HYGROTHERMAL BEHAVIOUR OF A HEMP CONCRETE WALL: COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

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ABSTRACT

The analysis of the hygrothermal behaviour of green building materials is investigated in this work. For this, a 1D heat, air and moisture transfer model was developed using Comsol Multiphysics® and applied to a hemp concrete wall. Particular attention is paid in the experimental determination of hygrothermal properties and their dependency with the temperature and the moisture content. To validate the model, a hemp concrete wall was monitored for 12 month under various boundary conditions. The results suggest in our case that accounting for the thermal dependence of the sorption isotherm is of high importance, whereas moisture thermal diffusion has only a minor effect on temperature and vapour pressure distribution.

INTRODUCTION

Green building materials, like hemp concrete, are currently interesting alternative products in the field of architecture and construction, since they have many environmental benefits, a potentially very low carbon life cycle (Garnier et al., 2012), and also interesting thermo-hydric properties, like a low thermal conductivity (Pierre et al., 2013) or an hygric buffering capacity (Collet et al., 2012). Even though the positive effect of common hygroscopic building material on building and HVAC system energy demand (Osanyintola et al., 2006), (Woloszyn et al., 2009) or on indoor air quality (Simonson et al., 2002) were extensively investigated, less works are dealing with green building material in general and hemp concrete in particular.

Tran Le et al. (2010) studied numerically the transient hygrothermal behavior of hemp concrete building envelope using the simulation environment SPARK. They confirmed that indoor relative humidity variations are more dampened and that the energy consumption is lower when hemp concrete is used in the envelope instead of cellular concrete. Nevertheless, a sensitivity analysis indicates that their results are mainly influenced by the thermal conductivity and less by the other transport coefficients and should be therefore validated by experiment data. In a recent experimental work, Shea et al. (2012) reported results on the hygrothermal performance of a hemp–lime building. Particularly, a simple steady-state spread-sheet model based on the knowledge of calculated U-values predicted whole building heat loss coefficient as 35.6 W/K whereas a value of 36.7 W/K was measured by a co-heating test. Furthermore, building monitoring indicate that the temperature and humidity variations inside the house are significantly dampened compared with the external environment. At the wall scale, a hemp concrete wall subject to sudden cooling reaches experimentally steady-state in 10 days, whereas the simulation performed by Evrard and De Herde (2010) with WUFI® predicts steady-state conditions in approximately 3 days. For his part, Samri (2008) compared directly its experimental results obtained on a hemp concrete wall with numerical simulations based on the Künzel's model implemented in Comsol Multiphysics®. However, the hygrothermal behaviour could not be accurately captured since the invasion of the embedded sensors caused uncertainties in the relative humidity measurement within the wall. Last, Aït Ouméziane et al. (2011) could validate Künzel's model accounting for hysteresis of the sorption curves on isothermal tests on a prefabricated hemp concrete wall, but failed when non-isothermal conditions are investigated.

In this work, HAM transfer model is used for investigating the hygrothermal behaviour of a sprayed hemp concrete wall under non-isothermal conditions. Comparing simulation results with the experimental ones should allow concluding on the importance of moisture thermal diffusion.

EXPERIMENTAL FACILITY

In order to investigate the hygrothermal behaviour of green building materials, an experimental facility was developed at laboratory LIMATB of the Université de Bretagne-Sud. It consists of a wall (with dimensions of 270 × 210 × 36 cm^3) placed between two climatic rooms which simulate indoor and outdoor climates (see Figure 1). In this study, a sprayed hemp concrete wall is tested. For evaluating temperature and relative humidity in time and in space as function of both boundary conditions, a monitoring is performed within each climatic room and at different positions within the wall with K thermocouples and capacitive humidity sensors (type SHT 75 from Sensirion). Further information on the experimental device can be found in (Colinart et al, 2013).

Figure 1 The biclimatic room at laboratory LIMATB of the "Université de Bretagne-Sud".

MATERIAL PROPERTIES

In addition to the experimental work, material properties are measured in the lab in order to guarantee the accuracy of the input parameters in the modeling.

Thermophysical properties

Thermal properties are evaluated at temperatures ranging between -3 °C and 30 °C and relative humidities ranging between 0% and 95% (Pierre et al., 2013). The heat capacity of the solid matrix c_{Ps} is determined by a calorimetric measurement (µ-DSC III, from Setaram). A value of 1000 J kg^{-1} K^{-1} is found. The intrinsic thermal conductivity is measured using the transient hot-strip technique (to avoid evaporation effects during the measurement). Results indicate that λ varies from 0.092 W m^{-1} K^{-1} (dry cold) to 0.122 W m^{-1} K^{-1} (hot moist). A Krisher's model can predict its temperature and moisture dependence.

Hygric storage and transfer properties

The isothermal adsorption and desorption curves are determined at 23 °C according to ISO 12571 using salt solutions to generate relative humidity. Results are similar to the ones of Collet et al. (2012). Additional measurements of the water content are performed at four temperatures (T = 0, 10, 20 and 30 °C) and three relative humidities (φ = 50, 75 and 90%) in a climatic chamber. The results are shown in Figure 2. The experimental data are curve-fitted with a GAB model that accounts for temperature:

$$w = \frac{0.015 \times CK\varphi}{(1-K\varphi)\left(1+K(C-1)\varphi\right)} \quad (1)$$

$$\text{where } C = 11\exp\left(\frac{E_1 - E_m}{RT}\right) \quad (2)$$

$$K = 0.94\exp\left(\frac{M_w L_v - E_m}{RT}\right) \quad (3)$$

where M_w (g·mol^{-1}) is the water molecular weight, $L_v \approx 2.42\ 10^3$ kJ.kg^{-1} is the heat of adsorption, $E_1 \approx 46.9$ kJ·mol^{-1} and $E_m \approx 43.4$ kJ·mol^{-1} are respectively monolayer and multilayer enthalpy of adsorption.

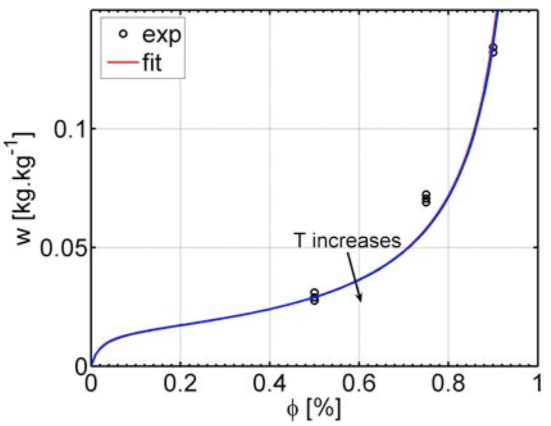

Figure 2 Hemp concrete water content as function of φ and T.

The water vapour transmission properties have been determined in accordance to ISO 12572. Dry cup (0/50%) and wet cup (50/85%) experiments were performed at 23 °C. Values of $\mu_{dry} = 8$ and $\mu_{wet} = 5$ are respectively found and are in agreement with the literature data (Collet et al., 2012). To date, data on liquid transfer coefficients are rather scarce in the literature. Measurements performed in the lab on other hemp concrete sample indicate an order of magnitude for the intrinsic permeability of ≈ 10^{-12} m^2. Evrard and De Herde (2010) adapted WUFI's liquid transfer coefficients for adsorption and redistribution to fit experimental profiles measured by NMR. Particularly, they obtained the following function for $\varphi < 0.95$:

$$D_l^w = \rho_s 10^{\left(\frac{\rho_s w}{32} - 10.9375\right)} \qquad (4)$$

where D_l^w is expressed in $kg_{H_2O}.m^{-1}.s^{-1}$. Last, Zaknoune (2011) estimated mathematical functions for the liquid diffusion coefficient of hemp-lime plaster using drying experiments and found D_l^w also in the order of $10^{-9} kg_{H_2O}.m^{-1}.s^{-1}$.

