How to analyse the performances of innovative variable diffusivity membranes integrated within prefabricated timber facades: Computer-based modelling and experimental analysis

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Abstract

Vapour barriers and retarders are often needed to improve the hygro-thermal performance of the building envelope. Their use is particularly important in prefabricated timber façades, especially when critical boundary conditions occur. In the literature, very little is known about the actual performance of complete envelope packages that integrate these membranes, since most previous studies focused on the analysis of single components. However, considering the growing interest and use of such timber facade elements, an analysis of the performance of integrated membranes is needed in order to improve the material function curves available in the data-sheets to enable the correct design of the whole wall structure. Thus, the novelty of this work lies in the validated analysis of a building envelope sample that integrates membranes with a variable vapour diffusivity.

The focus of the paper is more related to the experimental set-up and particular attention has been paid to the development of a relatively simple testing procedure to analyse the behaviour of such integrated membranes. The study seeks to investigate the behaviour of an envelope component integrating a hygro-variable membrane and a breathable membrane by using computer simulation and experimental facilities.

A thermo-hygrometric analysis of the element has been performed in Delphin, and an experimental methodology is presented, aiming to validate the numerical model, measuring the temperature and relative humidity in different layers. Two sets of boundary conditions have been accurately chosen as they are critical for the building component in terms of thermal and humidity transmission.

Results show very good agreement for one test condition. For the second condition, the measurement uncertainty was greater. One possible reason for this was the presence of condensate in the measurement box frame caused by the first test run. The experimental set-up developed is a relatively easy-to-replicate layout for the validation of similar complex packages. Compared to previous studies, the experimental set-up used in this research is simpler and less expensive.

Keywords

hygro-variable membrane, hygro-thermal analysis, delphin, timber façade, relative humidity measurement

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1 INTRODUCTION

Humidity can enter buildings in different ways: infiltration (caused by rain drainage or due to problems in wall-integrated supply ducts), capillary action (due to rising water from the ground), water vapour stored in materials during the building construction phase, and vapour generated by the occupants.

High levels of humidity combined with low interstitial temperature within the building envelope can cause problems such as superficial and internal condensation, reduction of the insulation capacity of materials, aesthetic degradation, and mildew growth (Lucas, Adelard, Garde, & Boyer, 2001). Hence, humidity levels not only influence the performance of materials, but can also become a problem for the comfort and health of occupants.

Therefore, it is crucial to carefully analyse the vapour diffusion within a building envelope in order to avoid these inconveniences and to preserve both the building integrity and the wellbeing of the occupants.

In cold climates, and during wintertime, problems with excessive humidity are usually caused by the poor ventilation of indoor spaces. The vapour produced within the building moves through the building envelope and condenses near colder layers. In order to prevent this behaviour, the humidity level near the wall surface should be reduced, for instance using a vapour retarder membrane on the warm side of the wall.

On the other hand, in hot and humid climates, the main source of vapour can be the outdoor air. In these conditions, condensation problems may occur near the inner layers of the wall, especially if the indoor environment is cooled. A possible solution to this issue is the use of breathable materials within the envelope, in order to let the humidity flow through the wall build-up, avoiding moisture being trapped in the material.

Vapour barriers and retarders are fundamental to control vapour diffusion through the building walls and therefore to regulate the hygrometric behaviour of the whole structure.

Previous research on in-situ existing wall and small single-material specimens have already been done (Litti, Khoshdel, Audenaert, & Braet, 2015) (Guizzardi, Derome, Vonbank, & Carmeliet, 2014) (Campbell, McGrath, Nanukuttan, & Brown, 2017), but few examples on more realistic multi-layer building samples that integrate variable permeability membranes have not been found in the literature.

Thus, this study aimed at investigating the behaviour of an envelope component that integrates a hygro-variable ("smart" vapour barrier) membrane named Clima Control 80 (Rothoblaas, 2017) and a breathable membrane named Traspir75 (Rothoblaas, 2017), by using computer simulation and experimental facilities.

The experimental set-up developed is a relatively easy-to-replicate layout for the validation of similar complex packages.

