

## 1–2-DIMENSIONAL NUMERICAL ANALYSIS OF HYDROTHERMAL TRANSFERS IN A MAHOGANY WOOD MATERIAL

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### ABSTRACT

*The paper present an investigation on the distribution of heat, and moisture to predict the behavior of massive mahogany considered as bio-based construction 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 mahogany wood 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 material ambience 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:** *Hydrothermal, transfer, mahogany material, variable thermal conductivity, bioresource*

### Nomenclatur

$cp$  – heat capacity, ( $\text{Jkg}^{-1}\text{K}^{-1}$ )  
 $Dm$  – moisture diffusion coefficient, ( $\text{m}^2\text{s}^{-1}$ )  
 $hh$  – heat convective exchange coefficient, ( $\text{Wm}^2\text{K}^{-1}$ )  
 $h'h$  – heat convective exchange coefficient varied along to ( $y$ ), ( $\text{Wm}^2\text{K}^{-1}$ )  
 $hl,v$  – latent heat of vaporization, ( $\text{Jkg}^{-1}$ )  
 $hm$  – mass convective exchange coefficient, ( $\text{kgm}^2\text{s}^{-1}\text{Pa}^{-1}$ )  
 $Jl$  – liquid flow density, ( $\text{kgm}^{-2}\text{s}^{-1}$ )  
 $Jv$  – water vapor flow density, ( $\text{kgm}^{-2}\text{s}^{-1}$ )  
 $kl$  – intrinsic permeability of the medium, ( $\text{m}^2$ )  
 $kp$  – total moisture infiltration, ( $\text{kgm}^{-1}\text{s}^{-1}\text{Pa}^{-1}$ )  
 $M$  – liquid molar mass, ( $\text{kg mol}^{-1}$ )  
 $P$  – total pressure, ( $\text{Pa}$ )  
 $Sl$  – water saturation degree, (–)  
 $T$  – temperature, ( $\text{K}$ )  
 $t$  – time, ( $\text{s}$ )  
 $ap$  – heat convection coefficients due to a water vapor pressure gradient, [ $\text{m}^2\text{s}^{-1}$ ]  
 $\varepsilon$  – porosity, (–)  
 $\theta_i$  – moisture content for the phase  $i$ , (–)  
 $\lambda$  – thermal conductivity, ( $\text{Wm}^{-1}\text{K}^{-1}$ )  
 $\rho$  – density of material, ( $\text{kgm}^{-3}$ )  
 $\omega$  – moisture content, ( $\text{kg kg}^{-1}$ )

## INTRODUCTION

The study of coupled heat and mass transfers in porous media concerns several areas of research such as textile materials (Fan, et al., 2000), wood drying (Ogbonda, 2018), granular materials (Sullivan, and Sabersky 2015.), transport in composite membrane (Imdakh, et al, 2005 ), soils media (Eluozo and Ogbonda, 2015), and thermal insulation (Leskovšek, and Medved ,2011). 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 (Ionescu, et al.2015).

Some authors resolved coupled heat and moisture transfer equations by analytical approaches (Chang, and Weng 2000) and others, by numerical solutions (Vasilyev, et al. 2015.). The comparison between analytical and numerical solution of heat and moisture transfers in hygroscopic porous building materials was summarized in (Abahri et al.2011). Crausse et al. (1996) compared spatial distributions of temperature and moisture in a wall using two models.

Furthermore, Mendes and Philippi (2007) and Mendes et al. (2003) 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.(2008) suggested a thickness optimization of the tested material by using numerical approach. At the experimental level, Talukdar et al.(2008) 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 (2006) 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 (Kameche, *et al.*,2017) where the presence of water vapor is neglected. Other authors consider the diffusion of water vapor but the portion of liquid water was neglected (Thomann, *et al.*2020). Indeed, whatever these potentials which will be adopted, the formulation of moisture transfer equations are equivalent to the model proposed by Funk and Wakili (2008). 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 (Tadeu, A., *et al* 2013.).

In a similar manner (Steehan et al.2010) 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, and moisture transfers are in the literature above. 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 (1975), 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).