Other Properties

Other properties of hemp concrete are dry density (ρ_s) of 400 kg.m^{-3}, porosity (ε) of 78%. Specific heat capacity c_p, density ρ, viscosity μ of liquid water (index l), vapor (index v) and dry air (index a) are constant and taken from the literature.

HAM TRANSFER MODEL

The modelling of heat, air and moisture transport processes in hygroscopic porous material has been an ongoing concern in building physics and usually involves major theories of Philip and De Vries (1957), Luikov (1957) or Whitaker (1977). All describe moisture transport as an addition of vapor and liquid flow (generally with Fick's and Darcy's Law) whereas heat balance equations is based on Fourier's Law. Subsequently, several models have been developed for different applications. The major difference between these models is related to the particular assumptions. In the case of green building materials, these include:

- Porous material is regarded as continuous, non-deformable and stabilized.
- Even if the material is heterogeneous at the microscopic scale, it is considered as homogeneous at the macroscopic scale.
- Local thermodynamic equilibrium is assumed at every point of the material.
- Gravity effects are neglected and total gas pressure is constant.
- Liquid water is supposed to wet the porous structure, i.e. $p_{cap} = p_g - p_l$.
- For simplification purpose, hysteresis is neglected in the sorption curve.

An other difference between these models lies in the choice of state variable and driving potential. Delgado et al. (2010) reviewed different models that have been incorporated into various software programs used in the field of porous building material. It comes that transport can be expressed in terms of temperature T and one of the following moisture state variables including moisture content (by volume u (kg.m^{-3}) or by mass w (kg.kg^{-1})), succion pressure s (Pa), relative humidity φ (%) or water vapor pressure p_v (Pa). For example, the software WUFI® solves the heat and moisture equations in terms of T and φ. In the present work, water vapour pressure p_v is used in the view of stating the moisture transfer processes through multi-layered component.

Constitutive equations

Darcy's law is used to describe the liquid and gas convective flow q_l and q_g. Since gas pressure is assumed to be constant, gas convective transfer vanishes. Therefore, liquid convective flow is written using Kelvin's and Clapeyron's law in the capillary and hygroscopic domains as:

$$q_l = -\left(D_l^{pv}\nabla p_v + D_l^T \nabla T\right) \quad (5)$$

$$\text{Where } D_l^{pv} = \frac{\rho_l}{\mu_l} K k_{rl} \frac{\rho_l RT}{M_w p_v} \quad (6a)$$

$$D_l^T = D_l^{pv} \frac{p_v}{T}\left(\ln\varphi - \frac{M_w L_v}{RT}\right) \quad (6b)$$

where K (m^2) and k_{rl} (-) are the absolute and relative permeabilities to the liquid phase.

As there is no gas convective transfer, dry air and vapour transport occurs by diffusion. Fick's law that is originally expressed as function of a concentration gradient (Fick, 1855) becomes:

$$q_v = -q_a = -\left(D_v^{pv}\nabla p_v + D_v^T \nabla T\right) \quad (7)$$

$$\text{Where } D_v^{pv} = \frac{M_w}{RT} f \, D_{v-air} \quad (8a)$$

$$D_v^T = D_v^{pv} \frac{p_v}{T} \quad (8b)$$

where f (-) is a factor that accounts for reduction of open pore area, increase of pore tortuosity or Knudsen diffusion (Philip and De Vries, 1957). This factor to a first approximation is equal to the inverse of dry vapour resistance factor μ_{dry} (-).

The dry air and water mass conservation equation can be described as:

$$\rho_s \frac{\partial w_a}{\partial t} = -\nabla . q_a \quad (9)$$

$$\rho_s\left(\frac{\partial w}{\partial p_v}\frac{\partial p_v}{\partial t} + \frac{\partial w}{\partial T}\frac{\partial T}{\partial t}\right) = -\nabla .\left(q_v + q_l\right) \quad (10)$$

where the thermal dependency of the water content is cinsidered (Dos Santos, 2009).

