Static vs Dynamic Hygrothermal Simulation for Cellulose-Based Insulation in Existing Walls: A Case Study Comparison

Matteo Bilardo – Politecnico di Torino, Italy – matteo.bilardo@polito.it
Fabrizio Giorgio – Politecnico di Torino, Italy – fabrizio.giorgio@polito.it
Enrico Fabrizio – Politecnico di Torino, Italy – enrico.fabrizio@polito.it
Francesco Prizzon – Politecnico di Torino, Italy – francesco.prizzon@polito.it

Abstract

When dealing with energy-saving topics, it is increasingly common to focus on the efficiency of existing systems, rather than adopting new ones. In the specific case of the building envelope this practice is supported by the difficulty in completely replacing opaque components of the envelope, such as external walls or roofs. This work involves the renovation of a cavity wall, with the aim of improving its energy performance. A traditional cavity wall has been modified by blowing a bio-based insulating material obtained from cellulose flakes inside the air cavity gap. Although an operation of this type leads to a significant increase in thermal performance of the wall, it is not equally obvious that it is effective in terms of humidity and vapor condensation. The purpose of this work is to evaluate the effect of the blowing process on the hygrometric performance of the opaque component to ensure correct compliance with the performance parameters established by Italian legislation in terms of vapor transmission and condensation phenomena. In order to study the hygrometric behaviour, a numerical model of the construction was developed and simulated. The simulation involved two different regulatory approaches, which were compared: a first calculation was carried out in steady-state conditions, according to the UNI EN ISO 13788 standard (ISO, 2012). Afterwards, a dynamic simulation following the UNI EN 15026 standard was performed (CEN, 2007). The results obtained by both the methods were analysed and compared. The results demonstrate that by adopting the calculation procedure in steady-state conditions, the phenomenon of interstitial condensation occurs. A different result is obtained by applying the calculation method in dynamic regime, according to which the vapor would not condense inside the structure.

1. Introduction

The fact that the construction sector is one of the main contributors to global energy consumption is now an established reality. Energy consumption of the European building stock is related to heating and cooling requirements, necessary to maintain an appropriate level of thermal comfort and IAQ within the living spaces (BPIE, 2015) and to climate scenarios (Bilardo et al., 2019). However, it is clear that the largest share of energy consumption in buildings does not come from new buildings, since they are subjected to an accurate design process from the energy point of view (Bourdeau et al., 2019). For this reason, when it comes to energy efficiency, it is of primary importance to consider the existing buildings' stock, responsible for higher energy utilization, with a consequent higher environmental impact.

The energy retrofit of the existing buildings therefore appears as a tool with great potential to achieve the objectives set out by the European commission (Cortiços, 2019). One possible way to improve the energy efficiency of an existing building is by considering an envelope retrofit. The renovation of the envelope aims to reduce the heat transfer of the envelope components in order to minimize energy needs and guarantee better thermal comfort of the indoor environment. This category of energy retrofit solution can sometimes be intrusive, modifying the external morphology of a building's façades by applying external insulation, or in interior spaces when applying insulating layers on the internal surfaces of the walls (Bottino-Leone et al., 2019).

Another possible solution is represented by the application of insulating materials inside the existing

