

## NUMERICAL ANALYSIS OF HEAT, AIR, AND MOISTURE TRANSFERS IN A WOODEN BUILDING MATERIAL

by

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*The present paper aims to predict the hygrothermal behavior of massive wood panel considered as bio-based building material. In this context, we developed a macroscopic model coupled no linear heat, air, and moisture transfers that incorporates simultaneously the effect of thermal diffusion and infiltration phenomenon on the building material. The model inputs parameters were evaluated experimentally according to the recognized standards of material's characterization. Therefore, numerous series of hygrothermal calculation were carried out on the 1-D and 2-D configuration in order to assess the dimensionless effect on such wooden material. Two types of boundary conditions were considered and examined. The first are at the material scale of wood drying process. The second type of conditions is at the wall scale, where the conditions of the building ambiance are considered. Moreover, the model sensitivity to the driving potentials coupling and to the parameters variability was considered and examined. It has been found that the coupling in the model had a remarkable impact on both kinetics of temperature and moisture content.*

Key words: *heat, air, and moisture transfer; wooden material, variable thermal conductivity, bioresource*

### Introduction

The study of coupled heat and mass transfers in porous media concerns several areas of research such as textile materials [1], wood drying [2], granular materials [3], transport in composite membrane [4], capillary-porous bodies [5], soils media [6], and thermal insulation [7]. Bio-based insulation materials, which have recently appeared as a serious candidate in the search of sustainable and energy-efficient materials, have typically a strong buffer performance as both their moisture storage and high transfer capillary [8].

Some authors resolved coupled heat and moisture transfer equations by analytical approaches [9, 10] and others, by numerical solutions [11]. The comparison between analytical and numerical solution of heat and moisture transfers in hygroscopic porous building materials was summarized in Abahri *et al.* [12]. Crausse *et al.* [13] compared spatial distributions of temperature and moisture in a wall using two models. Further, Mendes and Philippi [14] and Mendes *et al.* [15] proposed a new approach to solve this problem by decomposing the equations of heat and mass transfer into several sub systems. Al-Sanea *et al.* [16] suggested a

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thickness optimization of the tested material by using numerical approach. At the experimental level, Talukdar *et al.* [17] described an experimental transient moisture transfer facility in order to measure in continuous temperature, relative humidity and moisture accumulation within hygroscopic porous media. The measured and correlated property for these materials were used in the numerical work by Osanyintola and Simonson [18] in order to evaluate the hygrothermal behavior of a wooden insulation by estimating the effect of hygroscopic materials on energy consumptions in buildings.

However, the term of moisture can be taken as several physical states. Many models taken it form liquid water [19] where the presence of water vapor is neglected. Other authors consider the diffusion of water vapor but the portion of liquid water was neglected [20]. Indeed, whatever these potentials which will be adopted, the formulation of moisture transfer equations are equivalent to the model proposed by Funk and Wakili [21]. They are, in the most, described by the combination of Darcy and Fick laws. In fact, the presence of moisture implies an additional latent heat transport that many causes great discrepancies on the indoor air temperature and humidity values. A first simple study describing the evolution of moisture in building materials was treated by the Glaser-method [22]. After that Steeman *et al.* [23] have studied the capacity of porous hygroscopic materials to dampen the indoor humidity variations through moisture exchange.

The most used models in literature, describing heat, air, and moisture (HAM) transfers are 1-D [5, 9, 10, 12, 24, 25]. Few studies treated the coupled transfers in building materials in 2-D or 3-D [26]. In this present paper, we proposed a predicted HAM transfers model in a wooden slab in 2-D space. It is a macroscopic model describing and analyzing the hygrothermal behavior on a monolayer wall on the scale of the envelope for different climatic conditions. It focuses on a one material geometry, submitted to various boundary conditions. It proposes to do a purely numerical investigation in order to test the mathematical model and its sensitivity to the spatial dimension and the boundary conditions. The used model incorporates three driving potentials: temperature, moisture, and total pressure.

### Mathematical model

Literature supplied different models of coupled heat and moisture transfers in porous building materials. The choice of the appropriate potentials, driving transfers, is still a point of discussion of several researchers. The proposed model in this study is based on the theory of Luikov [5], which takes into account the terms of mass, air, and the total pressure gradient. However, a system of coupled equations is presented in this model, which is derived from the energy equation (heat transfer) and the mass balance of the moisture portion present in the porous medium. The mass balance is decomposed of mass balance in each species present in the porous medium (solid, liquid, gas). The principal potentials of transfer: temperature, moisture content and the total pressure are described (fig. 1).

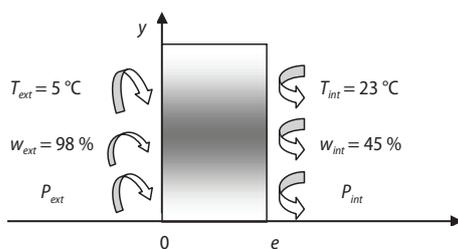


Figure 1. Physical problem (2-D)

The studied material is a wooden slab of 2.4 cm thickness, whose physical properties are experimentally obtained from the published works [27]. The objective, is to study, in 2-D domain ( $x, y$ ), the model sensitivity to the coupling of HAM transfers for such hygroscopic material. Some assumptions are supposed to establish the mathematical model:

- the porous medium is assumed unsaturated and undeformable, the solid matrix is supposed – homogeneous and isotropic,

- the chemical reactions and the heat transfer by radiation are neglected and the gas phase obeys to the ideal gas law, and
- thermal local hygroscopic equilibrium is assumed established and the different physical states present (solid, liquid, and gas) are in a thermodynamic equilibrium.

Most of building materials are considered porous, and composed of solid matrix and pores. In the pores, the moisture can be existed in two phases: liquid and vapor. The mass balance equation is comprised of various moisture driving potentials that translate the movement of the different existing phases occupying pores and the hygroscopic behavior of a porous construction material. Indeed, the mass balance, in this case, contains the proportion of water in its two forms: liquid and vapor. These proportions move due to the capillary forces for liquid transfer and vapor diffusion. However, the portion of dry air circling in pores is also considered in the mass balance [5, 12]:

- liquid phase 
$$\frac{\partial \theta_l}{\partial t} + \nabla(J_l) = \dot{m} \quad (1)$$

- vapor phase 
$$\frac{\partial \theta_v}{\partial t} + \nabla(J_v) = -\dot{m} \quad (2)$$

- dry air 
$$\frac{\partial \theta_a}{\partial t} + \nabla(J_a) = 0 \quad (3)$$

$$\frac{\partial(\theta_l + \theta_v)}{\partial t} + \nabla(J_l + J_v) = 0 \quad (4)$$

The liquid flow is described by the Darcy's law:

$$J_l = -k_l \rho (\nabla w - \delta_l \nabla T) - \alpha_l \nabla P \quad (5)$$

Similarly to the liquid flow, the vapor flow moves inside the porous building materials by diffusion. It is described by [5] and is governed by Fick's, which considered the effects of both vapor pressure and the air pressure:

$$J_v = -D \nabla \rho_v - \alpha_v \nabla P \quad (6)$$

The vapor density gradient,  $\nabla \rho_v$ , can be written by the following expression, where the gradient of temperature appeared in the vapor flow expression:

$$\nabla \rho_v = \left( \frac{\partial \rho_v}{\partial w} \right)_T \nabla w + \left( \frac{\partial \rho_v}{\partial T} \right)_w \nabla T \quad (7)$$

The air dry balance equation is function of the total pressure gradient and it is given:

$$C_a \frac{\partial P}{\partial t} = \text{div} \left[ \alpha_p \left( \frac{\partial P}{\partial x} u_x + \frac{\partial P}{\partial y} u_y \right) \right] - \dot{m} \quad (8)$$

where  $C_a = \varepsilon(1 - S_i)M/(\rho RT)$  is the storage capacity of dry air.

This form of conservation of energy is derived from general equation of heat transfer. It is explained by the presence of the gradient of temperature, the density of heat flow and the term of source due to a latent heat of phase change:

$$\rho c_p \frac{\partial T}{\partial t} = -\nabla \left[ -\lambda \left( \frac{\partial T}{\partial x} u_x + \frac{\partial T}{\partial y} u_y \right) + \delta_t \left( \frac{\partial \omega}{\partial x} u_x + \frac{\partial \omega}{\partial y} u_y \right) + k_p \left( \frac{\partial P}{\partial x} u_x + \frac{\partial P}{\partial y} u_y \right) \right] - h_{i,v} \quad (9)$$

### Numerical investigation

To solve the equations associated to the developed model, the COMSOL Multiphysics software was selected. This is a powerful environment for modeling and solving a variety of engineering and research problems. It is particularly suitable for the treatment of Multiphysics problems where several phenomena are studied simultaneously, as is the case of coupled heat and moisture transfers. The resolution of partial differential equations is done by the finite element method. This model was tested and validated, earlier, for a 1-D case into the study of Abahri *et al.* [12], where to total pressure contribution to the transfer was examined. In the following, we will propose a numerical solution for a 2-D case.

In this work, two scales of study and two types of boundary conditions has been taken in consideration. The first is at the scale of material, where the boundary conditions of wood drying were fixed similar to those of Abahri *et al.* [12]. The second condition is at the scale of wall, where the ambience building conditions are considered. In the case of drying wood, the wood is submitted to symmetrical hygrothermal loads of temperature, moisture content and pressure on its two external surfaces. These conditions are presented in tab. 1.

**Table 1. Initial conditions**

Drying wood	Temperature [°C]	$T(x,y,t=0) = T_0$	$T_0 = 10$
	Moisture content [kgkg <sup>-1</sup> ]	$\omega(x,y,t=0) = \omega_0$	$\omega_0 = 86$
	Total pressure [Pa]	$P(x,y,t=0) = P_0$	$P_0 = 101375$
Building ambience	Temperature [°C]	$T(x_{(0,e)},y,t=0) = T_0$	$T_0 = 5$
	Moisture content [kgkg <sup>-1</sup> ]	$\omega(x_{(0,e)},y,t=0) = \omega_0$	$\omega_0 = 75^\circ M$

The boundary conditions can be given:

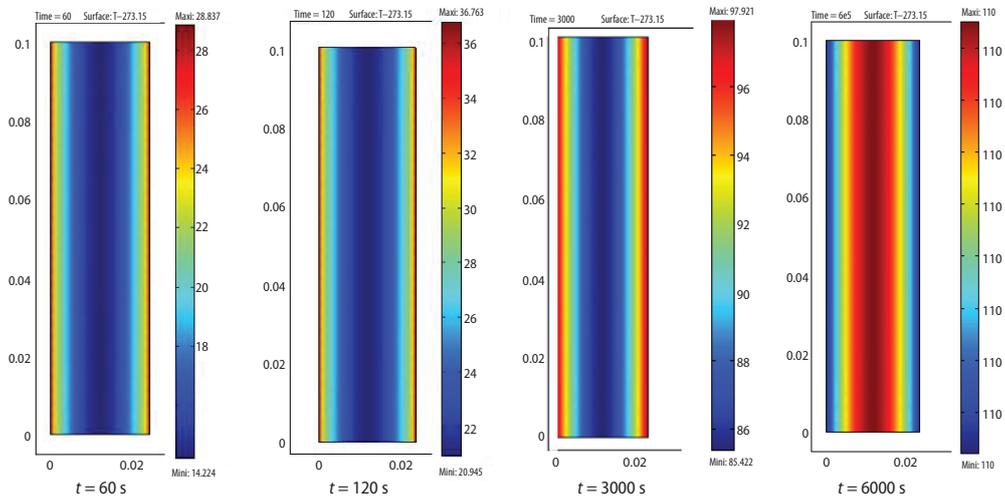
$$\lambda \frac{\partial T(x,t)}{\partial x} \Big|_{x=0,e} = h_n [T_{(0,t)} - T_a] + (1 - \chi) h_m [\omega_{(0,t)} - \omega_a] \quad (10)$$

$$k_m \frac{\partial \omega(x,t)}{\partial x} \Big|_{x=0,e} = h_m [\omega_{(0,t)} - \omega_a] \quad (11)$$

In this case, we extended the study into building ambience conditions, similar to the experimental underlined in [27]. These initial conditions are as illustrated in tab. 1.

The comparisons of 1-D and 2-D numerical results at the center and the surface of the wood slab are illustrated in the figures for several cases of boundary conditions presented in tab. 1.

Figure 2 show the temperature distribution over the surface in a 2-D configuration, at different times during drying of wooden material also illustrates, respectively, the temperature distributions in wooden slab sample at different times. The temperature distribution evolves rapidly at the beginning and then becomes stable. For the two firsts minutes, a larger temperature gradient was established, which explain the drying kinetics in of timber material. It can be seen that after two minutes, an apparition of symmetric refine orange layer on the both side of the wood slab. These layers correspond to an average temperature of 70 °C. Then, the tempera-

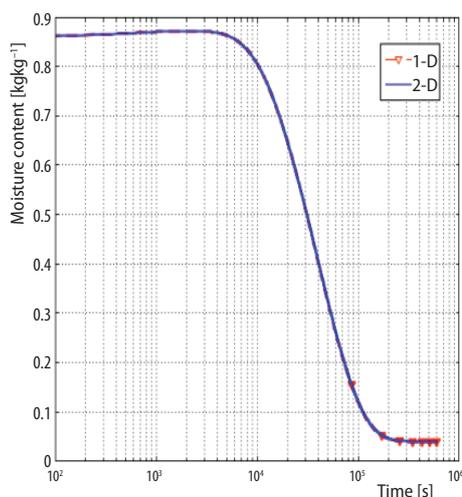


**Figure 2. Distributions of temperature at the surface of material at different times**  
 (for color image see journal web site)

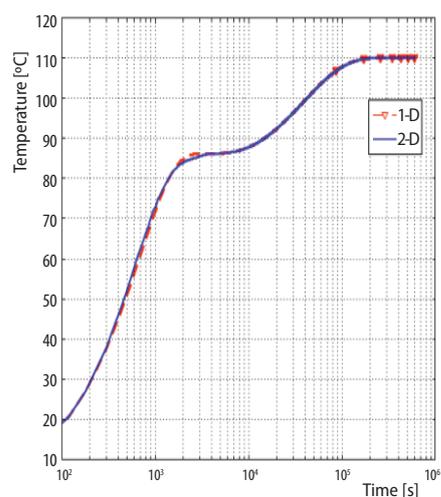
ture difference between the inner and outer region decreases more and more, until it reaches the equilibrium state of 110 °C.

The resolution of the coupling model of heat and moisture transfer in wooden material on 1-D and 2-D, gives almost the same result. In fact, from these figures we note that there is a real coincidence between the temperatures and moisture content profiles. This confrontation is shown for profiles either in the center or even at the surface of the material (figs. 3 and 4).

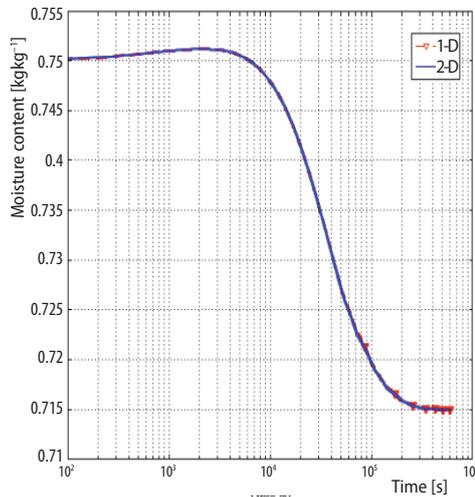
These figures show that there is no spatial variability between the evolution of temperature and moisture content in the material on 1-D and 2-D studies. The obtained temperature and moisture evolutions for both dimensional cases are logical since the material thickness is highly negligible compared to its height which is confirmed also by the chosen boundary condi-



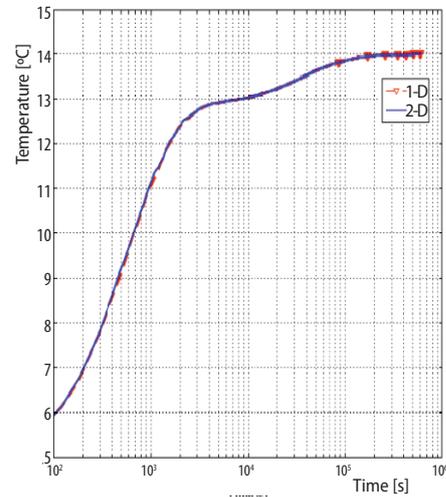
**Figure 3. Moisture content at the center on 1-D and 2-D on wood drying conditions**  
 (for color image see journal web site)



**Figure 4. Temperature profile at the center on 1-D and 2-D on wood drying conditions**  
 (for color image see journal web site)



**Figure 5. Moisture content at the center on 1-D and 2-D at  $T_0 = 5\text{ °C}$ ,  $HR = 75\%$**   
(for color image see journal web site)



**Figure 6. Temperature at the center on 1-D and 2-D at  $T_0 = 5\text{ °C}$ ,  $HR = 75\%$**   
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tions. In other manner the convection condition is mostly assumed to be homogeneous over the entire height of the material surfaces which is not all time representatives of the real building conditions (figs. 5 and 6).

In this context, Younsi *et al.*[28] investigated the 3-D case on wood slab revealing that the hygrothermal behavior on 3-D modeling is practically the same as the 1-D case. In contrast, this ascertainment was obtained only for the case of constants heat and mass convective coefficients which is not always representative of the boundary conditions of building.

In the present study, we tested the real convective effect by taking in consideration the variability of such coefficient function of the wall height. This variability is represented through the Nusselt number. It is a function of Reynolds number, Prandtl number, and  $H$  which is the height of the plate of wood:

$$Nu_y = \frac{h'_h y}{\lambda_{air}} \quad (12)$$

The Nusselt and Reynolds numbers are calculated by:

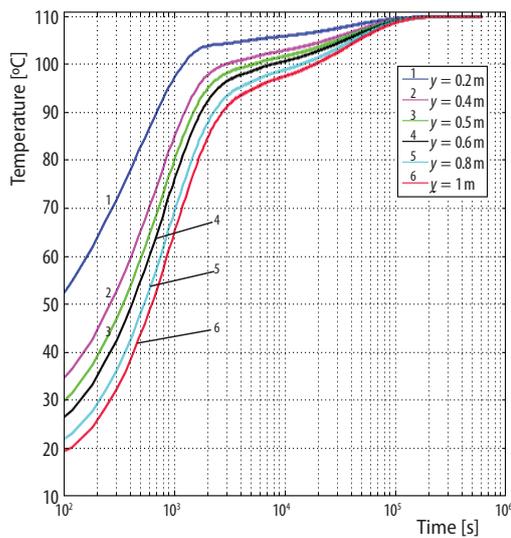
$$Nu_y = 0.332\sqrt{Re_y} \sqrt[3]{Pr}, \quad Re_y = \frac{\rho_{air} v_{air} H}{\nu_{air}}, \quad h'_h = \lambda_{air} \frac{0.332 \sqrt{\frac{\rho_{air} v_{air} H}{\nu_{air}}} \sqrt[3]{Pr}}{y} \quad (13)$$

So, a flat board of solid wood with constant surface temperature is submitted to a heat convective flow varied to along the height of panel during the process of drying. The other surfaces are submitted to boundary conditions where the heat convective coefficient stays constant. The temperature of drying has a value of 110 °C and the flow of air is considered laminar.

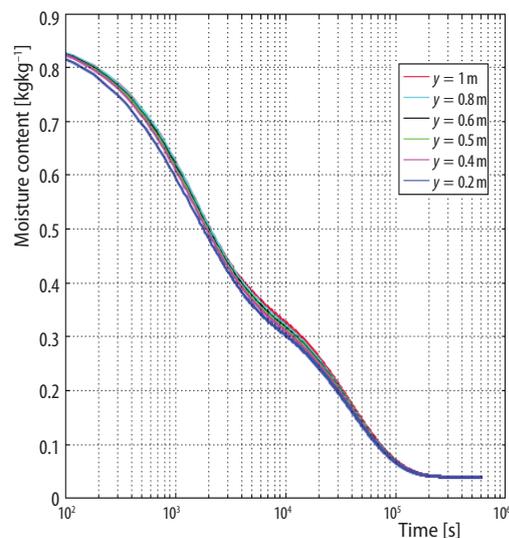
$$\lambda \frac{\partial T(x,t)}{\partial x} \Big|_{x=0} = h'_h [T_{(0,t)} - T_a] + (1 - \chi) h_m [\omega_{(0,t)} - \omega_a] \quad (14)$$

$$\lambda \left. \frac{\partial T(x,t)}{\partial x} \right|_{x=e} = h_h [T_{(0,t)} - T_a] + (1 - \chi) h_m [\omega_{(0,t)} - \omega_a] \quad (15)$$

The boundary condition of mass transfer is as the same given on eq. (11). The temperature and moisture content distribution function of the vertical position (material height) are presented in figs. 7 and 8, respectively.



