EVALUATION OF THE CONTRIBUTION OF HIGHLY HYGROSCOPIC AND VAPOUR PERMEABLE WALLS TO WHOLE BUILDING PERFORMANCE

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ABSTRACT
Moisture transfer has an impact on the energy performance and on the durability of the building walls. The objective of this study is to assess these impacts on a light wall mainly composed of wooden materials. To perform this study a coupled heat and moisture transfer model has been used and a simulation tool has been developed. Yearly simulations have been carried out for the outdoor climate of north-east of France considering different occupancy scenario for the indoors. The thermal flux exchanged between the wall and the indoor air has been calculated by several ways (pure thermal simulation, sensible heat, total heat) and a comparison of these fluxes has been performed.

INTRODUCTION
Moisture transfer has an impact on the energy performance and on the durability of building walls. However usual evaluation of building envelope performances is done using only thermal measurements and calculations, neglecting possible impacts of mass transfers. On the other hand, advanced modeling of heat-air-moisture (HAM) transfer in porous building materials has been largely developed and successfully used in the assessment of wall durability, moisture buffering capacity of walls as well as in the detailed studies of wall assemblies (see for example Janssen et al., 2007, Derome and Carmeliet, 2012, Labat et al. 2015; Rouchier et al, 2014). One of the still pending questions is: “is it necessary to use coupled HAM models to evaluate the contribution of walls to building performance?”.

The main objective of this paper is to evaluate the impact of moisture transfer on energy performance of a specific highly hygroscopic wall. Yearly simulations are performed for different indoor conditions and energy flows exchanges between the indoor air and the wall are discussed as an indicator of the energy performance. The durability of the wall is discussed by the analysis of relative humidity and temperature distribution in the wall and by comparing them to the conditions of spore germination. In order to get confidence in the presented results, the model used in this study is first described and validated. This study was done within the frame of an important national project, called Hygro-bat.

MODEL DESCRIPTION
Governing equations and main assumptions
The model developed to describe the coupled heat and mass transfers that take place inside walls is based on two governing equations, the energy and the mass balances. The mass transfers in a building wall can be due to transfer across the wall material of liquid water, water vapour or air. The heat transfers are due to the conduction and to the enthalpy flows associated to the mass transfers. The model developed for this study does not take into account the air transfer. Moreover, the gases are considered as perfect.

With those assumptions, the mass balance of a wall element can be expressed by:

$$\frac{d\rho_{w}}{dt} = -\text{div}(g_v + g_l)$$ (1)

Where $\rho_{w}$ (kg.m$^{-3}$) is the bulk density of the water (liquid and vapour), $g_v$ (kg.m$^{-2}$.s$^{-1}$) is the mass vapour diffusion flux and $g_l$ (kg.m$^{-2}$.s$^{-1}$) is the mass liquid diffusion flux.

The driving potential used to govern the mass diffusion fluxes are: the partial vapour pressure ($P_v$) for the vapour flux and the capillary pressure ($P_c$) for the liquid flux. The capacity of the material to absorb or desorb water is taken into account considering the sorption isotherm. Mass of vapour phase is neglected, therefore it has been considered that the sorption isotherms give directly the water absorbed (in liquid phase) by the material.

Considering these definitions and by neglecting the gravity effect the equation (1) can be transformed as:

$$\frac{d\rho_l}{dt} = -\text{div}[-\delta_i \text{ grad}(P_v) - k_l \text{ grad}(P_c)]$$ (2)

Where $\rho_l$ (kg.m$^{-3}$) is the bulk density of the liquid water, $\delta_i$ (s) is the water vapour permeability and $k_l$ (s) is the liquid water permeability.

Based on the assumptions previously introduced the heat balance of a wall element gives:
\[
\frac{dU}{dt} = -\nabla \cdot (q + g_v \cdot h_v + g_l \cdot h_l)
\]  

(3)

Where \( U \) is the internal energy (J), \( q \) is the thermal conduction flux (W), \( h_v \) and \( h_l \) are respectively the enthalpy of the vapour and of the liquid water.