Part of
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walls with an air gap. This construction type, typical of the 1960s-1970s in the Italian building stock, is very widespread and represents an attractive opportunity for energy efficiency improvements. The application of insulating materials inside an air gap is also advantageous from the point of view of the impact on the building envelope since it does not modify the external surface nor the internal volume. One of the most adopted techniques of interspace insulation is the injection of insulation material using a special nozzle. In this way the insulating material is arranged homogeneously in the volume occupied by the air, decreasing the U-value of the wall and improving the overall thermal performance of the envelope. Among the insulating materials used for this type of application, organic products are of particular interest. This is firstly because they have a low thermal conductivity value, comparable with classical insulating material, and secondly because they are often produced from regenerated industrial waste materials, thus feeding the processes of sustainable circular economy. Although obtaining excellent results in terms of thermal insulation and reduction of energy consumption, organic insulating materials often face some difficulties in hygrometric verification and moisture transport (Cascione et al., 2017). According to the current Italian legislation (established by the DM 26/06/2015), the absence of mould formation and the absence of interstitial condensation phenomena must be verified in the heat transfer surfaces with outside boundary conditions. These verifications must be carried out in accordance with the current technical regulation, represented by the UNI EN ISO 13788 standard (ISO, 2012). However, this standard reports a simplified calculation method in steady-state conditions, which tends to overestimate the risk of interstitial condensation due to diffusion phenomena only, and does not consider other physical phenomena that affect constructions, including the transport of moisture by capillarity or the hygroscopic capacity of the material.
To provide a more accurate determination of the hygrometric behaviour of a building construction, a more detailed analysis, based on dynamic properties of the envelope, is therefore required. A dynamic calculation method to describe the phenomena of moisture transport in a building construction is reported in the UNI EN 15026 standard (CEN, 2007). This standard, although not cited by the Italian legislation, provides the tools for a more accurate calculation of the hygrometric behaviour, sometimes leading to different results when compared to the steady-state conditions.
In the present work, the application of cellulose flakes in the air gap of an existing wall is examined (Lopez Hurtado et al., 2016). Through specific simulation tools, the hygrometric behaviour of the wall is discussed first in steady-state conditions (adopting UNI EN ISO 13788) and then in a dynamic condition (adopting UNI EN 15026). The study refers to a typical existing wall on which this type of energy retrofit must be applied. From the results that were produced, the adoption of stationary methods for hygrothermal verification is questioned.

2. Methodology

This work presents a detailed analysis of the hygrometric behaviour of a cavity wall subjected to an energy retrofit intervention by blowing flakes of cellulose within the air gap. The purpose of this analysis is to verify the hygrometric behaviour of the case study construction by comparing a stationary calculation method with a dynamic simulation method.
The methodology used to fulfil the purpose of the research is divided into three main parts, addressed in this work:

1) Characterization and specific modelling of the case study construction;
2) Hygrometric verification in steady-state conditions, in accordance with UNI EN ISO 13788;
3) Hygrometric verification in dynamic calculation conditions, in accordance with UNI EN 15026.

The objective of the analysis is the verification of the absence of risk of superficial and interstitial condensation as well as mould formation, in compliance with the current Italian legislation represented by the DM 26/06/2015. The reference weather conditions used for the simulation are those of Turin, a city in northern Italy with a humid subtropical climate.
The following calculation software tools were used to support the verification carried out:

- TerMus-G for steady-state conditions;
- WUFI® for dynamic simulation.

2.1 The Regulatory Issue

One of the problems that led to the development of this work is of a regulatory nature. The current Italian regulation scenario, defined by DM 26/06/2015, makes it necessary to design external construction where there is neither mould formation nor interstitial condensation. This results in a regulatory framework that is very restrictive and disadvantageous for natural-based material, such as cellulose flakes. Furthermore, the current legislation provides for the verification of the hygrometric performances through the UNI EN ISO 13788 standard, using a steady-state approach. This evaluation is therefore very limiting and often the results it produces are not reliable. However, more accurate methods can be used to evaluate the hygrometric behaviour of opaque elements, such as the evaluation of moisture transfer by numerical simulation described by the UNI EN 15026 standard.

2.2 Methodology for Stationary Calculation

The steady-state calculation method based on the UNI EN ISO 13788 standard consists of evaluating the trend of the vapour pressure and the saturation pressure inside the construction layers. A tool used to visualize these trends is the Glaser diagram. This graph, used to check the surface and interstitial condensation in the wall, is evaluated monthly with average boundary conditions, established by the legislation for each climatic location. Similarly, the conditions of the internal environment must also be known. The legislation proposes 5 types of internal environments, depending on the internal vapour production. To be consistent in the use of the weather data applied in the two simulation approaches, the same dataset was taken into consideration. The weather data used for the simulation come directly from the WUFI® software database and were developed by the Swiss institute TBZ (https://tbz.ch). Since the only national standard describing hourly weather data (UNI 10349) is not complete in terms of rain load, wind direction and speed, it was necessary to use hourly meteorological data developed by third parties. Table 1 summarizes the external and internal weather conditions adopted for the evaluation of the Glaser diagram in stationary conditions. For the steady-state evaluation, average monthly values of temperature and relative humidity were extracted from the hourly dataset.

