

Assessment of the risk of surface condensation on cultural heritage mechanical brick facades: the importance of surface temperature measurement. The case of a historic building in Valladolid.

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ABSTRACT

The assessment of the risk of surface condensation on the walls of Cultural Heritage buildings is crucial, since it has been identified that the analytical method used for new buildings can generate errors in these properties. The objective of this research is therefore focused on comparing the differences in surface temperatures between those calculated by the analytical method and those obtained by the in situ measurement. For its determination, the ambient and surface temperatures of the facade of a historic building have been measured, and heat flow tests have been carried out to estimate the conductivity of the walls. By contrasting the results obtained with the data calculated from the analytical system, it is concluded that this method is not entirely valid for this type of building.

Keywords: brick; cultural heritage; surface condensation; moisture; thermal flow test.

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Evaluación del riesgo de condensaciones superficiales en fachadas de ladrillo mecánico del patrimonio cultural: la importancia de medir la temperatura superficial. El caso de un edificio histórico en Valladolid

RESUMEN

La evaluación del riesgo de condensaciones superficiales en los muros de los edificios del Patrimonio Cultural es crucial, ya que se ha identificado que el método analítico empleado para edificios nuevos puede generar errores en estos inmuebles. El objetivo de esta investigación se centra por tanto en comparar las diferencias de temperaturas superficiales que existen entre las calculadas por el método analítico y las arrojadas por la medición in situ. Para su determinación, se han medido las temperaturas ambiente y superficial de la fachada de un edificio histórico, y se han realizado ensayos de flujo térmico que permitan estimar la conductividad de los muros. Al contrastar los resultados obtenidos con los datos calculados del sistema analítico, se concluye con que este método no es del todo válido para este tipo de edificios.

Palabras clave: ladrillo; patrimonio cultural; condensaciones superficiales, humedad, ensayo de flujo térmico

Avaliação do risco de condensação superficial em fachadas de tijolo mecânico do património cultural: a importância da medição da temperatura superficial. O caso de um edifício histórico em Valladolid.

RESUMO

A avaliação do risco de condensação superficial nas paredes de edifícios do património cultural é crucial, uma vez que foi identificado que o método analítico utilizado para edifícios novos pode gerar erros nestes edifícios. O objetivo desta investigação é, portanto, comparar as diferenças de temperaturas superficiais entre as calculadas pelo método analítico e as medidas in situ. Para determiná-lo, foram medidas as temperaturas ambiente e superficial da fachada de um edifício histórico e foram feitos ensaios de fluxo de calor para estimar a condutividade das paredes. Ao contrastar os resultados obtidos com os dados calculados a partir do sistema analítico, conclui-se que este método não é totalmente válido para este tipo de edifício.

Palavras-chave: tijolo; património cultural; condensações superficiais; humidade; ensaio de fluxo de calor.

1. INTRODUCTION

The accurate assessment of the thermal performance of facade components is important for a reliable evaluation of their energy efficiency. From 2002 to 2024, European Directives (EU, 2024) have progressively established requirements to improve the thermal efficiency of both new buildings and historical buildings. In the latter, it is not only necessary to consider the improvement in thermal performance to optimize energy consumption for conditioning, but also to take into account another factor, which is the risk of condensation, mainly on surfaces, since humidity is one of the elements that most influences the deterioration of the envelope of historical buildings, whose facades are made with porous materials such as brick."

There are various methods to estimate and quantify the thermal resistance of enclosures, from analytical formulations such as the calculations of the ISO 6946 standard (ISO, 2017) to

measurements carried out in situ or in the laboratory, such as the heat flow meter (HFM) method according to ISO 9869-1 (ISO, 2014) and the verification of the risk of condensation occurring, in this case, analytical studies as described in the ISO 13788 standard (ISO, 2012) or the Da DB-HE/2 (CTE, 2020).

In historic buildings, this surface thermal resistance value can represent more than 10% of the total thermal resistance value; however, in modern facades, which are usually built with several layers of thick insulating material, the percentage drops to between 3% and 5%. This data is relevant since these values of surface thermal resistance are the ones used in the estimation of the risk of surface condensation also in old buildings.

