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Cross-comparison of measured behavior of highly hygroscopic and vapor permeable walls exposed to different real climates

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Abstract

Experimental measurements are often used to validate or calibrate numerical models. Many authors report good agreement between experimental measurements and numerical simulations of thermal behaviour of walls, and notice stronger discrepancy while assessing moisture transfers. One of the possible reasons for this discrepancy is the difficulty to measure precisely and robustly hygrothermal transfers under real climate variations.
In order to check the robustness of hygrothermal measurements, in the present work records from two different experimental facilities are compared. Both have controlled indoor climate and similar, but not identical outdoor conditions (they are situated at about 400 km distance). The same vapour open and hygroscopic wall assembly is investigated on both cells. The results analysed show strong similarities in qualitative behaviour. Quantitative analysis using normalised values show good agreement in stable conditions. In strong dynamic conditions the analysis is more difficult; more work is needed in order to overcome the amplitude of boundary conditions.

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Keywords: Hygrothermal transfer, experimental measurements; vapour open building envelope, hygroscopic material, cross-comparison

1. Introduction

In building retrofitting as well as in numerous new constructions the moisture transport questions are important often from durability point of view. Energy saving issues are always targeted but simultaneous potential structure degradation is often neglected. Building energy simulation tools are efficient, but they do not involve coupled heat

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and moisture transfer analysis. Researchers who aim to compare simulated and measured data must handle the uncertainty related to a lack of reliable measured moisture transport data.

To study Heat, Air and Moisture (HAM) coupled transfers in building envelopes, many numerical studies have been done and many experimental facilities under controlled conditions or outdoor climate have been established [1]. Most of these studies concern realistic constructions, with high air and water tightness together with a vapor barrier, thereby limiting the impact of mass transfers on energy performance of the envelope. Yet moisture movements influence the temperature fields inside the walls [2] and indoor comfort [3]. There is a persisting need for precise assessment and understanding of the impact of mass transfer on the performance of highly hygroscopic wall assemblies, as well as for detailed validation of dedicated simulation tools [4].

In order to better assess the effects of coupled transfers within wall assemblies, two new experimental studies with highly vapor-permeable and very hygroscopic materials were performed. Two different facilities were set up, in order to ensure high confidence in the experimental results. The first facility includes two walls mounted on two existing PASSYS cells at INES (in South-Eastern France), the second one is an experimental hut located at LERMAB in Epinal (Eastern France). Both facilities had controlled indoor climate and walls are exposed to outdoor climate on the other side. Identical open-vapour, highly hygroscopic building envelope was mounted and instrumented on these facilities. A cross-comparison between the two facilities was run on the experimental results, in order to ensure the general character, robustness and repeatability of experimental data. After the description of the experimental facilities, some elements of this cross-comparison are reported in the present paper.

Nomenclature

λ	thermal conductivity [W/(m K)]	U	global heat transfer coefficient [W/m².K]
Pv	Vapour pressure [Pa]	T	Temperature [°C]
RH	relative humidity [%]		

2. Experimental setup

2.1. Tested walls

The envelope element studied is a timber-framed wall insulated by wood fibre (Fig. 1a). The structure of the wall is made up of two cross-pieces in spruce (λ = 0,09 W/(m K) at RH = 40 % and λ = 0,23 W/(m K) at RH = 98 %) of section 5×12 cm (one in bottom and one in top of the wall) connected by five vertical uprights of sections and material identical to that of the cross-pieces. The space formed by this structure is filled with 8 cm thick wood fibre panels (λ = 0,04 W/(m K) at RH = 40 % and λ = 0,08 W/(m K) at RH = 98 %), a strongly hygroscopic and vapour permeable material with a density ranging between 120-140 kg/m^3. In order to limit the thermal bridges related to the presence of the timber frame, a layer of 8 cm wood fibre is placed on the external surface. To protect the insulation from the rain, the external surface of wood fibre is covered with a mineral coating (approximately 3 mm thickness). This latter is impermeable for the liquid water but it does not constitute a barrier for the vapour (μ<25). The resulting envelope element is a light wall, strongly hygroscopic and vapour-permeable but liquid-tight.

