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Response surface analysis of the dimensionless heat and mass transfer parameters of Medium Density Fiberboard

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ABSTRACT

The development of predictive models to simulate heat and mass transfers in building envelopes is crucial for better energetic and environmental design of buildings. The models in the literature are based on heat and mass balance equations. Many of these use constant or briefly described input data. They use a dimensional formulation where the mechanisms involved are difficult to analyze. This article presents a dimensional analysis of Heat, Air and Moisture (HAM) transfer model where the thermophysical properties of the materials are taken as a function of the state variables describing the system. The analysis of the magnitude of the dimensionless numbers of the model and their response surface led to the estimation of the mechanisms governing HAM transfers for Medium Density Fiberboard. The methodology presented in this study can be very useful in the design phase since it allows the direct comparison of different families of wall elements.

1. Introduction

Building sector is responsible in France for more than 43% of energy consumption and 23% of greenhouse gas emissions [1]. It represents an important source of energy saving and greenhouse gas emission reduction. In that context, building thermal regulations are constantly evolving limiting energy consumption [2]. Much research has been carried out in recent years on buildings airtightness and thermal insulation as efficient ways for reducing energy losses. For this typology of buildings, pathologies due to the excess of moisture and discomfort in summer give rise for concern and much remains to be learnt on the complex behavior of that constructions. The development of sensitive predictive tools and an analysis methodology have become critical issue for controlling energy consumption and improving indoor air quality.

Building envelopes are subjected to thermal and hydric loading. Induced heat and mass transfers are strongly coupled in the case of some envelope elements, especially biosourced materials [3,4]. Indeed, kinetic constants such as the moisture diffusion coefficient and mass transfer phenomenon by mean of thermal-diffusion directly depend on the temperature and its gradient. Conversely, mass transfer impacts on heat transfer through the contribution of conduction in the liquid phase [5], liquid/vapor phase change and advection phenomenon. Thus, to control the energy behavior of building and its envelope, and to reduce the risk of condensation and its impacts on building and its occupants, it is important to develop design tools and methods capable of taking this complexity into account.

The main moisture transfer mechanisms in porous construction materials are moisture diffusion, capillary transfer, advection or the combination of all three. The importance of one mechanism in relation to the other depends on the hydric state of the material. This is closely linked to adsorption and retention phenomena characterized by sorption/desorption isotherms and water retention curves. At present, building energy simulation tools generally focus on predicting thermal energy consumption and simplify the effects of humidity observable in hygroscopic materials. The impact of the latter is not negligible.

An approach adopted for studying transfer mechanisms and their competition is dimensionless analysis. This is used to study a class of similar dimensional problems and the possible simplifications of models, taking into account dimensionless numbers resulting from the development of the dimensionless model. This approach is used in particular in fluid mechanics, mathematical and numerical methods to solve physical problems.

Regarding transfers in porous materials, mention can be made on the works of Younsi et al. [6] who proposed a parametric study on dimensionless numbers in the case of the industrial wood drying process. Pandey et al. [7] and Qin et al. [8] chose a dimensionless formulation in an analytical solution to Luikov's model [9] in a linear case without advection. Dantas et al. proposed a hybrid

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Nomenclature

Latin symbols

a_i	thermal or mass diffusivity [m^2/s]
Bi	Biot number [–]
c_p^i	specific heat capacity of component i [J/(kg·K)]
D	diffusion coefficient [m^2/s]
h	convection exchange coefficient
$\vec{j}_i$	i flux density
K	mass conductivity [s]
Ko	Kossovitch number [–]
L_{vl}	latent heat [J/kg]
Lu	Luikov number [–]
$\vec{n}$	normal to boundary s
p_i	pressure of fluid i [Pa]
Pe	Peclet number [–]
Pn	Posnov number [–]
r_i	specific constant of component i [J/(kg·K)]
rh	relative humidity [–]
T	temperature [K]

Greek symbols

β	ratio r_v/r_a : 0.604 [–]
λ	thermal conductivity [W/(m·K)]
ρ_i	interinsic concentration of i [kg/m^3]
ρ^i	effective concentration of i [kg/m^3]

Subscripts and Superscripts

a	dry air
amb	ambient air
dif	diffusion
g	gas ($v+a$)
l	liquid
m	moisture
q	heat
ref	reference
s	boundary
sat	saturation
v	water vapor
$*$	effective

model (numerical-analytical) to solve the same problem. Dimensional analysis was also privileged for performing sensitivity studies and for identifying parameters in a class of problems [10–12].