In the case of ancient brick walls, research supports that the factories operate homogeneously from a thermal perspective, as they are made up of two components: brick and cement mortar. It is estimated that the thermal resistance surface-to-surface is constant, except when there are variations in the moisture content of the wall (Camino et al., 2019). This value should be added to the surface thermal resistance values listed in documents such as ISO 6946 (ISO, 2017) to determine the total thermal resistance of the facade. Furthermore, it should be noted that the thermal resistance values presented in this standard are the same for all facades, regardless of conditions and systems. However, various studies (Kim et al., 2018; Santos et al., 2024) indicate that there is a variation in these values depending on different environmental conditions and construction systems (Litti et al., 2015; Bajno et al., 2020).

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Considering this background, in order to better understand the behavior of thick mechanical brick walls from the beginning of the 20th century, in the weather conditions of the city of Valladolid, two types of tests have been carried out, some in the laboratory and others in situ. This makes it possible to determine three aspects: on the one hand, whether the surface thermal resistance values that can be found in the standards are adequate when assessing the risk of surface condensation. Also, if it is feasible to use other methods such as the measurement of exterior and interior surface temperatures as a more reliable tool to better estimate this risk and, finally, to know the relevance that may have the differences in results between the two methods of analysis.

2. MATERIALS AND METHODS

2.1 In situ test of the facade wall

The first test of the study was carried out in situ, in the Valladolid City Hall building. This is a historic building, designed by the architect Enrique María Repullés y Vargas in 1898, whose elevations are shown in Figure 1. The test was carried out on the north-facing facade to avoid the incidence of the sun, coinciding, moreover, with the rehabilitation works that were being carried out on other floors of the building. This allowed us to measure and visualize the interior of the facade wall, confirming the initial hypothesis that it is made of pressed brick laid “Spanish style”. In total it has a thickness of 1.12 meters, formed by an outer sheet of “fine” brick and a lower quality pressed brick on the inside. The thin brick comes from “La gran tejería mecánica de D. Eloy Silió”, as is visible in the engraving of some pieces and, possibly, the other bricks of the wall, of poorer quality, also come from this tile factory.



Figure 1. Rear facade of Valladolid City Hall. a) Left: plan of the original project (AMVA); b) Right: current state (authors' photograph).

The test consisted of placing thermocouples on the inside and outside of the wall, in order to have the ambient and surface temperatures on both sides, as shown in Figure 2. The reading period was prolonged during the months of December and January, because these are the months with the lowest outside temperatures in Valladolid. Of all this time, the last week of December was selected for the study, since the greatest variation of temperatures was observed both in the heated interior and in the exterior, which made it possible to analyze the most extreme cases.

The four thermocouples used to measure temperatures have an accuracy of $\pm 0.05^{\circ}\text{C} \pm 0.05\%$ of the measured value. The data were stored in a data logger model Almemo 2590, of the Ahlborn brand with an accuracy of 0.03% (the accuracies are provided by the manufacturer).



Figure 2. In situ test on the north wall of the Valladolid City Hall, a) Left: exterior plate, b) Right: interior plate (authors' photograph).

2.2 Laboratory tests

To estimate the thermal conductivity of this type of walls, the values of the standards can be used, or a thermal flow test can be carried out. In this case, the latter possibility was chosen since it was considered that the conductivity values resulting from the test would be closer to the real values of the facade than those that could be taken from tables and standards. For this purpose, a test specimen was built with bricks from the same tile factory, using pieces taken from other buildings that have been rehabilitated. This specimen emulated the wall of a façade 22.5 centimeters long, 28 centimeters high and 22.5 centimeters thick, as shown in Figure 3.



Figure 3. Test specimen tested in laboratory (authors' photograph).

The thermal flow test was carried out in a constant regime using a highly insulated cold box located in the construction laboratory of the E.T.S. of Architecture of the University of Valladolid. The following measuring instruments were used for the measurement:

- Ahlborn model FQAD18TSI AMR heat flow meter (120 mm x 120 mm x 3 mm), which was placed outdoors (plate accuracy 0.02% of the measured value).
- Four thermocouples to measure surface temperature and ambient temperatures: outside and inside (to the box built in the laboratory) (accuracy $\pm 0.05^\circ\text{C} \pm 0.05\%$ of the measured value).
- A Data Logger model Almemo 2590, made by Ahlborn, for the storage of heat flow and temperature data (accuracy 0.03%).

