PARAMETRIC STUDY OF HYGROTHERMAL BEHAVIOUR OF A ROOM MADE OF HEMP CONCRETE

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ABSTRACT

Hygrothermal properties (such as thermal conductivity, sorption isotherm, moisture diffusivity…) 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 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 with variable coefficients 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 analytical data available in the literature. This model is then used to analyze the sensitivities of HAM model parameters on the indoor temperature and relative humidity profiles when the room is submitted to hygrothermal shock.

Keywords: HAM, simulation, hemp concrete, SPARK.

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 ((Tran le et al., 2010) , (Olalekan et al., 2006), (Kwiatkowski et al., 2009), (Hameury, 2005)).

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

Regarding 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 (2004) and Evrard (2008) 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 indoor temperature and relative humidity profiles of a hemp concrete room which is 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 model for a room level. Finally, the last section presents the sensitivities of HAM model parameters on the hygrothermal behaviour of a hemp concrete room.

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. The work of Collet (2004) allowed us to determine its hygrothermal properties for HAM model with variable coefficients. In the next part, this mathematical model will be presented.

MATHEMATICAL MODELS

Moisture transport in building envelope

Mechanisms of moisture transport in a single building material have been extensively studied ((Künzel, 1995), (Perdesen, 1992), (Mendes et al., 1997)). Most of the models have nearly the same origin Philip and de Vries model (Philip and al., 1957). In this article, we use the Umidus model (Mendes et al., 1997) in which moisture is transported under liquid and vapour phases.

The mass conservation equation can be written as:

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

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

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

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

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:

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

$$Cp_m = Cp_0 + Cp_l \frac{\rho_l}{\rho_0}\theta \quad (5)$$

Where

Cp_m 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:

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

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):

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

Boundary conditions take into account heat and phase change:

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

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

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:

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

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

NUMERICAL RESOLUTION AND VALIDATION

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 (Tran Le et al, 2009a).

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 ((Sowell et al., 2001), (Mendonça et al., 2002)).

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

Analytical validation of the whole building hygrothermal model

International Energy Agency (IEA) has published an analytical verification of the whole building hygrothermal model in the framework of Annex 41 project (Rode et al, 2005; Bednar and Hageentoft, 2005). These analytical results are used to validate our present model.

In this exercise, Bednar (2005) proposed an analytical solution of the response of the room relative humidity to a step-wise moisture load with moisture buffering in the surrounding building construction for isothermal conditions. The room is ventilated with outdoor air in which the ventilation rate, the outdoor humidity and temperature are constant.

The volume of simplified building is 6*8*2.7 m^3 in which the floor, the walls and the roof are made from a simple layer of 10 cm thick aerated concrete. The material properties of aerated concrete are showed in Table 1. The convective mass coefficient for the external surface $h_{M,e}$ is set to 0 m/s in order to avoid the water vapour loss from inside to outside. The convective heat transfer coefficients are 25 $W/m^2.K$ for the outdoor and indoor surfaces. The initial relative humidity and temperature in the building envelope components and the room are, respectively, equal to 30 % and 20 °C. The ventilation rate is 0.5 ach (air exchange for hour). The moisture production inside the room of 0.5 kg/h is assumed from 9 h to 17 h every day. The grid space discretization of the building envelope components (roof, walls and floor) is 2 mm and the time step is 60 seconds.

Table 1

Material properties of aerated concrete for the simulation.

Thickness (cm)	10
Density (kg/m^3)	650
Thermal conductivity (W/m.K)	0.18
Heat capacity (J/kg.K)	840
Water vapor permeability (kg/Pa.s.m)	3E-11
Moisture transfer coefficient for indoor condition (kg/Pa.s.m²)	$0{,}2.10^{-7}$

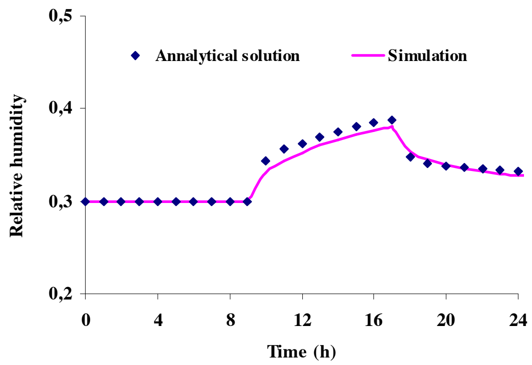

Figure 1: Comparison of indoor relative humidity profile of building between the analytical solution and numerical results for initial period

Figure 1 and Figure 2 present the comparison of indoor relative humidity profile between the analytical solution and numerical results for the first time and for the time when a quasi-steady state is established. Due to the moisture production inside the room (9h to 17h), the indoor relative humidity increases during this period and then decreases which is due to a constant ventilation rate and absence of moisture source. The results showed a good agreement between numerical and analytical results. Thus, the model is satisfying to investigate the hygrothermal behaviour of a hemp concrete room in the next section.

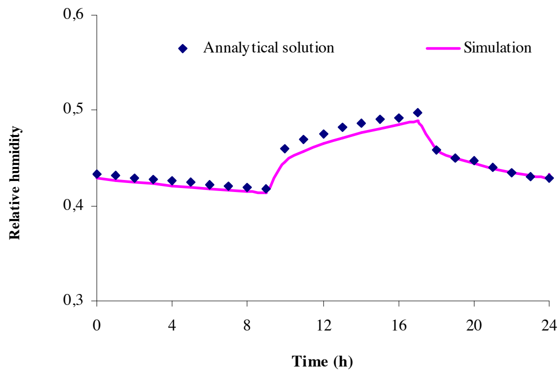

Figure 2: Comparison of indoor relative humidity profile of building between the analytical solution and numerical results after a quasi-steady state

NUMERICAL STUDIES

In our previous works (Tran Le et al., 2009b; Maalouf et al., 2011a-2011b), the hygrothermal behaviour of building envelope or building made of hemp concrete with constant coefficients model was investigated. However, in reality, hygrothermal material properties are function of moisture content (and other factors as temperature which are neglected in the study subject of this paper) in material that could affect the accuracy of simulation results. Therefore, variable coefficients model has been developed and used in this article.

Properties of hemp concrete

The available data of hemp concrete from Collet (2004) allow using the transport coefficients as a function of relative humidity or moisture content. Table 2 shows the material properties of hemp concrete used.

Concerning the sorption isotherm, the experimental data are curved fitted with a logarithmic model which is proposed by Merakeb (2009):

$$\ln\left(\frac{\theta}{\theta_s}\right) = a.\ln(\phi).\exp(b.\phi) \qquad (12)$$

For the hemp concrete case: a= 1.1, b=2.1 and θ_s =11.85 % (Tran Le et al., 2010).

Thermal conductivity for hemp concrete is a functionof moisture content (Collet., 2004):

$$\lambda = 0.106 + 0.7\theta \qquad (13)$$

Table 2

The basic material properties of hemp concrete Collet (2004)

Water vapor permeability (kg/Pa.s.m)	Mass density kg/m3	Thermal conductivity W/m K	Specific heat J/kg K
2.3E-11	413	0.106	1000

The moisture transport coefficients are variable as a function of moisture content derived from the formula as shown in above section.

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.

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 3.

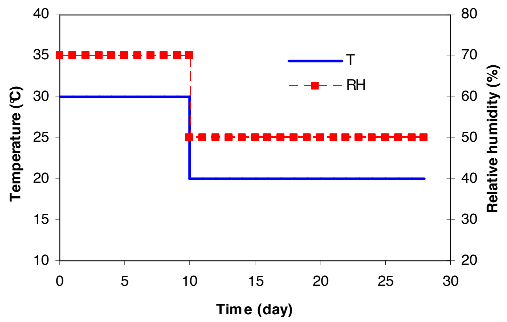

Figure 3: Outside relative humidity and temperature

Effect of coupled heat air and moisture transfer model

In order to study the effect of tacking into account the whole building heat and mass transfer on the indoor temperature and relative humidity, we study four models described in Table 3.

The computed results show that indoor relative humidity and temperature of both models **HAM** and **HAM_1** are very close and it is not depicted there. The simulated results of two models **Th** and **HAM** are presented in Figure 4 and Figure 5.

Figure 4 showed that tacking 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.

Table 3

Studied submodels

Model	Description
HAM	Whole building heat and mass transfer with variable coefficients model
HAM_1	Whole building heat and mass transfer neglecting effect of temperature gradient ($D_T = D_{T,v} = 0$)
Th	Take only heat transfer (dry basic material properties)

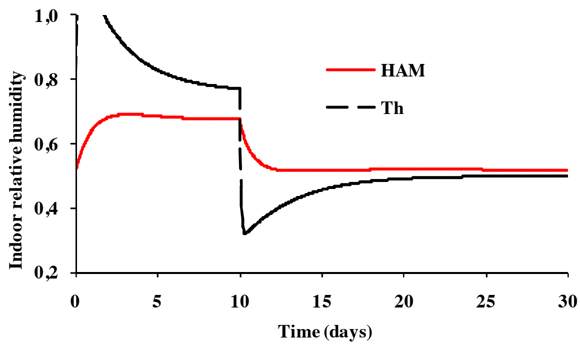

Figure 4: Indoor relative humidity profiles of two models (Th and HAM)

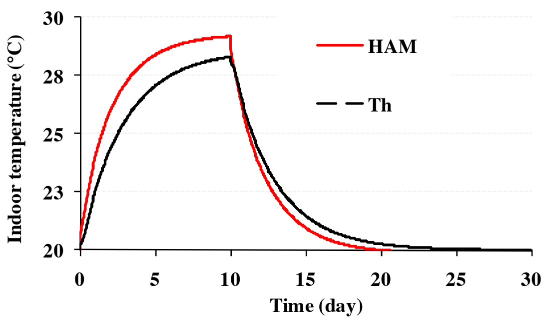

Figure 5: Indoor relative temperature profiles of two models (Th and HAM)

Figure 5 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, tacking 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.

Impact of spatial discretization and time increment

In this study, we analyse the effect of space discretization and time increment on the indoor relative humidity and temperature. 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 6.

It can be seen that more the mesh is finer, more the indoor relative humidity profiles are close. For the variable coefficients model, refining the grid gives negligible improvement for the response. The same conclusion is obtained for indoor temperature profile however its effect is small and it is not depicted there. 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.

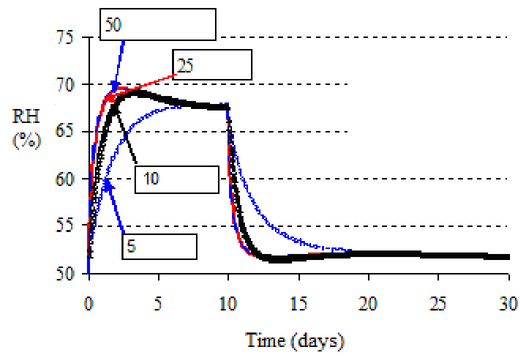

Figure 6: Impact of discretization on indoor RH (%)

Effect of initial conditions

Keeping in mind that initial water content conditions of walls depend on many factors as climate conditions, manufacture methods, etc. Following section aims to study their impact in which four initial conditions were studied as presented in Table 4.

Figure 7 and Figure 8 showed that initial condition has a very significant effect on indoor temperature and relative humidity profile.

Figure 7 showed that the more initial relative humidity is, the higher indoor relative humidity will be. That could be explained by the fact that the material releases more water vapour to the indoor air. Numerically, the relative humidity difference between two initial conditions with HR_init=20% and HR_ init=50% reaches 10% and this difference can reach 30% when initial relative humidity of HR_ init=50% pass to HR_ init=80%.

Table 4

Studied initial conditions

Initial condition	***Initial relative humidity in each wall layers***
Dry	0 %
Low humidity	20 %
Equilibrium	50 %
Wet	80 %

Concerning indoor temperature profile (Figure 8), increasing initial relative humidity leads to an decrease in indoor temperature. It can be explained by the boundary conditions in which the wall is exposed to phase change related to the water vapour exchanged with indoor air. More initial moisture content in wall is dry, heat flux due to condensation occurred is higher and therefore the indoor temperature will increase.

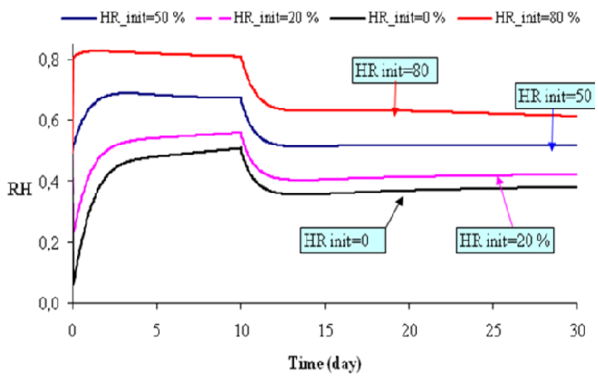

Figure 7: Effect of initial conditions on indoor relative humidity

Our results suggest that hygrothermal behaviour of a room is very sensitive to the initial conditions that have a very long-time effect. Therefore, it is needed to precise this information before performing a simulation.

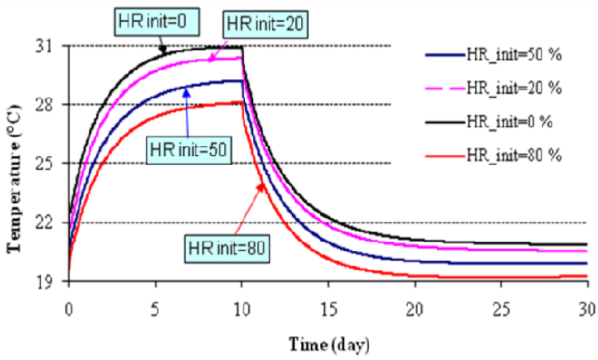

Figure 8: Effect of initial conditions on indoor temperature

Effect of ventilation rate

Figure 10 and Figure 9 showed that the effect of ventilation rate is clear on the indoor relative humidity and temperature.

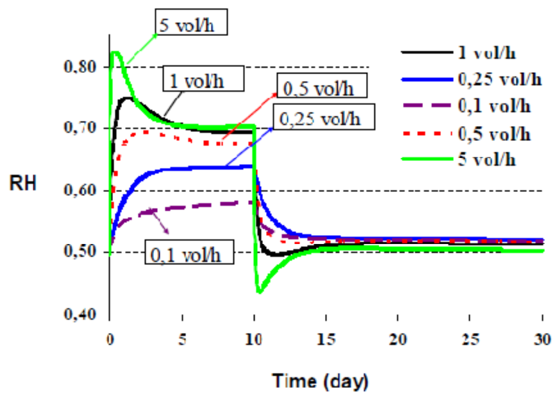

Figure 9: Effect of increasing ventilation rate on indoor RH

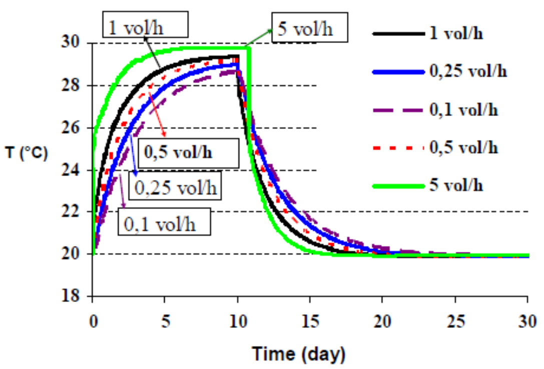

Figure 10: Effect of increasing ventilation rate on indoor temperature

Figure 10 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 desoprtion period due to the initial conditions (that were set to 50% of RH and 20°C).

Effect of effective exposed surface

Many authors concluded that the buffering effect increases with increasing active surface area (Hameury, 2005; Salonvaara et al., 2004; Tran le et al., 2010). Figure 11 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.

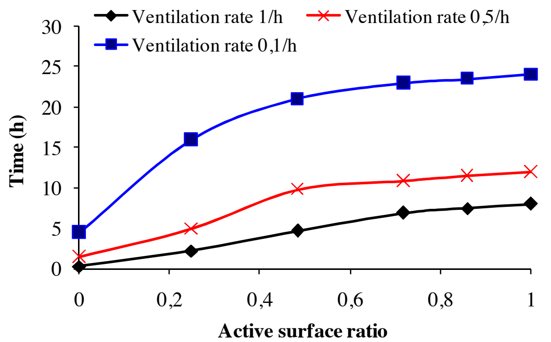

Figure 11: Time to half drop of the indoor relative humidity in the room as a function of the active surface ratio and the ventilation rate for sorption period (the first tens days)

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 of Salonvaara (2004).

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.

Considering now indoor 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 $\beta_i X_i$ called reduced sensitivity which is defined as:

$$\beta_i X_i = \beta_i \frac{\partial T}{\partial \beta_i} \text{ or } \beta_i X_i = \beta_i \frac{\partial HR}{\partial \beta_i} \qquad [14]$$

The reduced sensitivity to indoor temperature and relative humidity are presented in Figure 12 and Figure 13 in which $\partial\beta_i$ value is considered to be 25 % of β_i.

Concerning its effect on indoor thermal profile, Figure 12 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.

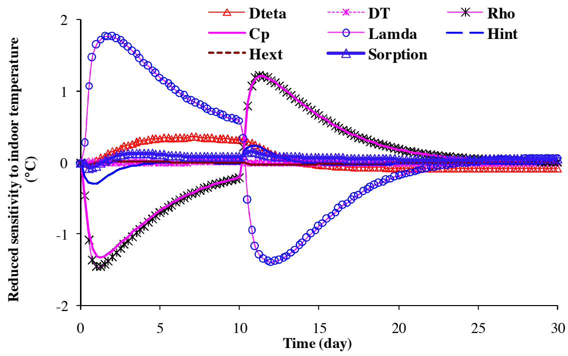

Figure 12: Reduced sensitivity to indoor temperature °C

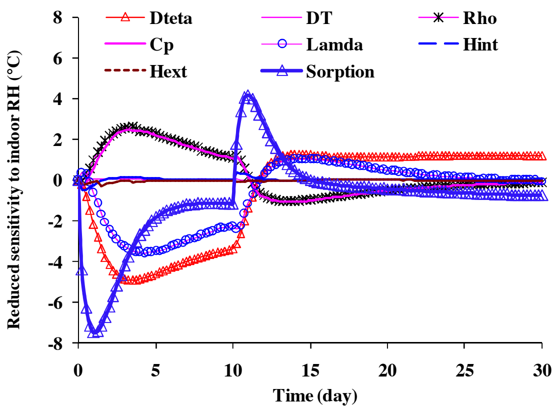

Figure 13: Reduced sensitivity to indoor relative humidity

As can be seen Figure 13, 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.

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 effect the prediction of simulation tool. Therefore, a detailed parametric study of hygrothermal behaviour of a room submitted to hygrothermal shock has been carried out in the present work.

Our results showed that tacking into account moisture transfer and having a fine space discretization of building envelope components are necessary to predict correctly the hygrothermal behaviour of room. The results also confirmed that effect of initial conditions on the indoor temperature and relative humidity is significant and long term. In addition, the ventilation rate and exposed surfaces have important impact. However, for a low ventilation rate, when the surface ratio is higher than 0.7, the performance is not affected by exposed surface. Finally, concerning the impact of hygrothermal properties, the indoor temperature and relative humidity are very sensitive to thermal properties, moisture transport coefficient due to moisture content gradient and sorption isotherm.

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
π	Water vapour permeability	$kg.m^{-1}\ s^{-1}.Pa^{-1}$

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