TECHNICAL REPORT

HEAT AND MOISTURE TRANSFER MEASUREMENT PROTOCOLS FOR BUILDING ENVELOPES

Mostafa KAZEMI (Liege University, Belgium)

Islam BOUKHELKHAL University of Constantine 3, Algeria)

Piotr KOSIŃSKI (University of Warmia and Mazury, Poland)
Shady ATTIA (Liege University, Belgium)

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Summary

1. Introduction

The temperature and humidity present in the building can cause energy consumption, degradation of building materials, and a feeling of discomfort for humans. Guidance is needed to control the flow of heat and humidity and is proven to work in building envelopes. This report present an overview on the measurements of heat and moisture transfer in walls are carried out using a multitude of scientific and professional instruments as well as several methods according to international standards.

2. Moisture transfer:

2.1. Methods based on standards for measuring moisture transfer in brick walls:

2.1.1. Gravimetric method (suggested by Prof. Kosinski):

The so-called “gravimetric method” is generally considered the most reliable method for the determination of the moisture content in brick walls. Gravimetric means ‘relating to the measurement of weight. The method consists of the sampling of powder or solid pieces from the masonry followed by gravimetric determination of the moisture content of the sample after drying. Because of the size of the samples needed, this method can be considered low-invasive.

The European Committee for Standardisation (CEN), Technical Committee for Cultural Heritage (TC346) in the recently established standard focused on the measurement of moisture content (MC) in cultural heritage materials [1], recommends weighing (EN 322:1993 and EN 13183-1:2002) next to conductivity (EN 13183-2:2002) and capacitance (EN 13181-3:2005) as one of the methods for the assessment of the moisture content.

In the following paragraph, a procedure for the gravimetric assessment of the moisture content and distribution in walls is described and commented. A detailed description of the sampling and interpretation of the data is given as well.

The sampling involves the extraction of material from the wall using dry drilling. A solid drill or a hollow drill (core drilling) can be used. The Italian Recommendation NORMAL 40/93 reports: “the use of low-speed drilling for material sampling is recommended to avoid samples heating and moisture loss by evaporation, as well as shrewd sampling points choice and proper standardization of the whole measuring procedure”

Drilling should be carried out at different heights (e.g. 0.2, 0.5, 1, 1.5 m up to the undamaged area) and depths (0-20 mm, 20- 50 mm, 50-100 cm up to the middle of the wall) along with a vertical profile. As the moisture content depends also on the type of material, it is recommended to sample in the same type of material (brick, stone, or mortar) at different heights. Information on the type of material and the presence of damage should be reported too, to correctly interpret the results. The samples, which should weigh at least 1-2 g, are collected in bottles or plastic bags, which are hermetically closed and transported to the laboratory.

When the sampling is repeated after an intervention against rising damp, to assess its effectiveness, this must take place on the same brick/stone unit drilled before the intervention, since the heterogeneity of (historical) building materials may lead to relevant differences in their moisture content.

Samples are then dried in an oven at 105°C for 24 h (Fig. 1). Moisture content (MC) is measured according to Eq. 1:

$$MC = ((\text{wet weight} - \text{dry weight}) / \text{dry weight}) \times 100\% \quad (1)$$

