infrastructures

MDPI

Article

Variability of the Hot Box Method in Assessing Thermal Resistance of a Double Leaf Brick Wall

Manuel Ribas [1], Eva Barreira [1,*] and Ricardo M. S. F. Almeida [1,2]

[1] CONSTRUCT-LFC, Departamento de Engenharia Civil, Faculdade de Engenharia (FEUP), Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal; up201806851@fe.up.pt (M.R.); ralmeida@estgv.ipv.pt (R.M.S.F.A.)

[2] Departamento de Engenharia Civil, Instituto Politécnico de Viseu, Campus Politécnico, 3504-510 Viseu, Portugal

* Correspondence: barreira@fe.up.pt

Abstract: The accurate thermal performance assessment of building components is critical for improving energy efficiency in buildings, mainly as space climatization accounts for a large percentage of energy consumption. The literature review points out multiple parameters that influence the measurement of the U-value using the HFM method. However, most of these studies are focused on in situ tests and little information exists on the variability of the results of the hot box method to assess thermal resistance. According to EN 1934, a baffle must be positioned between the surface of the specimen and the fans of the climatic chamber to maintain acceptable air temperature gradients and uniform air temperature distribution to minimize the convective effects. However, no clear information about its position is given. This study investigates the variability in the measurement of the thermal resistance of double leaf brick wall specimen using the hot box method, focusing on the effect of the layout configuration. An experimental campaign was carried out and three configurations were considered: no baffle, a baffle positioned 1.15 m from the wall, and a baffle positioned 0.05 m from the specimen. The experimental results demonstrate that baffle positioning significantly influences measurement variability. The best-performing configuration (P1) resulted in the lowest variability and the closest agreement with theoretical values, with an average R-value deviation of approximately 25%. These findings are relevant for optimizing testing protocols and improving the reliability of thermal resistance assessments. Furthermore, the results have implications for energy efficiency policies and building retrofitting strategies, aligning with global sustainability goals to reduce building energy demand and carbon emissions.

Keywords: hot box method; thermal resistance; masonry structure; measurement accuracy; baffle positioning

check for updates

Academic Editor: Daniel V. Oliveira

Received: 1 February 2025
Revised: 19 February 2025
Accepted: 21 February 2025
Published: 25 February 2025

Citation: Ribas, M.; Barreira, E.; Almeida, R.M.S.F. Variability of the Hot Box Method in Assessing Thermal Resistance of a Double Leaf Brick Wall. *Infrastructures* **2025**, *10*, 48. https://doi.org/10.3390/infrastructures10030048

1. Introduction

The building sector accounts for about 40% of European final energy consumption and is responsible for 35% of all CO_2 emissions. Residential buildings represent about 75% of the building-related energy use, with space climatization as the primary energy demand source, consuming nearly 80% of the total energy [1].

Space cooling is the fastest-growing energy use demand for buildings. Between 1990 and 2016, the energy consumption associated with air conditioning units more than tripled, and nowadays, it accounts for about 20% of global electricity usage [2].

Although in wealthier countries, an increase below 10% in air conditioning (AC) usage is expected due to climate change, countries with hot climates and expanding middle classes are expected to significantly increase their AC implementation, with some estimates pointing to an increase in their electricity consumption of up to 75% by 2050 [1,3]. While this study focuses on European trends, the global relevance of space cooling is evident, particularly in regions with expanding middle classes, where air conditioning demand is projected to increase significantly.

National policy agendas and international guidelines are increasingly focused on sustainability and energy efficiency as the inevitable consequences of global warming are gradually becoming more evident. The International Energy Agency [4] outlines some key adaptations the building sector must adopt to achieve net zero emissions by 2050. They include ensuring that all new buildings comply with zero-carbon-ready energy codes by 2030, making improvements in the energy efficiency of heating/cooling systems, increasing building retrofitting rates by at least 2%, integrating renewable energy technology, and incorporating dynamic and intelligent components/systems in buildings capable of adapting their performance to minimize energy consumption.

Worldwide efforts to create a more sustainable building environment require accurate and reliable thermal information, derived from real-use conditions assessed through in situ measurements. The most common thermal parameters used to evaluate the thermal performance of building components are the thermal resistance (R-value) and the corresponding heat transfer coefficient (U-value), normally assessed using the heat flow meter (HFM) method. Although international standards exist for applying the method in the laboratory and in situ [5,6], some issues still arise regarding the test procedures. According to De Wilde [7], it is of utmost importance to develop more precise thermal sensing methodologies to minimize the performance gap that persists between computational models and in situ building performance.

The in situ measurement of the thermal resistance using the HFM is described in ISO 9869-1 [5]. For heavy elements, the standard sets three convergence criteria to assure result reliability: (i) the duration of the test is at least 72 h; (ii) the deviation between the thermal resistance obtained at the end of the test and the value obtained 24 h before must be lower than ±5%; and (iii) the R-value obtained for the integer of 2/3 of the total period of analysis cannot deviate by more than ±5% relative to the final value of the thermal resistance. Moreover, the standard defines two calculation methods for determining thermal resistance: the average and dynamic methods. The average method requires a more extended test period as it assumes that thermal transmittance can be obtained by dividing the mean density of the heat flow rate by the mean temperature difference, given that the measurements converge to an asymptotical value. On the other hand, the dynamic method is more complex and requires solving a set of linear equations. However, it does not require long test durations and can be more suitable in scenarios with great variations in the heat flow rate and temperature.

Some previous studies have been designed to assess the reliability of the average and dynamic methods, described in ISO 9869-1 [5], with different results. Gaspar et al. [8] used the two methods on three façades. They noted that in all of the tested scenarios, the difference between the theoretical and the measured U-value was lower when the dynamic method was used. On the other hand, Lee et al. [9] designed a similar study that investigated the in situ thermal transmittance measured over an extensive period and registered lower average error rates when the average method was applied. This contrast in the conclusions of the two studies highlights and demonstrates the variability associated with this test and helps to confirm the relevance of the work presented in this article.