2 METHODOLOGY

2.1 EXPERIMENTAL SET-UP

In this work, the behaviour of a building envelope sample (0.5m x 0.5m), composed of the layers listed in Table 1, has been analysed through numerical modelling and experimental investigation. The layout was defined in collaboration with a local supplier of components for timber constructions to ensure the selection of a realistic configuration.

Hence, the choice of testing the layer composition that is reported in Table 1 has been agreed together with the company, in order to fulfil the requirements of the most hot and humid regions around the world, such as Asia or South America.

The Traspir75 membrane is commonly adopted in façade packages similar to the one analysed in this study because of its air and water tightness combined with a high vapour permeability, allowing the drying out of the humidity stored within the wall.

Moreover, instead of using a vapour barrier in the inner layers to reduce the amount of humidity entering the façade from the inside, it has been decided to adopt the Clima Control 80. In fact, if this membrane is exposed to high humidity levels, it transforms from a vapour barrier into a breathable product, guaranteeing that the structure remains dry.

	Material name	Thickness	Density	Specific heat	Thermal conductivity	Vapour diffusion resistance	Equivalent air layer thickness (SD)	Total U- value
INDOOR		[mm]	[kg/m^3]	[J/(kg*K)]	[W/(m*K)]	-	[mm]	[W/(m^2*K)]
Layer 1	Gypsum fibre board	12.5	1133.35	1228.37	0.34	16.83	0.21	0.23
Layer 2	Wood fibre insulation board	60	150	2000	0.04	3	0.18	
Layer 3	Clima Control 80 membrane	0.2	400	1700	0.20	1000÷25000	0.2÷5	
Layer 4	Wood fibre insulation board	100	150	2000	0.04	3	0.3	
Layer 5	OSB board	18	630	1880	0.13	280	5.04	
Layer 6	Traspir75 membrane	0.3	250	1800	0.30	67	0.02	
OUTDOOR								

TABLE 1 Layer composition and characteristics

The Clima Control 80 is a particular type of vapour barrier that can adapt its vapour diffusion resistance based on the surrounding relative humidity. In particular, the more it increases, the lower membrane SD is obtained (Table 2).

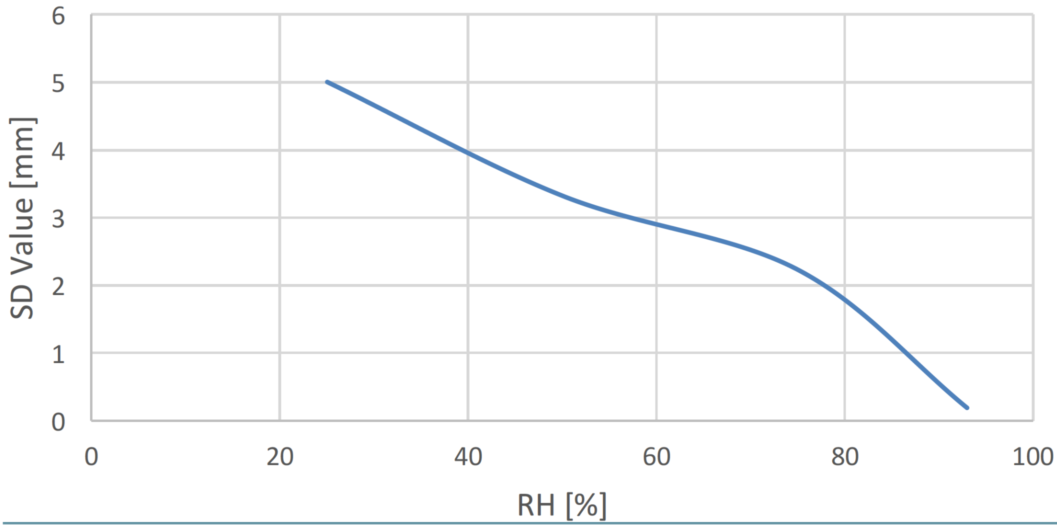

TABLE 2 Clima Control 80 membrane relation between surrounding RH and SD-value

EE08 by E+E sensors (RH→0÷100% ± 2%; T→-40÷80°C ± 0.2°C) have been placed between specimen layers for temperature and relative humidity monitoring. Fig. 1 shows the sensors' position within the materials. In particular, four internal sensors have been embedded into small cavities inside the wood fibre insulation boards: position 1 is at gypsum – insulation (60mm) interface; position 2 is at insulation (100mm) – Clima Control 80 interface; position 3 is at OSB – insulation (100mm) interface; position 4 is at Clima Control 80– insulation (60mm) interface.