Using the test data and applying the ISO-9869-1 averaging procedure, the thermal conductance was calculated by applying the following formula:

$$\Lambda = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{si,j} - T_{se,j})} \quad (1)$$

Λ : thermal conductivity [$\text{W}/(\text{m}^2 \cdot \text{K})$]

q : flux flow density $= \Phi/A$ [W/m^2]

T_{si} : internal surface temperature [$^\circ\text{C}$]

T_{se} : external surface temperature [$^\circ\text{C}$]

Once the conductance is obtained, the thermal conductivity is calculated, considering that the wall thickness is 22.5 centimeters.

$$\lambda = \Lambda \cdot d \quad (2)$$

λ : thermal conductivity [$\text{W}/\text{m} \cdot \text{K}$]

$d = 0.225$ m is the thickness of the specimen.

2.3 Estimation of internal and external surface temperatures and surface thermal resistances

The next step was to estimate the interior and exterior surface temperatures based on the conductivity of the facade wall and the surface thermal resistances of the DA DB-HE 2 document. The calculation of the surface temperature was made from the total and surface thermal resistance and both exterior and interior ambient temperatures:

$$\theta_n = \theta_{n-1} + \frac{R_n}{R_T} \cdot (\theta_i - \theta_e) \quad (3)$$

$\theta_n \dots \theta_{n-1}$ are the temperatures of each layer [°C]

$R_1, R_2 \dots R_n$ are the thermal resistances of each layer [$\text{m}^2 \cdot \text{K} / \text{W}$]

R_T is the total thermal resistance of the building component [$\text{m}^2 \cdot \text{K} / \text{W}$]

θ_e is the external temperature

θ_i is the internal temperature

For the calculation, the three existing methods have been used, choosing the most appropriate in each part of the process, so that the thermal conductance of the wall has been calculated with the conductivity value of the brick wall resulting from the laboratory test; the values of surface thermal resistance are those dictated in the ISO 6946 standard, $R_{se} = 0.04 \text{ W}/(\text{m}^2 \cdot \text{K})$ and $R_{si} = 0.13 \text{ W}/(\text{m}^2 \cdot \text{K})$ (the plaster has not been taken into account) and the ambient temperatures are those obtained from the in situ test. From this test, the values taken every 15 minutes have been taken, to analyze the results in several cases.

2.4 Comparison of surface temperatures

Once these values were obtained, the surface temperatures measured in the test were compared with the one calculated according to the DA DB-HE / 2 to check the relationship between both and the real possibility of producing surface condensation on the analyzed wall.

For this purpose, the different situations were studied and those with the largest and/or smallest differences between their values were selected. The analysis was carried out with extreme values that could lead to condensation: two cases of interior surface temperatures and two cases of exterior surface temperatures.

2.5 Verification of the risk of condensation for the extreme cases analyzed

In order to check whether there was a risk of condensation on the wall of the building under study, the surface temperature values obtained from the tests and those obtained from the formulas of the standard were used in this phase of the work. The relative humidity that would have to be present on the inside and outside of the wall for condensation to occur was calculated, following the guidelines of DA DB-HE / 2 for the cases under study. In this way, the possible risk of condensation could be checked.

3. RESULTS

3.1 In situ tests on the north wall

The results of the tests for the week selected for the analysis have been transferred to the graph in Figure 4, where the values of the exterior and interior temperatures, both ambient and surface, are shown. The average wall temperature calculated is the half-sum of the surface temperatures.

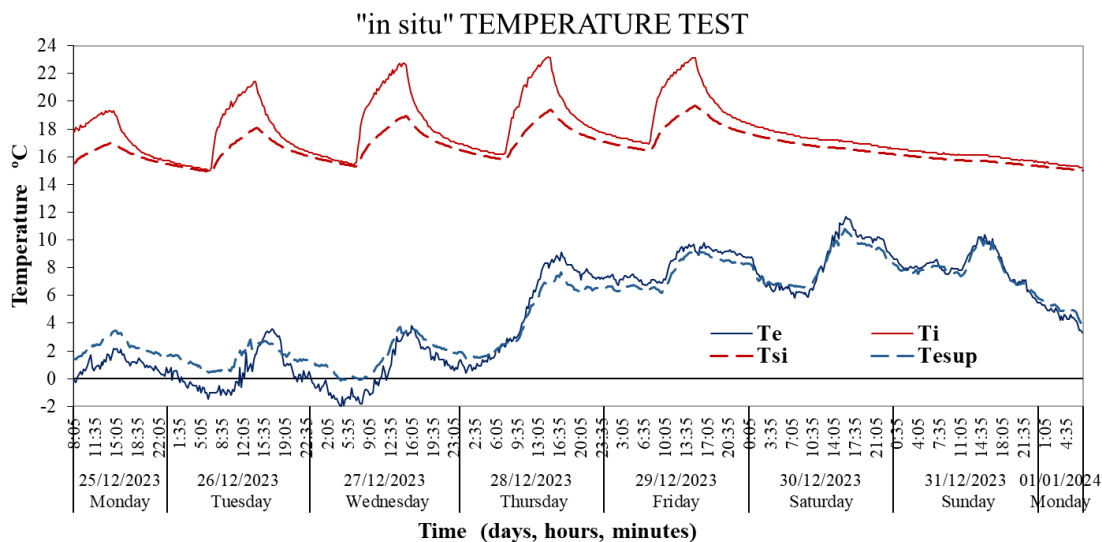


Figure 4. Results of the in situ temperature test of the façade wall.

The first consideration to be considered in this test is that this is an administrative building with regulated heating periods during the day and, also, during the week, so the reading was taken from Monday to Sunday.

This makes it easier to understand the temperature oscillations inside the building, whose values depend on the building's operating hours, so that the highest temperatures are reached at noon, when the heating has been running for several hours. At the same time, the graph clearly shows that in all in situ measurements of the interior, the surface temperature is lower than the ambient temperature.

For the condensation evaluation study, of all the values recorded during the week of the test, the cases with the most extreme values in the interior are analyzed:

- Case 1: Highest temperature: it was recorded on Thursday, with a value of 23.2°C, and a surface temperature of 19.3°C. The difference between both temperatures was 3.9°C. The difference between both temperatures was 3.9 °C.
- Case 2: Lowest temperature: it was recorded on Sunday, with a temperature of 15.2 °C, and a surface temperature of 15°C. The difference between both temperatures was 0.0°C. The difference between the two temperatures was 0.2°C.

Regarding outdoor temperatures, the extreme values were on the following days:

- Wednesday recorded the lowest ambient temperature of the entire period, with -2 °C and 0.1 °C of surface temperature. In this case, the ambient temperature was 2.1 °C lower than the surface temperature,
- Saturday was when the highest ambient temperature was reached, rising to 11.7°C and a surface temperature of 10.7°C. Between the two there is a difference of -1°C.
- The greatest difference (negative) between surface and ambient outside temperatures was recorded on Thursday, with a value of -1.9 °C. The ambient temperature was 8.6°C and the surface temperature was 6.9°C.
- Tuesday had an outside ambient temperature of -0.5°C and a surface temperature of 1.7°C, with the greatest difference (positive) between both, 2.2°C.

3.2 Laboratory Specimen Test

The results of the tests carried out on the specimen in the laboratory are shown in the graph in Figure 5. A conductance value $\Lambda = 3.63 \text{ W/ (m}^2 \cdot \text{K)}$ and a thermal conductivity value of 0.82

$W/(m \cdot K)$ were obtained.

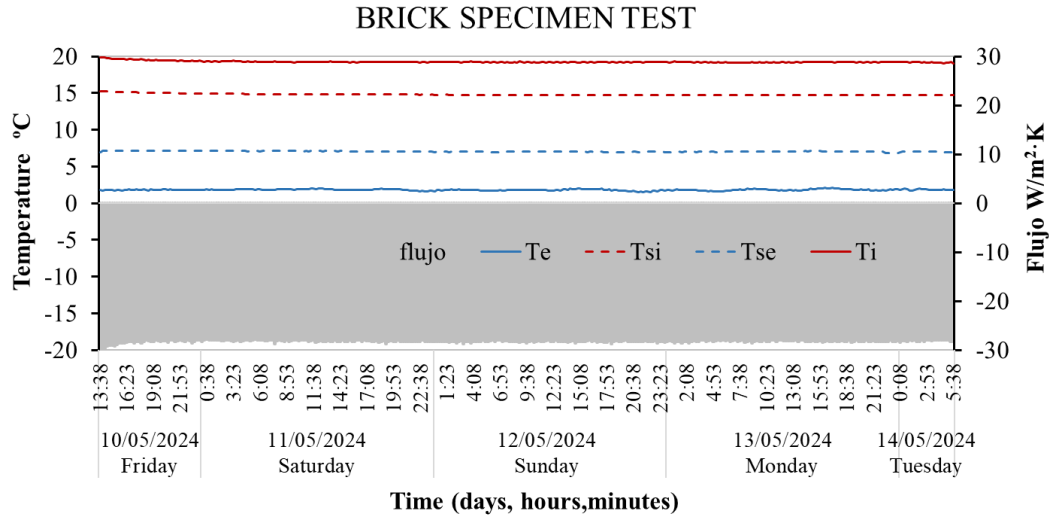


Figure 5. Graph showing the results of the brick specimen test.