On the other hand, Meng et al. [10] developed an in situ measurement technique using the HFM that incorporates a box attached to the external surface of the wall under study to create a more stable environment. This way, the variability of the exterior surface temperature reduces, as exposure to wind and solar radiation is restrained. According to the authors, a higher measurement accuracy is obtained, especially under adverse outdoor conditions, while remaining a straightforward and easy to apply procedure.

There are several sources of uncertainty associated with both the testing procedure and the equipment used. According to Trethowen [11], heat flux sensors can introduce measurement errors due to their physical presence, disrupting the natural heat flow. These errors are caused by a reduction in heat flux beneath the sensor and heat leakage around its edges. The author suggests that larger sensors can reduce measurement errors and minimize the dependence on surface heat transfer coefficients. More recently, Meng et al. [12] analyzed the measurement accuracy associated with variations in a group of independent variables and confirmed that a bigger heat flux sensor can improve accuracy. Additionally, they discussed the importance of choosing the correct sensor size, especially in masonry structures with heterogeneous heat flow distributions, recommending a heat flow meter length–width ratio close to two.

Regarding the location of the devices, Meng et al. [12] investigated four typical block wall structures with randomly arranged heat flow and temperature sensors and observed that the maximum U-value error due to the random thermocouple location is close to 6%. However, the error due to the random location of heat flow meters can increase up to 26%. Regarding masonry structures, where sensors can be positioned aligned with mortar joints, the authors recommend pasting them in different positions over different horizontal and vertical alignments. Also, Cesaratto and Carli [13] noted significant deviations in the results of heat flow measurements carried out in the same building element but placed in different positions.

ISO 9869-1 [5] emphasizes the importance of maintaining direct thermal contact between the building element and the whole surface area of the heat flux sensor, which is typically ensured by applying a thin layer of thermal contact paste. Gaspar et al. [14] investigated the influence of defective thermal contact, materialized by applying a PVC film between the wall and the sensor surface. The results showed that this procedure can result in measured thermal transmittances 19 to 27% lower than when the sensor was directly pasted on the wall surface.

The duration of HFM tests is a widely discussed topic, with multiple attempts by several authors to balance a more reasonable and doable procedure with a smaller duration with a longer test with more accurate and reliable results. Lee et al. [15] performed a U-value analysis adopting four different durations for the measurements (3, 7, 11, and 15 days), to assess the variability and reliability of the obtained data. The authors noted that HFM measurements require at least a seven-day test to obtain reliable results. Gaspar et al. [16] observed that the test duration necessary for achieving the convergence criteria specified in ISO 9869-1 [5] depends also on the temperature difference. They state that for a temperature difference above 19 °C, a test duration of 72 h leads to a U-value deviation from the theoretical one of 1.9%. On the other hand, when the temperature difference was between 11 °C and 13 °C, the minimum duration was 120 h, and the deviation from the theoretical value was 7.3%.

Desogus et al. [17] also registered a lower uncertainty in the results when the temperature difference between the environments separated by the building component was higher. They performed two sets of measurements, using ambient temperature differences of 10 °C and 7 °C. Ficco et al. [18] observed that temperature differences are the most critical factors for ensuring measurement accuracy and noted that a value below 10 °C can lead to unacceptable uncertainties. More recently, Lee et al. [15] studied the influence of temperature difference and measurement duration on result reliability considering the conditions described in the ISO 9869-1 [5] standard, noting that HFM measurements performed for seven days and with a temperature difference of 10 °C provided highly reliable results. However, a further increase in the test duration or temperature difference did not significantly improve the accuracy of the U-value estimations.

Besides ensuring a high temperature gradient, the literature also points to the importance of maintaining steady state conditions, i.e., keeping both the interior and the exterior environments as constant as possible [17,19]. Cesaratto et al. [20] observed that a 1 °C/day drift in the outdoor temperature caused a U-value deviation from −7% to +2% compared to the theoretical value.

Other climate parameters that are referred to in the literature as influencing the in situ measurements with the HFM method are the solar radiation incident on the surface, water content of the materials, and wind velocity. Ahmad et al. [21] evaluated the thermal performance of two reinforced concrete walls with different orientations. They observed that the east-facing wall registered a higher U-value than the north-facing wall, since the first was exposed to solar radiation for a longer period. Similarly, Peng and Wu [22] studied three similar façades facing west, south, and north and registered higher variability in the values of the south-facing wall, explained by the incremental heat flux derived from solar radiation.

Litti et al. [23] monitored the hygrothermal behavior of a brick masonry heritage building in Antwerp. The authors point out that the brick masonry did not dry homogeneously and registered an increase in the thermal transmittance of up to three times in the wet areas compared to the dry ones. Wang et al. [24] developed a multi-layered wall heat transfer model based on the finite method to analyze the heat response of the wall under different wind velocities. They state that the wind variation of close to 0 to 6 m/s led to a 1.3 °C temperature variation. On the other hand, the same fluctuation in the wind velocity implied a much higher variation in the heat flux through the wall, reaching 97 W/m^2.

The influence of air movement and fan positioning within climatic chambers on hot-box measurements is also a critical factor. Nevertheless, specific studies focusing solely on fan positioning are rather limited. The ASTM C1363 [25] standard emphasizes the importance of controlling air velocity to simulate natural convection conditions. It specifies that air velocities should not exceed 0.50 m/s to maintain natural convection within the metering chamber. This guideline underscores the necessity of careful fan placement and speed regulation to prevent forced convection, which could skew heat transfer measurements. However, hot-box apparatus designs often incorporate fans to maintain uniform temperature distributions. Alhawari and Mukhopadhyaya [26] presented the design, construction, and calibration processes of a small-scale hot box apparatus, highlighting the importance of controlling the air flow velocity. To that end, they used multiple small fans mounted to circulate air downwards in the hot chamber and upwards in the cold chamber at constant velocities.

In summary, the literature review points to multiple parameters that influence the measurement of the U-value using the HFM method. However, most of these studies are focused on in situ tests and little information exists on the variability of the results of the hot box method to assess thermal resistance. On the other hand, according to the last national enquiry (Census 2021), exterior walls in brick masonry are used in around half of the Portuguese building stock [27], highlighting the great importance of accurately evaluating the thermal behavior of heterogeneous walls.