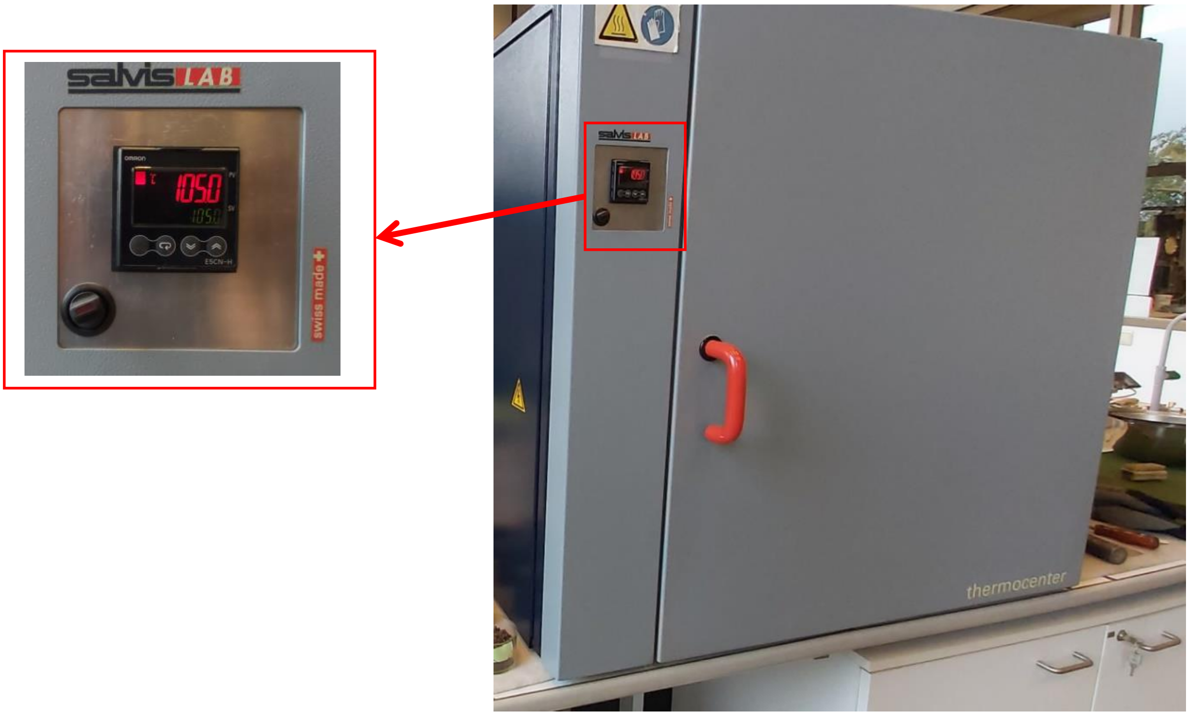

Fig. 1. Oven for drying samples at 105 °C.

2.1.2. Literature review for the in-situ measurements of moisture transfer in brick wall

Moisture within walls can have a serious detrimental impact on buildings and undermine their long-term durability and integrity. It promotes biodegradation contributing to problems such as mold growth, staining, and poor internal environment. Furthermore, moisture is known to reduce thermal performance and cause deterioration of insulation materials [1].

Moisture content can be measured using various direct and indirect methods. Said [2] reviewed in situ moisture measurement methods of walls and categorized them according to measurement principles; resistance, voltage, and capacitance methods which are based on electrical properties of materials that vary with the material's moisture content. Thermal-based methods have also been used for moisture measurement. Innovative methods using neutron probes [3, 4], nuclear magnetic resonance (NMR) [5], Medical ECG electrodes [6], and fiber optic sensors [7] have also been used by researchers.

Among the destructive direct methods, the most reliable results are obtained when using the destructive direct gravimetric method [8]. It allows the moisture value to be determined on the surface of the tested partition, as well as in its thickness. When using it, however, it is necessary to collect in-situ samples of material for laboratory tests [9].

In the case of non-destructive methods, their undoubted advantage is the fact that there is no interference in the structure of a wall and there is, therefore, an opportunity to research any number of measuring points. However, out of the many non-destructive methods for the testing of the moisture content in brick walls that have been described in the literature, only a few of them allow the moisture content and its distribution in a wall to be reliably assessed [10, 11].

3. Heat transfer:

3.1. International standards for the in-situ measurements of heat transfer in walls

3.1.1. ISO 9869-1 (2014)

This standard describes the heat flow meter method for the measurement of the thermal transmission properties of plane building components, primarily consisting of opaque layers perpendicular to the heat flow and having no significant lateral heat flow. In this standard, the thermal resistance of a wall is measured using two thermocouples mounted opposite to each other on two sides of the wall and a heat flux sensor mounted next to the thermocouple on one side, preferably the interior side because of higher stability in temperature.