**Figure 7. Variation of temperature profiles along the vertical (y) axis**  
 (for color image see journal web site)



**Figure 8. Variation of moisture content profiles along the vertical (y) axis**  
 (for color image see journal web site)

We can note from these two figures, that the temperature profile depends heavily of the vertical position (y), which confirms the necessity of taking into account the 2-D dimension in this work. In fact the temperature is high at the points near to (y = 0), then decrease gradually on approximating the maximum height of the wooden plate. The convection effect is therefore shown on the surface which is not the case for the moisture content. The smaller slight variations of these profiles are due to slight assignment by the coupling in the model.

In the previous part (1-D and 2-D model sensitivity), we did assumption that all the HAM model parameters were constants. In this part, we evaluated the impact of the parameters variability and the model coupling on the material hygrothermal behavior.

That is why, we proposed to study the 2-D case of the previous same monolayer configuration constituted of a wooden slab of 2.4 cm thickness at the wall scale. The same boundary conditions of building ambience were kept and applied to the considered wall. Two parameters are analyzed and considered variables: the thermal conductivity and the moisture diffusion coefficient.

In reality the thermal conductivity is a variable parameter which depends to the term of moisture [26]. The choice of the thermal conductivity that present a key parameter of the model and a motor of heat transfer. The same case for the moisture diffusion coefficient, which is considered variable function of the moisture content. They are given:

$$\left\{ \begin{array}{l} \lambda = \lambda_0 + 0.475\theta \\ D_m = D_0(-18.14 \cdot 10^{-4} \omega + 1) \end{array} \right. \quad \text{where} \quad \left\{ \begin{array}{l} \lambda_0 = 0.107 \text{ W/mK} \\ \theta = \frac{\rho}{\rho_{eau}} \omega \\ D_0 = 2.61 \cdot 10^{-5} \text{ m}^2/\text{s} \end{array} \right.$$

The following figures illustrate the profiles of temperature and moisture content, at the center of material, with constants and variables parameters: figs. 9 and 10, represent the sensibility of HAM model to the thermal conductivity and figs. 10 and 11 represent the sensibility of model to the vapor diffusion coefficient.