3.3 Estimation of the interior surface temperature

The interior surface temperatures were estimated as a function of the wall conductivity and surface thermal resistances of the standard. For this purpose, a joint analysis was made of the ambient and surface temperature values recorded during the in-situ test and the calculated surface temperatures, as shown in Figure 6. Using the same criteria as for the in-situ test, the results of the extreme indoor values were analyzed:

- Case 1: Thursday, when the measured indoor temperature is 23.2°C, the calculated surface temperature is 22.0°C.
- Case 2: Sunday, when the measured indoor temperature is 15.2 °C, the calculated surface temperature is 14.2 °C.

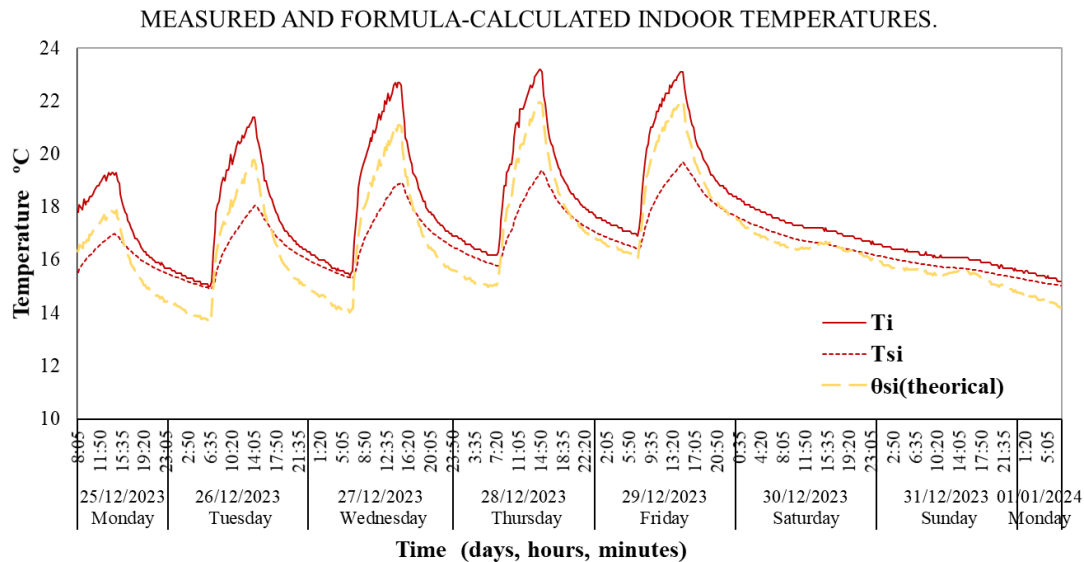


Figure 6. Graph showing the comparison between measured and formula-calculated indoor temperatures.