Two different boundary conditions were created on the different sides of the specimen during the analyses. On one side, the temperature and relative humidity level were maintained by a mono-zonal climatic chamber. On the other side, it was decided to use a dummy climatic chamber made from wood, which is very well insulated for both thermal and vapour diffusion purposes. This box was made of OSB panels (18mm thick), covered internally with pressed insulation material (Styrodur 2500C, 60mm thick).

During the two performed tests, the box was plugged by the specimen on one side, as shown in Fig.2, and the whole block was inserted into the main climatic chamber. The desired temperature inside the box was set using a thermostat connected to a heating coil, while the relative humidity of the air was set using salt solutions.

In this way, it was possible to impose a thermal and vapour flux from one side of the tested component to the other.

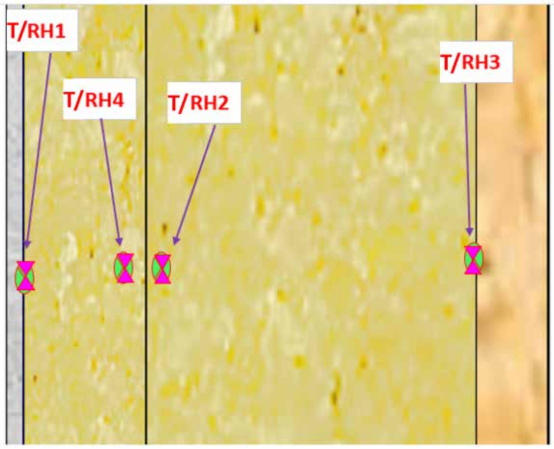

FIG. 1 Sensors' position inside the specimen

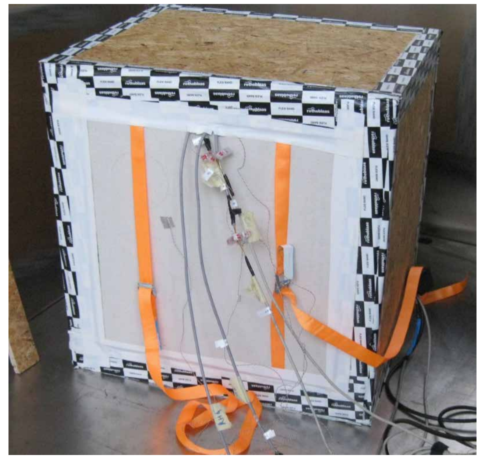
FIG. 2 Specimen closing the box

2.2 BOUNDARY CONDITIONS

In order to analyse the behaviour of the component under critical temperature and high humidity conditions, two tests were undertaken. In the first one, typical hot and humid conditions for the outdoor environment were used. In particular, the temperature was set to such a high value (Fig. 3) to take into account the possible effect of direct sun irradiation on the façade.

In the second test, typical cold and very humid winter conditions were used (Fig. 4).

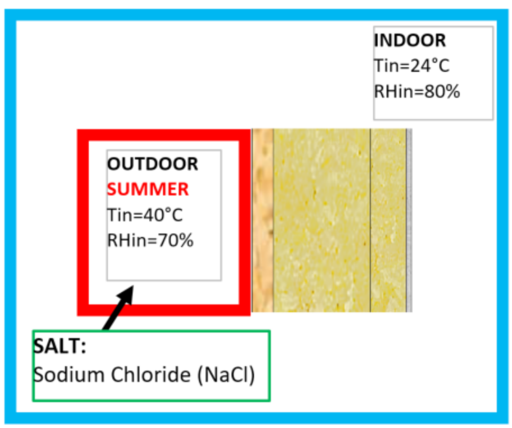

FIG. 3 Boundary conditions TEST 1 (hot/humid summer outdoor conditions)

