Effect of simulation parameters on the hygrothermal behaviour of a wall and a room made of hemp-lime concrete

A.D. Tran Le , C. Maalouf , O. Douzane , L. Lahoche , T.H. Mai, M. Lachi, T. Langlet

Abstract**—**Hygrothermal properties (such as thermal conductivity, sorption isotherm, moisture diffusivity etc.) are required for all Heat, Air and Moisture transfer (HAM) models. The objective of this work is to study the effect of different parameters of HAM model and simulation conditions on the prediction of temperature and relative humidity in a wall and a room made of hemp concrete which is known to have a low environmental impact. After presenting its physical properties, we present equations of the HAM model for a simple layer wall and for a building. Simulations are done with the environment SPARK suited to complex problems. Numerical model was validated by comparing the numerical results to experimental data available in the literature. This model is then used to analyze the sensitivities of HAM model parameters and modeling conditions on temperature and relative humidity profiles.

Keywords**—**HAM, simulation, hemp concrete, SPARK.

NOMENCLATURE

Symbol	**Definition**	**Unity**
C	Specific heat	$J.kg^{-1}.K^{-1}$
C_0	Specific heat of dry material	$J.kg^{-1}.K^{-1}$
C_l	Specific heat of water	$J.kg^{-1}.K^{-1}$
D_T	Mass transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
$D_{T,v}$	Vapor transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
D_θ	Mass transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
$D_{\theta v}$	Vapor transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
h_M	Mass transfer convection coefficient	$m .s^{-1}$
h_T	Heat transfer convection coefficient	$W.K^{-1}.m^{-2}$
L_v	Heat of vaporization	$J.kg^{-1}$
T	Temperature	°C
t	Time	s
x	Abscise	m
θ	Moisture content	$m^3.m^{-3}$
λ	Thermal conductivity	$W.m^{-1}.K^{-1}$
ρ_0	Mass density of dry material	$kg.m^{-3}$
ρ_l	Mass density of water	$kg.m^{-3}$
ρ_v	Mass density of vapor water	$kg.m^{-3}$
ϕ	Relative humidity	%
ρ_i	Air density	$kg.m^{-3}$
Φ	Heat flux	W
Q_m	Air flow rate	$kg.s^{-1}$
Φ_{source}	Heat source power	W

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I. INTRODUCTION

Regarding indoor hygrothermal comfort, relative humidity is an important parameter influencing perceived indoor air quality and human comfort. High moisture levels can damage construction and inhabitant's health. High humidity harms materials, especially in case of condensation and it helps moulds development increasing allergic risks. Consequently, several researchers have studied the use of various hygroscopic materials to moderate indoor humidity levels. The material that absorbs and desorbs water vapour can be used to moderate the amplitude of indoor relative humidity and therefore to participate in the improvement of the indoor quality and energy saving [1-4].

In order to study the hygrothermal behavior of building envelope and its effect on hygrothermal comfort, a simulation should be done because it is cheaper and detailed than the test in situ.

Concerning the simulation tools, hygrothermal properties (such as thermal conductivity, sorption isotherm, moisture diffusivity coefficients…) are required for all Heat, Air and Moisture transfer (HAM) models. For the same materials, hygrothermal properties which are measured by different laboratories can be different. For example, the experimental works of Collet [5] and Evrard [6] showed that the specific heats of hemp concrete (with the mass density of 413 and 440 kg/m3) are respectively 1000 and 1530 J/kg.K. That significant difference of 34.6 % observed from this comparison shows that a sensitivity study concerning the effect of HAM model properties on the simulation results is necessary. In addition, effect of the model complexity and simulation conditions are also worth to investigate. Therefore, the purpose of this paper is to give a detailed parametric study of their effects on the temperature and relative humidity profiles of a hemp concrete wall and a room which are submitted to hygrothermal shock.

First, we present the mathematical models and their implementation in SPARK. Then we present simulation benchmark for coupled heat and mass transfer in building materials. Finally, the last section presents the sensitivities of HAM model parameters on the hygrothermal behavior at the wall and at the building levels.

It should be noted that hemp concrete was chosen in this study because this vegetable material can be considered as a good compromise between insulation, energy efficiency, moisture buffering capacity purpose and green material. In the next part, the mathematical model will be presented.

II. MATHEMATICAL MODELS AND NUMERICAL RESOLUTION

A. *Moisture transport in building envelope*

Mechanisms of moisture transport in a single building material have been extensively studied [7-9]. Most of the models have nearly the same origin Philip and de Vries model [10]. In this article, we use the Umidus model [9] in which moisture is transported under liquid and vapour phases. The schematic representation of heat and moisture transfer through the wall is presented in Figure 1.

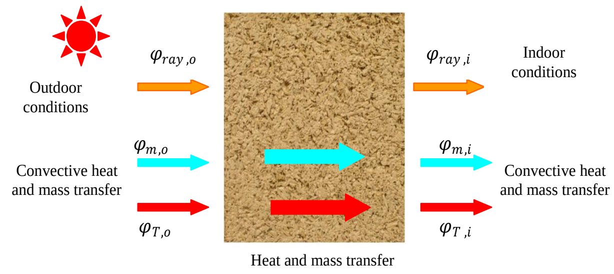

Figure 1: schematic representation of heat and moisture transfer through the wall.

The mass conservation equation can be written as:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left(D_T\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial x}\left(D_\theta\frac{\partial\theta}{\partial x}\right) \tag{1}$$

With the boundary conditions (x=0 and x=L):

$$-\rho_l\left(D_T\frac{\partial T}{\partial x}+D_\theta\frac{\partial\theta}{\partial x}\right)\Bigg|_{x=0,e}=h_{M,e}\left(\rho_{ve,a,e}-\rho_{ve,s,e}\right) \tag{2}$$

$$-\rho_l\left(D_T\frac{\partial T}{\partial x}+D_\theta\frac{\partial\theta}{\partial x}\right)\Bigg|_{x=L,i}=h_{M,i}\left(\rho_{ve,s,i}-\rho_{ve,a,i}\right) \tag{3}$$

The phase change occurring within porous materials acts as a heat source or sink, which results in the coupled relationship between moisture and heat transfer. The heat balance can be described as:

$$\rho_0 Cp_m\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+L_v\rho_l\left(\frac{\partial}{\partial x}\left(D_{T,v}\frac{\partial T}{\partial x}\right)+\right.$$
$$\left.+\frac{\partial}{\partial x}\left(D_{\theta,v}\frac{\partial\theta}{\partial x}\right)\right) \tag{4}$$

$$\mathrm{C_{pm}}=\mathrm{C_{p0}}+\mathrm{C_{pl}}\frac{\rho_l}{\rho_0}\theta \tag{5}$$

Where

C_{pm} is the average specific heat which takes into account the dry material specific heat and the contribution of the specific heat of liquid phase.

λ is the thermal conductivity depending on moisture content.

The moisture transport coefficient related to moisture content gradient is evaluated as:

$$D_\theta=\pi\frac{P_{vs}(T)}{\rho_l}\frac{\partial\phi}{\partial\theta} \tag{6}$$

By neglecting the effect of temperature gradient on liquid transpor, the water transport coefficient due to thermal gradient should be calculated as below (Abadie et al., 2005) [11]:

$$D_T=D_{T,v}(\theta,T)=\frac{\pi}{\rho_l}.\phi.\frac{\partial P_{vs}}{\partial T} \tag{7}$$

Boundary conditions take into account heat and phase change:

$$-\lambda\frac{\partial T}{\partial x}-L_v\rho_l\left(D_{T,v}\frac{\partial T}{\partial x}+D_{\theta,v}\frac{\partial \theta}{\partial x}\right)_{x=0,e}=h_{T,e}\left(T_{a,e}-T_{s,e}\right)+L_v h_{M,e}\left(\rho_{ve,a,e}-\rho_{ve,s,e}\right) \quad (8)$$

$$-\lambda\frac{\partial T}{\partial x}-L_v\rho_l\left(D_{T,v}\frac{\partial T}{\partial x}+D_{\theta,v}\frac{\partial \theta}{\partial x}\right)\Bigg|_{x=L,i}=h_{T,i}\left(T_{s,i}-T_{a,i}\right)+L_v h_{M,i}\left(\rho_{ve,s,i}-\rho_{ve,a,i}\right) \quad (9)$$

B. Air model

In order to model heat and mass transfer in the room, we used the nodal method, which consider the room as a perfectly mixed zone. The energy equation and the mass balance equation for room air can be written as:

$$\rho_i c_p V\frac{\partial T}{\partial t}=\Phi_{West}-\Phi_{East}+\Phi_{South}-\Phi_{North}+\Phi_{Bottom}-\Phi_{Top}+\Phi_{Source} \quad (10)$$

$$V\frac{\partial \rho_i}{\partial t}=Q_{mWest}-Q_{mEast}+Q_{mSouth}-Q_{mNorth}+Q_{mBottom}-Q_{mTop}+Q_{mSource} \quad (11)$$

C. Numerical resolution and Simulation Environment SPARK

In order to solve the previous equation system, the numerical solution is based on the finite difference technique with an implicit scheme. The detail of this numerical resolution for the variable coefficients model can be found in [12].

To solve this system of equations, we used the Simulation Problem Analysis and Research Kernel (SPARK) which is especially suited to solve efficiently differential equation systems [13-14].

We have just presented the physical model used and its numerical resolution, in the next section, we present the hygrothermal model validation, which is very important for any developing simulation tools.

III. MODEL VALIDATION

To validate the presented model, the simulation results were compared with experimental data obtained from Samri's work [15].

The specimen studied was a hemp lime concrete envelope with a thickness of 30 cm submitted to a gradient of temperature and relative humidity as shown in Figure 2. The small wall is insulated on lateral sides in order to provide adiabatic conditions and ensure one-dimensional heat and mass transfer. A monitoring of relative humidity and temperature in the mid of the wall is performed with thermocouples and humidity sensors. Concerning the boundary conditions, outdoor air temperature and relative humidity are controlled by a climatic chamber while internal side of wall is exposed to indoor climate of laboratory. In this study, outdoor temperature and relative humidity vary in a static step from 30 to 20°C and 70% to 30% relative humidity (Figure 2).

Heat transfer coefficients are $h_{T,e}$= 15 W/m^2.K for the indoor surface which is subjected to the laboratory conditions. The mass convection coefficient was calculated by using Lewis relation and considering Lewis number equals to 1. For outdoor surface, we apply the Dirchlet conditions for temperature and relative humidity.

The physical properties values of hemp concrete used in the test are presented in Table 1.

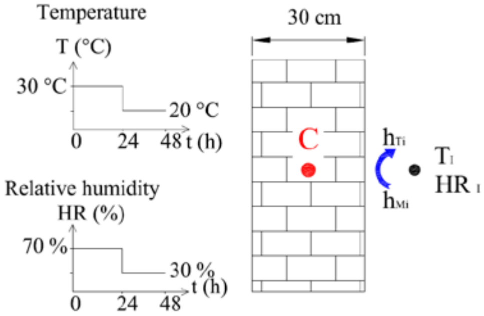

Figure 2: The experimental specimens and conditions.

Figure 3 and Figure 4 present the comparison between numerical results and experimental data from [15]. As can be seen in this figure, a good agreement is achieved in which computed and experimental results show the same increase/decrease tendency of relative humidity and temperature with time due to outdoor relative humidity and temperature gradient.

Mass density	Thermal conductivity	Specific heat	Dteta
kg/m3	W/m K	J/kg K	m²/s
329	0.095	1122	2,8e-7

Table 1: Physical properties of hemp concrete used in the test [15].

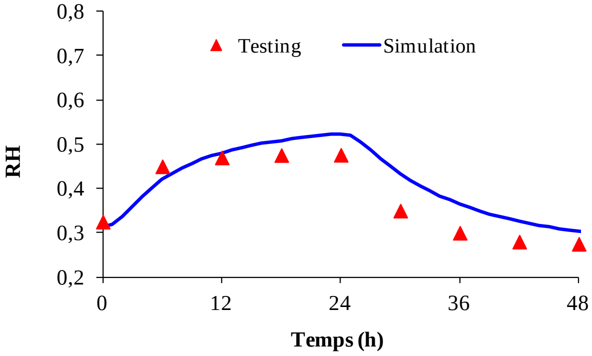

Figure 3: Model validation for relative humidity profiles in the middle of the wall (point C).

