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New measurement procedure for U-value assessment via heat flow meter

Massimiliano Scarpa, Paolo Ruggeri*, Fabio Peron, Mario Celebrin, Massimiliano De Bei

University IUAV of Venice, Dorsoduro 2206, Venice, 30123, Italy

Abstract

Methods for building envelope inspection are well known since 70's. However, measurement instruments and software improve, making methods for building envelope inspection susceptible to further improvements. In particular, the present paper deals with building envelope assessments performed via heat flux meters and reports the outcomes of a monitoring campaign verifying a measurement procedure proposed by the authors. Such a procedure is aimed at the improvement of the accuracy and reliability in the on-field measurement of the U-value of building constructions. In detail, the proposed method exploits an experimental device providing controlled local heating aimed at speeding up the measurement process and limiting temperature fluctuations, with possible improvements over the calculation of the final U-value. The advantages and limits of this measurement procedure are explained in this paper, together with possible future improvements.

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Keywords: heat flow meter; measurement procedure; U-value

1. Introduction

The assessment of building envelope thermal characteristics is critical for the reliable assessment of building energy performances, for energy certification, energy audits and design in case of renovations. Moreover, the reliable assessment of the thermal performances of building constructions is necessary in the case of field verification for the fulfilment of design U-values or for litigations about building construction quality level. The U-value is the parameter

* Corresponding author. Tel.: +39-041257-1485; fax: +39-041257-1483.
E-mail address: pruggeri@iuav.it

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that mostly characterizes the thermal behaviour of the building construction, especially if ventilation is limited by heat recovery [1]. The assessment of the U-value may take place through standard calculation methods. These methods are based on the calculation of building construction thermal parameters starting from the material layers (and related thermal properties) present in the building construction, according with ISO 7345 [2] and ISO 6946 [3]. In this case, mainly 3 sources of data may be used in U-value assessment. The first uses Abacus: the material layers constituting the building construction and consequent thermal properties are defined by basing on abaci of typical building constructions in analogous buildings, by considering the year of construction or renovation, location and intended use of the building, as well as the building construction's thickness. The second uses design data. The assessment of the material layers constituting the building construction derives from design technical sheets, where available. The third uses endoscopy. The series of layers composing the building construction is assessed by visual inspection and measurement of building construction material layers via endoscopy. Another way to obtain the U-value is the hot box method [4]. It consists in measuring the thermal parameters of the building construction in laboratory, by imposing well-defined boundary conditions taking place in two contiguous thermally controlled rooms sharing the building construction itself. This method is used in testing laboratories for the evaluation of reference building constructions.

Another experimental method uses heat flow meter, for on-site measurement [5, 6] of the thermal behaviour of the building construction and consequent derivation of the main thermal parameters.

Moreover, also assessment procedures based on thermography are used under specific conditions [7]. In order to avoid uncertainties consequent to the actual building realization and the thermal properties of material layers, the heat flow meter method should be preferred, when existing buildings are considered. Anyway, this method requires long measurement periods and the reliability of the derived results is relevantly affected by the presence of fluctuations of internal heat gains and indoor and outdoor temperatures. In particular, the measurement procedure currently used in the frame of the heat flow meter method is characterized by the many sources of uncertainty and the consequent uncertainty contributions (ISO 9869-1 [8]):

- $u_{Sensors}$. This uncertainty is due to the calibration of the heat flow meter and temperature sensors and is equal to about 5 %, after a correct calibration;
- $u_{Data\ logger}$. This uncertainty is related to the accuracy of the data logging system and is usually negligible;
- $u_{Contact}$. This uncertainty is due to the contact thermal resistance between the heat flow meter plate and the internal side of the building construction, approaching about 5 % after a careful installation;
- $u_{Superposition}$. This uncertainty is due to the influence of the thermal field consequent to the superposition of the heat flow meter over a limited area at the internal side of the building construction and is equal to about 2–3 %;
- $u_{Boundary\ conditions}$. This uncertainty is due to the random variation of the temperatures and heat flows consequent to indoor temperature variation and heat gains and to outdoor weather conditions. It can be lowered down to ± 10 %;
- $u_{Temperature\ distribution}$. This uncertainty is due to uneven temperature distribution in the room air and to the difference between air and radiant temperatures, approaching about 5 %.