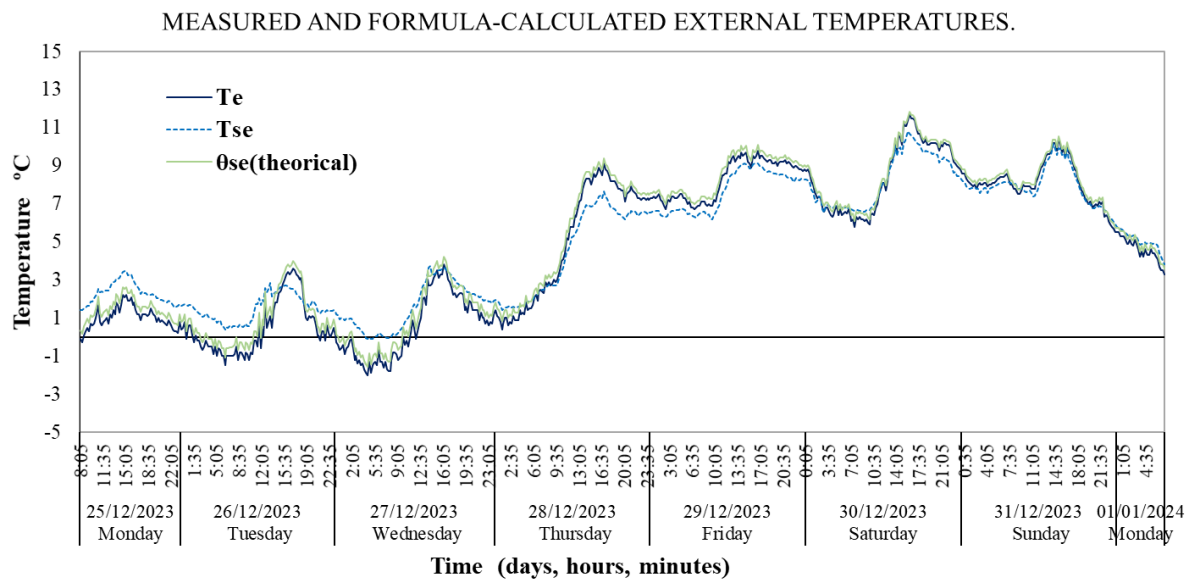


Figure 7. Graph of the evolution of outdoor temperatures: ambient and surface

Regarding the outside temperatures, the same study process is carried out, comparing the temperatures extracted in-situ with those calculated. The most significant data correspond to the highest ambient temperature, which was 11.7°C, calculating a surface temperature of 11.8 °C, and to the lowest ambient temperature recorded, which was -2°C, calculating a surface temperature of -1.5 °C, as shown in Figure 7.

3.4 Estimation of the risk of condensation in the four extreme cases indicated.

To estimate the risk of condensation, the saturation pressure at the various temperatures and the indoor relative humidity at which surface condensation could occur in the two extreme cases established, with the temperatures measured and calculated indoors, were calculated. For case 1, in Table 1 and for case 2, in Table 2.

Table 1. Results case 1

Test	°C	Psat(Pa)	Φ indoor
Θ _{si} (measured)	19.3	2,237	74%
Θ _{si} (calculate)	22.0	2,642	88%

In case 1, the possibility of condensation is analyzed when the interior temperature obtained from the test is the highest of all those carried out, which corresponds to 23.2°C. The indoor relative humidity does not exceed 55%, therefore, with the measured surface temperature of 19.3°C and with the surface temperature calculated according to DA DB-HE/2 of 22.0°C there would be no risk of surface condensation.

If the calculations are made according to the DA method, in the case of taking the measured surface temperature to estimate the minimum indoor humidity value, there will be a risk of surface condensation with a relative humidity equal to or higher than 74%. When the surface temperature calculated according to the DA is taken, this value rises to 88%.

Table 2. Results case 2

Test	°C	Psat(Pa)	Φ indoor
Θ_{si} (measured)	15.0	1,709	99%
Θ_{si} (calculate)	14.2	1,619	93%

Case 2 analyzes the possibility of interior surface condensation occurring at 15.2°, when the interior temperatures are the lowest of all those extracted from the in-situ tests. Condensation could occur based on the surface temperature measured during the test if there was an indoor humidity of 99%. In the case of taking the calculated surface temperature, the indoor humidity would have to be 93% or more. This means that we are in the opposite situation to the assumption made in case 1, taking the higher indoor temperature, so that, for the calculated surface temperature, the risk of condensation occurs at lower ambient humidity than at the temperature measured during the test.

4. CONCLUSIONS

When the walls are made of thick masonry, as in the typology studied, it has been observed that the measured and calculated surface temperatures are different. It must be taken into account that the façade faces north and that the data obtained are valid for the climate of Valladolid. This is due to the fact that in the calculation the values are estimated on the basis of a surface thermal resistance factor that is the same for all types of facades and climatic and environmental situations, whereas the data obtained from in situ measurements are specific to each case and moment (Xue et al., 2022).

For the values obtained from the interior, the surface temperatures are always lower than the ambient temperatures, both for the values obtained from the tests and for the calculated values. However, in the data obtained from the outside of the wall, there are cases in which the measured temperatures are lower than the ambient temperatures, a situation that can be observed when there are significant variations in the external temperature, a circumstance that is not taken into account when an analytical study is carried out according to the regulations.

The theoretical calculations carried out according to the parameters of the standard do not correctly estimate the risk of surface condensation, in the case under study. According to the surface temperature measured during the test, condensation would occur at lower relative humidity.

The values of internal and external surface thermal resistance given in the standard are not valid for thick brick walls, since there is a large difference between the surface temperatures measured during the test. The risk of condensation is largely dependent on these convective transfer values. This leads to the conclusion that the lower the value, the higher the risk of surface condensation (Aelenei, et al. 2008).

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