EN 1934 [6] establishes the procedure to assess the thermal resistance of masonry structures using the hot box method. Although the standard specifies the boundary conditions, stating that the specimen must be placed between a hot and a cold chamber to achieve a steady state of heat flow, no detailed information is given regarding the apparatus designs. Nevertheless, it stresses the importance of positioning a baffle between the surface of the specimen and the fans of the climatic chamber, designed to maintain acceptable air temperature gradients and uniform air temperature distribution to minimize the convective effects. The standard suggests, for example, a distance of 0.04 m between the baffle and the specimen surface for an air velocity of 2 m/s.

While previous studies focused on in situ methods, little research has been conducted on the variability of the hot box method. The lack of information regarding the impact of the test conditions on the measurement using the hot box method, in addition to the fact that a larger heterogeneity of the specimen increases the complexity of the prediction of the test accuracy, form the outline of the topic of this work. Thus, the aim is to contribute to increasing the knowledge in this area by evaluating the influence of the position of the sensors on the wall and air velocity near the surface under study on the accuracy of the results when assessing the thermal resistance of masonry walls via the hot box method using HFMs. The main novelty of this work is in its investigation of the impact of the layout configuration on the variability of results in the hot box testing of heterogeneous walls.

This study addresses this gap by investigating how different baffle positions affect the variability of thermal resistance measurements of a double-leaf brick wall specimen. These findings contribute to improving test reliability and optimizing experimental configurations for laboratory assessments. Moreover, these insights could be extended to other building components and configurations.

This research is guided by the hypothesis that the positioning of the baffle significantly affects the accuracy and variability of thermal resistance measurements in hot box tests and aims to address the following questions:

1. How does baffle positioning influence the variability of temperature and heat flux measurements?
2. Which configuration provides the most accurate and stable thermal resistance results?
3. Can these findings inform improvements in experimental protocols and testing standards?

2. Methodology

To assess the impact of the test conditions on the measurement of thermal resistance, a double leaf wall specimen in hollow brick masonry with dimensions of 1.90×1.90 m^2 was built in a walk-in climatic chamber. A commercial ETICS was used as external coating, which corresponds to a very common solution for the energy retrofit of walls in Portugal. From inside to the outside, the wall consists of a cement-based mortar, a hollow brick panel, an air gap, a hollow brick panel and an ETICS with 6 cm of EPS, corresponding to a theoretical thermal resistance between surfaces of 2.48 m^2·°C/W (Table 1).

Table 1. Thermal properties and theoretical U-value of building element.

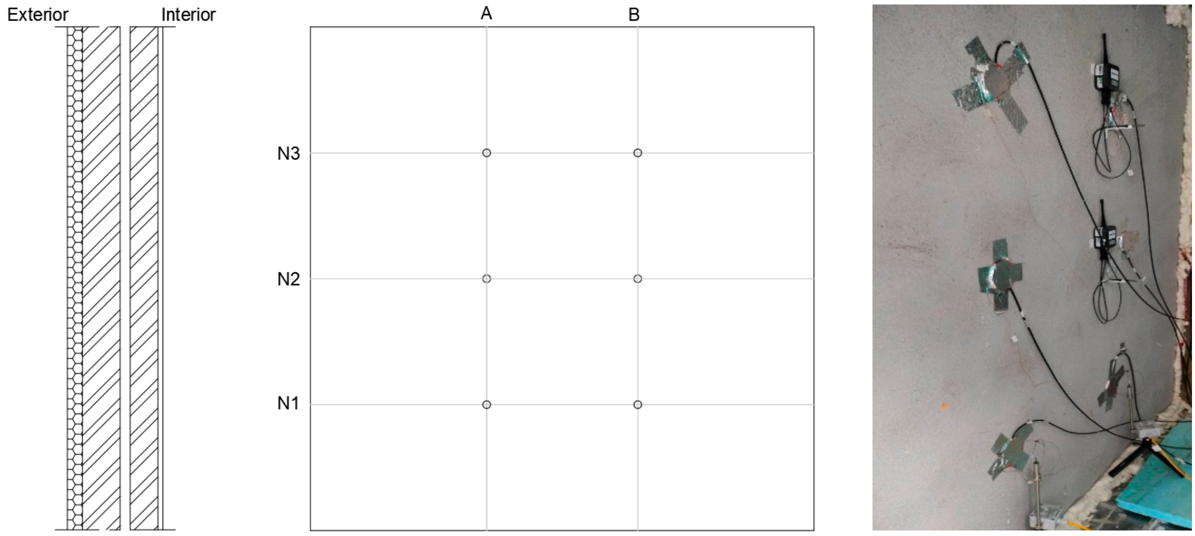
Material Layer (Outside to Inside)	Thickness (cm)	Thermal Conductivity [W/(m·°C)]	Thermal Resistance [m^2·°C/W]
Acrylic-based mortar	Neglectable	-	-
EPS	6.0	0.037	-
Hollow brick	15.0	-	0.39
Air gap	6.0	-	0.18
Hollow brick	11.0	-	0.27
Cement-based mortar	2.0	1.3	-

The test procedure mainly followed EN 1934:1999 [6], which established the boundary conditions for the thermal resistance determination of masonry structures via hot box method using heat flow meters (HFM). The hot box method measures heat flux across a specimen under steady-state conditions. Heat flux sensors capture conductive heat flow, while thermocouples monitor temperature variations. The thermal resistance (R-value) is then calculated as the ratio between temperature gradient and heat flux. Some adaptations were implemented during the measurements to meet specific characteristics of the climate chamber that was used. According to the standard, the specimen must be assembled between a hot and a cold climatic chamber to achieve a steady state of heat flow. In this experimental campaign, the interior surface of the specimen faced a climatic chamber maintained at constant 40 °C. On the cold side, it was not possible to guarantee a constant temperature, but an insulated box the same size as the wall was positioned attached to the surface to minimize the influence of temperature fluctuations in the laboratory (Figure 1). Due to this variability in air temperature on the cold side, the procedure described in ISO 9869-1 [5] was followed to calculate thermal resistance. The standard proposes assuming a moving average of the heat flow values and the differences between surface temperatures for a test duration of no less than 72 h. The test duration followed ISO 9869-1 [5] guidelines and aligns with industry standards and past studies [28,29], ensuring measurement convergence.