Due to the presence of low temperature levels, heat transfer has been attributed to conductive and convective effects only:

$$q_{th} = -\lambda\nabla T + q_l h_l + q_v h_v + q_a h_a \quad (11)$$

For the energy balance equation, it comes:

$$\overline{\rho_s c_P}\frac{\partial T}{\partial t} = -\nabla .\left(\left(-\lambda - L_v D_v^T\right)\nabla T - L_v D_v^{pv}\nabla p_v\right) - \left(q_l c_{Pl} + q_v\left(c_{Pv} - c_{Pa}\right)\right)\nabla T \quad (12)$$

where $\overline{\rho_s c_P}$ (J.m^{-3}.K^{-1}) is the specific heat capacity of the structure given by the mixing law:

$$\overline{\rho_s c_P} = \rho_s\left(c_{Ps} + c_{Pl} w + c_{Pa} w_a\right) \quad (13)$$

Boundary and initial conditions

Heat and moisture transfer equations are applied to one-dimension for building walls. Boundary conditions ($x = 0$ and $x = L$) are:

$$q_v = \beta\left(p_v^{ext} - p_v^{surf}\right) \quad (14)$$

$$q_{th} = h\left(T_{ext} - T_{surf}\right) + L_v q_v \quad (15)$$

with h (W.m^{-2}.K^{-1}) and β (kg.m^{-2}.s^{-1}) respectively the convective heat and vapor transfer coefficient. Particularly, β is calculated from h by Lewis's relation:

$$\beta = \frac{M_w}{RT}\frac{1}{\rho_a c_{p,a} Le^{2/3}} \quad (16)$$

Under atmospheric circumstances, i.e., for most building applications, $Le^{2/3} \approx 0.9$. Initial conditions are taken from the experiments.

Numerical resolution

To obtain the temperature and vapour pressure field across the hemp concrete wall, the coupled and nonlinear partial differential equations were formulated in the ‘‘PDE Modes” of COMSOL Multiphysics® and solved based on an explicit scheme. Even if there are a large number of hygrothermal simulation tools (Delgado et al., 2010), COMSOL Multiphysics® offers flexibility in the equation and boundary conditions writing and may solve equations with variable time stepping (here the same as the experimental ones), whereas standard time step size in WUFI® is one hour.

RESULTS

In the present work, two experiments are performed: in the first one, temperature is increased from 23 °C to 32 °C while relative humidity is kept constant at 50%; in the second one, temperature is still increased whereas relative humidity is decreased from 50% to 30% so that outdoor vapour pressure is kept constant at 1400 Pa, (see Figure 3). Both experiments allow investigating the influence of temperature gradients on moisture transfer.

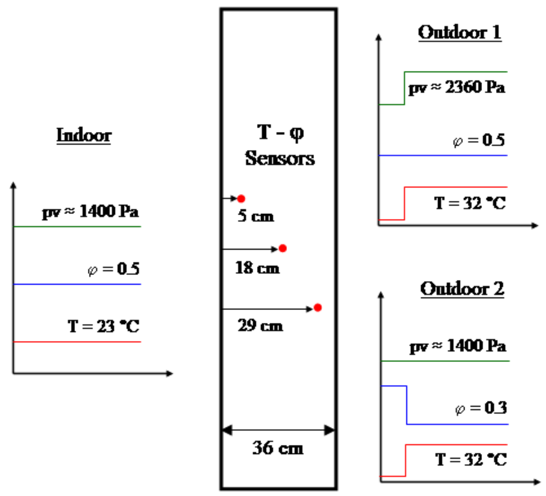

Figure 3 Applied boundary conditions and localisation of the sensors.