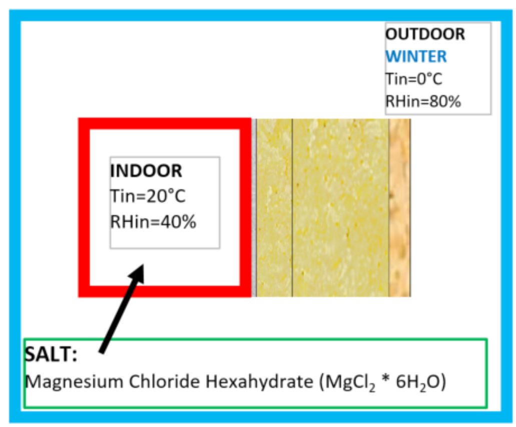

FIG. 4 Boundary conditions TEST 2 (cold/humid winter outdoor conditions)

The duration of each test was determined after considering the necessary time it would take to reach the thermal and humidity flux steady-state conditions in the specimen, accepting a difference of 0.1 W/m^2 (heat flux) and 0.1 g/m^2h (humidity flux) between entering and exiting fluxes, respectively. These values were assessed through a preliminary simulated numerical model. Finally, it was decided to let each test run for almost 15 days.

In the following figures (Fig. 5, Fig. 6), the monitored boundary conditions for the second test are reported. Conditions for TEST 1 are not shown because no relevant differences with designed conditions were present.

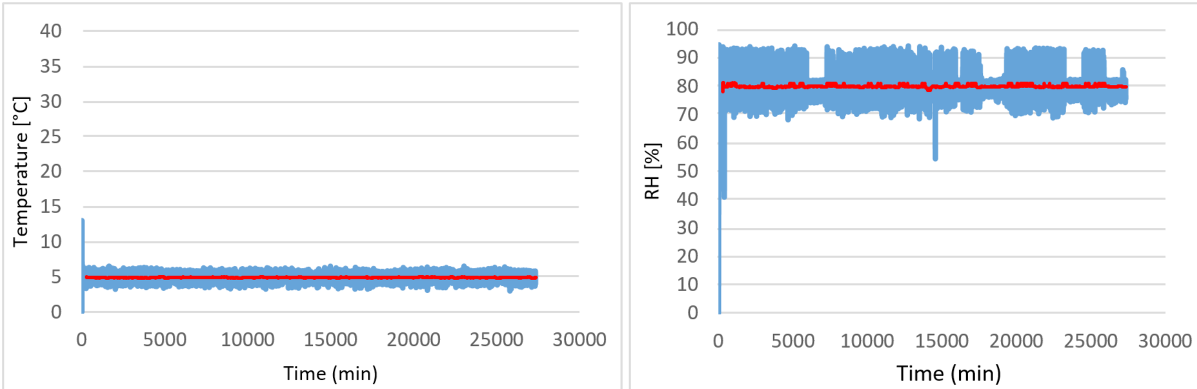

FIG. 5 Climatic Chamber Temperature (left) & RH (right) - TEST 2

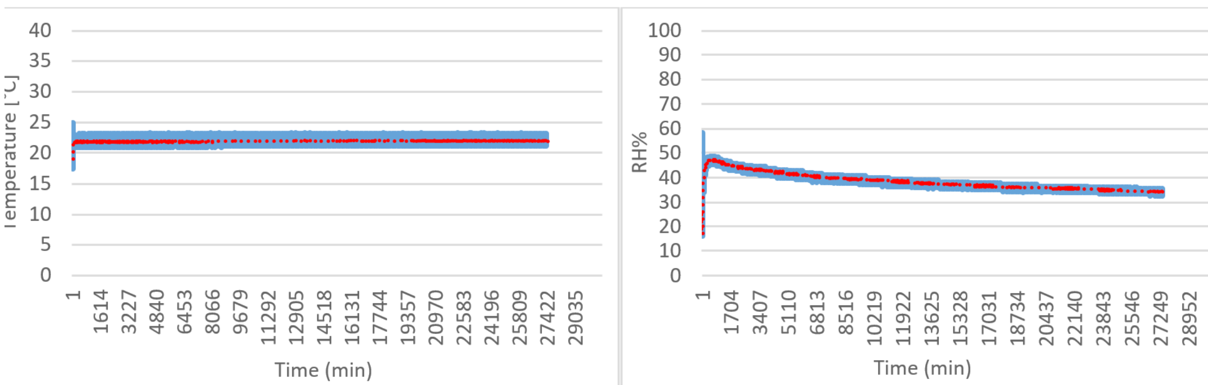

FIG. 6 BOX Temperature (left) & RH (right) - TEST 2

3 RESULTS

In this section, the results of the monitoring campaign are compared with those calculated by the numerical model built in Delphin 5.

All the results for temperature and relative humidity are referred to specific positions (namely 1, 2, 3, and 4) within the specimen. These positions are presented in Fig. 1.

The presented values obtained with the model were reached following a calibration process on some uncertain parameters, mainly related to the humidity transfer function of those materials whose technical sheet was not available.

3.1 TEST 1 – HOT/HUMID OUTDOOR CONDITIONS

In this test, NaCl solution has been used within the BOX to generate the desired humidity rate (RH=70%).
In Fig. 7 and Fig. 8, the monitored and measured trends for temperature and relative humidity at each material interface are presented.

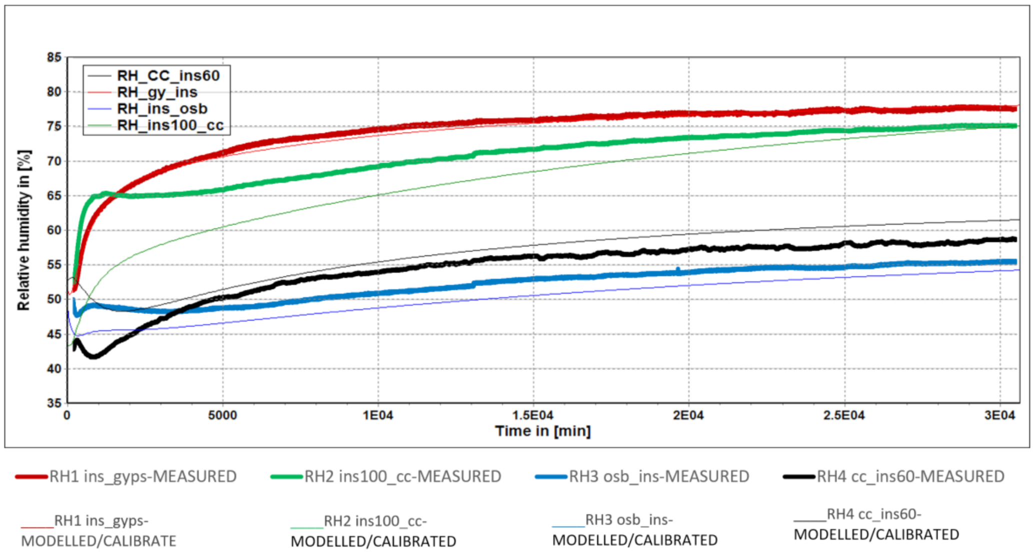

FIG. 7 Relative humidity trends – measured data (thick line) & modelled data (thin line) – TEST 1