Table 1 – Monthly weather boundary conditions

	External		Internal	
	T [°C]	φ [%]	T [°C]	φ [%]
Jan	1.8	73.0	20.0	56.0
Feb	3.9	73.5	20.0	55.1
Mar	8.1	77.3	20.0	45.4
Apr	11.9	66.2	20.0	47.1
May	16.0	74.7	18.0	66.4
Jun	19.5	74.6	21.1	68.1
Jul	23.0	76.7	23.3	64.2
Aug	22.0	75.1	22.6	71.3
Sep	18.2	81.4	18.8	71.5
Oct	12.4	88.6	20.0	63.3
Nov	6.3	72.7	20.0	58.8
Dec	2.6	73.7	20.0	57.1

2.3 Methodology for Calculation in Dynamic Regime

The dynamic calculation method has hourly time-varying boundary conditions. The weather conditions include both the meteorological conditions of the chosen location and a hygro-thermal profile within the building. Hourly temperature and relative humidity have been likewise considered to set the internal conditions. Based on the calculation method proposed by the UNI EN 15026 standard, the internal air temperature is derived from the trend of the external temperature through the application of a linear function. The calculation of the internal temperature, however, respects some limits: it is kept constant at 20 °C when the external temperature drops below 10 °C - by heating - and does not exceed 25 °C when the outside temperature exceeds 20 °C - by cooling. With a similar linear correspondence, UNI EN 15026 also defines the dynamic trend of internal relative humidity, which however has been increased by 5% compared to the calculation value.

The dynamic simulation was performed over a period of two years, with a simulation step of 1 hour. A simulation period of two years was preferred over a single year since hygrometric phenomena develop with longer times and usually follow seasonal trends. The adopted calculation profile made it possible to use the first simulation year to calibrate the model and generate realistic values of inputs for the second simulated year, which was the only one considered for the analysis of the results presented in this paper. The simulation of the model involved both the resolution of the heat transport and conservation equations (Equation 1 and 2) and the moisture transport calculation (Equation 3), which considers the capillary transport phenomena, the latent heat involved in the gas-liquid phase transition (temperature function) and all the hygrometric functions presented in Section 3.2.

$$\left(c_m \cdot \rho_m + c_w \cdot w\right) \cdot \frac{\partial T}{\partial t} = -\frac{\partial\left(q_{sens} + q_{lat}\right)}{\partial x} \tag{1}$$

$$q_{sens} = -\lambda(w) \cdot \frac{\partial T}{\partial x} \tag{2}$$

$$g_v = \frac{1}{\mu(\varphi)} \delta_0 \frac{\partial p_v}{\partial x} \tag{3}$$

The results obtained from the simulation consist of the hourly trend of temperature and relative humidity, as well as the verification of condensation phenomena. To take the most critical case into consideration, the orientation of the wall was fixed to the North direction. Fig. 1 summarizes the physical phenomena taken into consideration by the models used in the two calculation methods applied to the case study in this work.

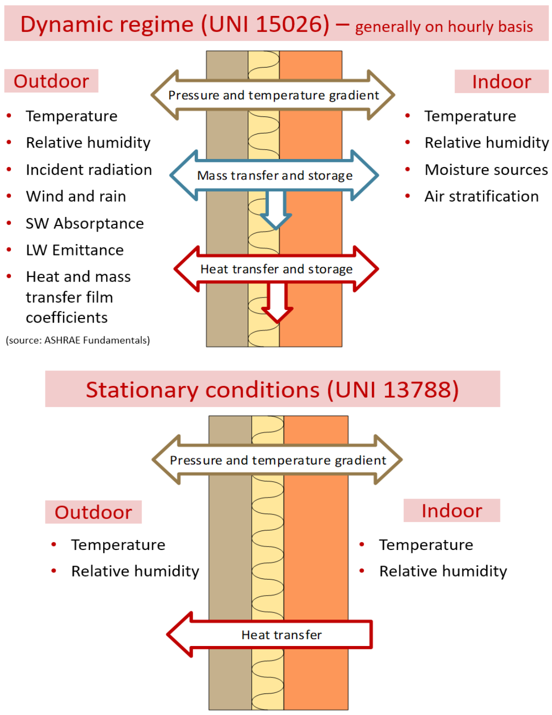

Fig. 1 – Dynamic vs stationary boundary conditions

3. Case Study Construction

The analysed construction is composed of the following elements, listed from the outer to the inner layer:

1) Exterior plaster (0.015 m)
2) Perforated brick (0.12 m)
3) Air gap filled with injected cellulose (0.19 m)
4) Perforated brick (0.08 m)
5) Interior plaster (0.015 m)

The insulating material used to increase the performance of the building envelope is natural cellulose, applied in the air gap of the structure through a blowing process. In order to make the numerical analysis as similar as possible to the real case, the flakes of cellulose produced by NESOCELL® s.r.l. were used as the reference product. The manufacturer provided the technical characteristics of the product to allow a detailed characterization of the model. The analysis presented in this document is therefore specific and related only to this case study. Given the variable nature of the phenomena connected to it (weather conditions, thickness of the layers, construction elements, etc.), this analysis cannot be fully applied to similar building constructions.

3.1 Thermophysical Properties of Materials

The thermophysical parameters of the cavity wall were derived from the technical standard UNI/TR 11552:2014, depending on the elements used and the typical year in which this type of construction was frequently realized (1960s–1970s). Table 2 collects the thermophysical parameters of each layer.

Table 2 - Thermophysical parameters

Layer	Material	s	ϱ	C	λ	R
1	Exterior plaster	1.5	1800	1000	0.9	-
2	Perforated brick	12	800	1000	0.4	0.31
3	Air gap	19	1.25	1008	-	0.18
4	Perforated brick	8	800	1000	0.4	0.2
5	Interior plaster	1.5	1400	1000	0.7	-

After an initial comparison with the original wall, the air layer was replaced in the model by the layer of cellulose flakes, whose thermophysical properties are collected in Table 3.

Table 3 - Thermophysical parameters for the cellulose flakes

Layer	Material	s	ρ	C	λ	R
3_new	Cellulose	19	55	2150	0.038	-

3.2 Characterization of the Hygrometric Properties of Materials

For the modelling of the hygrometric behaviour of the materials in lack of certified or experimental data, materials with the same thermophysical characteristics as those defined in the previous paragraph were identified within the WUFI® database. The hygrometric characterization of cellulose flakes was instead the result of an experimental phase conducted in a laboratory environment and provided by the manufacturer (Table 4). The additional thermo-hygrometric parameters of the materials are:

- Porosity ε [m^3/m^3]
- Vapor diffusion resistance factor μ [-]
- Reference moisture content w_{80} [kg/m^3]
- Free water saturation w_f [kg/m^3]
- Moisture absorption coefficient A [$kg/(m^2s^{0.5})$]

Table 4 - Hygrometrical properties of the construction layers

Layer	Material	ε	μ	w_{80}	w_f	A
1	Exterior plaster	0.24	19	45	210	0.017
2	Perforated brick	0.6	15	13	193	-
3_new	Cellulose	0.93	1.2	6.6	494	0.56
4	Perforated brick	0.6	15	13	193	-
5	Interior plaster	0.3	7	40	204	0.016

In addition to these parameters, in order to evaluate the thermo-hygrometric performance of the construction dynamically, it was necessary to define the following correlation curves:

a) Thermal conductivity vs temperature
b) Thermal conductivity vs moisture content;
c) Free water transport coefficient vs moisture content;
d) Vapor diffusion resistance factor vs relative humidity;
e) Moisture vs relative humidity.

Every single material was characterized by these parameters. For the sake of brevity, Fig. 2 shows the curves a), b) and c) for the cellulose flakes only.