As a consequence, in case of well performed in-situ measurements, the minimum expectable combined (in quadrature) accuracy is around 14 %. Under real applications, considering the presence of people, heat gains, indoor temperature fluctuations and other differences from desirable measurement conditions, the total accuracy may be far worse, especially because of higher uncertainty due to boundary conditions.

Moreover, the standard heat flow meter application takes long time, according to the recommendations present in (ISO 9869-1 [8]), usually from 3 days up to 7 days and more, in the case of high-inertia walls.

Finally, the conventional measurements via heat flow meter are reliable only when relevant temperature differences are present between the internal and the external environments. In this regard, Desogus et al. [9] show the HFM measurement uncertainty is about 10 % with temperature difference of 10 K between external and internal surfaces, and the measurement accuracy increases with the temperature difference. Moreover, the application in summer conditions is usually not recommended. In literature, Ahmad et al. [10] had accurate results also in summer conditions, but in very particular conditions: very hot summer days, and indoor set-point temperature equal to 22 °C.

The measurement procedure presented in this paper is aimed at the improvement of the building construction U-value assessment, thus allowing a wider spread of in-situ measurements of building construction thermal transmittance, by decreasing uncertainty due to the boundary conditions, hence of final uncertainty, shortening the time span necessary for reliable assessment and allowing reliable assessments even under summer conditions.

In the following section the proposed procedure and equipment are described, as well as the boundary conditions for the performed on-situ measurement, whereas section 4 contains the results obtained and the related discussion.

2. Methods

This section starts from the brief description of the proposed measurement procedure (2.1) and continues by describing in detail the measurement apparatus (2.2) and procedure (2.3). Finally, the description of the specific site and measurement conditions are given for the in-situ measurement campaign (2.4) used as a verification of the measurement procedure in this paper.

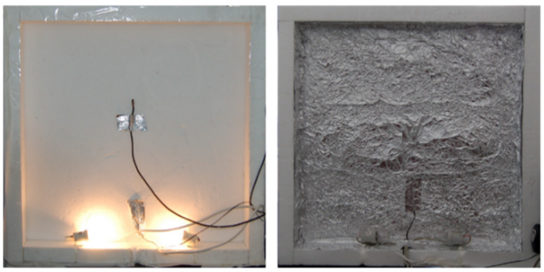
2.1. Brief description of the procedure

The proposed method consists in the imposition of local constant high temperature on the internal side of the building construction under examination, through an electrical heater covered by an insulation layer, in the shape of a sort of hot box. The temperature inside the hot box is kept constant in order to ensure stable boundary conditions and a significant temperature difference between internal and external environments, even in summer.

2.2. The measurement apparatus

In particular, in the frame of this research activity, two different heating boxes were developed, in order to choose the best apparatus configuration. The two boxes share the following characteristics: the external dimensions are 800 mm x 800 mm x 120 mm (L x W x H); the internal dimensions are 700 mm x 700 mm x 70 mm (L x W x H). It is made of high density polystyrene (thermal conductivity: 0.03 W/(m·K)). The polystyrene can resist to high temperatures (up to 80 °C) and its stiffness allows a convenient strength of the box. The heating apparatus is composed of 2 incandescent lamps, controlled by a temperature control system. The temperature control system consists of the following elements in a rheostat, for the regulation of the maximum available heating power and a digital thermostat (coupled with an NTC 25° thermistor, with $u_{Meas} = \pm 0.3$ K).

The boxes differ because of the internal covering: hot box “A” has no internal covering; hot box “B” is provided with an internal covering made of an aluminium sheet, crumpled in order to diffusively distribute the light emitted by the 2 incandescent lamps.



(a) (b)

Fig. 1. Hot box “A” (a) and hot box “B” (b).

Each hot box will be placed on the internal side of the building construction, in contiguous positions, and each of them will host a heat flow meter (HFM), in order to perform a simultaneous and effective comparison. Moreover, in on the same building construction, a conventional heat flow meter application is simultaneously performed as well, in order to get a direct comparison with the proposed measurement procedure. As a consequence, the measurement campaign consists in three simultaneous measurements.