2.2. INES facility

INES experiments use the PASSYS test cells, presented previously in [5, 6], and shown in Fig 2.a. The PASSYS test cells were originally designed to test passive solar components under real weather conditions. Two of them (Passys 1 and Passys 2) were used in the present experiment in order to precisely control indoor conditions on one side of the tested façade. Both cells are located on the CEA-INES experiment platform in Le Bourget du Lac France. They are 8.44 m long, 3.6 1m wide and 3.8 m high. The cells are made of a metallic frame insulated by 48 cm of polystyrene and mineral wool to have 5 highly insulated (U=0.09 W/m².K), water and vapour proof walls. The 6th face is reserved for a wall of maximum 3.6*3.3 m² to be tested. Each cell is placed on a dedicated rotating platform, for a free choice of orientation of the tested wall. Each cell has a HVAC system to control indoor temperature (15 to 35°C with +/-1°C tolerance) and relative humidity (air moisture content from 6 to 14 g/kg of dry air +/- 10 %).

In each tested wall 83 sensors are implemented. Temperature and relative humidity sensors are placed in different specific areas within the wall: current part, close to timber frame and within thermal bridges due to PASSYS cells frame (fig. 1b). There are also different locations within the thickness: between the layers of insulation, in the middle of each layer (a dedicated hole was made), and on the two sides of the roughcast. 8 sensors are placed in rooms' volumes, measuring temperatures and relative humidity.

For exterior conditions, a weather station, located 50 m from the cells, records the temperature and the relative humidity. A pyranometer is placed vertically on each façade, in order to anticipate errors due to calculation of the global radiation on each wall taking into account surrounding buildings, by recording that radiation.

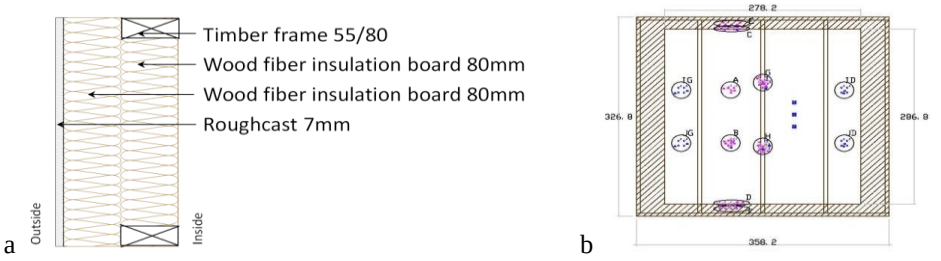


Fig. 1. (a) Wall structure (b) Measurement points in the walls mounted on PASSYS test cell;.

2.3. LERMAB test cells

The test facility built at the LERMAB Laboratory at the School of Wood Science and Timber Engineering (ENSTIB) in Epinal, France was designed for the study of the hygrothermal behavior of four vertical walls (same assembly as the one mounted at INES platform) exposed to real atmospheric boundary conditions (fig. 2b and 2c). The internal dimensions of the test cell are 3.34 m wide, 3.34 long with a height of 2.40 m. Its 4 vertical walls are facing the four major orientations (N, E, S, W).

In order to minimize the heat and moisture transfers through the other parts of the cell the floor, the ceiling as well as the access door are largely insulated and air and vapor tightened. Additionally, many precautions were taken to ensure a good air and water vapor tightness of these parts. The temperature and the relative humidity within the test cell are controlled. The temperature and humidity profiles within the walls thickness are measured with thermo-hygrometers (Sensirion SHT75) placed at different thicknesses during the construction phase. All sensors were positioned in a measurement area at mid-height and mid-width of the walls.

Fig. 2. (a) Photography of one of INES cells, (b) Photography of LERMAB test cell, (c) LERMAB test cell structure.