Assuming that the specific heat of the material \( (C_{\text{m}} \text{J.kg}^{-1} \cdot \text{K}^{-1}) \), the specific heat of the liquid water \( (C_l) \) and the enthalpy of evaporation of the water \( (h_l) \) are constant, the equation 3 can be developed as follow:

\[
\frac{d}{dt}\left[ \rho_m C_{\text{m}} T + \rho_l C_l T + \rho_v (C_l T + h_l) \right] = -\nabla \cdot \left[ \lambda_v \nabla T - g_v (C_l T + h_l) - g_l C_l T \right]
\]  

(4)

Where \( T \) (°C) is the temperature and \( \lambda_v \) (W.m\(^{-1}\).K\(^{-1}\)) is the thermal conductivity of the wall material.

**Boundary conditions**

The internal and external surface of the wall exchange heat and mass with their environment. These surfaces exchange heat by natural and forced convection and by infrared radiation. In order to simplify the model a global heat exchange coefficient \( (\alpha) \) is used to describe the convective and radiative heat transfer at the wall surfaces. The wall may also absorb solar irradiance. Considering the conventions defined in the following section, the mass outflow across the internal surface \( (g_v^{\text{int}}) \) can be expressed as follow:

\[
g_v^{\text{int}} = \beta^{\text{int}} \left( P_v^{\text{int}} - P_v^{\text{surf} \text{ int}} \right)
\]  

(5)

Where \( P_v^{\text{int}} \) and \( P_v^{\text{surf} \text{ int}} \) (Pa) are respectively the partial vapour pressure in the indoor air and at the internal surface, \( \beta^{\text{int}} \) (kg.m\(^{-2}\).Pa\(^{-1}\).s\(^{-1}\)) is the mass transfer coefficient at the internal surface. The latter is calculated from the global heat exchange coefficient and the Chilton-Colburn equation.

The heat flow across the internal surface \( (q_v^{\text{int}}) \) is calculated by:

\[
q_v^{\text{int}} = \alpha^{\text{int}} \left( T^{\text{int}} - T^{\text{surf} \text{ int}} \right) + g_v^{\text{int}} h_v
\]  

(6)

The liquid transfer (rain adsorption) is not taken into account in this model. The mass outflow across the external surface is thus calculated as the internal one:

\[
g_v^{\text{ext}} = \beta^{\text{ext}} \left( P_v^{\text{ext}} - P_v^{\text{surf} \text{ ext}} \right)
\]  

(5)

The heat flow across the external surface \( (q_v^{\text{ext}}) \) is calculated by:

\[
q_v^{\text{ext}} = \alpha_v^{\text{ext}} \left( T^{\text{ext}} - T^{\text{surf} \text{ ext}} \right) + g_v^{\text{ext}} h_v + \chi l
\]  

(6)

Where \( \chi \) is the wall absorptivity (in the solar spectral band) and \( l \) is the solar irradiance on the vertical surface (W.m\(^{-2}\)).

**Simulation tool and validation**

Based on the equations introduced in the previous sections, a 1 D-simulation tool has been developed within the DYMOLO software, already successfully used in building simulations (Wetter et al. 2014). The spatial discretisation of the equations has been done with the finite volume method and the time integration is performed with the Dassl algorithm implemented in DYMOLO. This software is based on the object-oriented Modelica language. This approach allows simulation of complex wall (composed by several material) and easy changes of the wall configuration. The main inlet parameters of the simulation tool are the internal and external conditions (temperature, relative humidity and solar radiation), the geometrical (thickness) and the material properties of the wall layers (thermal conductivity, mass heat capacity, vapour diffusion resistance factor, sorption isotherm ...). From these data, the simulation tool calculates the temperature field and humidity in the wall and the mass and heat flows exchanged within the wall and the environments.

In order to validate this simulation tool, simulations have been performed considering the wall configuration and the operating conditions of an experimental setup developed by a project partner. The experimental bench is described in Rafidiarison et al. (2015). The studied wall is a timber-frame wall insulated by wood fibre, protected at the external surface by a mineral coating. The simulation results (Fig 1 and 2) show a good agreement with the experimental measurement in description of both temperatures and relative humidity behaviour.