First Experiment

Figures 4 show the experimental and numerical results for the first experiment. For clarity, uncertainty bounds in the temperature (± 0.5 °C) and vapour pressure measurements (± 1 mbar) are not included in the graphs, but should be kept in mind. Due to the temperature gradient, we observe that temperature increases within the material. Particularly, one observe that temperature in the wall center (x = 18 cm) starts to increase only 12 hours after the change in the set points, indicating that hemp concrete may provide a good thermal inertia to the building envelope. Furthermore, temperature changes imply light evaporation phenomena that are observed in the increase of relative humidity and therefore vapour pressure.

Five simulation cases (Sim 1 to Sim 5) are also investigated on Figure 4. First, base case simulation is performed with the HAM model (Sim 1) and is directly compared with results obtained with Kunzel's model (Sim 2). Then, three points are investigated: the influence of the sorption curve (Sim 3), of moisture thermal diffusion (Sim 4) and of liquid transfer (Sim 5). For all simulations, indoor and outdoor convective transfer coefficients h are set to 3 W m^{-2} K^{-1}.

The following conclusions can be drawn: first, the hygrothermal behaviour of hemp concrete is roughly well caught in terms of kinetics and of temperature and vapour pressure levels although it still remains an uncertainty in the measurements. On the one hand, a sensitivity analysis (not presented here) indicates that taking constant values for the transport parameters D_l^w, μ and λ is sufficient to well reproduce this experiment. On the other hand, accounting for the thermal dependence of the sorption curve is of high importance (Sim 3 vs. Sim 1 & 2): in this case, simulations performed with HAM and Kunzel's model are similar. Nevertheless, this point must be confirmed for other experiments or boundary conditions. Since evidence for moisture thermal diffusion is largely discussed in the literature (Janssen, 2011), a test was performed by setting D_l^T and D_v^T to 0 (Sim 4 vs. Sim 1): no difference is observed with the base case simulation, and therefore the large vapour pressure gradient across the wall is mainly responsible for the vapour transfer. Last, the influence of liquid transfer is investigated. Indeed, pore size distribution of hemp concrete includes mainly open intergranular macropores (d > 0.05 µm) and micropores (intrinsic porosity of hemp and lime). Assuming that there is no connectivity between the micropores, liquid water transfer is neglected and $q_l = 0$ (Sim 5 vs. Sim 1): liquid water should evaporate into the macropores and vapour should be transferred through them. In that case, simulations tend to better catch the vapour pressure variations, but also to lightly overestimate the temperature.