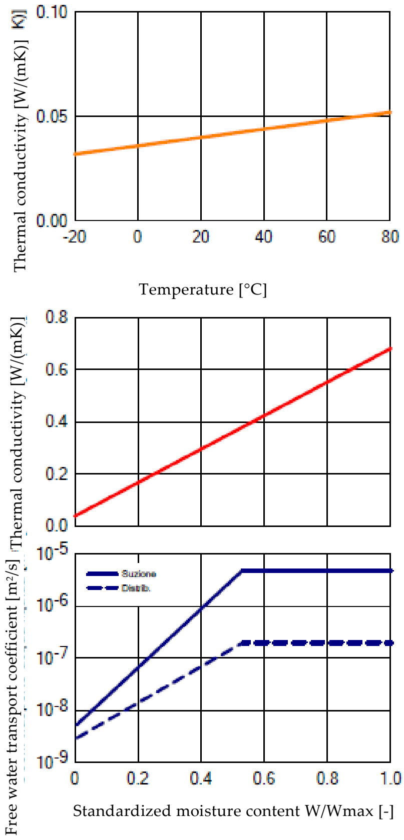

Fig. 2 - Dynamic hygrometrical functions used for the numerical model for the cellulose flakes

4. Simulation Results and Discussion

In this section, the results of the calculations and simulations are presented and commented. A preliminary evaluation was carried out on the initial cavity wall before it was subjected to the energy retrofit process. Fig. 3 shows the Glaser diagram for the cavity wall. This result follows the UNI EN ISO 13788 standard and it was carried out during the critical month of January. The result in steady-state conditions confirms the absence of condensation phenomena. The relative pressure never reaches the saturation pressure value, even if very close values are reached at the critical interface between the air gap and the external perforated brick layer.

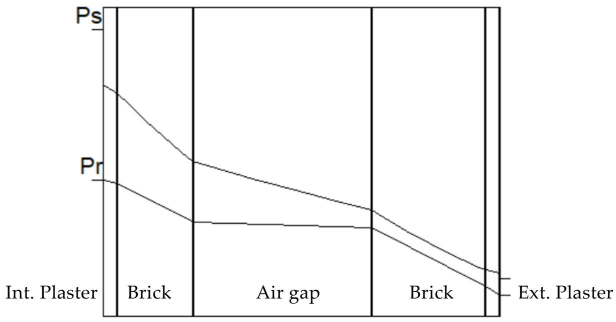

Fig. 3 – Glaser diagram evaluated in steady-state conditions for the cavity wall

4.1 Hygrometric Behavior of Retrofitted Wall (Steady-State Conditions)

The same analysis in steady-state conditions was conducted for the retrofitted wall, where the air gap was filled with cellulose flakes. As can be seen from Fig. 4, the trend of the saturation pressure p_s becomes lower than the relative pressure p_r (evaluated in the absence of interstitial condensation) at the interface between the cellulose and the external perforated brick. This phenomenon, described by the Glaser diagram in the figure, leads to the risk of interstitial condensation at the interface between the two elements.

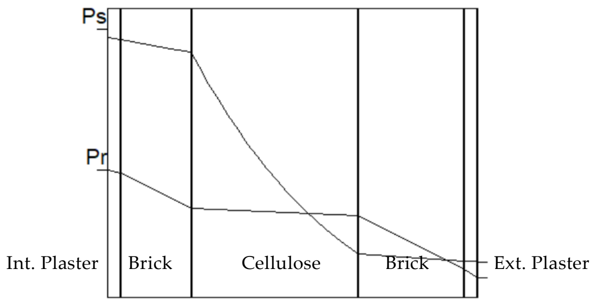

Fig. 4 – Glaser diagram evaluated in steady-state conditions for the retrofitted wall

The results of the analysis, conducted in the critical month of January, demonstrated the limits of the steady-state verification defined by the UNI EN ISO 13788 standard, because of which the construction of the case study is subjected to interstitial condensation. The annual amount of vapor condensed inside the wall was 466 kg/m^2. Although this result does not support the adoption of retrofitting solutions with bio-based materials of this type, the application of real cellulose flakes in cavity walls leads to different results. Indeed, in real cases of retrofit involving cellulose flakes being blown into a wall, the interstitial condensation phenomenon does not occur, leaving the wall dry and with regular hygrothermal performance (Nicolajsen, 2005). This discrepancy between real applications and design calculations brings to light the obvious limitations of the calculation of hygrometric performance in steady-state conditions, based on simplified calculation methods that generally lead to precautionary results.