Each measurement apparatus consists of 1 heat flow meter according to (ISO 9869-1) and using wi-fi communication (u_{Meas} = ± 5 %); 1 crumpled sheet of aluminium, placed on the HFM and on the whole wall internal surface covered by the hot box, thus limiting temperature fluctuations and consequent fluctuations in heat flow measurement; 1 surface temperature sensor (PT100) placed between the HFM and the surface, on the internal side of the building construction, using a wi-fi communication (u_{Meas} = ± 0.2 K); 1 surface temperature sensor (PT1000) placed on the external side of the wall, using wi-fi (u_{Meas} = ± 15 %); 2 environmental temperature sensors (PT100) placed in the air, at 5 cm from the internal and external wall surfaces respectively, using wi-fi communication (u_{Meas} = ± 5 %), 1 electrical consumption transducer; 1 data logger, wirelessly collecting data from HFM and temperature sensors.

The couples of lamps contained in hot box “A” and hot box “B” are commanded by the related thermostat included in the hot box itself, in order to keep a fixed set-point temperature (in the frame of this research activity, equal to about 55 °C) within the hot box. Typical temperature set points may range from 50 °C to 70 °C: the higher the set point temperature, the lower the fluctuation in heat flow measurement. This way the uncertainty due to variable internal and external boundary conditions ($u_{Boundary\ Conditions}$) is expected to greatly decrease, thus allowing the user to obtain reliable results in short measurement periods, even in case of measurements performed in summer climate.

The hot box is much larger than the hosted HFM, so that no side effect is perceived by the HFM. Moreover, the whole wall area within the hot box is covered by the sheet of aluminum. These actions imply the further limitation of $u_{Superposition}$. Moreover, the wide heated area implies the uniformity of the surface temperature around the heat flow meter, hence the cancellation of $u_{Temp\ Distribution}$ and $u_{Contact}$.

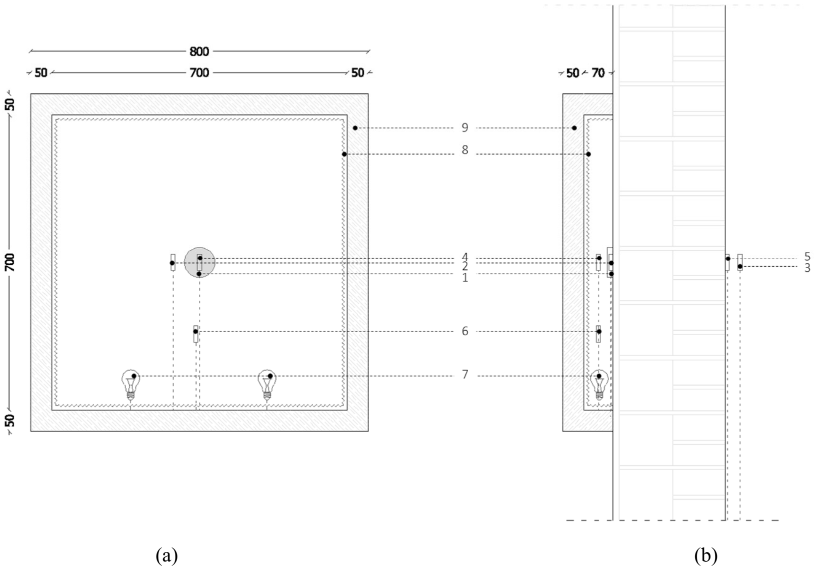


Fig. 2. (a) Frontal view of the basic hot box and (b) side view of the basic hot box. Legend: 1) heat flow meter (HFM); 2) temperature sensor on the internal surface; 3) temperature sensor on the external surface; 4) temperature sensor in the internal air; 5) temperature sensor in the external air; 6) thermistor connected to the temperature control system; 7) 2 incandescent lamps; 8) crumpled aluminum foil; 9) high density polystyrene.

2.3. Description of the measurement procedure

This subsection describes the measurement procedure followed in the frame of this research activity:

1) Calibration of the temperature sensors in a calibration bath where a high accuracy resistance temperature is placed and used as a reference;
2) Assessment of the wall areas available for the measurement campaign, via a thermocamera, which is used in order to identify possible thermal bridges, discontinuities or irregularities within the building construction, thus ensuring the measurement reliability;