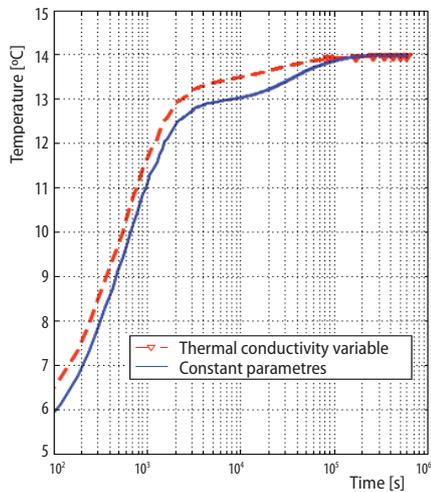


Figure 9. Sensitivity of temperature profile to the thermal conductivity

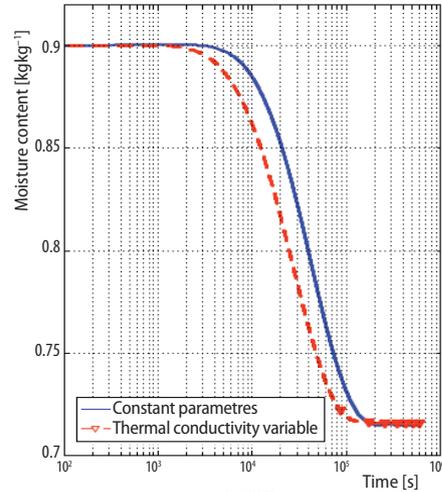


Figure 10. Sensitivity of moisture content profile to the thermal conductivity

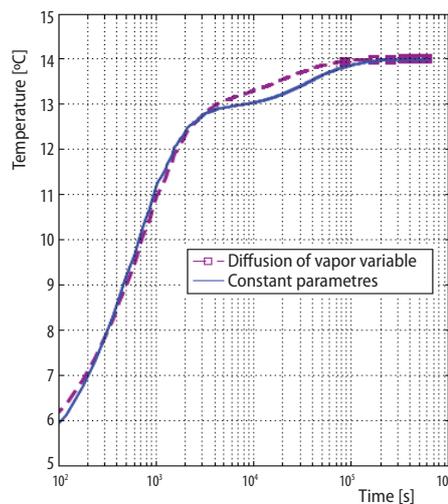


Figure 11. Sensitivity of temperature profile to the vapor diffusion coefficient

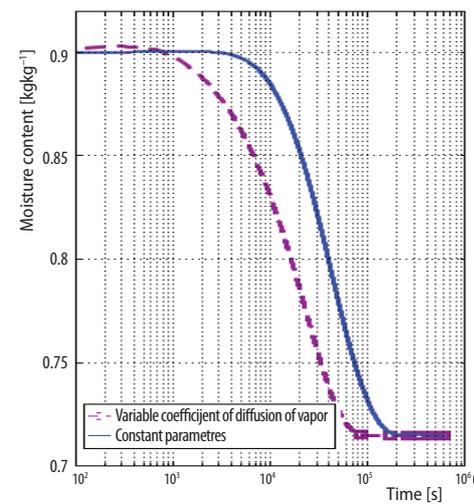
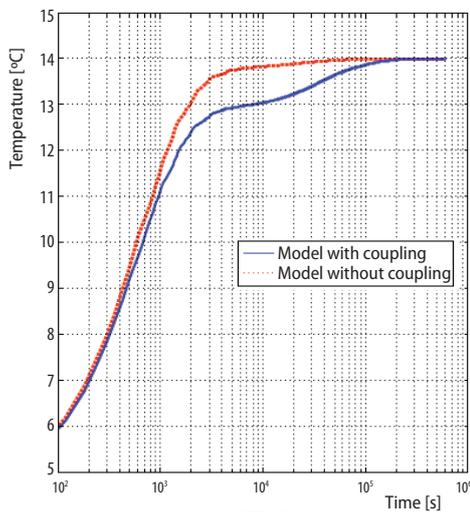


Figure 12. Sensitivity of moisture content profile to the vapor diffusion coefficient

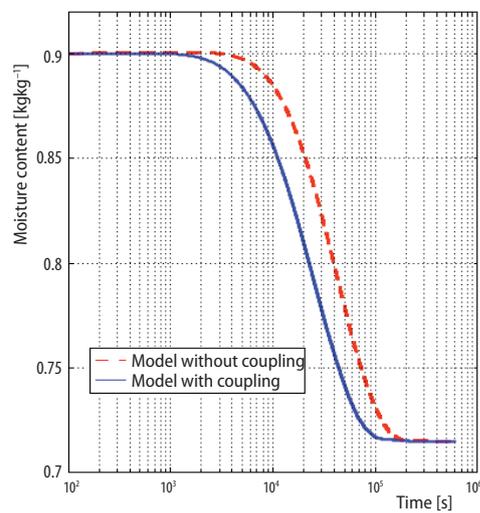
Figures 9-12 show a notable difference between the temperature and moisture content profiles when considering variables parameters. Concerning the sensitivity to the thermal conductivity a slight impact to the hygrothermal transfer was observed. This parameter is strongly dependent on the water content of the materials. This explains the increase of the temperature in fig. 9 on varying the term of thermal conductivity. However, in fig. 10, the transfer of the water content decreased in the case of variable thermal conductivity. At first, the moisture content has the tendency to be the same as the case of constant thermal conductivity at the value of  $10^3$  seconds. From this value, the moisture content decreases in the case of variable conductivity. The moisture content is also affected when considering the variations of the moisture diffusion coefficient as shown in fig. 11. Indeed, this coefficient does not disturb the thermal transfer according to the temperature profiles obtained in fig. 12.