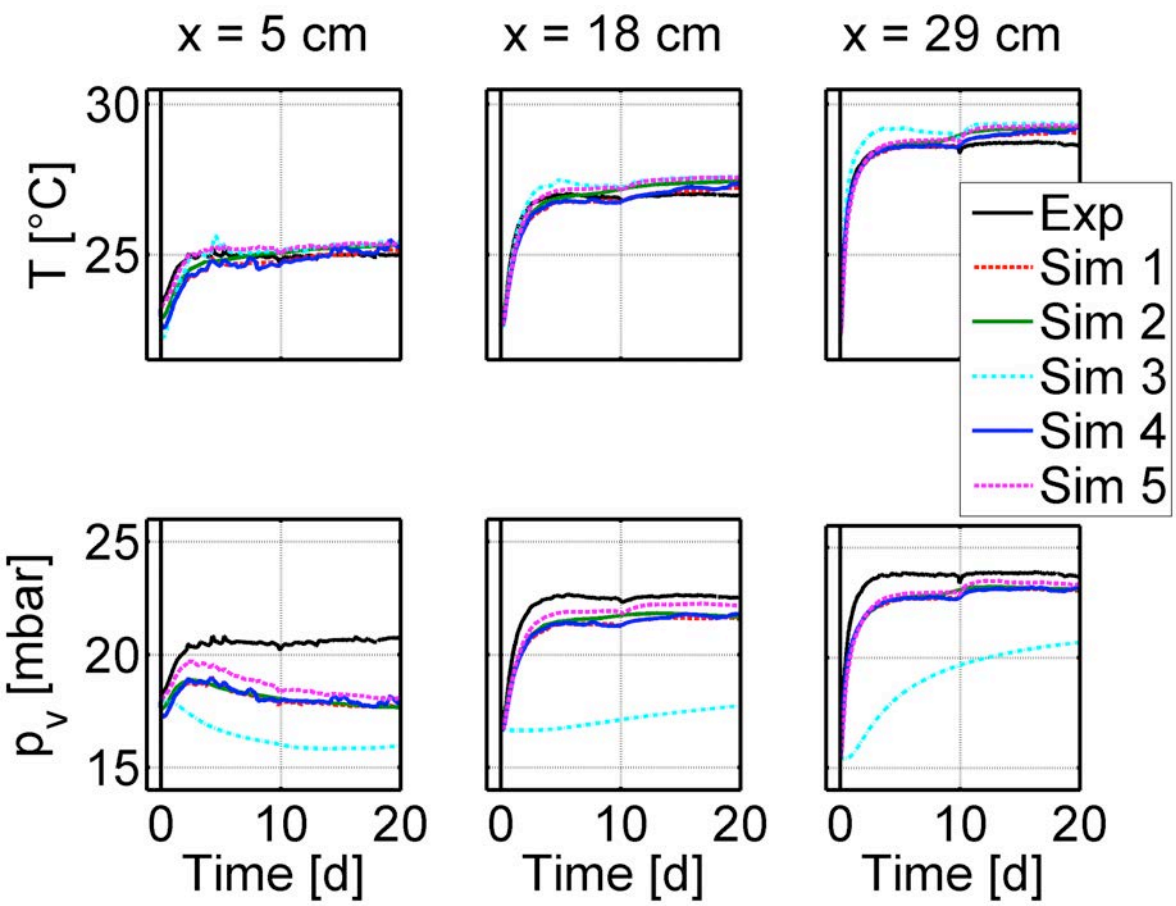

Figure 4 T and p_v responses of the hemp concrete wall subjected to temperature gradient and vapour pressure gradient (Exp 1).

Second Experiment

Identical simulations are performed for the second experiment for which no pressure gradients are applied. Results are plotted on Figure 5. They confirm that accounting for the temperature dependence of the sorption curve is still necessary to catch the hygrothermal trends (Sim 3 vs. Sim 1 & 2). Contrary to the first experiments, neglecting liquid water transfer brings no improvement in the simulation (Sim 5 vs. Sim 1). Furthermore, we still observe that thermal diffusion is of no importance (Sim 4 vs. Sim 1). It confirms the point of view of Janssen (2011) who states that thermal diffusion must be assumed a mere consequence of deviating from the true potential. However, this experiment shows that when temperature gradient is associated without a vapour pressure gradient, evaporation occurs in the first days close to the outdoor (at x = 29 cm) according to Kelvin-Laplace equation and p_v locally increases. Then, as a vapour pressure gradient exists between the wall and the chambers, a slow vapour transfer take place since hemp concrete exhibits a high water vapour resistance factor. After 15 days, vapour pressure within the wall has not reached the steady state and is still higher than the boundary condition, indicating that the moisture contained in the wall could condensate if the temperature should decrease. This last remark indicates that a hemp concrete wall should be initially sufficiently dried out initially since moisture diffusion is a slow process and a high moisture content affect the thermal performance of the building envelope.

CONCLUSION

Green building materials like hemp concrete are still at a pioneer stage and still require many more efforts to gain knowledge on its transient hygrothermal behavior. In this view, a comparison between experimental data obtained on a wall subjected to conjugate temperature and vapour pressure gradients and numerical results derived from a HAM model was proposed by paying attention in the evaluation of the material properties. A roughly good agreement was found for different conditions. Particularly, we found that the thermal dependence of the sorption curve should be taken into account when vapour pressure is used as a driving potential and results are similar to the one's obtained with Künzel's model. Furthermore, simulation results show that moisture thermal diffusion is of no importance when the temperature gradient is associated with or without a vapor pressure gradient. On the other hand, temperature variations induce local evaporation phenomena in the porous structure and therefore create vapour pressure gradients which cause vapour diffusion.