(**a**) (**b**)

Figure 1. Apparatus for hot box method: (**a**) hot side; (**b**) cold side.

Six HFMs with a measuring range from −2000 to +2000 W/m^2 and a nominal sensitivity of 60 × 10^{-6} V/(W/m^2) were pasted on the interior surface. Twelve K-type thermocouples were glued onto the interior (hot side) and exterior (cold side) surfaces. The sensors were positioned on each surface along three levels (N1, N2, and N3) and two alignments (A and B) (Figure 2). Since cement mortar is applied to the horizontal surfaces and vertical joints in the construction of these brick walls, creating an additional thermal heterogeneity that increases the complexity of the heat transfer phenomenon, extra care is needed when defining the sensor placement. To mitigate this effect, the heat flux sensors and thermocouples were positioned in the central area of the brick, using infrared thermography to identify the correct location. The data were processed by the data acquisition system PC400 and registered in 10 min intervals.



(**a**) (**b1**) (**b2**)

Figure 2. Test configuration: (**a**) cross-section of wall; (**b1**,**b2**) position of thermocouples (6 on inner surface and 6 on outer surface) and HFM (6 on inner surface). (**b1**) Schematic drawing; (**b2**) photograph of inner surface.

Three test configurations were considered to assess the effect of the baffle positioning on the variability of the measurements carried out to calculate the thermal resistance of the specimen, while maintaining all of the remaining boundary conditions (Figure 3). In the first configuration (P0), the measurements were conducted without a baffle; in the second, (P1) the baffle was positioned 1.15 m away from the wall inner surface and directly facing the heat vents of the climatic chamber; and in the third (P2), the baffle was positioned at 0.05 m from the inner surface of the wall. Each test lasted until the temperature difference and the heat flux approached an asymptotical value for at least 72 h, assuring the reliability of the data and the convergence with the restriction criteria described in ISO 9869-1 [5]. The average method was used to calculate the R-value since the tests were performed under laboratory conditions with low fluctuations in temperature difference and heat flow rate.

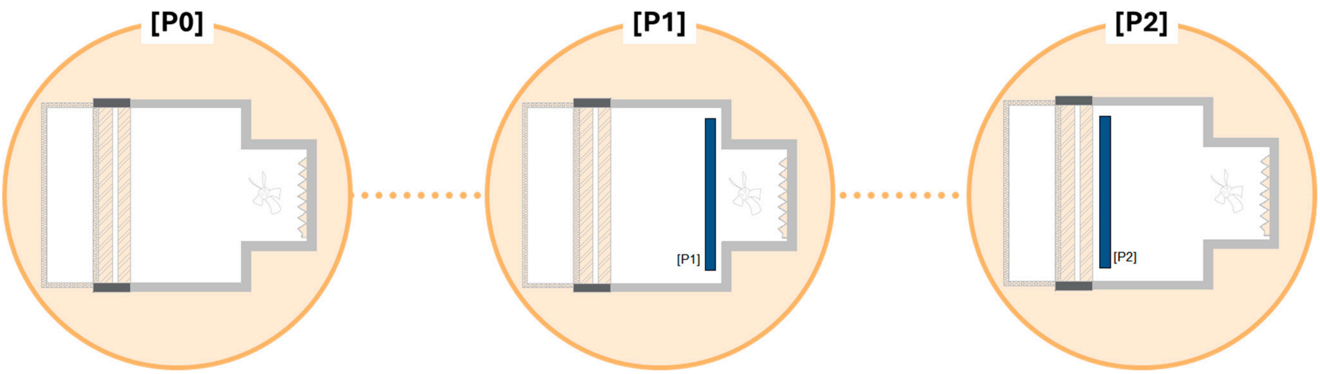


Figure 3. Schematic layout of tests: (**P0**) no baffle; (**P1**) baffle at 1.15 m from wall; (**P2**) baffle at 0.05 m from wall.

3. Results and Discussion

The measurements corresponding to the three configurations were performed from the beginning of May to the beginning of June. The air temperature on the hot side was kept constant at 40 °C, guaranteeing a minimum temperature difference between the two environments during the entire experimental campaign of approximately 13 °C. Figures 4–6 show the variation in the interior surface (hot side) temperature and the heat flux of the six points assessed, over a 72 h measurement, for each configuration: (i) P0—no baffle (Figure 4); (ii) P1—baffle at 1.15 m (Figure 5); and (iii) P2—baffle at 0.05 m (Figure 6).

To validate the reliability of the results, temperature and heat flux trends were analyzed over time. Figures 4–6 depict variations in these parameters across different configurations. Convergence was assessed using the procedure established by ISO 9869-1 [5], confirming that steady-state conditions were reached within the 72 h test period. The measurements obtained for configuration P0, where no baffle was used (Figure 4), registered the highest surface temperature as the wall was not protected from the airflow. Nevertheless, this configuration guaranteed a more homogeneous air temperature distribution on the hot side. Analyzing the height impact, thermocouples on the intermediate level (N2) recorded the highest temperatures, varying from 39.5 °C to 39.8 °C. The lowest temperatures were registered at level N1 (39.1 °C to 39.4 °C). On the other hand, the heat flow sensors registered higher variability between different locations. The highest values were measured at level N1 (13.5 W/m^2 to 15.1 W/m^2). Generally, alignment A registered lower values than alignment B, with the sensor on the intermediate level (N2) measuring the lowest value (9.7 W/m^2). The differences observed in this test result from the effect of convection near the wall surface. In this configuration, there is no baffle, so the air movement inside the climate chamber is unrestricted, leading to higher air velocities and a more heterogeneous distribution near the wall surface. This heterogeneity in airflow results in different heat flux measurements in alignments A and B regardless of their symmetric nature.