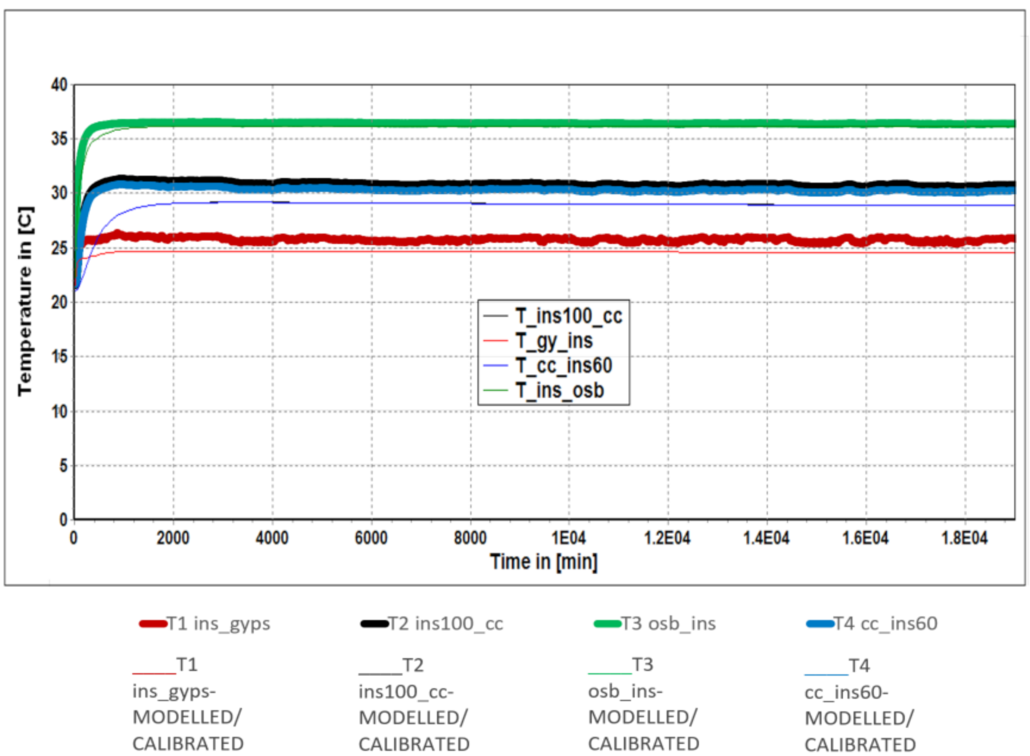

FIG. 8 Temperature – measured data (thick line) & modelled data (thin line) – TEST 1

Fig. 9 presents the comparison between measured (both calibrated and not) and calculated relative humidity, after having reached stationary conditions for vapour flux across the specimen.

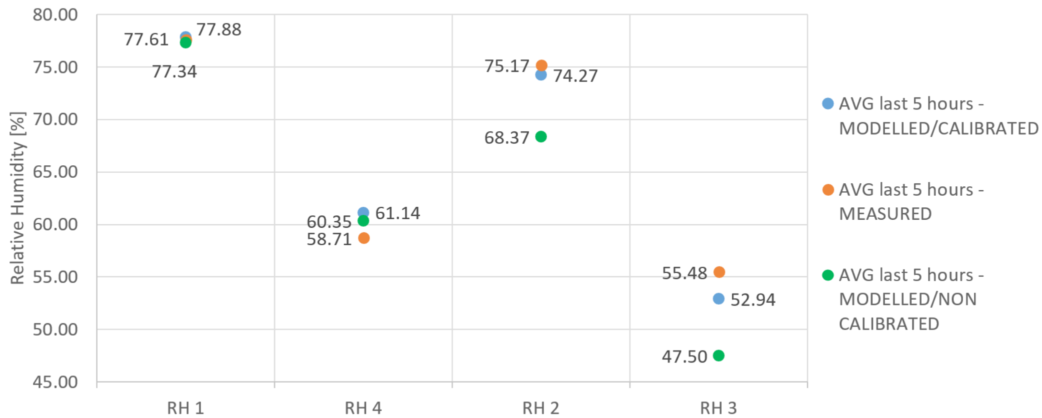

FIG. 9 Comparison between RH values measured & modelled, after stationary conditions (averaged on last 5 hours) – TEST 1

Table 3 and Table 4 present the standard deviation and the absolute value between calculated and monitored values for each sensor in the final hours of the simulation (after stationary conditions occurred).

RMSE(RH1)	RMSE(RH2)	RMSE(RH3)	RMSE(RH4)
0.18	1.11	2.56	2.38

TABLE 3 Root mean square error RH values - TEST 1

MAE(RH1)	MAE(RH2)	MAE(RH3)	MAE(RH4)
0.17	1.11	2.56	2.38

TABLE 4 Mean absolute error RH values – TEST 1

3.2 TEST 2 – COLD/HUMID OUTDOOR CONDITIONS

In the second test, $MgCl_2$ solution was used in order to create the desired humidity conditions within the BOX (RH=40%).

In Fig. 10, Fig. 11, Fig. 12, and Table 5, the results of the comparison between monitored and calculated data are reported for TEST 2. It can be noticed that complete steady state conditions have not yet been reached.