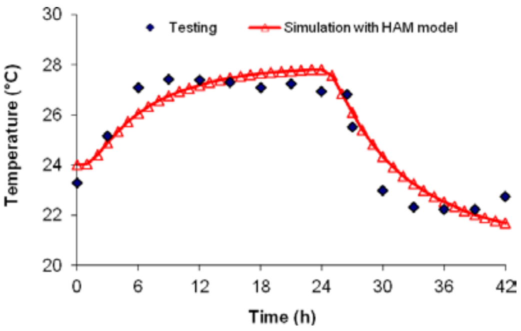

Figure 4: Model validation for temperature profiles in the middle of the wall (point C).

Our previous studies have shown that the moisture transfer in hemp concrete effects on the energy storage and thermal inertia in simple layer wall [16-18]. To better understand the influence of moisture transfer and each parameter of the physical model on the results in the middle of the wall, a sensitivity analysis is done.

IV. NUMERICAL STUDIES

A. *Effect of hygrothermal properties on the relative humidity and temperature profiles in a wall*

In this part, we consider the same simulation conditions as shown in Figure 2.

1) *Effect of coupled heat air and moisture transfer model*

In this subsection, we consider two models HAM and Th which are described as:

- Th: Simulation without taking into account the mass transfer;
- HAM: Simulation with taking into account the coupled heat and mass transfer.

Figure 5 shows the variation of temperature in the middle of the wall for both Th and HAM model. The results reveal that taking into account the moisture transport has great effect on the temperature prediction and the maximum difference of temperature for both models can reach 2°C. It can be seen that in the absorption period the temperature of HAM model is higher than the one of Th model while it is smaller during the desorption period. The phenomenon can be explained by the heat released or absorbed due to phase change during the sorption process.

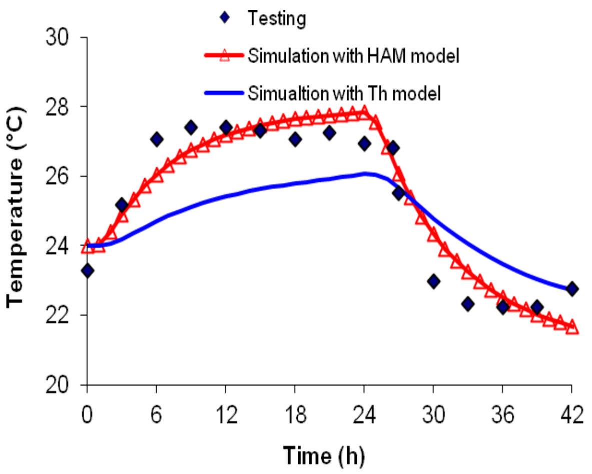

Figure 5: Effect of HAM et Th models on the temperature profiles in the middle of the wall.

In conclusion, taking into account the coupled heat and moisture transfer is necessary to predict correctly the hygrothermal behaviour of buildings. Therefore, **HAM** model is used for the next sections.

2) *Impact of spatial discretization and time increment*

We analyse the effect of space discretization and time increment on the relative humidity and temperature variations. It has been shown that time increment effected very slightly the results (4 minutes, 1 minute, 30 seconds). Concerning the second one, the wall was discretized into 10, 25 nodes, 50 nodes (reference case) and its effect on relative humidity and temperature is presented in Figure 6 and Figure 7.

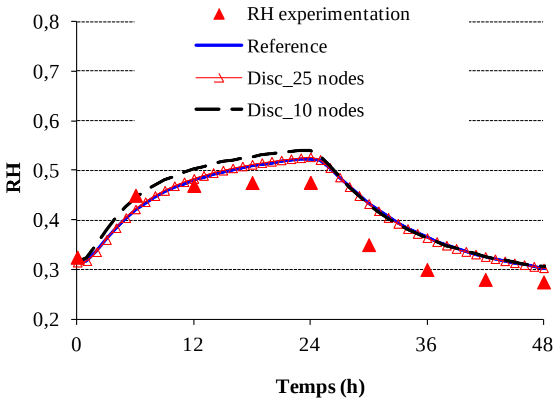

Figure 6: Impact of discretization on relative humidity variation (%)

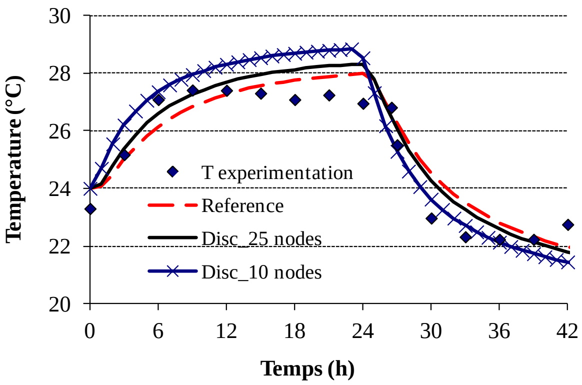

Figure 7: Impact of discretization on temperature variation (%)

It can be seen that more the mesh is finer, more the relative humidity profiles are close. The same conclusion is obtained for temperature profile however its effect is clearer. The difference of temperatures and relative humidity for the discretizations in 10 and 50 nodes can reach 0,9 °C and 1.7 % respectively. The discretization in 50 nodes is used for the next simulations.

3) *Effect of hygrothermal material properties and hygrothermal convection coefficients*

In this section, we studied the effect of hygrothermal properties and hygrothermal convection coefficients on temperature and relative humidity profile. We considered the same wall and varied its physical properties and parameters of 25% (sorption isotherm, moisture diffusion coefficient, specific heat, mass density, thermal conductivity, internal and external convection coefficients).

Considering now temperature and relative humidity as a function of time: T=T(X,t,β) and HR=HR(X,t,β) where X and t are independent variables and β is a parameters vector. The effect of hygrothermal properties will be investigated from the product βiXi called reduced sensitivity which is defined as

$$\beta_i X_i = \beta_i \frac{\partial T}{\partial \beta_i} \text{ or } \beta_i X_i = \beta_i \frac{\partial HR}{\partial \beta_i} \qquad (12)$$

The reduced sensitivity to indoor temperature and relative humidity are presented in and Figure 9 in which $\partial\beta_i$ value is considered to be 25 % of β_i.

Concerning its effect on indoor thermal profile, Figure 8 showed that it is very sensitive to thermal properties as thermal conductivity, specific heat and mass density while effect of moisture transport coefficients and sorption isotherm are small.

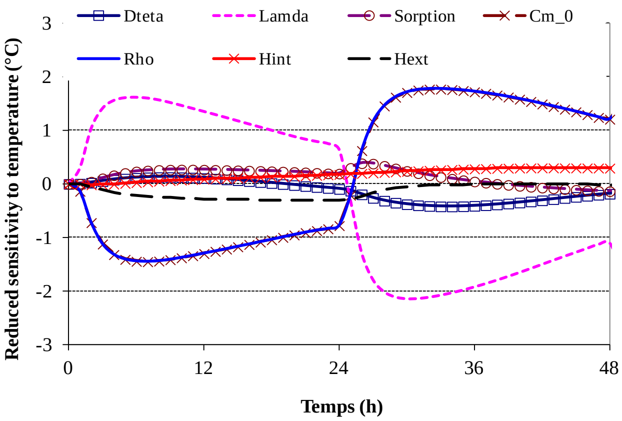

Figure 8: Reduced sensitivity to indoor temperature (°C)

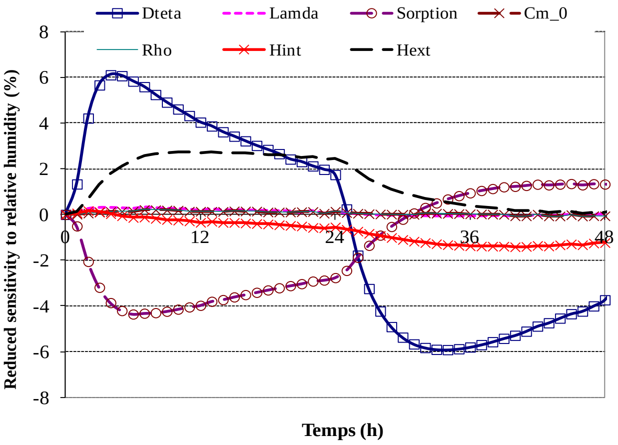

Figure 9: Reduced sensitivity to indoor relative humidity

As can be seen Figure 9, relative humidity at the middle of the wall is very sensitive to sorption isotherm and to moisture transport coefficient under a moisture content gradient. Beside, effect of thermal properties of materials is also significant compared to other parameters.