3. Results and discussion

3.1. Overview and repeatability under same conditions.

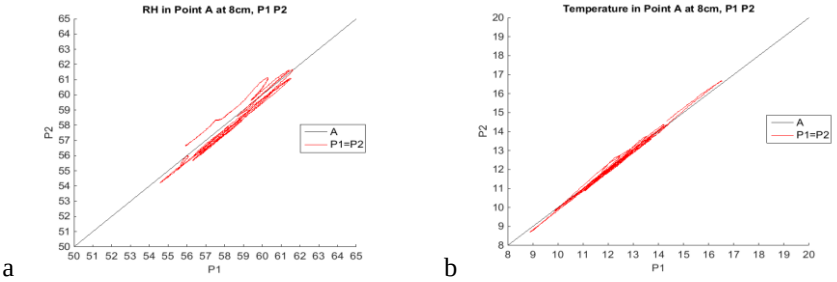
INES cells were operating from March 2013 to January 2015, while the LERMAB cell is operating since October 2013. On all cells different scenarios were applied with fixed indoor air humidity and temperature, wall orientation.

Moreover in Passys 1 the wall composition was modified in December 2013. Some changes in indoor conditions were performed. Table 1 gives an overview of tested conditions.

	Date	02/10/2013	09/10/2013	18/11/2013	18/12/2013	27/01/2014	03/02/2014	06/02/2014	13/03/2014	16/04/2014
Passys 1	Internal Temperature (°C)	20								
	Internal Relative humidity (%)	60		40					60	
	Orientation	North	South							
	Wall composition	16 cm of wood fibre + mineral coating			20 cm of wood fibre + mineral coating		1 cm of OSB + 20 cm of wood fibre + mineral coating			
Passys 2	Internal Temperature (°C)	20								
	Internal Relative humidity (%)	60			40				60	
	Orientation	South								
	Wall composition	16 cm of wood fibre + mineral coating								
LERMAB cell	Internal Temperature (°C)	20								
	Internal Relative humidity (%)	40				60		40		60
	Orientation	4 walls, North, South, East, West								
	Wall composition	16 cm of wood fibre + mineral coating								

Table 1. Overview of the experimental campaign

As a preliminary step in this study, repeatability under identical conditions was tested. This was done using results from INES facility. Indeed, in spring 2013, both PASSYS cells were subjected to identical boundary conditions. Period from 29/03/2013 to 11/04/2013 was selected to carefully verify registered data. Fig 3 shows an example of conducted cross-comparison. A very good agreement between both cells can be seen.



a b

Fig. 3. Preliminary cross-comparison: Relative humidity (a) and temperature (b) in the middle of the wall : Passys 1 measurements vs Passys 2.

3.2. Repeatability under different conditions.

While the verification of measurements under same conditions is a straightforward task, the challenge lies in the attempt to compare the measurements achieved under slightly different conditions. This is the case when we try to compare measurement achieved in LERMAB and INES cells: as both cells are about 400 km away, the outdoor climate is similar but not identical, while similar indoor conditions were achieved. First, simultaneous periods with identical and stable indoor conditions were identified:

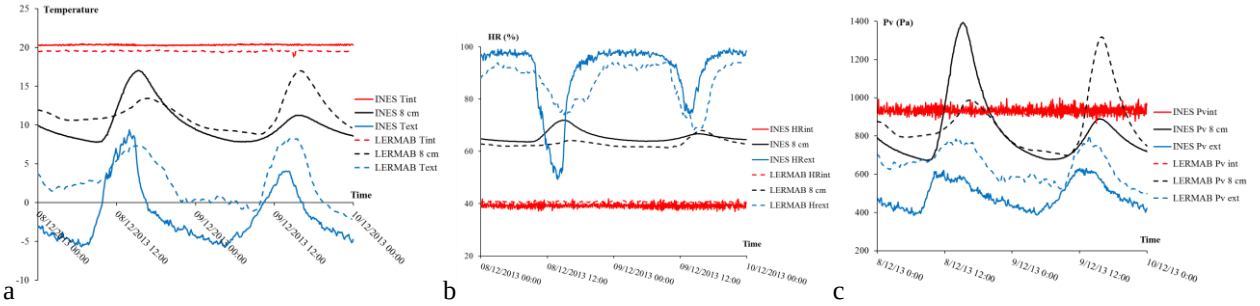
- Winter conditions: 25/11/2013 to 12/12/2013
- Spring conditions: 05/03/2014 to 13/03/2014, with indoor RH at 40 %, then from 20/04/2014 to 20/05/2014 with indoor air at 60 %.