3) Hypothesis about the building construction composition. Basing on design drawings, visual inspection or year of construction (or renovation), hypotheses about the layers constituting the building construction may be assumed. That is useful for determine whether air voids may be present in the building construction. That is necessary because the presented measurement procedure might be error-prone in the case of vertical walls including air voids. As a matter of fact, the local overheating might induce relevant convective cells in the air voids, thus implying the measurement of U-values lower than in regular operation. It is also necessary for determine the range of U-value of the building construction. That is useful in order to define the maximum heating power to be assigned to the couple of incandescent lamps, in order to limit on-off cycles du to set-point temperature control;
4) Installation of the HFM. It must adhere to the internal side of the building construction, possibly through the use of thermally conductive paste. At the center of the heat flow meter surface, temperature sensor is placed, used to record the surface temperature and as a feedback for the thermostat operation. The HFM is then covered by crumpled aluminum foil, as large as the area covered by the hot box;
5) Installation of the hot box, on the internal side of the building construction under investigation. The hot box must firmly adhere to the internal side of the building construction and should be placed in the upper area of the building construction, in the case of vertical walls with possible air voids, so that the convective cells occupy just a limited region of the building construction surface;
6) Definition of the set-point temperature within the hot box. The set-point temperature within the hot box should be set between 50 °C and 70 °C, depending on the expected average outdoor temperature, in order to avoid relevant variation of material thermal properties and ensure sufficient temperature difference between the building construction's internal and external sides;
7) Assessment of the maximum heating power and consequent regulation of the rheostat, according to Eq. (1) where A_{hotbox} is the area covered by the box [m^2], $U_{wall,estimated}$ is the estimate thermal transmittance of the wall [W/m^{2}K], U_{hotbox} is the thermal transmittance measured by the hot box [W/m^{2}K] Θ_{setP}, $\Theta_{OutdEnv}$, Θ_{IndEnv} are the temperatures of the set-point and external and internal environment [°C]:

$$P_{Max} = A_{HotBox} \cdot \left(U_{Wall,Esimated} \cdot \left(\theta_{SetP} - \theta_{OutdEnv}\right) + U_{HotBox} \cdot \left(\theta_{SetP} - \theta_{IndEnv}\right)\right) \tag{1}$$

8) Launching the measurement, with acquisition time step equal to 15 minutes;
9) Assessment of the wall thermal conductance. The calculation of the wall thermal conductance was performed by the Average Method presented in ISO 9869-1.

2.4. Description of the boundary conditions of the specific measurement campaign

The proposed HFM measurement procedure was applied to an external wall with the following characteristics (derived from wall core driving, as shown in Fig. 2, and corresponding wall layer characteristics, listed in Table 1). It is located in the ground floor and its orientation is NW. The total estimated thermal conductance is 1.87 W/(m²·K) and the total estimated U-value is 1.38 W/(m²·K).

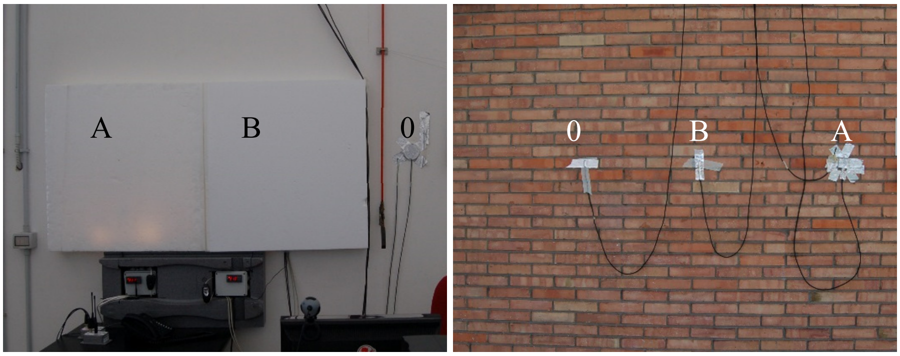
Of course, the values of material thermal conductivity are estimated (since some of them may vary within a wide range of values), hence also the derived values of thermal conductance and U-value. Moreover, the bricks layers are just leant against each other, with no filling and joint between them, hence with possible thin air voids between them and consequent uncertainty in the calculation of the wall thermal characteristics. The consequent influence on the thermal conductance assessment can be easily quantified via the two assumptions as explained below.