B. *Effect of hygrothermal properties on the indoor relative humidity and temperature profiles*

1) *Simulation conditions*

In this paper, we will study a room that has a space area of 3x5 m^2 and a volume of 42.8 m^3. The ceiling and the walls of 20 cm thickness are in contact with outdoor conditions. It is considered that no moisture diffusion occurs through the floor. Concerning the moisture transport coefficients, they are derived from [5].

Heat transfer coefficients are $h_{T,e}$= 25 W/m^2.K for the outdoor surfaces and $h_{T,i}$= 8 W/m^2.K for indoor surfaces. The mass convection coefficients were calculated by using Lewis relation and considering Lewis number equals to 1.

The initial relative humidity and temperature in the walls and the studied room were respectively equal to 50 % and 20 °C. Room is ventilated at 0.5 ach with the outside conditions. We will study the hygrothermal behaviour of the room when the outside temperature and relative humidity change suddenly to 30° C and 70 % for 10 days then its outside conditions return to initial condition (so 20°C and 50% of RH) as shown in Figure 10.

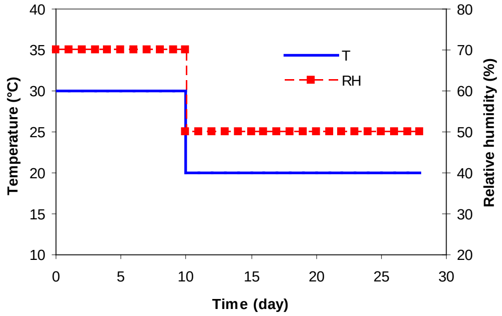

Figure 10: Outside relative humidity and temperature

2) *Effect of coupled heat air and moisture transfer model*

The simulated results of two models **Th** and **HAM** are presented in Figure 11 and Figure 12.

Figure 11 showed that taking into account the whole building moisture transfer has a great effect on indoor relative humidity. For **Th** model, the condensation phenomena take place in the room from 2 hours after simulation beginning while this is not observed for HAM model. That can be explained by the fact that the moisture buffering capacity of hemp concrete walls (for **HAM** model) can dampen the variation of indoor relative humidity of the room.

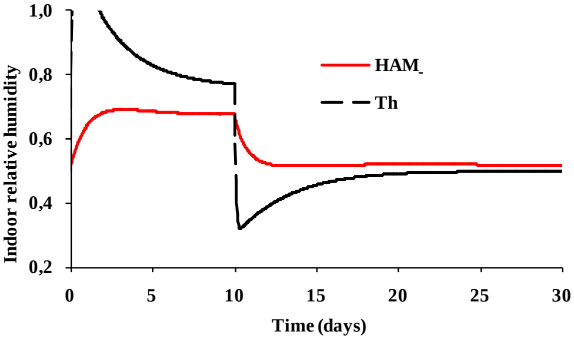

Figure 11: Indoor relative humidity profiles of two models (Th and HAM)

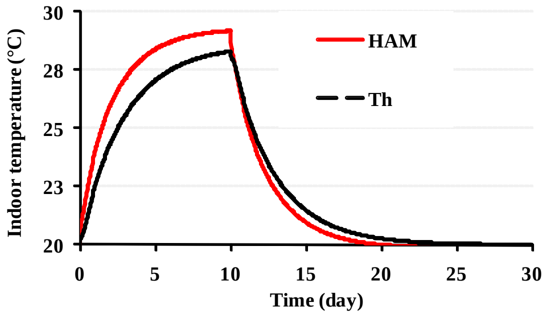

Figure 12: Indoor relative temperature profiles of two models (Th and HAM)

Figure 12 presents the variation of indoor temperature of two models. During the fist 10 days (sorption period), the indoor temperature of **HAM** model varies more rapidly and its value is larger than that of **Th** model with a maximum difference of 1.3°C. Concerning desorption period (from 10 days after simulation beginning), a maximum difference of 0.6°C is observed between two models. This result is due to thermal conductivity that is bigger for **HAM** model than the one of **Th** model.

In conclusion, taking into account the coupled heat and moisture transfer is necessary to predict correctly the hygrothermal behaviour of buildings. Therefore, **HAM** model is used for the next sections.

3) *Impact of spatial discretization and time increment*

It has been shown that time increment effected very slightly the results (4 minutes, 1 minute, 30 seconds). Concerning the second one, each component (wall, roof) was discretized into 5, 10, 25 and 50 nodes and its effect on indoor relative humidity is presented in Figure 13 .

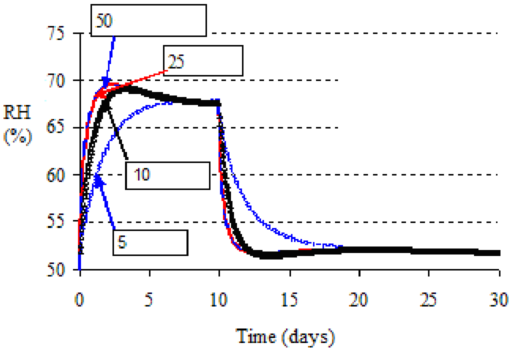

Figure 13: Impact of discretization on indoor RH (%).

4) *Effect of ventilation rate*

Figure 14 and Figure 15 showed that the effect of ventilation rate is clear on the indoor relative humidity and temperature.

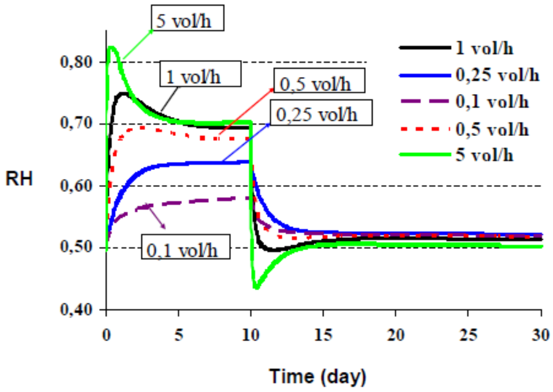

Figure 14: Effect of increasing ventilation rate on indoor RH

It can be seen that more the mesh is finer, more the indoor relative humidity profiles are close. The difference of T and RH between the discretization in 5 and 50 nodes can reach 0,4 °C and 6,3 % respectively. The results for the 25 nodes case is very close to that of 50 case; therefore, discretization in 25 nodes is used for the next simulations which reduces significantly the calculation time.

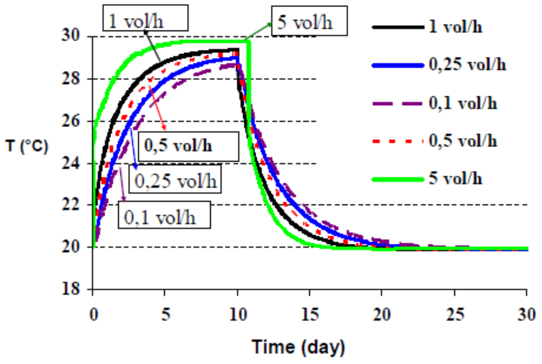

Figure 15: Effect of increasing ventilation rate on indoor temperature

Figure 15 shows that as the ventilation rate increases, indoor relative humidity decreases and tends to Th model presented above. Numerically, increasing ventilation rate from 0.25 ach to 1 ach increases the maximum value of relative humidity from 64% to 75%.

There is notice that the gap of indoor temperature and relative humidity as a function of ventilation rate for adsorption period is bigger than that of desorption period due to the initial conditions (that were set to 50% of RH and 20°C).

5) *Effect of effective exposed surface*

Many authors concluded that the buffering effect increases with increasing active surface area ([4]; [19] ; [1]). Figure 16 present time to half drop of the indoor relative humidity in the room as a function of the active surface ratio and the ventilation rate for sorption period. When the active surface ratio is equal to 0, the walls are totally closed to moisture transfer and when it is equal to 1, all the walls are exposed to moisture transfer with indoor air.