When the baffle is introduced (P1 and P2), the surface temperature drops when compared to the configuration without a baffle (P0). This decrease is more marked for configuration P1, where the baffle is farther away from the wall (Figure 5). In fact, when the baffle is closer to the fans, the homogenization of the air temperature inside the climate chamber is restricted and the setpoint of 40 °C is not even reached, conditioning the surface temperatures. However, since the air flow inside the climate chamber is lower, a stratification of the surface temperature corresponding to the stack effect can be observed, with lower temperatures measured at the lower level (N1) and higher temperatures at the higher one (N3), regardless of the alignment. The heat flow measured in this configuration presents the lowest values of the three that were tested, with levels N2 and N3 presenting similar trends in both alignments. However, on level N2 (the intermediate one) the differences between alignment A and B are slightly greater. Additionally, it can be stated that heat flow is always higher in A than in B, which is not in accordance with what was found in configuration P0.

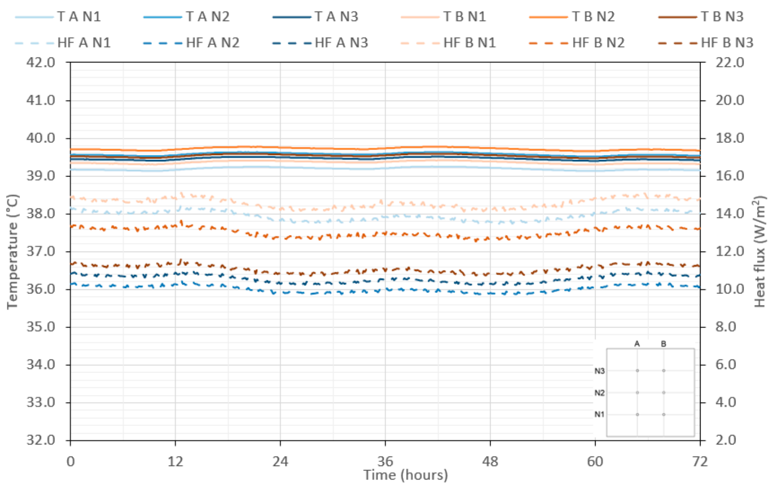


Figure 4. Temperature (T) and heat flux (HF) over time for configuration P0—no baffle.

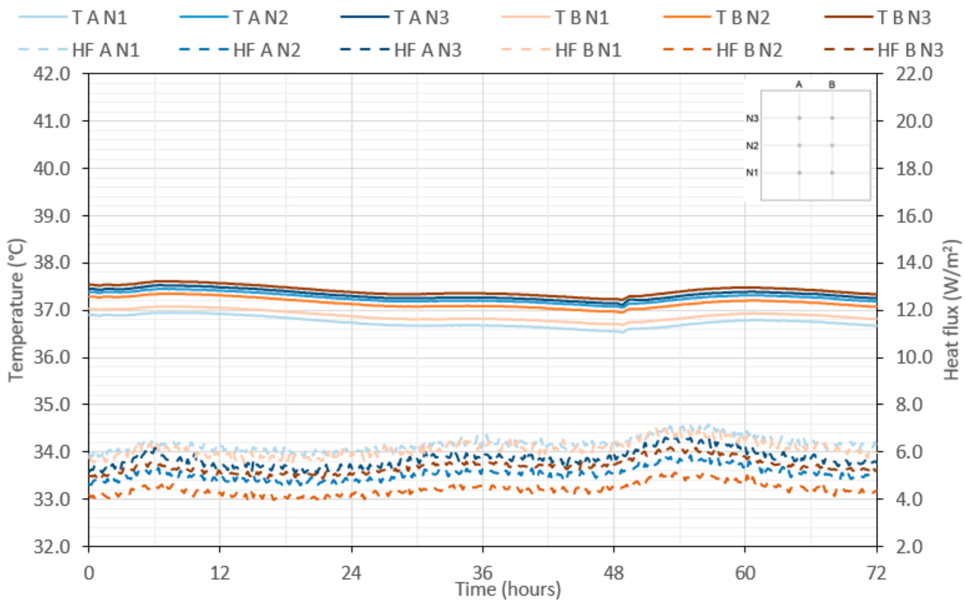


Figure 5. Temperature (T) and heat flux (HF) over time for configuration P1—baffle at 1.15 m.

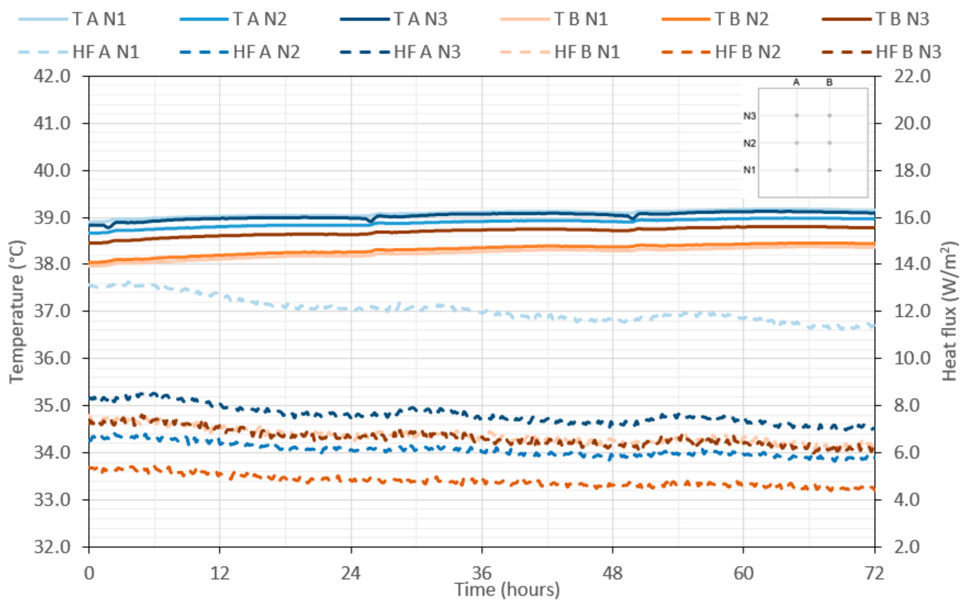


Figure 6. Temperature (T) and heat flux (HF) over time for configuration P2—baffle at 0.05 m.