The heat flow meter measurement method is also suitable for components consisting of quasi-homogeneous layers perpendicular to the heat flow, provided that the dimensions of any inhomogeneity close to the heat flow meter (HFM) is much smaller than its lateral dimensions and are not thermal bridges which can be detected by infrared thermography.

ISO 9869-1:2014 describes the apparatus to be used, the calibration procedure for the apparatus, the installation and the measurement procedures, the analysis of the data, including the correction of systematic errors, and the reporting format. This standard introduces the Average and the Dynamic Methods to measure R_c-value (thermal conductive resistance) as described in the following.

3.1.1.1. Average Method

In the Average Method, the R_c-value of a wall, based on measurements of ΔT (the surface temperature gradient), q (the heat flux), and t (the time interval), can be derived as follows:

$$R_c = \frac{\sum_{t=0}^{m} \Delta T^t}{\sum_{t=0}^{m} q^t} \tag{2}$$

To report an acceptable R_c-value based on the Average Method, the main criteria to fulfill and stop the measurement include the following:

- The measurement period should take at least 72 h
- The value calculated at the end of the data set should not deviate more than ±5% from the respective value obtained 24 h before.
- The resulting value when applying the method to the first 67% of data should not deviate by more than ±5 % from the respective value when analyzing the last 67% of the data.
- The change in the stored heat in the wall should not be more than 5 % of the heat passing through the wall over the measuring period.

3.1.1.2. Dynamic Method

In the Dynamic Method, the internal wall heat flux q_i (W/m^2) at each time interval t_i is calculated by the following equation:

$$q_i = \frac{1}{R}\left(T_{si}\, i - T_{se}\, i\right) + K_1 \dot{T}_{si}\, i + K_2 \dot{T}_{se}\, i + \sum_{n} P_n \sum_{j=i-p}^{i-1} \dot{T}_{si}\, j \left(1-\beta_n\right) \beta_n (i-j) + \sum_{n} Q_n \sum_{j=i-p}^{i-1} \dot{T}_{se}\, j \left(1-\beta_n\right) \beta_n (i-j) \tag{3}$$

A linear system of equations is created and is expressed in a matrix form as:

$$\vec{q} = X \cdot \vec{Z} \tag{4}$$

$\vec{Z}$ an array including all the unknown parameters, including R-value, and X the matrix containing the measured temperatures with their derivatives.

The solution that minimizes the sum of the differences $S^2 = (q_{i,calc}-q_i)^2$ between calculated and experimental heat fluxes is calculated by solving the following equation:

$$\vec{Z} = \left[(X)'(X)\right]^{-1}(X)'\vec{q} \tag{5}$$

To report an acceptable R_c-value based on the Dynamic Method, the main criteria to fulfill the measurement include the following:

- The goodness of fit between the experimental and the calculated values of heat flux indicates the accuracy of the result.
- The uncertainty (as it is defined by the standard) should be lower than 10% for probability 0.90.

3.1.2. ASTM C 1155-95

This standard describes how to obtain and use data from in-situ measurements of temperatures and heat fluxes on building envelopes to compute thermal resistance. This standard provides an estimate of that value for the range of temperatures encountered during the measurement of temperatures and heat flux. The equipment can be installed according to ASTM C 1046-91. ASTM C 1155-95 introduces the Summation and the Sum of Least Square Methods. The methods require the measurement of the internal and external surface temperature and the internal heat flux for at least three days and they are R_c-value measurements as described in the following.

3.1.2.1. Summation method

In the Summation Method, the R_c-value of a wall, based on measurements of ΔT (the surface temperature gradient), q (the heat flux), and t (the time interval), can be derived as follows:

$$R_c = \frac{\sum_{t=0}^{m} \Delta T^t}{\sum_{t=0}^{m} q^t} \tag{6}$$

To report a unique R_c-value result:

A convergence factor (CR_n) is defined:

$$CR_n = \frac{R(t) - R(t-n)}{R(t)} \tag{7}$$

- The value n is a time interval chosen by the user and varies between 6 and 48 h.
- The factor CR_n should remain below 0.10 for at least 3 periods of n.

