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Numerical Investigation of Hygrothermal Behavior on Porous Building Materials

Faiza Mnasri, Kamilia Abahri, Mohammed El Ganaoui, Slimane Gabsi

Abstract**—**Most of the 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. Thus, 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. This study suggests to resolve a hygrothermal mathematical model of heat and mass transfers in different porous building materials by a numerical investigation. Thereby, the evolution of temperature and moisture content fields has been processed. So, numerous series of hygrothermal calculation on several cases of wall are exposed. Firstly, a case of monolayer wall of massive wood has been treated. In this part, we have compared the numerical solution of the model on one and two dimensions and the effect of dimensional space has been evaluated. In the second case, three building materials (concrete, wood fiberboard and wooden insulation) are tested separately with the same boundary conditions and their hygrothermal behavior are compared. The evaluation of the exchange of heat and air at the interface between the wall and the interior ambiance is carried.

Keywords**—**Building materials, heat transfer, moisture diffusion, numerical solution.

I. Introduction

THE study of coupled heat and mass transfers in porous media is a process which occurs frequently in many engineering applications, such as oil extraction [1], textile materials [2], wood drying [3], granular materials [4], transport in composite membrane [5], capillary-porous bodies [6] and building materials [7]. The resolution of this type of models can be carried out by different investigations. Chang et al. [8] have resolved a coupled model of heat and moisture transfers by an analytical approach. Some other authors used numerical solutions [9], [10]. The typical heat and mass transfer model is governed by Luikov equations [12], which takes into account the terms of mass, air and the total pressure gradient.

At the scale of building, three modes of transfer are combined. In this context, several researches have been devoted to study the mode of coupled heat and moisture transfer [13], [14]. Many models have taken account of the term moisture content from water [15], [16], where the presence of water vapor is neglected. Thomann et al. [17] have considered the diffusion of water vapor but the portion of liquid water was negligible. Thus, a first study which described the evolution of moisture in building materials has been processed by the Glaser-method [18]. After that, Mendes et al. [19] studied the capacity of porous hygroscopic materials to dampen the indoor humidity variations through moisture exchange [20]. Bio-based materials, which have recently appeared as a serious candidates in the search of sustainable and energy-efficient materials, have typically a high buffer performance [21], [22]. However, in building materials, heat and moisture models needed to be increased the accuracy of heat and moisture transfer calculation between outdoor and indoor environments in order to create a better inside thermal comfort.

In this study, we presented a numerical investigation for a model predicted heat transfer, air transport and moisture diffusion in porous building materials. The resolution has been carried by the finite element method. The study suggests different categories of building materials (concrete, wood fiberboard and wooden insulation). Input parameters are evaluated experimentally using continuous driving potentials and considerable constants for all the tests discussed. The object is to evaluate the hygrothermal behavior of these different materials, which are submitted to the same boundary conditions. Initially, the temperature and relative humidity of the wall are at 20 °C and 50% respectively.

II. Problem Formulation

A. Description of Physical Problem

A typical model of heat and moisture transfers in porous building materials is presented. Initially, a wood slab material is submitted at uniform temperature and moisture content. The boundaries are in contact with the hot surrounding gas, thus resulting in a convection boundary condition for both the temperature and moisture potential as shown in Fig. 1.

Physical phenomena coupled heat and moisture transfers are the result of the simultaneous transport of gas and liquid phases in porous medium. They are expressed by combinations of the phenomenological laws of Darcy and Fick [11]. The heat flow results in a variation of the gradient of temperature and moisture transfers. It is done via the gas phase containing air and water vapor. Molecular diffusion reflected the movement of the water vapor which appears in moist air

M. Faiza is with the University of Lorraine, IUT of Longwy, 54400 Cosnes et Romain, France (phone: +33 6 58 52 33 59; e-mail: faiza.mnasri@univ-lorraine.fr).

A. Kamilia is with the University of Paris-Sacly, ENS of Cachan, 61, avenue du Président Wilson, 94235 Cachan Cedex, France (e-mail: kamilia.abahri@lmt.ens-cachan.fr).

EL. Mohammed is with University of Lorraine, IUT of Longwy, 54400 Cosnes et Romain, France (e-mail: mohammed.el-ganaoui@univ-lorraine.fr).