Most of construction 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 (Luikov, 1975, Abahri, *et al.* 2011)

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

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

$$\frac{\partial(\theta_l + \theta_v)}{\partial t} + \nabla(J_L + J_V) = 0 \quad 3.$$

By Darcy's low, liquid flow is given by

$$J_l = -k_l \rho (\nabla w - \delta_l \nabla T) - \alpha_l \nabla P \quad 4.$$

Similarly to the liquid flow, the vapor flow moves inside the porous building materials by diffusion. It is described by Luikov(1975) and is governed by Fick's, which considered the effects of both vapor pressure and the air pressure,

$$J_v = -D \nabla \rho_v - \alpha_v \nabla P \quad 5.$$

The vapor density gradient,  $\nabla \rho_v$ , can be written as

$$\nabla \rho_v = \left[ \frac{\partial \rho_v}{\partial w} \right]_T \nabla w + \left[ \frac{\partial \rho_v}{\partial T} \right]_w \nabla T, \quad 6.$$

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

$$\rho c_p \frac{\partial T}{\partial t} = -\nabla \left[ -\lambda \left( \frac{\partial T}{\partial x} u_x + \frac{\partial T}{\partial y} u_y \right) + \delta_t \left( \frac{\partial w}{\partial x} u_x + \frac{\partial w}{\partial y} u_y \right) + k_p \left( \frac{\partial p}{\partial x} u_x + \frac{\partial p}{\partial y} u_y \right) \right] - h_{l,v} \quad 7.$$

### Numerical investigation

To solve the equations associated to the developed model, the MATTLAB 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.* (2011), where to total pressure contribution to the transfer was examined.

Numerical solution for a 2-D case is applied. 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.* (2011). The second condition is at the scale of wall, where the ambiance 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 Ambiance	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

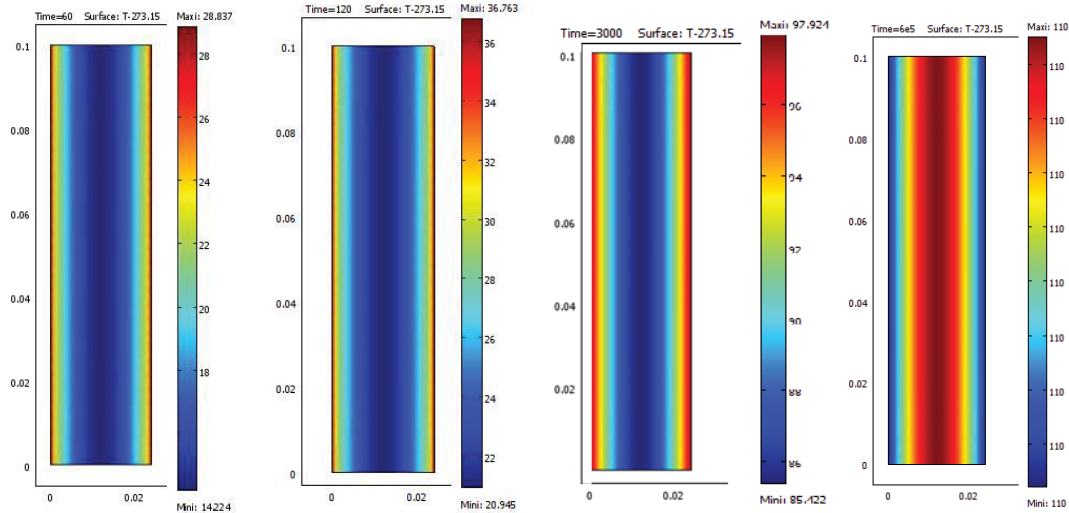
$$\lambda \left. \frac{\partial T(x,t)}{\partial x} \right|_{x=0,e} = h_h [T_{0,t} - T_v] + (1 - \chi) h_m [w_{0,t} - w_v] \quad 8.$$

$$k_m \frac{\partial w(x,t)}{\partial x} = h_m [w_{0,t} - w_v] \quad 9.$$

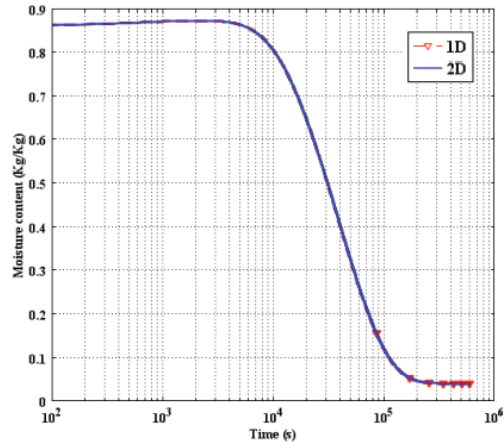
Similar to the experimental underlined in Abahri *et al.*(2016). These initial conditions are as illustrated in tab. 1. The comparisons of 1-D and 2-D numerical results at the center and the surface of the wood slab are illustrated in the figures for several cases of boundary conditions presented in 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 temperature difference between the inner and outer region decreases more and more, until it reaches the equilibrium state of 110 °C.