For more results, the coefficient of variation of results should be less than 10%.

3.1.2.2. Sum of Least Square Method

In the Sum of Least Square Method, to estimate the R_c-value, the masonry is assumed to be thermally equivalent to a homogenous and one-layered wall with the real thickness, d, and unknown thermal properties.

The governing equation of conductive heat transfer in the assumed wall is:

$$\frac{\partial}{\partial x}\left(k_{eq}\frac{\partial T}{\partial x}\right) = (\rho C_p)_{eq}\frac{\partial T}{\partial t} \tag{8}$$

where k_{eq} and $(C_p)_{eq}$ are the thermal conductivity and the heat capacity of the equivalent wall respectively.

The equation can be solved with the Crank-Nicholson method, assuming the thermal properties, $k_{eq,}$ and $(C_p)_{eq}$, and defining the measuring data as boundary conditions.

The calculated heat flux or temperature values are compared with the experimental values.

To report an acceptable R_c-value based on the Dynamic Method, the main criterion to fulfill the measurement include the following:

- The goodness of fit between the experimental and the calculated values of heat flux indicates the accuracy of the result.

For more results, the uncertainty remains within 10% at a 95% confidence interval.

3.2. Devices available at labs for the in-situ measurements of heat transfer in wall

3.2.1. Devices at SBD Lab

3.2.1.1. U-Value and Heat Flux Measurement Kit

This device allows measuring the U-Value with superior accuracy (Fig. 2). Its features include as mentioned below:

- Product: gSKIN® KIT-2615C
- Article Number: A-163479
- Calibrated Plug-and-Play solution.
- Measurement of U-value (W/(m²K)), heat flux (W/m²), and 2 temperatures (°C).
- Compatible with standards ISO 9869 and ASTM C1046 /ASTM C1155.
- Stores up to 2 million data points.
- Battery lifetime >1 month.
- High sensitive thermal detectors.
- Read-out software included.
- Compact design.
- USB interface.
- Comes with MOUNT-1235 (double sided adhesive tape)
- Heat Flux Range Min / Max [W/m²]: ±300
- Heat Flux Resolution [W/m²]: <0.22
- Temperature Accuracy [°C]: ±0.5 (-10...+46 °C) ±2.0 (-55...+125 °C)
- Min. Sensor Sensitivity (S) [µV/(W/m²)]: 7.0
- Software: Installation - SW sent by email / via download link
- Logger Dimensions (mm): 52 x 20 x 15
- Operating Temperature Range Min/Max [°C]: -40 / 100 (-25 / 65 for Logger)
- Operating System: Windows 2000 / XP / Vista / 7 / 8
- Calibration Accuracy [±%]: 3
- Calibration Temperature Range Min/Max [°C]: -30 / 70
- Heat Flux Sensor Cable Length [m]: 1.5 (with connector)
- Temperature Sensor 1 / 2 Cable Length [m]: 5.0 / 1.0
- Measurement Frequency: 1/s to 1/h

Fig. 2. U-Value Kit device.

3.2.2. Devices at Lab of Prof. Kosinski

3.2.2.1. Heat flow meter Fox 600; LaserComp

The instrument serves as a tool for measuring the coefficient of thermal conductivity of building materials (Fig. 3). Its features include as mentioned below:

- The range of the measuring lambda coefficient varies from 0.01 till 0.2 $Wm^{-1}K^{-1}$, measuring accuracy is ~1%, repeatability ~0.2%, reproducibility ~0.5%.
- Max temperature of the hot plate is 80°C, and the minimum temperature of the cold plate is 20°C.
- The stability of the sustained temperature is +-0.03°C.
- Thickness accuracy is +-0.025mm.
- Max sample dimensions: 600X600mm.
- Minimal sample dimensions: 450x450mm.
- Max sample thickness: 200mm.
- Measuring area: 300x300mm.
- The instrument can work separately or with cooperation with the software WinTherm installed on a standard PC.

Fig. 3. Heat flow meter device.