The actual conductivity of brick and plaster used in the investigated wall is assumed from technical material database exhibiting variation ranges usually within ± 0.05 W/(m·K). In the frame of this calculation the midrange values are used as a reference; the presence of thin air layers (typically, 2–3 mm thick) between the first and the second row of bricks may add additional thermal resistance, quantified as follows: R_{Air} = 0.0025 m / 0.027 W/(m·K) = 0.09 (m²·K)/W. As a consequence, under these hypotheses, the thermal conductance calculated for the wall mentioned above may range between 1.42 W/(m²·K) and 2.07 W/(m²·K).

Table 1. Main characteristics of the material layers composing the building construction under examination.

Position	Material	Thickness, m	Estimated thermal conductivity, W/(m·K)	Estimated thermal resistance, m²·K/W
External side	Facing solid brick	0.125	0.700	0.179
Intermediate	Hollow rick	0.125	0.350	0.357
Internal side	Plaster	0.015	0.900	0.017
Total		0.265	–	0.536

Heat flows and wall temperatures were measured in three regions of the same wall, as shown in Fig. 3, corresponding to configurations named "0" (i.e. conventional measurement according to standard ISO 9869), "A" (i.e. by hot box "A") and "B" (i.e. by hot box "B"), so that it was possible to compare the results of hot boxes "A" and "B" with the ones obtained with the standard method (ISO 9869). The measurement campaign was performed from the 12th of April 2016 to the 18th of April 2016, i.e., in mild climate.



(a) (b)

Fig. 3. Position of heat flow meters "A", "B" and "0" (a) and corresponding surface temperature sensors (b), on internal and external sides.

3. Results and discussion

The data collected during on-field measurements are exhibited in Fig. 4 together with consequent U-value assessment. Fig. 4(a, c, e) show the values of outdoor air temperature, outdoor and indoor side surface temperatures and heat flow measured by the HFM. While in the case of basic HFM configuration (named "0"), the internal surface temperature varies between 20 °C and 25 °C, with no transient behavior, in the case of hot boxes "A" and "B" the internal surface temperature is kept between 40 °C and 45 °C, after a 24 h transition period. Consequently, the temperature difference across the wall is higher and subject to narrower fluctuations (in terms of percentage), compared with the standard configuration ("0"). Moreover, the consequent heat flows are higher and always positive, while configuration "0" shows both positive and negative heat flow values. During the execution of the measurement campaign, configuration "A" suffered the failure of the lamps, probably due to frequent on-off cycles performed in previous measurements. Then the lamps had to be substituted, and, for this reason, the internal side of the hot box had to be temporarily accessed. This fact explains sudden decrease heat flux present in Fig. 3(c).

Fig. 4(b, d, f) show the values of thermal conductance calculated after the measurements, for different time intervals. The first time intervals ("25–48", "49–72", "73–96", "97–120" and "121–144") refer to 24 h periods, and in particular to the 2nd, 3rd, 4th 5th days respectively). Time intervals 24 h long have been chosen to calculate the thermal conductance of the wall removing the effect of thermal inertia, because at the end of the 24 h period the outdoor conditions are expected to be very similar to the ones taking place at the beginning of the 24 h period. These calculations were performed in order to determine how stable the calculation of the thermal conductance when referring to measurements taken in different days. The following values of the thermal conductance ("25–48", "25–72", "25–96", "25–120" and "25–144") were calculated starting from the 24th hour, and extending the calculation to the following 1, 2, 3, 4 and 5 days respectively. These calculations allowed the authors to verify how many days are needed to achieve a stable value of the thermal conductance. All of these calculations did not consider the first 24 h period considered as a transition period. The thermal conductance values are shown in comparison with their mean (C-MEAN) and show unreliable results in the case of configuration “0”, because of the low temperature difference across the wall, whereas configurations “A” and “B” allow the user to achieve a reliable value of the thermal conductance after 3 days from the very beginning of the measurement campaign (“25–144” is supposed to be the most correct calculation of the thermal conductance).