G. Slimane, is with Unit of Research: Environment, Catalysis and Analysis Processes, National SchoolEngineers of Gabès, Street Omar Ibn ElKhattab, 6029, Gabès, Tunisia (e-mail: slimane.gabsi53@gmail.com).

under the effect of a difference in the concentration of water vapor or a partial pressure gradient of the vapor.

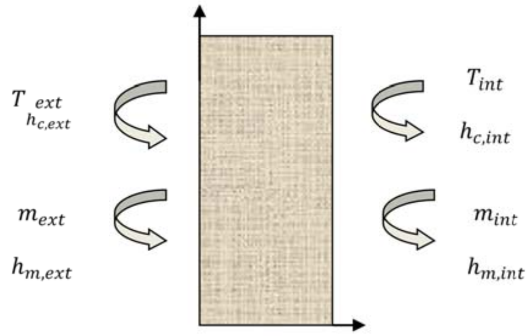

Fig. 1 Description of problem

In this study, we present, at the first, a comparison of numerical resolution in one and two dimensions. This test case aims to evaluate the effect of dimensional space into the numerical solution of hygrothermal model. After this, we continued the modeling in two-dimension space, in the following of the study, for different kinds of building materials.

B. Assumptions

The model is based onto the following set of assumptions:

- The material is considered homogeneous;
- The thermo-physical properties are assumed constant;
- The local thermodynamic equilibrium between the fluid and the porous matrix is supposed;
- The initials conditions of the moisture content and temperature distribution in the wall are uniform;
- The heat transfer by radiation is negligible;
- The withdrawal and the degradation of the material have been neglected.

C. Mathematical Formulation

The constitutive model describing two-dimensional heat and moisture transfer for building material are given by [18] as:

$$\rho C_p \frac{\partial T}{\partial t} - \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = C_m \rho(\varepsilon h_{lv} + H)\frac{\partial m}{\partial t} \tag{1}$$

$$\rho C_m \frac{\partial m}{\partial t} = D_m\left[\left(\frac{\partial^2 m}{\partial x^2} + \frac{\partial^2 m}{\partial y^2}\right) + \delta\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)\right] \tag{2}$$

T[K] is the temperature, m[°M] is the moisture potential, t[s] is time, x[m] and y[m] are the location coordinates, C_p [J/(kg.K)] and C_m [kg/(kg.°M)] are heat and moisture capacities of the medium, λ [W/(m.K)] is the thermal conductivity of material, and D_m [kg/(m.s.°M)] is the moisture diffusion coefficient, ρ [kg/m3] is the dry solid density, ε is the ratio of vapor diffusion coefficient to coefficient of total moisture diffusion, H[J/kg] is the latent heat, δ [kg moisture/(kg.K)] is the thermal gradient coefficient and h_{lv} [kJ/kg] is the heat of phase change.

D. Boundary Conditions

Initially the wall is subjected to an initial temperature $T_0 = 20°C$ with an initial relative humidity $HR_0 = 50\%$. It is submitted to boundary conditions type Dirichlet, which represented the externals climatic excitations and the interior ambience in the envelope. These conditions are presented as in Table I.

TABLE I
BOUNDARY CONDITIONS

$T(x=0, y, t) = T_{int}$	$T_{int} = 23°C$
$T(x=e, y, t) = T_{ext}$	$T_{ext} = 5°C$
$\omega(x=0\ , y, t) = m_{int}$	$\omega_{int} = 45°M$
$\omega(x=e\ , y, t) = m_{ext}$	$\omega_{ext} = 98°M$

III. RESULTS AND DISCUSSIONS

To solve the equations associated to the developed model, the COMSOL Multiphysics software was chosen. The resolution of partial differential equations (EDP) is done by the finite element method.

Firstly, a comparison of 1D and 2D numerical results at the center and at the surface of the wood slab is carried in order to evaluate the effect of dimension space in numerical solution. These comparisons are illustrated in Figs. 2 and 3. These figures show that there is no spatial variability between the evolution of temperature and moisture content in the material on one and two dimensions 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 conditions.

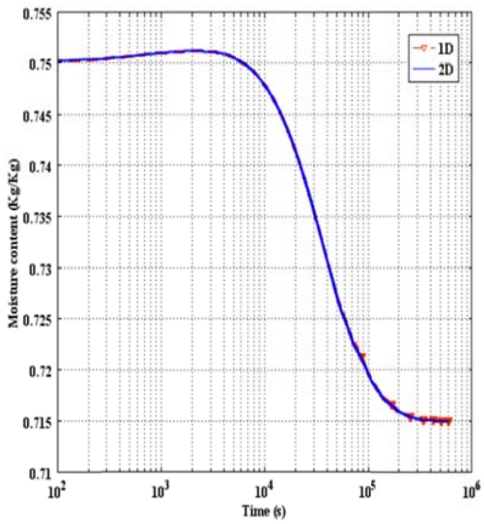

Fig. 2 Moisture content in wood building material on 1D and 2D model

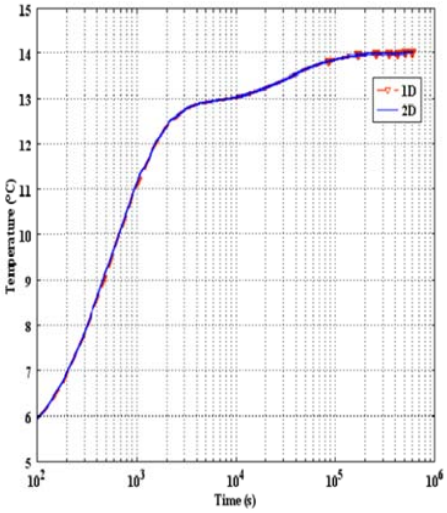

Fig. 3 Temperature at the center on 1D and 2D model

In the Figs. 4 and 5, the temperature and moisture distributions are presented. The visualizations show a good hygrothermal response of wood material that has translated well insulated to keep a suitable internal environment with the initial conditions.

Figs. 6 and 7 represented a comparison between the temperature profile and water content at the surface and at the center of the wall. A big difference is noted between these hygrothermal behaviors.

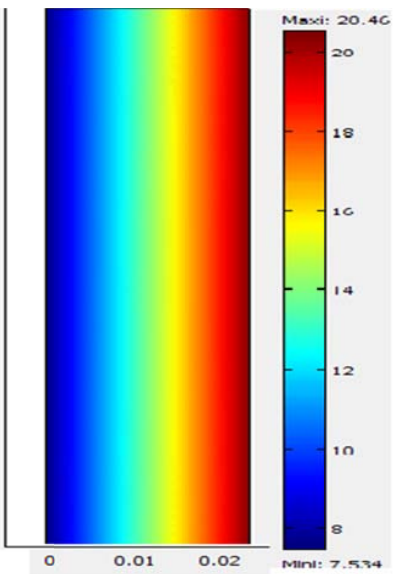

Fig. 4 Distribution of temperature in the building wood material

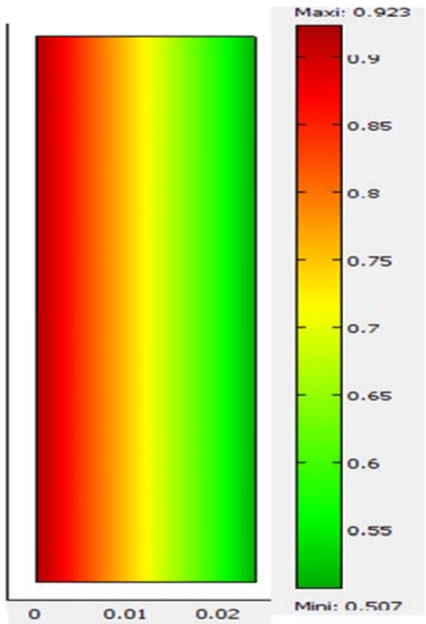

Fig. 5 Distribution of moisture content in the building wood material

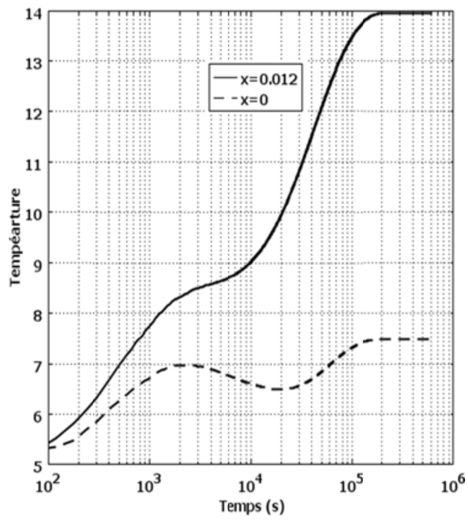

Fig. 6 Temperature at the center and at the surface of the wood building material

We can note from Figs. 5 and 6 that the temperature and moisture profiles depend heavily on the position in the wall. The point at the surface shows an important hygrothermal reponses than the point at the center. That is explained by the exterior conditions imposed at the surface of the wall.

In the following of this work, three materials were tested in same climatic conditions of temperature and relative humidity. The objective is to compare the hygrothermal responses of these three hygroscopic materials by numerical simulation. These materials are used in building construction, which are a concrete material, a wood fiberboard and a material of massive wood.

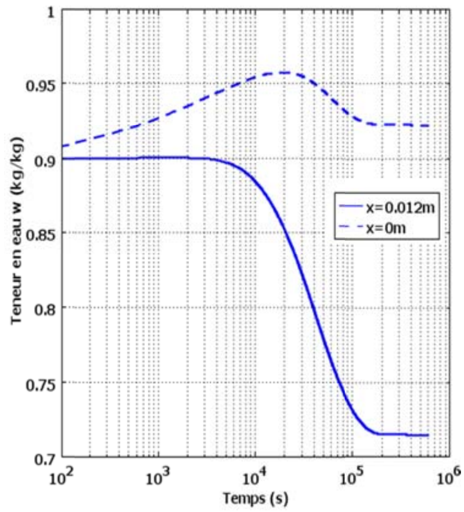

Fig. 7 Moisture content at the center and at the surface of the wood building material

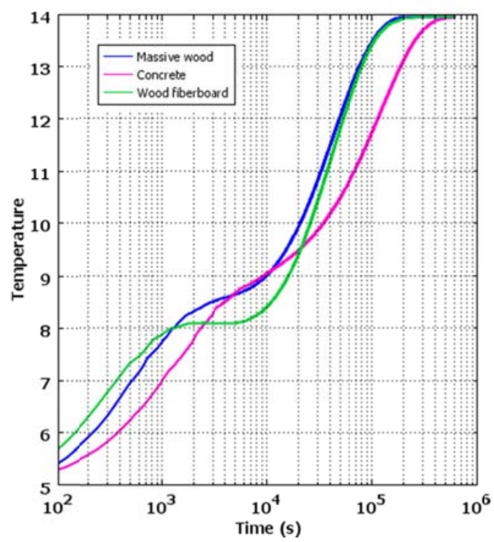

Fig. 8 Profiles of temperature for three different building materials in a same boundary conditions

Figs. 7 and 8 show the temperature profiles which correspond to the thermal behavior of the three materials proposed, previously. Kinetic temperature of concrete is faster than wood materials. This is explained by its thermal conductivity which is higher compared to the two other materials. Thus, bio-based materials have a better thermal resistance in the wall. However, for the hydric response, wood fiberboard has the best hydric regulation.

IV. Conclusion

This paper presents a numerical model for the coupled heat and moisture transfer in porous building materials. The object was to evaluate and to analyze the hygrothermal behavior of these materials. The evolution of temperature and the content moisture fields have been processed in two cases on dimension for a wood building material. The analysis of the effect of dimensions space shows that there is no spatial variability between the evolution of temperature and moisture content fields in the material. The second part has shown that bio-based building materials had a better hygrothermal behavior compared to a concrete material.

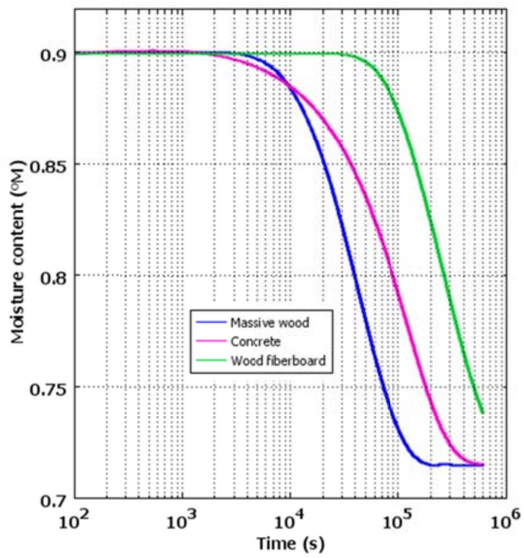

Fig. 9 Profiles of moisture content for three different building materials in a same boundary conditions

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