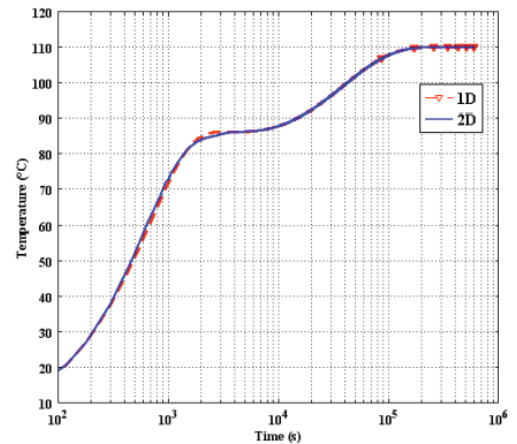
The resolution of the coupling model of heat and moisture transfer in wooden material on 1-D and 2-D, gives almost the same result. In fact, from these figures we note that there is a real coincidence between the temperatures and moisture content profiles. This confrontation is shown for profiles either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



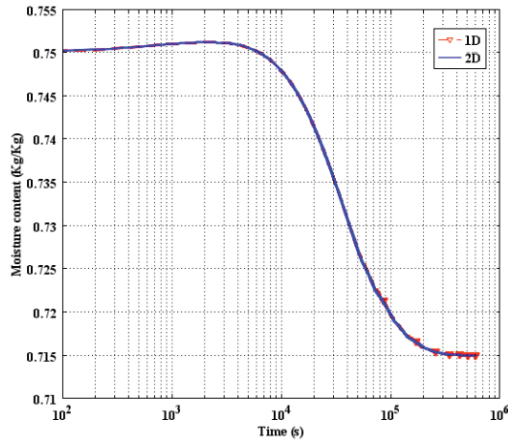
**Figure 2. Distributions of temperature at the surface of material at different times**



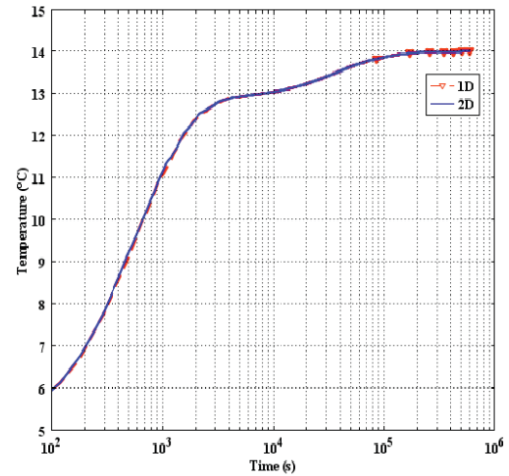
**Figure 3. Moisture content at the center on 1-D and 2-D on wood drying conditions**



**Figure 4. Temperature profile at the center on 1-D and 2-D on wood drying conditions**



**Figure 5. Moisture content at the center on 1-D and 2-D at  $T_0 = 5\text{ }^\circ\text{C}$ ,  $HR = 75\%$**



**Figure 6. Temperature at the center on 1-D and 2-D at  $T_0 = 5\text{ }^\circ\text{C}$ ,  $HR = 75\%$**

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).

Younsi *et al.*(2006) 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:

$$Nu_y = \frac{h_h^i y}{\lambda} \quad 10.$$

The Nusselt and Reynolds numbers are calculated by:

$$Nu_y = 0.332\sqrt{Re},$$

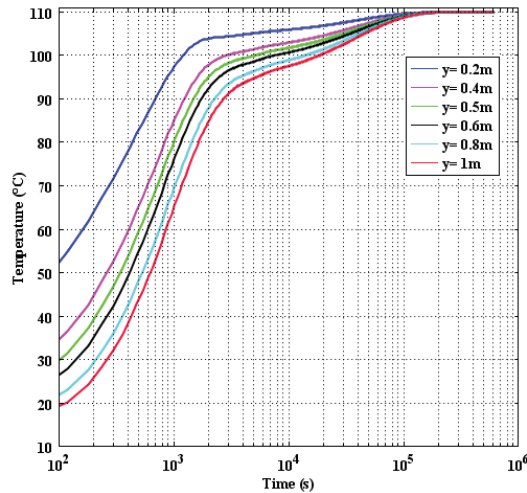
$$Nu_y = \sqrt[3]{Pr}$$

$$Re_y = \frac{\rho v H}{\nu}$$

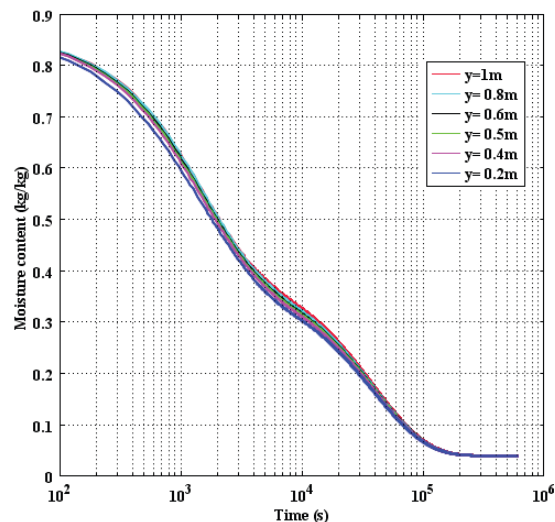
$$h_h^i = \lambda \frac{0.332 \sqrt{\frac{\rho v H^3 \sqrt{Pr}}{\nu}}}{y} \quad 11.$$

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  $110\text{ }^\circ\text{C}$  and the flow of air is considered laminar The boundary condition of mass transfer is as the same given on eq. (8). The temperature and moisture content distribution function of the vertical position (material height) are presented in figs. 7 and 8, respectively

$$\lambda \frac{\partial T(x,t)}{\partial x} \Big|_{x=0,e} = h_h [T_{0,t} - T_v] + (1 - \chi) h_m [w_{0,t} - w_v] \quad 12.$$



**Figure 7. Variation of temperature profiles along the vertical (y) axis**



**Figure 8. Variation of moisture content profiles along the vertical (y) axis**

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 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 . 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 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 model to the thermal conductivity and figs. 10 and 11 represent the sensibility of model to the vapor diffusion coefficient

$$\left\{ \begin{array}{l} \lambda = \lambda_0 + 0.475\theta \\ D_m = D_0(-18.14 \cdot 10^{-1} w + 1) \end{array} \right. \text{ where } \left\{ \begin{array}{l} \lambda_0 = 0.107W/mK \\ \theta = \frac{\rho}{\rho_{eu}} \omega \\ D_0 = 2.16 \cdot 10^{-4} m^2/s \end{array} \right.$$

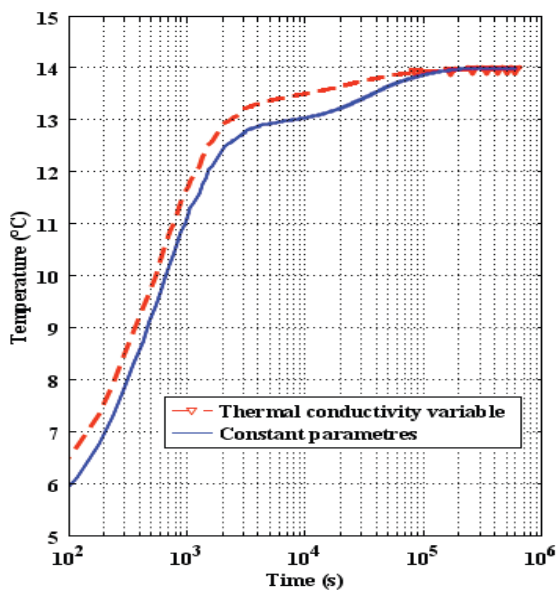
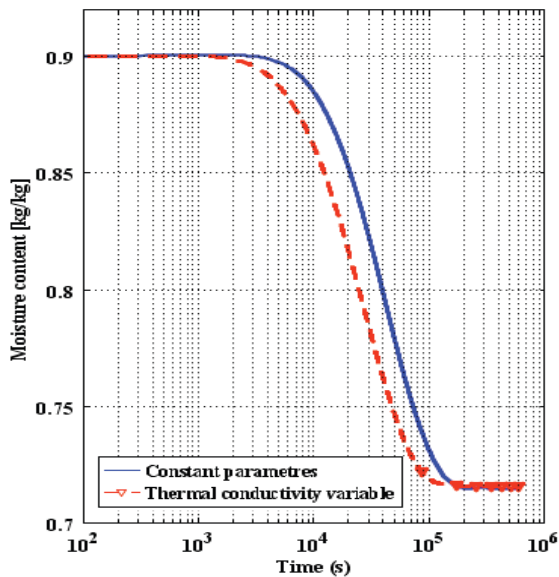


Figure 9. Sensitivity of temperature profile to the thermal conductivity



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

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<sup>3</sup> 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, the impact of coupling on the prediction of hygrothermal transfers evaluated. The hygrothermal behavior when considering the model driving potentials coupling is discussed. 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, it is 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.

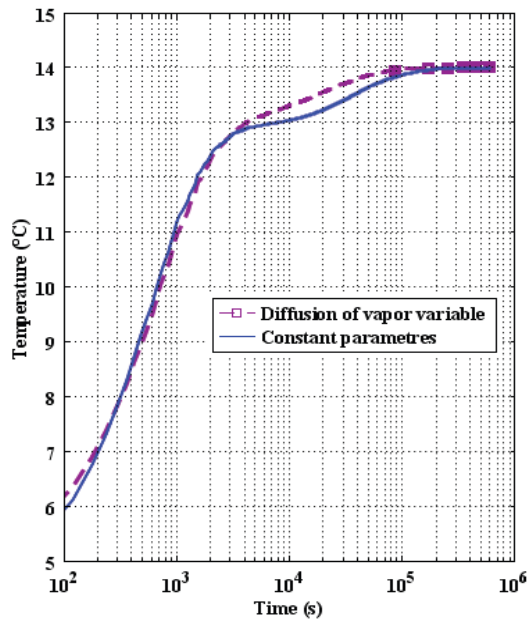


Figure 11. Sensitivity of temperature profile to the vapor diffusion coefficient

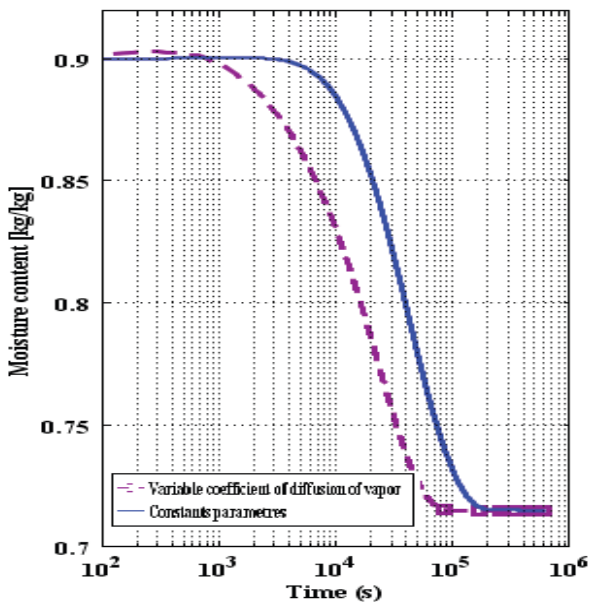


Figure 12. Sensitivity of moisture content profile to the vapor diffusion coefficient

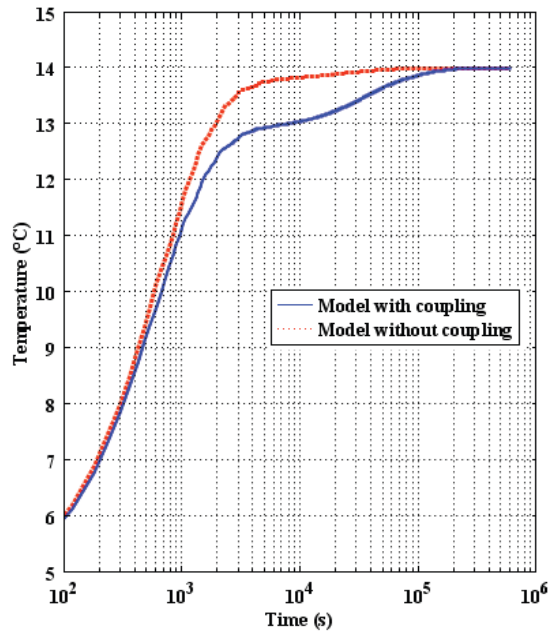
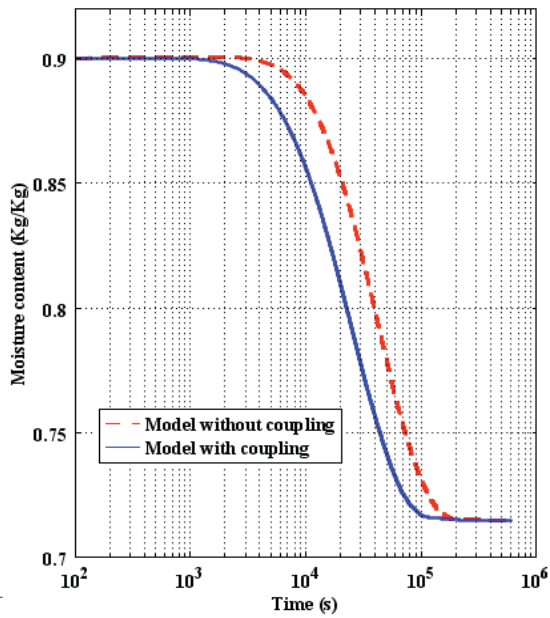


Figure 13. Sensitivity of temperature evolution in the time to the model coupling



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

## CONCLUSIONS

2 dimensional 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 ambiance 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.

## REFERENCES

- (1) Abahri, K., *et al.* (2016), Sensitivity Analyses of Convective and Diffusive Driving Potentials on Combined Heat Air and Mass Transfer in Hygroscopic Materials, *Numerical Heat Transfer, Part A: Applications*, 69, (10) 1079-1091
- (2) Abahri, K., *et al.*, (2011), Contribution to Analytical and Numerical Study of Combined Heat and Moisture Transfers in Porous Building Materials, *Building and Environment*, 46 (7). 1354-1360
- (3) Al-Sanea, S. A., *et al.* (2005), Effect of Electricity Tariff on the Optimum Insulation-Thickness in Building Walls as Determined by a Dynamic Heat-Transfer Model, *Applied Energy*, 82 (4) 313-330
- (4) Chang, W. J., Weng, C. I., (2000), An Analytical Solution to Coupled Heat and Moisture Diffusion Transfer in Porous Materials, *International Journal of Heat and Mass Transfer*, 43 (19), 3621-3632
- (5) Crausse, P., *et al.* (1996), Effect of Hysteresis Phenomena on the Hydric Properties of Porous Materials: Comparison of Two Simulation Models of the Thermohydric Behavior of Building Walls, *Revue Generale de Thermique*, 35 (410) 95-106
- (6) Fan, J., *et al.*, (2000) Heat and Moisture Transfer with Sorption and Condensation in Porous Clothing Assemblies and Numerical Simulation, *International Journal of Heat and Mass Transfer*, 43 (16) 2989-3000

- (7) Funk, M., and Wakili, K. G., (2008), Driving Potentials of Heat and Mass Transport in Porous Building Materials: A Comparison between General Linear, Thermodynamic and Micromechanical Derivation Schemes, *Transport in Porous Media*, 72 (3). 273-294
- (8) Hagentoft, C. E., (2012) HAMSTAD-Final Report: Methodology of HAM-Modeling, *Report R-02*, 8, Chalmers University of Technology, Gothenburg,
- (9) Imdakm, A. O., Matsuura, T., (2005), Simulation of Heat and Mass Transfer in Direct Contact Membrane Distillation (MD): The Effect of Membrane Physical Properties, *Journal of Membrane Science*, 262 (1). 117-128
- (10) Ionescu, C., *et al.*, (2015), The Historical Evolution of the Energy Efficient Buildings, *Renewable and Sustainable Energy Reviews*, 49 , 243-253
- (11) Kameche, Z. A., *et al.*, (2014), Assessment of Liquid Water and Gas Permeabilities of Partially Saturated Ordinary Concrete, *Construction and Building Materials*, 65, 551-565
- (12) Kunzel, H. M., (1995) *Simultaneous Heat and Moisture Transport in Building Components, One- and Two-Dimensional Calculation Using Simple Parameters*, IRB-Verlag, Stuttgart, Germany
- (13) Leskovšek, U., Medved, S. (2011), Heat and Moisture Transfer in Fibrous Thermal Insulation with Tight Boundaries and a Dynamical Boundary Temperature, *International Journal of Heat and Mass Transfer*, 54 (19-20,) 4333-4340
- (14) Luikov, A. V., (1975), Systems of Differential Equations of Heat and Mass Transfer in Capillary-Porous Bodies (Review), *International Journal of Heat and Mass Transfer*, 18 ( 1) 1-14
- (15) Mendes, N., Philippi, P. C., A Method for Predicting Heat and Moisture Transfer Through Multilayered Walls Based on Temperature and Moisture Content Gradients, *International Journal of Heat and Mass Transfer*, 48 (2005), 1, pp. 37-51
- (16) Mendes, N., *et al.*, (2003), Moisture Effects on Conduction Loads, *Energy and Buildings*, 35 (7) 631-644
- (17) Osanyintola, O. F., Simonson, C. J., (2006), Moisture Buffering Capacity of Hygroscopic Building Materials: Experimental Facilities and Energy Impact, *Energy and Buildings*, 38 (10). 1270-1282
- (18) Philip, J. R., De Vries, D. A., Moisture Movement in Porous Materials under Temperature Gradients, *Eos, Transactions American Geophysical Union*, 38 (1957), 2, pp. 222-232
- (19) Plumb, O. A., *et al.*, (1985), Heat and Mass Ttransfer in Wood During Drying, *International Journal of Heat and Mass Transfer*, 28 (9) 1669-1678

- (20) Qin, M., *et al.*, (2006), An Analytical Method to Calculate the Coupled Heat and Moisture Transfer in Building Materials, *International Communications in Heat and Mass Transfer*, 33 (1) 39-48
- (21) Steeman, M., *et al.*, (2010), Impact of Whole-Building Hygrothermal Modelling on the Assessment of Indoor Climate in a Library Building, *Building and Environment*, 45 (7) 1641-1652
- (21) Steeman, M., *et al.*, (2010), Impact of Whole-Building Hygrothermal Modelling on the Assessment of Indoor Climate in a Library Building, *Building and Environment*, 45 (7) 1641-1652
- (22) Sullivan, W. N. and Sabersky, R. H., (1975), Heat Transfer to Flowing Granular Media, *International Journal of Heat and Mass Transfer*, 18 (1) 97-107
- (23) Talukdar, P., *et al.* (2007), An Experimental Data Set for Benchmarking 1-D, Transient Heat and Moisture Transfer Models of Hygroscopic Building Materials, Part I: Experimental Facility and Material Property Data, *International Journal of Heat and Mass Transfer*, 50 (23) 4527-4539
- (24) Tadeu, A., *et al.* (2003), Steady-State Moisture Diffusion in Curved Walls, in the Absence of Condensate Flow, Via the BEM: A Practical Civil Engineering Approach (Glaser Method), *Building and Environment*, 38, (5) 677-688
- (25) Thomann, F. S., *et al.*, (2015) A Hygrothermal Modelling Approach to Water Vapour Sorption Isotherm Design for Mesoporous Humidity Buffers, *Microporous and Mesoporous Materials*, 211, 113-123
- (26) Van Schijndel, A. W. M. (2013), Modeling and Solving Building Physics Problems with FemLab, *Building and Environment*, 38, (2) 319-327
- (27) Vasilyev, G. P., *et al.*, (2015), Simulation of Heat and Moisture Transfer in a Multiplex Structure, *Energy and Buildings*, 86, 803-807
- (28) Younsi, R., *et al.* (2006), Three-Dimensional Simulation of Heat and Moisture Transfer in Wood, *Applied Thermal Engineering*, 6 (11). 1274-1285