In configuration P2, with the baffle closer to the wall (Figure 6), not only can no pattern of temperature stratification be found (considering the different levels), but also no association exists between the values measured in alignments A and B. In fact, both surface temperature and heat flux distributions are quite a lot more random when compared to the other configurations. The maximum temperature (39.2 °C) was recorded at alignment A and level N1 and the minimum (38.0 °C) at alignment B and level N1. Although no trend can be pointed out regarding surface temperatures, the heat flow shows a behavior similar to the one found in configuration P1, with higher values measured in alignment A than in B. Position AN1 (alignment A and level N1) stands out as a clear outlier since its values range between 11.2 W/m^2 and 13.2 W/m^2, while at the other positions, the values vary from 4.4 W/m^2 to 8.6 W/m^2.

Figure 7 shows the boxplot representation of the temperature and heat flux measured on the wall for the three configurations under study. The results show that a lower variability in surface temperature can be found when no baffle is used (P0), although this configuration corresponds to a higher variability in the heat flux. This is related to the fact that, as no protection element is used, the air temperature inside the climatic chamber is kept uniform and acceptable air temperature gradients are guaranteed. However, the air velocity near the wall is higher due to the direct effect of the fans, which induces higher variability on the measured values of the heat flux due to convective effects. The baffle has a clear positive effect on the heat flux, decreasing the variability in both configuration P1 and P2. From all of the scenarios analyzed, configuration P1 was the one that allowed for lower surface temperatures and a lower heat flux, with lower variability on both parameters.

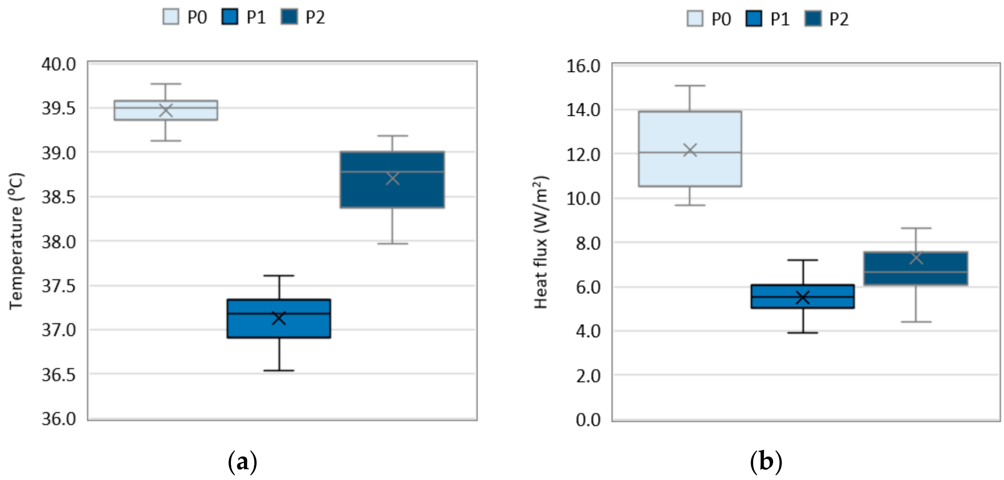


Figure 7. Boxplot representations of the three configurations under study (P0—no baffle; P1—baffle at 1.15 m; P2—baffle at 0.05 m), showing (**a**) temperature and (**b**) heat flux.

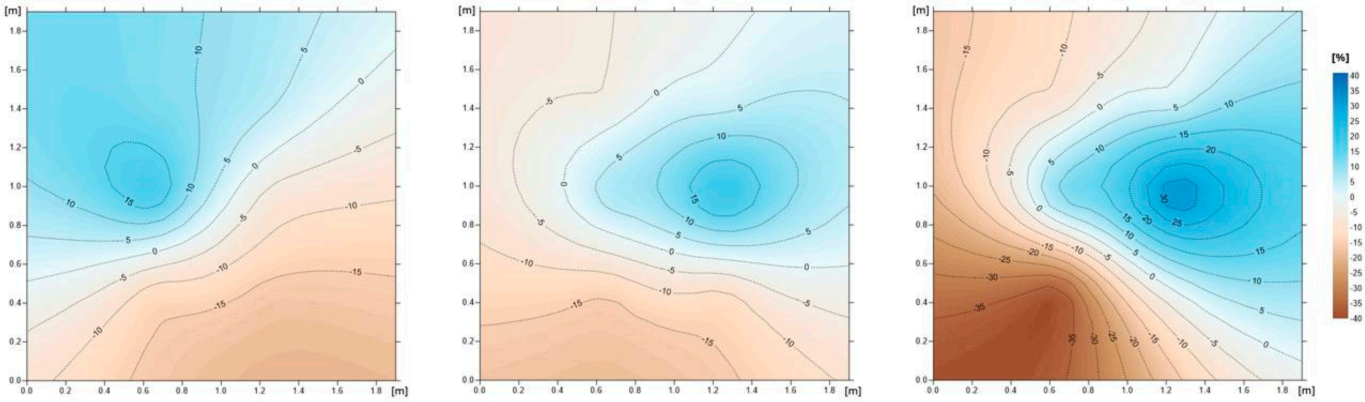
For each configuration that was assessed (P0—no baffle, P1—baffle at 1.15 m, and P2—baffle at 0.05 m), and using the temperature difference and the heat flux on the six measured points (Figure 2b1), the R-values were calculated in accordance with the procedures described in ISO 9869-1 [1] for the average method. Table 2 shows the calculated R-values and the respective averages. Values vary between 0.99 $m^2 \cdot °C/W$ and 1.36 $m^2 \cdot °C/W$ for configuration P0, 1.54 $m^2 \cdot °C/W$ and 1.22 $m^2 \cdot °C/W$ for P1, and 0.91 $m^2 \cdot °C/W$ and 2.07 $m^2 \cdot °C/W$ for P2, showing that with configuration P1, the obtained values are more similar to the theoretical thermal resistance (2.48 $m^2 \cdot °C/W$).