4.2 Hygrometric Behavior of the Retrofitted Wall (by Dynamic Simulation)

A more detailed modeling of the same construction and of the elements in each of the layer made it possible to simulate the case study in a dynamic calculation regime, as proposed by the UNI EN 15026 standard. Through the dynamic simulation, the hygrometric conditions of the wall were computed hour by hour. After simulating the thermo-hygrometric behavior of the construction for 2 consecutive years (for the North-facing wall scenario), the set of curves of the values assumed by the temperature [°C], by the relative humidity [%] and by the moisture content of the wall [kg/m^3] are shown in Fig. 5. Focusing on the temperature trend, the effectiveness of thermal insulation performed by the NESOCELL® cellulose flakes considerably attenuates the variation of the external temperature. As can be seen from the annual variation in relative humidity, 100% is never reached inside the wall, a value that corresponds to the vapor condensation. Values corresponding to 100% relative humidity only occur close to the external surface of the wall and are due to its interaction with the external rain load, set by the weather conditions adopted for the simulation.

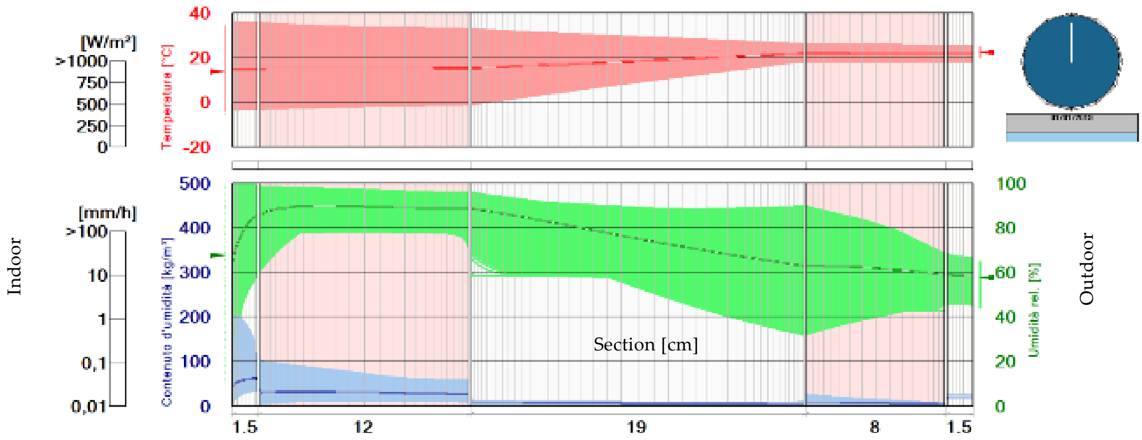

Fig. 5 – Set of curves of the temperature (red), relative humidity (green) and moisture content (blue) trends within the construction layers during the dynamic simulation period (second year only)

Moreover, in terms of moisture content, represented by the blue band and expressed in kg/m³, the cellulose flakes have excellent characteristics, maintaining very limited values compared to common insulating materials. To better understand the hygrometric behavior of the cellulose flakes, a punctual analysis of the simulation results was carried out, taking into consideration the critical interface between the cellulose layer and the external perforated brick, where vapor condensation was reached by calculation in steady-state conditions. In addition to the more critical scenario of the North-facing wall, the more favorable scenario of the South-facing wall was also taken into consideration. Fig. 6 reports the trend of relative humidity during the 2-year simulation period for the North (red) and South (green) simulated directions at the critical interface (cellulose – external brick). The results obtained, in contrast to the steady-state verification, show that the construction of the case study presents no risk of interstitial condensation, with values below 95% in the worst-case scenario.

Analysing the relative humidity distribution during the simulated period shown in Fig. 7, it can be seen that the seasonal effect of the RH value is clear when the wall faces North. In contrast, for a south-facing wall, the hygrometric performances, in addition to being better, are also more constant during the year. A different result occurs for the interface temperature, which is not as sensitive to the orientation as the relative humidity. The simulation results of the two scenarios are comparable without any substantial difference (Fig. 8).