3.2.3. Other devices that can measure the heat transfer

3.2.3.1. HFP01 & HFP03 Hukseflux heat flux sensor

HFP01 is the world's most popular sensor for heat flux measurement in the soil as well as through walls and building envelopes (Fig. 4). The total thermal resistance is kept small by using a ceramics-plastic composite body. The sensor is very robust and stable. It is suitable for long-term use in one location as well as repeated installation when a measuring system is used at multiple locations.

HFP03 is the high-sensitivity version of HFP01. It differs in sensor technology and has a larger size. The sensor working principle and considerations for use are the same.

Fig. 4. HFP01 heat flux sensors in use on a wall.

3.3. Literature review for the in-situ measurements of heat transfer in wall

Two international standards are currently available for the estimation of the thermal resistance of building envelope components using in-situ measurement data − ISO 9869 and ASTM C 1155 & C 1046 [12, 13, 14]. The ISO 9869 standard introduces the Average and the Dynamic Method, while ASTM C 1155 standard introduces the Summation and the Sum of Least Square Method. All methods require the measurement of the internal and external surface temperature and the internal heat flux for at least three days. The Average and the Summation methods are similar to each other with their main advantages being the simplicity in use and the rapid export of results, making them the most widely used methods. However, their precision strongly depends on the measuring conditions [12, 13, 15]. On the other hand, the Sum of Least Square and the Dynamic method, are more likely to provide reliable results regardless of the measuring conditions [12, 13], but require the development of complex algorithms and computational tools for the analysis of the time series data due to their sophisticated methodology. For this reason, these methods are less commonly used. The main limitation of all the standardized methods is that the precision of the R-value measurement depends on the measuring conditions and the duration of the measuring period. Generally, the optimum measuring conditions are the high-temperature difference with low-temperature variations. Flanders et al. [16] analyzed the estimations of R-value using the two ASTM methods (Summation and Sum of Least Square method) and concluded that the agreement between the two methods was within 1–13% for cases with high internal and external surface temperature difference. Deconinch and Roels [15] and Gaspar et al. [17] compared the two ISO methods (Average and Dynamic method) in terms of different measuring conditions and they concluded that the Average method performs equally well to the Dynamic method when the measuring conditions are optimum. In the case of low-temperature difference, only the Dynamic method leads to reliable results. Gaspar et al. [18] tried to improve the accuracy of in situ measurement of low U value facades, using the widely used HFM ISO 9869-1 [12] method and exploring the limits of its conditions. The results showed that temperature differences above 19 °C required a test duration of 72 h, while for lower temperature differences the test duration must be prolonged. The accuracy of temperature sensors had a greater impact on the accuracy of measurement in the initial cycles of the test. Likewise, the accuracy of ambient temperature sensors was found to have a considerable influence on the uncertainty of measurements. Roulet et al. [19] compared the same two methods regarding the influence of the indoor/outdoor temperature difference. They concluded that the results of the two ISO methods were stable when the indoor temperature was constant before and during the measuring period. Desogus et al. [20] investigated the results of the Average method for two different measuring conditions. They concluded that the measuring conditions, and particularly the surface temperature difference, greatly influence the results. The smaller the temperature difference the less precise were the results. The second critical measuring parameter is the required duration of the measurements. It can be defined as the minimum duration required by the method to provide reliable results. According to the standards, this duration can range from 72 h to more than 7 days, depending on the method, the measuring conditions, and the type of the tested wall. In the case of the Average and Summation methods, it is referred to as convergence time and is determined by different criteria for each method. However, in the case of the Dynamic and the Sum of Least Square methods, it is not clearly defined. Gaspar et al. [17] showed that the accuracy of the Dynamic method was significantly improved by extending the measuring period. From the above brief literature review, it becomes clear that the main weaknesses of the standardized R-value measurement methods, namely the effect of the measuring conditions and the duration of the measuring period, are limiting the usability of the methods and can potentially increase the uncertainty of the results. Gasparet al. [17] suggested that further investigation regarding the optimum measuring period is needed to improve the reliability of the results. Furthermore, Desogus et al. [20] have concluded, that it is difficult to achieve ideal environmental measuring conditions especially in mild climates and the solution to that could be the selection of the appropriate method among the available standardized technique.