Following this approach, the purpose of our study is to analyze the interactions of different transfer mechanisms. This entails integrating in particular the effect of advection, including for heat transfer, while considering the nonlinear nature of transfers and their couplings. This approach is intended for buildings. The objective comprises two steps:

1. The dimensionless formulation of a Heat, Air and Moisture (HAM) model incorporating the main mechanisms involved in the nonlinear case and the identification of the key dimensionless numbers determining the hygrothermal behavior of an element of the envelope.
2. Estimation of dimensionless numbers for the case of a Medium Density Fiberboard (MDF).
3. An analysis bearing on the global transfer properties of a very hygroscopic material and on the subsequent dimensionless numbers evaluated through their response surfaces in a range of temperature, moisture and pressure characteristic of building. The transfer and storage properties are taken as variable which allows taking more precise account of the interactions involved during the transfer.

2. Mathematical modeling and dimensionless formulation

For a building application, the phenomenon of advection through porous materials has received only little attention in the literature, which has most usually focused on the effect on moisture transfer without considering its impact on heat transfer. The model presented in this article permits predicting hygrothermal transfers including advection effects. It is based on the works of Luikov [9] and is built on the basis of energy, moisture (in liquid and vapor form) and dry air conservation equations. The densities of heat and mass fluxes (Eqs. (1)–(4)) are expressed using constitutive Fourier, Fick and Darcy laws:

$$\vec{j}_q^{\,\mathrm{dif}} = -\lambda^* \vec{\nabla} T \tag{1}$$

$$\vec{j}_v = -D_v^* \rho_g \vec{\nabla}\left(\frac{\rho_v}{\rho_g}\right) - \frac{\rho_v}{\rho_g} K_g^* \vec{\nabla} p_g \tag{2}$$

$$\vec{j}_a = -\frac{\rho_a}{\rho_g} K_g^* \vec{\nabla} p_g \tag{3}$$

$$\vec{j}_l = -K_l^* \vec{\nabla} p_l \tag{4}$$

The mass balance equations are given by the expressions (5) and (6). The moisture balance results from the sum of liquid water and water vapor conservation equations with as transfer phenomena diffusion under gradient of concentration, advection under total pressure gradient and liquid water movements by capillarity:

$$\frac{\partial \rho^m}{\partial t} = -\vec{\nabla} \cdot (\vec{j}_l + \vec{j}_v) \tag{5}$$

$$\frac{\partial \rho^a}{\partial t} = -\vec{\nabla} \cdot (\vec{j}_a - \vec{j}_v^{\,\mathrm{dif}}) \tag{6}$$

The energy conservation equation (Eq. (7)) is obtained from an enthalpy balance by expressing the enthalpies of the different phases and elements constituting the system. The hypothesis of local equilibrium is chosen with the result that the temperatures between the different phases and constituents are the same:

$$\rho_s c_p^* \frac{\partial T}{\partial t} + \left[(c_p^l \vec{j}_l + c_p^v \vec{j}_v + c_p^a \vec{j}_a) \cdot \vec{\nabla}\right] T = -\vec{\nabla} \cdot \vec{j}_q^{\,\mathrm{dif}} - L_{vl} \vec{\nabla} \cdot \vec{j}_v \tag{7}$$

The local equilibrium hypothesis is acceptable because the kinetics of adsorption, phase change and sensitive exchange between fluid and solid phases are much faster than the kinetics of diffusion and convection in the fluid phases. This hypothesis is widely used to describe hygrothermal transfers in building materials [9,13–15,4].

Regarding the boundary conditions (Eqs. (8) and (9)), we consider a sensible and latent convective hygrothermal transfer:

$$(\vec{j}_v + \vec{j}_l) \cdot \vec{n}\,|_s = h_m\,(\rho_v^s - \rho_v^{\mathrm{amb}}) \tag{8}$$

$$\vec{j}_q^{\,\mathrm{dif}} \cdot \vec{n}\,|_s = h_q\,(T^s - T^{\mathrm{amb}}) + L_{vl}\,(1-\sigma_v)\,h_m\,(\rho_v^s - \rho_v^{\mathrm{amb}}) \tag{9}$$

The potentials chosen to describe the transfer are temperature T, vapor concentration ρ_v and air pressure p_g. Using the ideal gas and Dalton's laws, the definition of capillary pressure and Kelvins equation (linking capillary pressure to relative humidity), it is possible to transform Eqs. (2)–(4) to express them as a function of the potentials chosen. Balance equations become: