standardization. Standard ISO 6946, Building components and building elements: Thermal resistance and thermal transmittance: Calculation method. 2007.

Kus H, Özkan E, Göcer Ö, Edis E. Hot box measurements of pumice aggregate concrete hollow block walls. Construct Build Mater 2013;38:837–45.

Morales MP, Juárez MC, López-Ochoa LM, Doménech J. Study of the geometry of a voided clay brick using rectangular perforations to optimize its thermal properties. Appl Therm Eng 2011;31:2063–5.

Peng C, Wu Z. In situ measuring and evaluating the thermal resistance of building construction. Energy Build 2008;40:2076–82.

Trethowen H. Measurement errors with surface-mounted heat flux sensors. Build Environ 1986;21(1):41–56.

Wakili KG, Tanner C. U-value of a dried wall made of perforated porous clay bricks: Hot box measurement versus numerical analysis. Energy Build 2003;35:675–80.