Atsonios et al. [21] compared different methods given by ISO 9869 and ASTM C 1155 for heat transfer. All methods were employed for the Measurement of the R-value of three different building walls (a lightweight dry-wall construction, rubble, and a brick wall). According to the results, the mean temperature difference between the surfaces of the wall and the direction of heat flow during the day strongly influence the duration of the required measuring period and the variability of the results. In particular, the Average and Summation methods require a high-temperature difference and, as a consequence, a stable direction of heat flow to provide acceptable and reliable results in a short measuring period. In cases where the temperature difference is lower than 3 ˚C, the results of the Average and Summation methods have high and not acceptable coefficients of variation, respectively. Hence, the Average and Summation methods should not be used when the temperature difference is too low or their criteria should be stricter.

Ahmad et al. [22] studied hollow reinforced precast concrete walls based on standards ASTM C1155 [13], ASTM C 1046–95 [14], and ISO 9869 [12] in Saudi Arabia finding 6 days enough for satisfaction of the convergence criteria. However, such a short period is generally insufficient for obtaining results, especially, in countries with less stable climates [23]. Smaller temperature gradients along two sides [24] and heavy construction of walls are other shortcomings [13] of such measurements. In Scotland, with a monitoring period of 17 days, Baker [25] compared the in-situ measurement results based on ISO 9869 [12] with the ones obtained in the lab, resulting in a good agreement. The study was further developed [26] by studying a greater number of case studies where he showed the necessity of longer periods of in-situ measurements for achieving satisfactory results.

It can be stated there are two main problems with which the Average method for the heat transfer can be associated: First, the long duration of the measurements due to unstable boundary conditions [26, 12], and second, the problem of R_c-value precision. The duration required for the R_c-value to be reported, fulfilling the criteria of ISO 9869 [12], can be very long. This becomes a barrier and therefore, makes it difficult for the method to be applied often in practice. To tackle this issue, Rasooli and Itard [27, 28] assessed the advantage of using two sides' different heat flux time series in R_c-value measurements for heterogeneous and homogeneous walls based on ISO 9869 [12]. In the case of a heterogeneous wall, the insulation on the exterior surface makes the exterior R_c-values graph much more stable and converging very quickly, whereas having the insulation on the interior side, the one from the interior side is more stable and converges quicker. Moreover, when the insulation layer in the middle of the wall in between the two bricklayers, the interior R_c-value converged more quickly than the one from the outdoor due to higher stability of the inside temperature than the outside temperature. In the case of a homogeneous wall, the average R_c-value has been shown to converge much quicker (up to 10 times quicker) to the actual value than interior and exterior R_c-value.