**SIMULATION CONDITIONS**

The presented simulation tool is used to investigate the impact of moisture transfer on thermal performance and on durability of a light wall, strongly hygroscopic and vapour-permeable but liquid-tight. The wall is located in north of France.
Configuration of the wall and material properties

The studied wall is mainly composed by wood-based materials (Fig. 2). It is composed from the outside to the inside by: a wood cladding, a ventilated air gap, a rainscreen, 120 mm of wood fiber and 78 mm of CLT (Cross-Laminated Timber) panel. The physical properties of the CLT panel has been considered equivalent to that of a massive panel of spruce. The main properties of considered for this study are summarized in the table 1. The behavior of this wall is analysis for both south and north orientations.

The air gap is highly ventilated and it has been assumed that in the north configuration there is no solar radiation absorbed by the wall external surface. Therefore:
- For north orientation the temperature and the relative humidity of the air in the air gap are considered equal to that of the external conditions.
- For south orientation a preliminary calculation of heat balance in the air gap was performed by a project partner, including solar radiation absorbed by the cladding. The temperature and relative humidity of the air in the air gap obtained by these calculations are used as boundary conditions on the external surface of the rainscreen.

The thickness of the rainscreen is low compared to those of the other material layers (the wood fiber and the CLT). For this study the mass of this element has been considered too low to impact the dynamic behavior of the wall. The accumulation terms in the energy and mass balances of the rainscreen are thus neglected.

<table>
<thead>
<tr>
<th>Table 1. Main transfer properties of materials</th>
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<tbody>
<tr>
<td>Thermal conductivity (W.m⁻¹.K⁻¹)</td>
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<tr>
<td></td>
</tr>
<tr>
<td>CLT</td>
</tr>
<tr>
<td>Wood-fibre</td>
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<tr>
<td>rainscreen</td>
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</table>

Internal and external conditions

The analyses presented in this study are based on annual simulations performed considering the following internal and external solicitations.

The external conditions are the temperature and the relative humidity of the city of Nancy (climate of the north-east of France).

For the internal conditions several temperature and humidity scenario have been considered. For temperature, a heating period is considered (from October to April). For the rest of the year, the temperature was pre-calculated by a project partner, using a whole building performance simulation tool. Free-floating temperature was calculated in a light-weight detached house under Nancy climate file. This temperature is used as indoor temperature from May to September in both scenarios.

For all scenarios the indoor relative humidity is determined by a method that correlates vapor content of the indoor air with the external one and with the level of moisture production (\(\rho_{\text{int}} = \rho_{\text{ext}} + w/n\)). This method, proposed by Abelé et al. (2009), allows describing different occupancy scenarios of a building. For this study two internal scenarios corresponding to residential building uses have been considered (Fig. 4):

For the first scenario the humidity production is constant with the factor \(w/n = 3\) g.m⁻³ (corresponding to dwellings with medium level of occupation). The temperature during the heating period (from October to April) is constant and equal to 20 °C.

The second scenario considered a more realistic occupancy behavior for a residential building with fluctuating humidity production and moving heating temperature set-points during the days. The humidity
production is higher from 7 to 8 am and from 6 to 8 pm with a w/n = 4.5 than during the rest of the day with a w/n = 2 (mean production is equal in both scenarios). During the heating period the temperature is equal to 20°C from 7 am to 10 pm it decreases linearly until 12 pm to reach 17°C. Between 0 am to 5 am the temperature is constant (17°C) and it increases linearly to reach 20°C at 7 am.

The external and internal global heat exchange coefficient ($\alpha_{\text{tot}}$) are considered constant and respectively equal to 12 and 7 W.m$^{-2}$.K$^{-1}$.