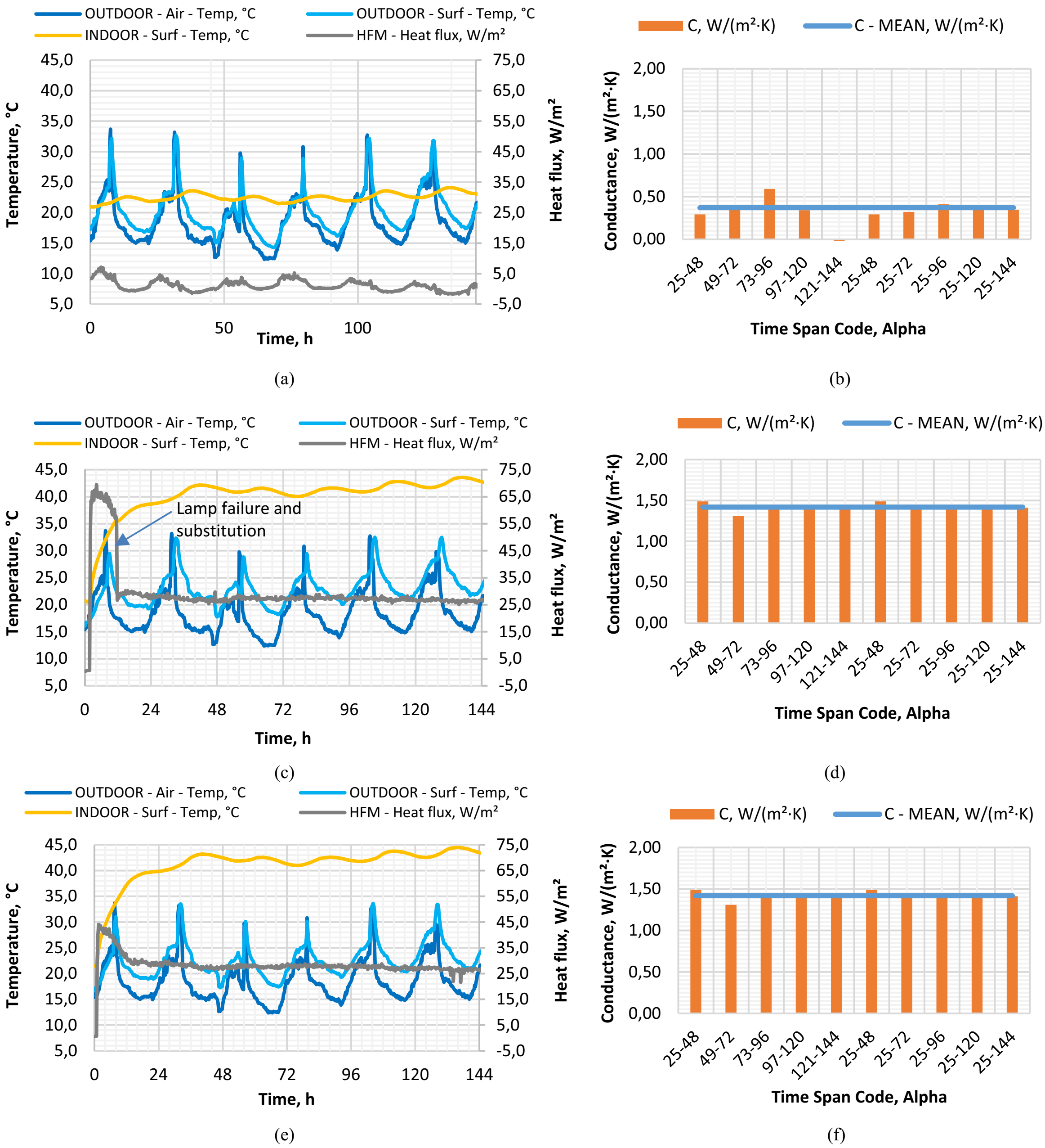


Fig. 4. Results of the measurements and thermal conductance for HFM configurations “0” (a and b), “A” (c and d) and “B” (e and f).

4. Conclusions

The present paper has explored the opportunities given by the measurement procedure proposed by the authors. The data were collected in a measurement campaign performed in spring 2016, in a period where usual heat flow meter measurement could not give reliable results. The proposed measurement procedure shows the following advantages:

- It shortens the measurement campaign duration;
- It allows the user to perform in-situ thermal conductance measurements even in warm climates or periods;
- To increase the measurement accuracy.

These advantages are consequences of the lower fluctuations in the measured temperature difference and heat flow, as well as of the constant and high temperature kept within the hot box.

In the following steps of this research activity, the same measurement procedure will be further validated in colder winter conditions and in summer conditions as well, in order to calculate wall dynamic thermal characteristics too. Further developments will explore the influence of hot box size on the reliability of the measurements, depending on the wall thickness and expected thermal resistance.

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