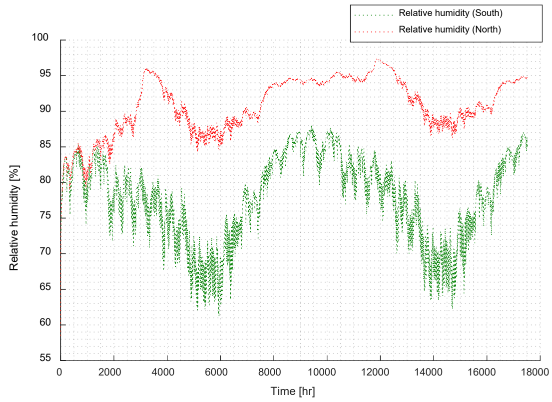

Fig. 6 – Relative humidity trend on the cellulose - external perforated brick interface. Results from 2-year dynamic simulation

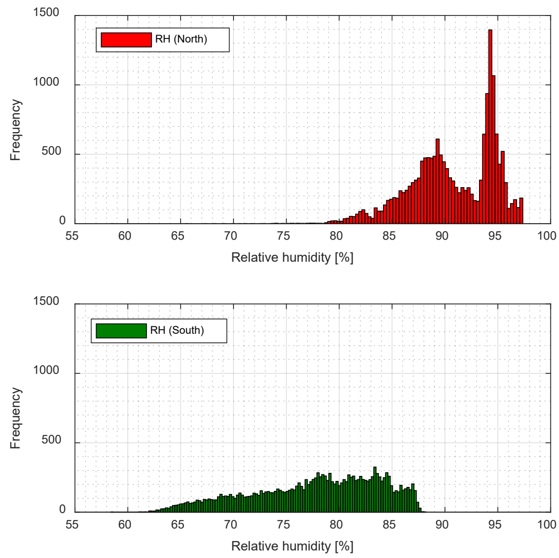

Fig. 7 – Relative humidity frequency for a north-facing wall (red) and a south-facing wall (green)

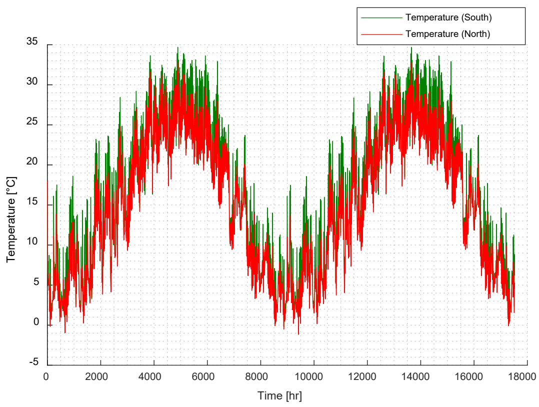

Fig. 8 – Temperature trend on the cellulose - external perforated brick interface. Results from 2-year dynamic simulation

5. Conclusion

The hygrometric analysis carried out using the two calculation methods proposed by the current technical standards has demonstrated the limits of the steady-state verification and the need to adapt the current legislation to the most advanced dynamic calculation. The two calculation methods presented were applied to a real case study and led to different results. The analysis presented in this paper showed the accuracy of dynamic calculation methods in describing the hygrometric behaviour of the case study wall. The adoption of the calculation method proposed by UNI EN 15026 is therefore decisive in the detailed characterization of specific walls, especially with organic materials. In particular, the case study analysed, which investigated the use of cellulose flakes inside a cavity wall, demonstrated how different calculation approaches can lead to contrasting solutions.

Acknowledgement

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Nomenclature

Symbols

T	Temperature (°C)
RH	Relative humidity (%)
I	Solar radiation (kWh/m^2)
ρ	Density (kg/m^3)
c	Specific heat (J/kg°C)
q	Heat (J)
t	Time (s)
g	Mass flow rate (kg/s)
λ	Thermal conductivity (W/m°C)
x	Distance (m)
δ	Vapour permeability (kg/msPa)
w	Water content (kg/m^3)
s	Thickness (m)
C	Heat capacity (J/°C)
R	Thermal resistance (W/m^2°C)
ε	Porosity (m^3/m^3)

Subscripts/Superscripts

sens	Sensible
lat	Latent
v	Vapour
w	Water

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