Moreover periods with change of indoor conditions were identified. However this could not be done simultaneously on both sites. They correspond to the increase or the decrease of indoor RH between 40 and 60 % under winter or spring conditions. Here, only South orientation is investigated.

3.3. Time evolution.

Fig. 4 shows the temporal evolution during two typical days in winter. Indoor climate is stable (20 °C and 40 % RH in both cells) and outdoor temperature oscillates between -5 °C and +8 °C for INES and between 0 °C and +8 °C for LERMAB. During both days and in both cells the heat flows from inside to the outside. The temperature in the middle of the wall (8 cm) is in between indoor and outdoor values and follows the daily increase with about 2 hours' time-shift. Outdoor relative humidity is close to 100 % at night, and goes down to 50 % for INES and 65 % for

Epinal during the day. Global solar radiation received on horizontal surface was 799 and 1126 kWh/m² at LERMAB, and 1920 and 970 kWh/m² at INES, the 8th and 9th of December respectively.



a b c

Fig. 4. Temperature (a) Relative humidity (b) and Vapour pressure (c) in INES and LERMAB cells. Indoor, outdoor and mid-wall (8cm depth) values are shown.

It is also very interesting to look on partial vapour pressures, showed in Fig 4c. Indeed, indoor vapour pressure is very stable, and the outdoor vapour pressure varies between 400 and 600 Pa for INES, and between 500 and 800 Pa for LERMAB, following daily variations of outdoor temperature and humidity. However in the middle of the wall (at 8 cm depth) the situation is more complex. During night, vapour pressures at 8 cm in the wall are situated approximately in between indoor and outdoor values. However this changes during the daytime. The increase in vapour pressure at 8 cm follows the outdoor increase, with a time shift of approximately 2 hours. The amplitude of the vapour pressure rise at 8 cm is much higher than the amplitude of the increase outdoors. The vapour pressure at 8 cm reaches, and even surpasses the indoor value (the 8/12 for INES and the 9/12 for LERMAB), which means that vapour flux inverses. Such behaviour was already observed by other researchers [2; 7]. This phenomenon can clearly be explained by thermal conditions: 8/12 at INES there is an important rise in outdoor temperature, connected with a stronger solar radiation, while 9/12 at LERMAB was warmer with higher solar radiation.

3.4. Normalised profiles

From previous analysis we can clearly see the similar behaviour of both experimental facilities. In order to generalise the results, it is important to gain some independence regarding boundary conditions. This can be done by using normalisation with respect to boundary conditions. The following formula is used:

$$Normalized\ Value_{(X,t)} = \frac{Measured\ Value_{(X,t)} - Measured\ Value_{(INT,t)}}{Measured\ Value_{(EXT,t)} - Measured\ Value_{(INT,t)}} \quad (1)$$

Where *Value* represents temperature, vapour pressure or relative humidity, INT means indoor air, EXT - outdoor air and X is the coordinate of the point within the wall (4, 8, 12 or 16 cm). All values are taken at the same time *t*.