Reference

1. R. Walker, S. Pavía, M. Dalton, Measurement of moisture content in solid brick walls using timber dowel, Mater. Struct. 49 (7) (2016) 2549–2561.
2. Said MN (2004) Moisture measurement guide for building envelope applications. Research Report 190. Building Envelope and Structure Program, Institute for Research in Construction, National Research Council Canada.
3. Larsen PK (2004) Moisture measurement in Tirsted Church. J Arch Conserv 1(10):22–35
4. Hansen MH (2005) Measurement of moisture content in basement brick walls—a comparison of different methods. In: Proceedings of the 7th Nordic building physics symposium, Icelandic Building Research Institute, & Royal Institute of Technology, Reykjavik, Iceland.
5. Pel L, Huinink H, Kopinga K (2002) Ion transport and crystallization in inorganic building materials as studied by nuclear magnetic resonance. Appl Phys Lett 81(15): 2893–2895.
6. Sass O, Viles HA (2006) How wet are these walls? Testing a novel technique for measuring moisture in ruined walls. J Cult Herit 7:257–263.
7. Healy W, Luo S, Evans M, Sucheta A, Liu Y (2003) Development of an optical fiber-based moisture sensor for building envelopes. In: Proceedings of the 24th AIVC conference & BETEC conference—ventilation, humidity control and energy, Washington DC.
8. Hoła, A. Measuring of the moisture content in brick walls of historical buildings the overview of methods. In Proceedings of the 3rd International Conference on Innovative Materials, Structures and Technologies (IMST 2017), Riga, Latvia, 27–29 September 2017.
9. A. Hoła; Ł. Sadowski, Verification of a nondestructive method for assessing the humidity of saline brick walls in historical buildings, Applied Sciences, 10(19), 2020.
10. Adamowski J, Hoła J and Matkowski Z 2007 Drying and renovation of flooded buildings *Naprawy i Wzmocnienia Konstrukcji Budowlanych* vol **2** (Bielsko-Biala: PZITB) pp 5-43.
11. Karyś J et al. 2001 *Protecting buildings against biological corrosion* ed J Ważny and J Karyś (Warsaw: Arkady).
12. ISO, 9869, Thermal Insulation – Building Elements – In situ Measurement of thermal Resistance and Thermal Transmittance, 1994.
13. ASTM, C 1155-95 (Reapproved 2001): Standard practice for determining thermal resistance of building envelope components from the in-situ data.Annual Book of ASTM Standards, 2001. 04.06.
14. ASTM, C 1046-95 (Reapproved 2001): Standard practice for in-situ measurement of heat flux and temperature on building envelope components. Annual Book of ASTM Standards, 2001. 04.06.
15. A.-H. Deconinck, S. Roels, Comparison of characterisation methods determining the thermal resistance of building components from on site measurements, Energy Build. 130 (2016) 309–320.
16. S.N. Flanders, A.O. Desjarlais, T.J. Kunz, A comparison of two techniques for R-value calculcation, using winter in-situ data, Thermal Envelops VI/HeatTransfern in Walls I-Principles (1995) 151–161.
17. K. Gaspar, M. Casals, M. Gangolells, A comparison of standardized calculation methods for in situ measurements of fac¸ ades U-value, Energy Build. 130(2016) 592–599.
18. K. Gaspar, M. Casals, M. Gangolells, In situ measurement of façades with a low U-value: Avoiding deviations, Energy Build. 170 (2018) 61–73.
19. C. Roulet, J. Gass, I. Marcus, In situ U value measurement: reliable results in short time by a dynamic interpretation of the measurement, ASHARE Trans. 93(1987) 1371–1379.
20. G. Desogus, S. Mura, R. Ricciu, Comparing different approaches to in situ measurement of building components thermal resistance, Energy Build. 43(10) (2011) 2613–2620.
21. Atsonios IA, Mandilaras ID, Kontogeorgos DA, Founti MA. A comparative assessment of the standardized methods for the in–situ measurement of the thermal resistance of building walls. Energy Build 2017;154:198–206.
22. A. Ahmad, M. Maslehuddin, L.M. Al-Hadhrami, In situ measurement of thermal transmittance and thermal resistance of hollow reinforced precast concrete walls, Energy Build. 84 (2014) 132–141.
23. Trust, E.S., Post-construction testing—a professionals guide to testing housing for energy efficiency (2005 edition). 2005.

24. G. Desogus, S. Mura, R. Ricciu, Comparing different approaches to in situ measurement of building components thermal resistance, Energy Build. 43(10) (2011) 2613–2620.
25. P. Baker, In Situ U-value Measurements in Traditional Buildings–preliminary Results, Historic, Edinburgh, 2008.
26. P. Baker, U-values and Traditional Buildings: in Situ Measurements and TheirComparisons to Calculated Values, Historic Scotland Technical Paper, 2011,pp. 10.
27. A. Rasooli, L. Itard, In-situ characterization of walls' thermal resistance: an extension to the ISO 9869 standard method, Energy Build. 179 (2018) 374–383.
28. A. Rasooli , L. Itard , C.I. Ferreira , A response factor-based method for the rapid in-situ determination of wall's thermal resistance in existing buildings, Energy Build. 119 (2016) 51–61.