In this part, we evaluated the impact of coupling on the prediction of hygrothermal transfers. We discussed the hygrothermal behavior when we consider the HAM model driving potentials coupling. In this case all the model terms are taken into account and dependent on each to other. However, in the decoupling case the coupling terms are not taken into account in the model, *i. e.* the temperature equation is independent from the moisture content and the pressure.

From the figs. 13 and 14, we found that coupling affect the evolution of temperature us the evolution of moisture content. In fact, for temperature evolution, the coupling model contribute to stabilize the material and to keep a lows thermal gradients. Similarly for the moisture content evolution, the coupling in the model gives a good result for the moisture content and which do not let it achieve higher values as in the case of no coupling. These higher values in case of no-coupling disrupt hygrothermal behavior of the wall and that can be analyzed, often by some thermal and hydric degradation.



**Figure 13. Sensitivity of temperature evolution in the time to the model coupling**



**Figure 14. Sensitivity of moisture content evolution in the time to the model coupling**

## Conclusions

This paper presents numerical analysis for the coupled heat and moisture transfer in porous bio based materials. The 2-D was used to describe the heat and moisture migration processes within a porous wooden slab.

The model inputs parameters were evaluated experimentally according to the recognized standards of materials characterization. Therefore, numerous series of hygrothermal calculation were carried out on the 1-D and 2-D configurations in order to assess the dimensionless effect on such wooden material. Two types of boundary conditions were considered and examined. The first are at the material scale where the conditions of wood drying were analyzed. The second type of conditions was on the wall scale, where the building ambience conditions are considered.

In the first step, a comparison between the resolution of model in 1-D and 2-D is established. The effect of 2-D resolution is just shown when we are taken in account the dependence of the boundary conditions on the vertical axis. It concerns the massive surrounding convective condition (wind or inner natural or ventilation flow).

The sensitivity of model is treated in the second step. The simulation results show that the thermal and the vapor affect the moisture migration in the building envelope (wall) by the contribution of the coupled terms in partial differential equations and they affect slightly less the temperature profile.

## Nomenclature

$C_a$ – storage capacity of dry air, [s <sup>2</sup> m <sup>-2</sup> ]	$M$ – liquid molar mass, [kg mol <sup>-1</sup> ]
$c_p$ – heat capacity, [Jkg <sup>-1</sup> K <sup>-1</sup> ]	$P$ – total pressure, [Pa]
$\bar{D}_m$ – moisture diffusion coefficient, [m <sup>2</sup> s <sup>-1</sup> ]	$R$ – ideal gas constant, [Jmol <sup>-1</sup> K <sup>-1</sup> ]
$h_h$ – heat convective exchange coefficient, [Wm <sup>2</sup> K <sup>-1</sup> ]	$S_i$ – water saturation degree, [-]
$h'_h$ – heat convective exchange coefficient varied along to ( $y$ ), [Wm <sup>2</sup> K <sup>-1</sup> ]	$T$ – temperature, [K]
$h_{i,v}$ – latent heat of vaporization, [Jkg <sup>-1</sup> ]	$t$ – time, [s]
$h_m$ – mass convective exchange coefficient, [kgm <sup>2</sup> s <sup>-1</sup> Pa <sup>-1</sup> ]	<i>Greek symbols</i>
$J_a$ – dry air flow density, [kgm <sup>-2</sup> s <sup>-1</sup> ]	$\alpha_p$ – heat convection coefficients due to a water vapor pressure gradient, [m <sup>2</sup> s <sup>-1</sup> ]
$J_l$ – liquid flow density, [kgm <sup>-2</sup> s <sup>-1</sup> ]	$\varepsilon$ – porosity, [-]
$J_v$ – water vapor flow density, [kgm <sup>-2</sup> s <sup>-1</sup> ]	$\theta_i$ – moisture content for the phase $i$ , [-]
$k_i$ – intrinsic permeability of the medium, [m <sup>2</sup> ]	$\lambda$ – thermal conductivity, [Wm <sup>-1</sup> K <sup>-1</sup> ]
$k_p$ – total moisture infiltration, [kgm <sup>-1</sup> s <sup>-1</sup> Pa <sup>-1</sup> ]	$\rho$ – density of material, [kgm <sup>-3</sup> ]
	$\omega$ – moisture content, [kgkg <sup>-1</sup> ]

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