Fig 5a shows the normalised temperature evolution at different depths in the wall. Here, during night periods, a very good correspondence of not only quantitatively but also qualitatively can be seen. According to heat transfer theory in steady state, values remain constant. However during daytime the evolution is complex, because of transient phenomena. Dynamic phenomena are due to weather conditions. From temporal evolution time shift could easily be estimated. It is approximately 3h at 4cm, 2h at 8cm, 1h at 12cm and 0h at 16cm. A modified normalisation is then proposed, accounting for the time shift:

$$Normalized\ Dt\ Value_{(X,t)} = \frac{Measured\ Value_{(X,t)} - Measured\ Value_{(INT,t)}}{Measured\ Value_{(EXT,t-Dt)} - Measured\ Value_{(INT,t)}} \quad (2)$$

Dt being the time shift corresponding to depth X. Fig 5.b shows the Normalised temperature with phase shift. As anticipated, the normalised temperatures are more stable. However some disturbances are still present, during the daytime, especially on the 8th of December for INES and on the 9th of December for LERMAB. Both normalisations of vapour pressure are plotted in Fig. 5.c and 5.d. Accounting for time-shift in temperatures enables to smooth the plots. However variations remain important, especially during days with higher solar radiation (8/12 for INES and 9/12 for LERMAB).

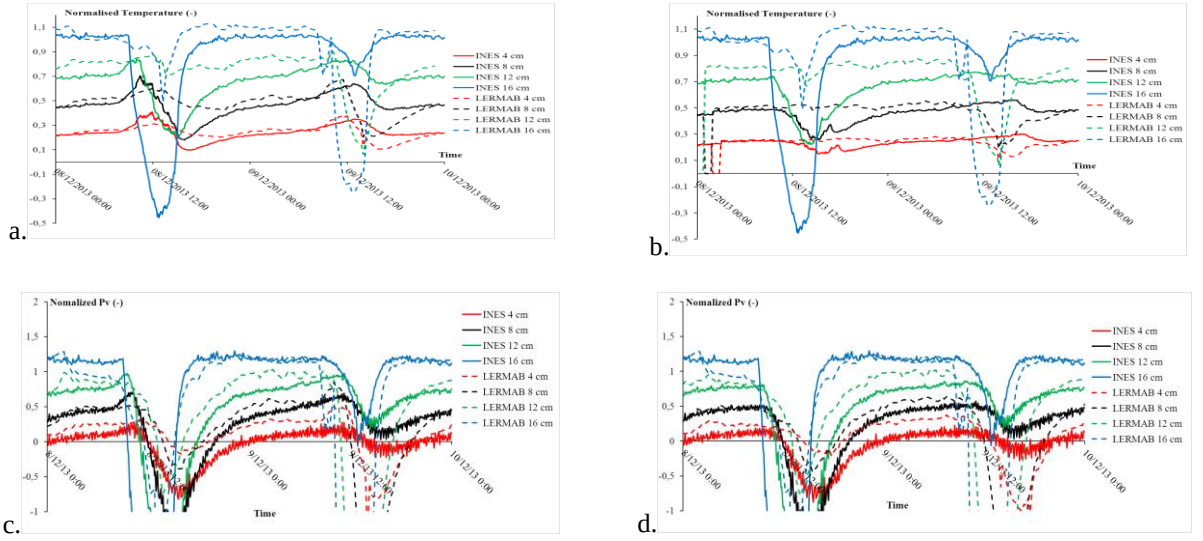


Fig. 5. a) Normalised temperature; c) Normalised temperature with phase shift c) Normalised vapour pressure; d) Normalised vapour pressure with phase-shift. INES and LERMAB cells, different depths in the wall.

4. Conclusion

Hygrothermal profiles in a vapour open, hygroscopic, insulation material, registered in two different experimental facilities under slightly different outdoor climate were analysed. The objective was to verify the robustness of hygrothermal measurements, to highlight important phenomena and try to propose analysis independent from boundary conditions. The measurements in both cells reported the same physical phenomena: daily variation of temperature and relative humidity, solar driven vapour flow, etc., with similar qualitative and quantitative variations. This analysis was done using dimensional and normalised profiles.

Time shift was included in the normalisation it enabled to stabilise temperature profiles and slightly smoothed vapour pressure profiles. In future work, it is important to analyse more in detail impact of solar radiation, and to analyse the periods with changing indoor conditions.

Acknowledgements

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