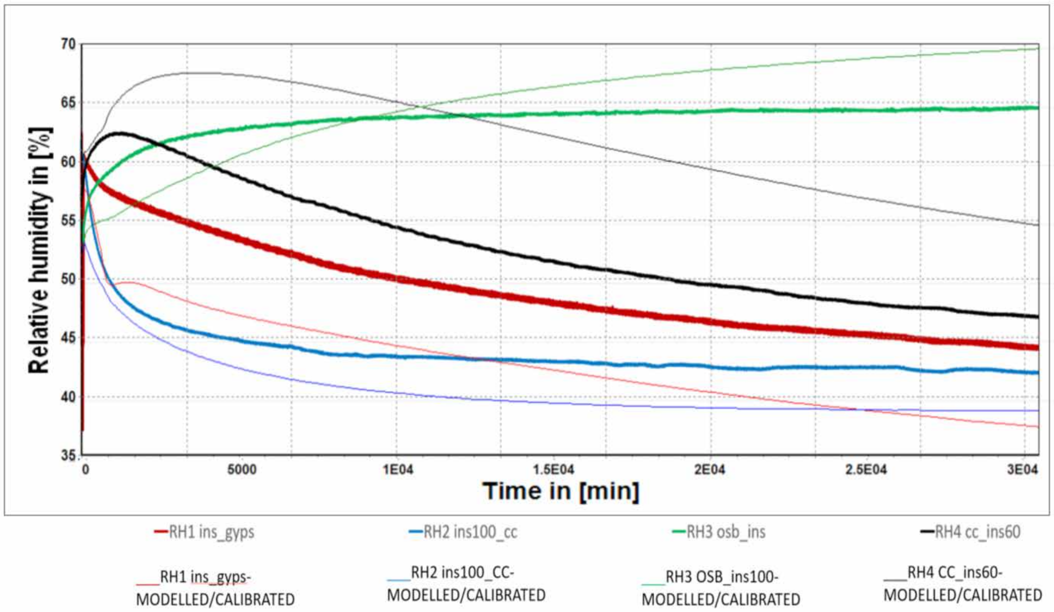

FIG. 10 Relative humidity trends – measured data (thick line) & modelled data (thin line) – TEST 2

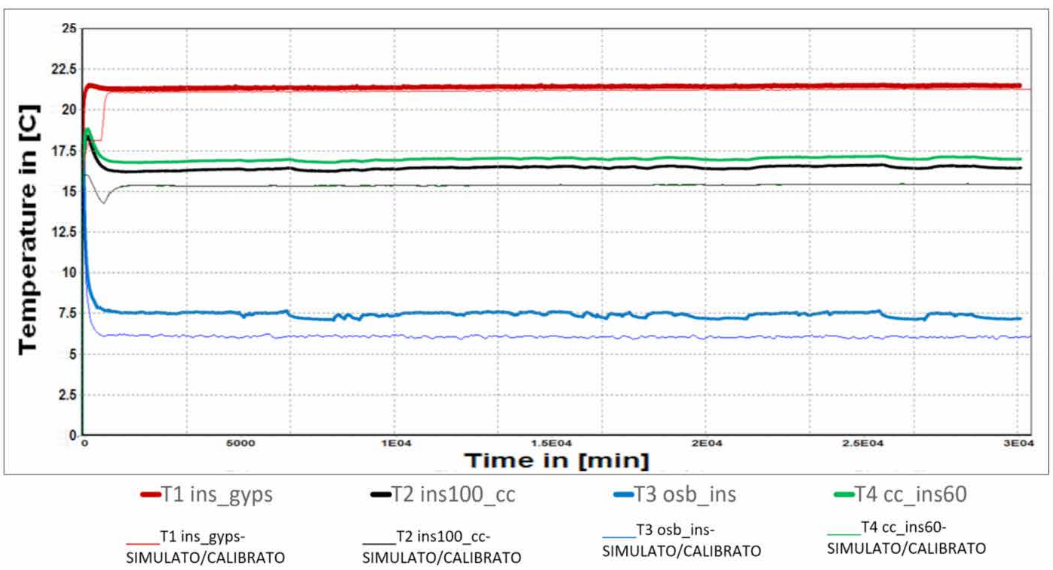

FIG. 11 Temperature – measured data (thick line) & modelled data (thin line) – TEST 2