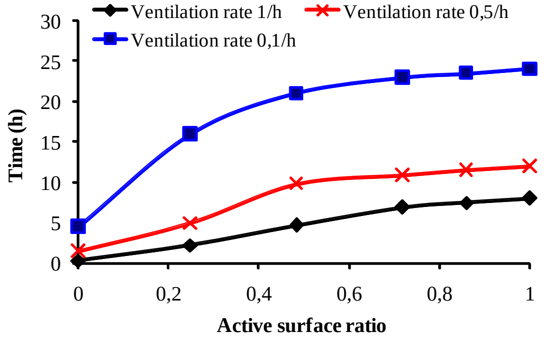

Figure 16: Time to half drop of the indoor relative humidity in the room as a function of the active surface ratio and the ventilation rate for sorption period (the first ten days)

In the studied case, when the ventilation rates are low, the variation of the time half-drop tends to an asymptotic value and the performance is no more affected by the active surface ratio (for values higher than 0.7). This conclusion is in concordance with observation in [19].

6) *Effect of hygrothermal material properties and hygrothermal convection coefficients*

In the last section, we studied the effect of hygrothermal properties and hygrothermal convection coefficients on indoor temperature and relative humidity.

The reduced sensitivity to indoor temperature and relative humidity are presented in Figure 17 and Figure 18 in which $\partial\beta_i$ value is considered to be 25 % of β_i .

Concerning its effect on indoor thermal profile, Figure 17 showed that it is very sensitive to thermal properties as thermal conductivity, specific heat and mass density while effect of moisture transport coefficients and sorption isotherm are small.

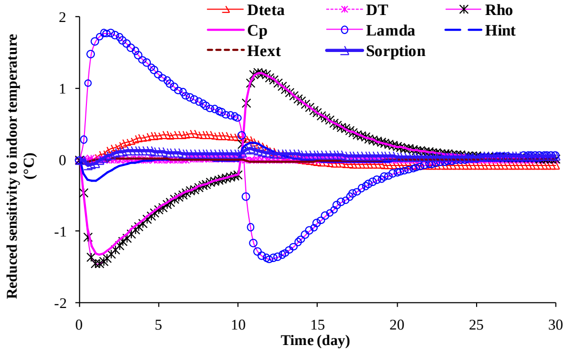

Figure 17: Reduced sensitivity to indoor temperature °C

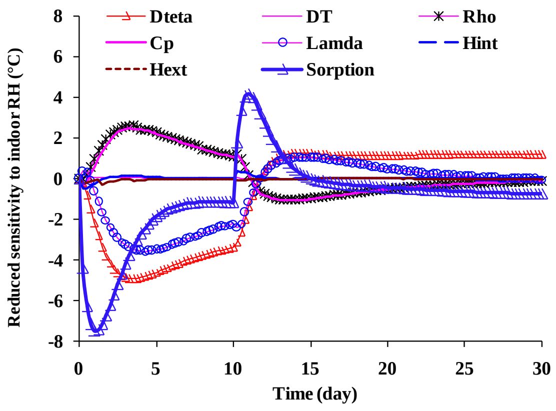

Figure 18: Reduced sensitivity to indoor relative humidity

As can be seen Figure 18, indoor relative humidity is very sensitive to sorption isotherm and to moisture transport coefficient under a moisture content gradient. Beside, effect of thermal properties of materials is also significant compared to others.

V. CONCLUSION

Material properties, simulation conditions have to be defined and considered for any HAM models. Otherwise, inaccurate estimation of hygrothermal properties, initial conditions and boundary conditions can affect the prediction of simulation tool. Therefore, a detailed parametric study of hygrothermal behaviour of a wall and a room made of hemp concrete submitted to hygrothermal shock has been carried out in the present work.

Our results showed that taking into account moisture transfer and having a fine space discretization of building envelope components are necessary to predict correctly the hygrothermal behaviour. Concerning the impact of hygrothermal properties, the temperature and relative humidity profiles are very sensitive to thermal properties, moisture transport coefficient due to moisture content gradient and sorption isotherm.

In addition, at the whole building level, the ventilation rate and exposed surfaces have important impact on indoor and relative humidity profiles. However, for a low ventilation rate, when the surface ratio is higher than 0.7, the performance is not affected by exposed surface.

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