**Impact of the meshing**

To perform the simulations the material layers are discretized in several control volumes. More the number of nodes is high and more the simulation results are accurate and the time to simulate is high. The choice of the number of nodes is thus a compromise between the accuracy of the results and the simulation time. To ensure that the simulation results are not significantly impacted by the meshing a sensibility analysis of the number of nodes has been carried out.

$$\Delta X = \frac{1}{n} \sum_{i=1}^{n} [X_{n_{\text{nodes}}/\text{mat}} - X_{n_{\text{nodes}}/\text{mat}}^\text{max}]$$  \hspace{1cm} (7)$$

Where n = number of time steps. The figures 5 and 6 show this criteria applied to the temperature ($\Delta T$) and the relative humidity ($\Delta RH$) at different thickness of the wall in function of the number of nodes per layer. These figures show that the points that are the most impacted by the variation of the number of nodes are located at the external surfaces of the wall. They also indicate that for a number of nodes higher than approximately 20 the gain of increasing the number of nodes is lower than the typical measurement error encountered to experimentally measure these parameters.

Due to this analysis the number of nodes per material layer has been fixed at 31 for all the simulations performed for this study.

**Impact of the initial conditions**

The simulation parameters are initialized considering a linear evolution across the wall between outdoor and indoor conditions at the first iteration. Because of the dynamic behavior of the wall the simulation result could be impacted by the initialization conditions. The independence from the initialization conditions is achieved when the wall reaches a periodic quasi-steady state condition considering a year period. To reach this quasi-steady state in this study the month before the studied period have been simulated considering the same indoor and outdoor conditions as the studied year.

To analyze the impact of the length of the initialization period, the state of the wall at the end of
The studied period is compared to that at the beginning according to the following criteria:

\[ \Delta X_{\text{ini-final}} = X_{\text{ini}} - X_{\text{final}} \]  

(8)

The figures 5 and 6 show this criteria applied to the temperature \((\Delta T_{\text{ini-final}})\) and the relative humidity \((\Delta RH_{\text{ini-final}})\) at different thickness of the wall in function of the number of month simulated for the initialization \((nb\_month\_initialization)\).

These figures show that with an initialization period of 7 months the wall reaches a periodic quasi-steady state. Due to this analysis the initialization period used for this study the simulation have been carried out considering an initialization period of 7 months.

**RESULTS AND DISCUSSION**

To investigate the impact of the moisture transfer on the thermal performance of the wall the following parameters are calculated and compared:

- The monthly averaged thermal flux exchanged at the indoor wall surface without considering the moisture transfer in the wall (pure thermal simulation) \((q_{th,sh})\). For this simulation the material properties are considered at the relative humidity of 50 % for each material.

\[ q_{th,sh} = \frac{1}{n} \sum_{n=1}^{n} \alpha_{nt} \left( T_{nt} - T_{th} \right) \]  

(9)

Where \(T_{th}\) is the internal surface temperature considering pure thermal simulations and \(n\) is the number of simulation steps for a month.

- The monthly averaged sensible thermal flux exchanged at the inlet wall surface considering both heat and moisture transfer in the wall \((q_{th,HAM})\).

\[ q_{th,HAM} = \frac{1}{n} \sum_{n=1}^{n} \alpha_{nt} \left( T_{nt} - T_{HAM} \right) \]  

(10)

Where \(T_{HAM}\) is the internal surface temperature considering heat and moisture simulations.

- The monthly averaged total thermal flux (sensible + latent) exchanged at the inlet wall surface considering the heat and moisture transfer in the wall \((q_{tot})\).

\[ q_{tot} = \frac{1}{n} \sum_{n=1}^{n} \left[ \alpha_{nt} \left( T_{nt} - T_{HAM} \right) + \delta_{nt} h_{v} \right] \]  

(11)

To complete this analysis the standard deviation of these fluxes are presented for each scenarios and each wall orientation.

To investigate the impact of the moisture transfer on the wall durability, relative humidity at the interface between the wood fiber and the CLT have been plotted as the function of temperature for each simulation. The risk of spore germination is function of the temperature and the humidity but also of the substrate (nutriment and salt content, the environment (ph), time and atmosphere (oxygen content)). In order to simplify the analysis, the limit of spore germination considered for this study is the Lowest Isopleth for Mould for the Optimal culture medium (the most unfavorable case) given in (Sedlbauer et al., 2003). The results obtained for the first and the second scenario are introduced and discussed in the followings sections.