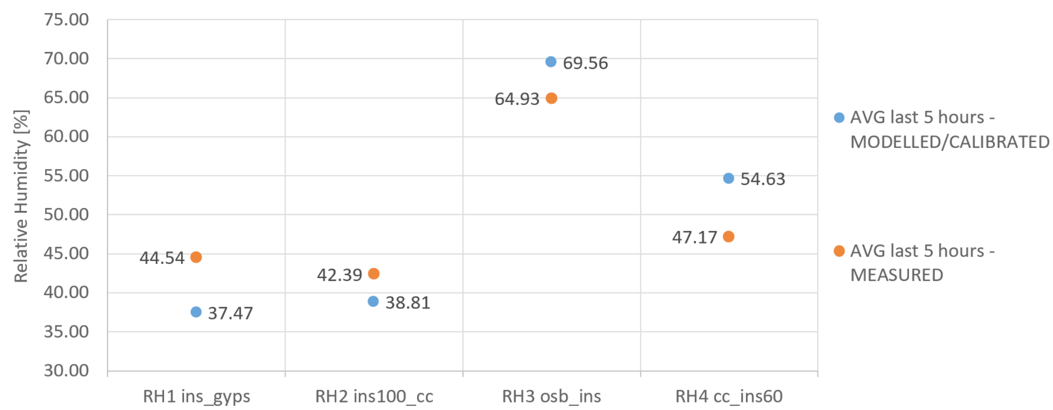

FIG. 12 Comparison between RH values measured & modelled, after stationary conditions (averaged on last 5 hours) – TEST 2

RMSE, MAE (RH1)	RMSE, MAE (RH2)	RMSE, MAE (RH3)	RMSE, MAE (RH4)
10.1	4.89	4.61	8.39

TABLE 5 Root mean square error & Mean absolute error RH values - TEST 2

4 DISCUSSION

In both tests, the measured temperature values are in agreement with the model results. This is due to minor uncertainties relating to the heat transfer process. The only small issues regarding the temperature are caused by the climatic chamber`s difficulty in maintaining conditions around 0°C in a stable way during TEST 2.

On the other hand, the relative humidity results (especially in TEST 2) show more discrepancies between the model and the reality. Possible explanations for this are as follows.

Firstly, it is noticeable from Fig. 5 and Fig. 6 that the relative humidity boundary conditions, both in the box and in the climatic chamber, have quite low stability: for the box, this can be due to a non-optimal dosage of the salt solution. Regarding the instability of RH level in the climatic chamber, the main problem is related with the too low operative temperature set in the machine (~ 0°C).

Although the results of the first test are in good agreement with the simulation, another source of errors in the tests can be related to the sensor positioning inside the specimen. In fact, while RH simulation results from Delphin represent the moisture contained in material`s pores, the E+E sensors that have been used in this experimental activity measure the humidity level in the small air cavity in the material in which they are inserted.

Another cause of uncertainty that is likely to have affected the second test is the inadequate estimation of drying time. Some humidity, trapped in the sample from the previous test, may have slightly influenced the results of the second test.

Finally, it should be taken into account that the physical properties' functions of all the materials used in the model, in particular those of less known materials within our specimen (e.g. OSB layer and vapour retarders), can themselves present small uncertainties.

In the future, this kind of study and experimental setup would allow for the reduction of uncertainties related to the material function by undertaking a step-by-step test and calibration of each layer.

5 CONCLUSIONS

It can be concluded that, in the first test, there is a good match between simulation and calculated data, with a maximum difference in stationary condition (value assumed as the average in the last 5 simulation hours) of 4% for RH and 1°C for temperature.

The less conclusive agreement of the second test is likely to have been caused by the above-mentioned possible reasons. Thus, considering the overall results of the performed analyses, it can be concluded that the modelling of the smart vapour barrier was successful. Overall, the methodology applied to this study, albeit with a limited budget, revealed itself to be a solid approach for the investigation of thermal and hygrometric phenomena in a building envelope sample.

Further analyses could investigate the hygro-thermal behaviour of the samples, using a double climatic chamber in order to set more stable boundary conditions across the specimen. Moreover, a comparison between different sensor typologies could be done (e.g. dimension, accuracy, output typology), in order to consolidate this approach to measuring within envelope components. Future studies should extend these analyses to more complex façade systems to investigate eventual problems related to the integration of components such as ventilation machines, PV modules, or solar thermal panels.

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