For further work, we intend to confirm the present results by analyzing the sensitivity of the main parameter and eventually including hysteresis phenomenon in the modelling. In addition, we aim to study the hygrothermal behaviour of these materials for multi-layered walls as usual in construction design and integrating the results in simulation at the whole building level.

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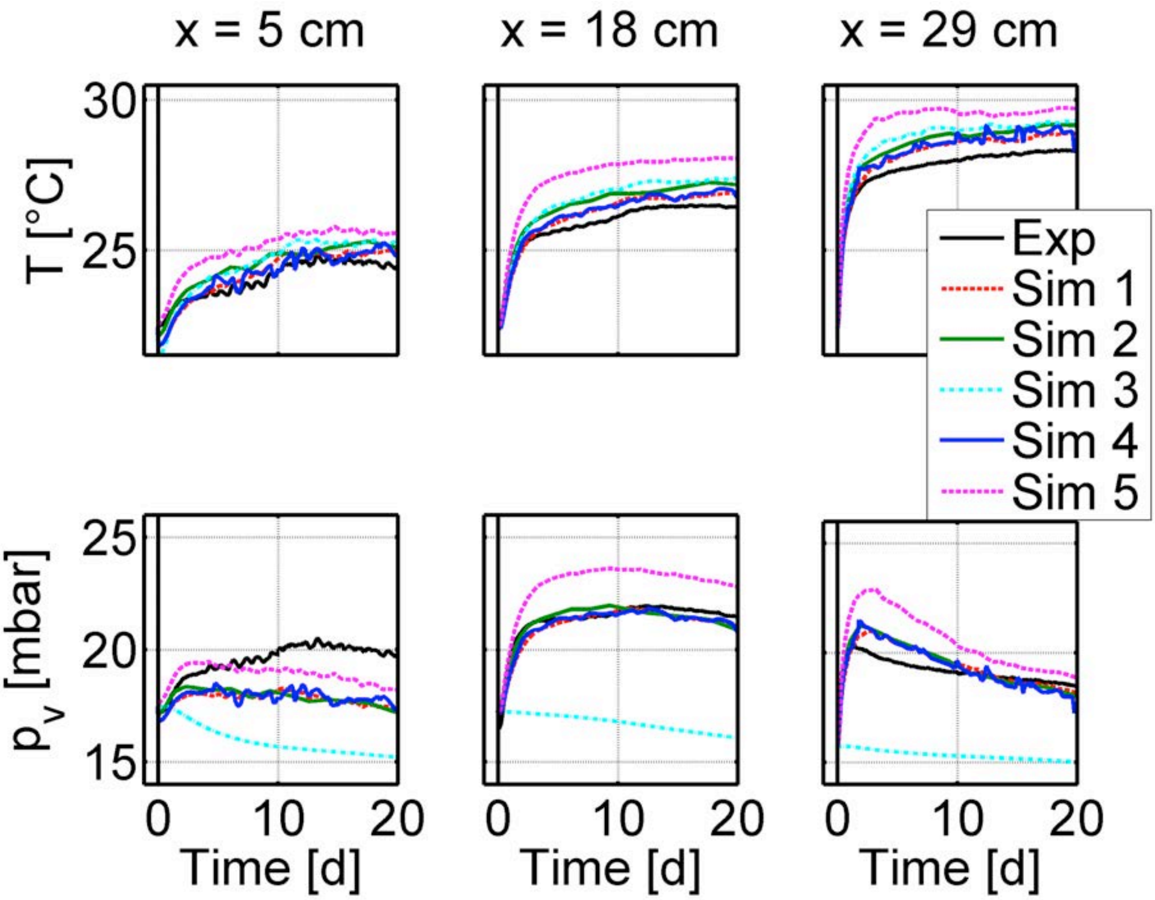

Figure 5 T and p_v responses of the hemp concrete wall subjected to temperature gradient and relative humidity gradient (Exp2).

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