Table 2. R-values (m^2 °C/W) at the 6 locations for each configuration (P0—no baffle, P1—baffle at 1.15 m, and P2—baffle at 0.05 m).

Location	P0	P1	P2
AN1	0.99	1.54	0.91
AN2	1.36	1.95	1.72
AN3	1.26	1.72	1.38
BN1	0.95	1.60	1.51
BN2	1.06	2.22	2.07
BN3	1.21	1.85	1.54
AVE	1.14	1.81	1.52

Figure 8 shows 2D color maps with the relative differences between the average value of the thermal resistance of the wall and the values calculated at the six locations under study, for P0, P1, and P2. The results clearly show much higher variability in the R-value when the baffle is closer to the wall (Figure 8c), pointing to a greater impact of convective flows and air heterogeneity near the wall. Indeed, the variation regarding the average value reaches almost 40% in both alignment A and B at lower–medium levels (N1 and N2).

Higher variations at N1 and N2 are also obtained in configurations P0 and P1, although with different spatial distributions. The maximum difference between the R-values at each point and their average is around 15% in both configurations.



(**a**) (**b**) (**c**)

Figure 8. Two-dimensional maps showing the relative differences between the average value of the thermal resistance of the wall and the values calculated at the six locations under study. (**a**) P0—no baffle; (**b**) P1—baffle at 1.15 m; (**c**) P2—baffle at 0.05 m.

Although both configurations P0 and P1 perform better in terms of higher homogeneity of the calculated R-values at the six locations, the baffle has a clear positive effect when assessing the absolute value and comparing it with the expected one. Indeed, as Figure 9 displays, the deviation regarding the theoretical R-value is lower in configuration P1 (around 25%), increasing to almost 55% in P0. Moreover, the variability increases considerably in P0, mainly due to higher variations in the heat flux.

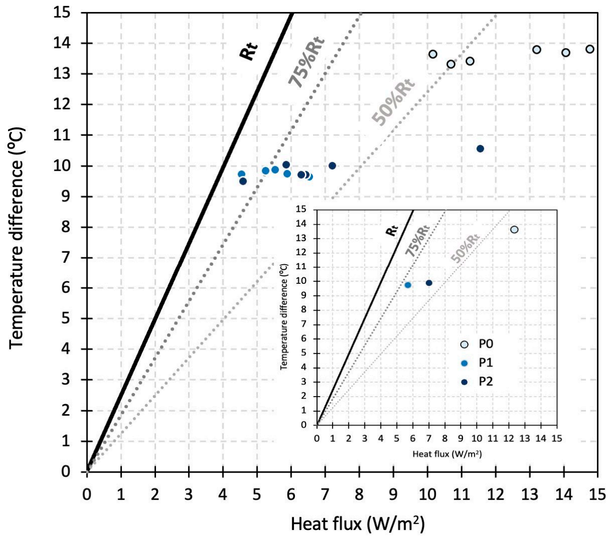


Figure 9. Temperature vs. heat flux for P0—no baffle, P1—baffle at 1.15 m, and P2—baffle at 0.05 m.

4. Conclusions

To assess the impact of the test conditions on the measurement of the thermal resistance of a double leaf wall in hollow brick masonry via the hot box method using an HFM, a laboratory experimental campaign was carried out, considering three different configurations: (i) P0, with the measurements being conducted without a baffle; (ii) P1, using a baffle positioned at 1.15 m from the wall; and (iii) P2, with the baffle positioned closer to the wall, at 0.05 m. The results showed the following:

- The layout of the test has a great impact on the variability in surface temperature and heat flow. Overall, heat flow showed higher variability when no baffle was used, as pointed out in the literature, although the baffle increases the variability in surface temperature. The direct exposure to forced convection by the fans of the heating system of the climatic chamber resulted in unsuitable data, since the heat flow meters strictly assess conductive heat flow and any additional heat source can significantly impact the measurements.
- The position of the baffle according to the specifications of EN 1934, which suggests the positioning of a baffle at 0.04 m from the specimen for an air velocity of 2 m/s, seems not to be suitable for the apparatus used during this experimental campaign. Indeed, the baffle being located at greater distance from the wall surface seemed to guarantee better results, as the R-values, calculated in accordance with the average method of ISO 9869-1, presented lower variability between the six positions that were assessed and their average value was closer to the theoretical one, although with a deviation of around 25%.
- This work highlights the importance of an adequate layout of the test, confirming the importance of measuring in several positions to increase the reliability of the results and pointing out the main role of the baffle positioning, as it can greatly influence the thermal behavior of the entire system (the specimen and surrounding environment) with a special emphasis on convective flows and direct radiative heat exposure.
- This study focused on a single wall configuration under controlled conditions. Future research should explore the influence of different masonry types, data trends under varying environmental conditions, calibration of computational modeling to validate experimental findings and to perform a sensitivity analysis, and practical guidelines for standardizing baffle placement in hot box testing.

Author Contributions: Conceptualization, E.B. and R.M.S.F.A.; methodology, E.B.; software, R.M.S.F.A.; formal analysis, E.B., R.M.S.F.A. and M.R.; investigation, M.R.; resources, E.B.; data curation, R.M.S.F.A.; writing—original draft preparation, M.R.; writing—review and editing, E.B. and R.M.S.F.A.; supervision, R.M.S.F.A.; project administration, E.B.; funding acquisition, E.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by Base Funding UIDB/04708/2020 with DOI 10.54499/UIDB/04708/2020 (https://doi.org/10.54499/UIDB/04708/2020) of the CONSTRUCT—Instituto de I&D em Estruturas e Construções, funded by national funds through the FCT/MCTES (PIDDAC).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request due to privacy restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Environment Agency (EEA). Available online: https://www.eea.europa.eu/en (accessed on 20 January 2025).
2. Randazzo, T.; De Cian, E.; Mistry, M.N. Air conditioning and electricity expenditure: The role of climate in temperate countries. *Econ. Model.* **2020**, *90*, 273–287. [CrossRef]
3. Sherman, P.; Lin, H.; McElroy, M. Projected global demand for air conditioning associated with extreme heat and implications for electricity grids in poorer countries. *Energy Build.* **2022**, *268*, 112198. [CrossRef]
4. Bouckaert, S.; Pales, A.F.; McGlade, C.; Remme, U.; Wanner, B.; Varro, L.; Spencer, T. *Net Zero by 2050: A Roadmap for the Global Energy Secto*; International Energy Agency: Paris, France, 2021.
5. *ISO Standard 9869-1:2014*; Thermal Insulation-Building Elements-In-Situ Measurement of Thermal Resistance and Thermal Transmittance. Part 1: Heat Flow Meter Method. International Standardization Organization: Geneve, Switzerland, 2014.
6. *EN 1934*; Thermal Performance of Buildings—Determination of Thermal Resistance by Hot Box Method Using Heat Flow Meter—Masonry. CEN: Brussels, Belgium, 1999.

7. De Wilde, P. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Autom. Constr.* **2014**, *41*, 40–49. [CrossRef]
8. Gaspar, K.; Casals, M.; Gangolells, M. A comparison of standardized calculation methods for in situ measurements of façades U-value. *Energy Build.* **2016**, *130*, 592–599. [CrossRef]
9. Lee, Y.-J.; Moon, J.-H.; Choi, D.-S.; Ko, M.-J. Application of the Heat Flow Meter Method and Extended Average Method to Improve the Accuracy of In Situ U-Value Estimations of Highly Insulated Building Walls. *Sustainability* **2024**, *16*, 5687. [CrossRef]
10. Meng, X.; Gao, Y.; Wang, Y.; Yan, B.; Zhang, W.; Long, E. Feasibility experiment on the simple hot box-heat flow meter method and the optimization based on simulation reproduction. *Appl. Therm. Eng.* **2015**, *83*, 48–56. [CrossRef]
11. Trethowen, H. Measurement errors with surface-mounted heat flux sensors. *Build. Environ.* **1986**, *21*, 41–56. [CrossRef]
12. Meng, X.; Yan, B.; Gao, Y.; Wang, J.; Zhang, W.; Long, E. Factors affecting the in-situ measurement accuracy of the wall heat transfer coefficient using the heat flow meter method. *Energy Build.* **2015**, *86*, 754–765. [CrossRef]
13. Cesaratto, P.G.; De Carli, M. A measuring campaign of thermal conductance in situ and possible impacts on net energy demand in buildings. *Energy Build.* **2013**, *59*, 29–36. [CrossRef]
14. Gaspar, K.; Casals, M.; Gangolells, M. Influence of HFM thermal contact on the accuracy of in situ measurements of façades' U-value in operational stage. *Appl. Sci.* **2021**, *11*, 979. [CrossRef]
15. Lee, Y.-J.; Moon, J.-H.; Choi, D.-S.; Ko, M.-J. Influences of Average Temperature Difference and Measurement Period on Estimation of In Situ Thermal Transmittance of Building Exterior Walls Using the Average Method of ISO 9869-1. *Energies* **2024**, *17*, 1177. [CrossRef]
16. Gaspar, K.; Casals, M.; Gangolells, M. In situ measurement of façades with a low U-value: Avoiding deviations. *Energy Build.* **2018**, *170*, 61–73. [CrossRef]
17. Desogus, G.; Mura, S.; Ricciu, R. Comparing different approaches to in situ measurement of building components thermal resistance. *Energy Build.* **2011**, *43*, 2613–2620. [CrossRef]
18. Ficco, G.; Iannetta, F.; Ianniello, E.; Alfano, F.R.D.; Dell'isola, M. U-value in situ measurement for energy diagnosis of existing buildings. *Energy Build.* **2015**, *104*, 108–121. [CrossRef]
19. Walker, R.; Pavía, S. Thermal performance of a selection of insulation materials suitable for historic buildings. *Build. Environ.* **2015**, *94*, 155–165. [CrossRef]
20. Cesaratto, P.G.; De Carli, M.; Marinetti, S. Effect of different parameters on the in situ thermal conductance evaluation. *Energy Build.* **2011**, *43*, 1792–1801. [CrossRef]
21. Ahmad, A.; Maslehuddin, M.; Al-Hadhrami, L.M. In situ measurement of thermal transmittance and thermal resistance of hollow reinforced precast concrete walls. *Energy Build.* **2014**, *84*, 132–141. [CrossRef]
22. Peng, C.; Wu, Z. In situ measuring and evaluating the thermal resistance of building construction. *Energy Build.* **2008**, *40*, 2076–2082. [CrossRef]
23. Litti, G.; Khoshdel, S.; Audenaert, A.; Braet, J. Hygrothermal performance evaluation of traditional brick masonry in historic buildings. *Energy Build.* **2015**, *105*, 393–411. [CrossRef]
24. Wang, F.; Wang, D.; Wang, X.; Yao, J. A data analysis method for detecting wall thermal resistance considering wind velocity in situ. *Energy Build.* **2010**, *42*, 1647–1653. [CrossRef]
25. *ASTM C1363-19*; Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus. ASTM—American Society of Testing Materials: West Conshohocken, PA, USA, 2024.
26. Alhawari, A.; Mukhopadhyaya, P. Construction and Calibration of a Unique Hot Box Apparatus. *Energies* **2022**, *15*, 4677. [CrossRef]
27. Björk, F.; Enochsson, T. Properties of thermal insulation materials during extreme environment changes. *Constr. Build. Mater.* **2009**, *23*, 2189–2195. [CrossRef]
28. Soares, N.; Martins, C.; Gonçalves, M.; Santos, P.; da Silva, L.S.; Costa, J.J. Laboratory and in-situ non-destructive methods to evaluate the thermal transmittance and behavior of walls, windows, and construction elements with innovative materials: A review. *Energy Build.* **2019**, *182*, 88–110. [CrossRef]
29. Shen, Z.; Brooks, A.L.; He, Y.; Shrestha, S.S.; Zhou, H. Evaluating dynamic thermal performance of building envelope components using small-scale calibrated hot box tests. *Energy Build.* **2021**, *251*, 111342. [CrossRef]