**Scenario 1**

Monthly averages of the thermal fluxes are introduced in the figure 9 for both north and south wall orientations. In the north configuration the indoor thermal fluxes are always negative (loss of heat, both in winter and summer). Concerning the south orientation, due to the absorbed solar radiation, the heat losses are lower in winter than that observed for the north wall and there are heat gains from May to September. This figure shows that the thermal flux calculated from the thermal model \((q_{th,sh})\) underestimated heat exchanges during both losses and gains periods. This can be explained by two effects: the impact of latent heat transported by moisture flow and the impact of humidity on thermal conductivity of the wall material. Once the impact of the humidity on the thermal conductivities of the materials is considered, that of the wood fiber evolves between 0.042 and 0.048 W.m\(^{-1}\).K\(^{-1}\) and that of the CLT between 0.09 and 0.12 W.m\(^{-1}\).K\(^{-1}\) over the simulating period. For the north orientation the total heat losses \((q_{tot})\) are higher than the sensible losses \((q_{th,HAM})\) from December to September but are lower in October and November. During the first part of the year the internal wall surface adsorbed water vapor that increases the latent losses but reduces the sensible ones due to the adsorption phenomenon (exothermic process). However after the summer period the internal surfaces desorb water that increases the sensible losses (endothermic phenomenon). The same analysis can be done for the south orientation.

**Scenario 2**

The behavior of the wall and the phenomenon that take place in the wall are identical in the second
scenario than those described for the first one. The figure 12 shows that the thermal losses in winter are slightly lower than those obtained with the scenario 1. This is probably due to the reduction of the temperature during nights. The fluctuation of the humidity production seems to have a negligible impact on the heat fluxes and one the variability of those heat fluxes (fig. 13). Indeed the fluxes and there standard variations are similar for the first and the second scenario during the no heating period. However during the heating period because of the change of temperature during days and nights the variability of the heat fluxes are higher in winter than in summer for the second scenario.

The relative humidity plotted against temperature at wood-fiber / CLT interface is presented in Fig. 14. An isopleth curve from (Sedlbauer, 2003) is plotted as well giving an indication of wall durability. On these curves the impact of the scenario was negligible; however they depend on wall orientation. The comparison between these two scenarios demonstrates that in this configuration the change of the indoor conditions has a low impact on the long term behavior of the wall. It is only partly in agreement with (Kehrer et al, 2003) who suggested that the impact of moisture related phenomena on heating load is negligible for cellulose insulation. In our work, the change of indoor temperature and indoor moisture profiles influences significantly the variability of the internal heat fluxes.

![Figure 9 Internal thermal fluxes for the first scenario](image1)

![Figure 10 Standard deviation of the internal thermal fluxes for the first scenario](image2)
CONCLUSION

A coupled heat and moisture model has been presented and a simulation tool has been developed using the DYMOLA software and validated. This simulation tool has been used to investigate the impact of moisture transfer on the thermal performance and on the durability of a light-weight wall mainly composed by wood-based material. Simulations have been performed for a climate from north-east of France considering different occupancy scenarios for the building. The simulation results show that with this wall configuration:

- Pure thermal simulations underestimate the exchanged internal fluxes.
- There is no risk of spore germination in the wall.
- The variation of the indoor vapor production has a negligible impact on the long term durability of the wall.
behavior of the wall, however it increases the variability of the internal fluxes.

- The fluctuation of the indoor temperature (temperature lower during the night) slightly reduces the heat loads and significantly increases the variability of the internal fluxes. Therefore precise simulations of energy performance at building level need to take into account moisture-related phenomena for highly hygroscopic walls.

Although simulation tools that had been developed for this study has been validated by comparison with experimental results and with other simulation tools’ results. Results presented in this study are highly dependent on materials properties. Because of experimental difficulties to obtain these values, the uncertainty on these parameters could be sizeable. A sensitivity analysis on the main material properties should confirm the results obtained.

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