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Development of a numerical model of heat and mass transfer in biosourced materials

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ABSTRACT

ABSTRACT: Biosourced materials are renewable and can be used as thermal insulation throughout the building envelope. In this work, a numerical modeling of the coupled heat and mass transfer through these porous biosourced materials has been carried out in order to determine the temperature and humidity profiles circulating within them. The system of balance equations was highlighted and discretised in space and time. Programming, followed by numerical simulations on several reference materials, was carried out on the PYTHON software. During the programming, semi-explicit Euler methods, followed by splitting or fractional pitch methods, were used. Temperature and relative humidity profiles were presented for the different reference materials tested. The results show that the numerical produced is stable and convergent. These results were compared with those of various authors in the literature in order to validate them.

Keywords: Temperature; humidity; porous biosourced materials; coupled heat and mass transfer; semi-explicit; splitting method.

1.0 INTRODUCTION

Biosourced materials are a category of materials derived from biomass. These materials are renewable and can be used as thermal insulation throughout the building envelope. Coupled heat and mass transfer through biosourced materials have been addressed numerically in the literature theoretical models found in the works of Vries, 1958 [1], Tariku et al., 2010 [2], Qin et al., 2009 [3,4], Philip et al., 1957 [5,6], Künzel, 1995 [7], Oumé-ziane, 2013 [8], Abahri et al., 2011 [9], Moissette et al., 2009 [10], Zaknoune et al., 2012 [11], Rafidiarison et al., 2015 [12], Piot, 2009 [13] and Traoré, 2011 [14]. Different types of biosourced can be used [1,2,7,8,15].

To obtain the system of equations governing coupled heat and mass transfer, the law of continuity is applied for the moisture flows as well as for the heat flow within the wall of biosourced materials [9]. For moisture, this law indicates that the variation of moisture in a volume element of the material is determined by the divergence of moisture flow densities across the surface of the material. Similarly, the enthalpy variation in a volume element is determined by the divergence of heat flux densities across the surface of the material.

Their buildings in Haïti are built without solar protection. In this country, the is a high average sunshine rate of value 6 kW/m2 day, a high average temperature of 26 °C and an average relative humidity of 76 % throughout the year [16]. A high use of air conditioning and mechanical ventilation in some buildings is done daily. It is therefore necessary to protect and improve the thermal performance of the building envelope in a tropical climate by using biosourced materials.

The objective of this paper is to develop a numerical model to study heat and mass transfer in biosourced materials produced in a humid tropical climate. These materials can be used as thermal insulation in buildings in this climate.

2.0 STUDY OF TRANSFER PHENOMENA FOR AN UNDERSTANDING OF HEAT AND MASS IN BIOSOURCED MATERIALS BY FINE MODELING

2.1 System of balance equations

In order to show the system of equations balance through a porous wall, it is considered to be composed of homogeneous and isotropic biosourced insulating materials, with a thickness "e" negligible compared to its length L (L >> e) represented in Figure 1. Other hypotheses considered are air velocity is constant and air flow is laminar. The system of equations for the balance of coupled moisture and temperature transfers can be approximated in one dimension (1D). In this the other Cartesian components in the directions (y and z) are negligible. The system can be written as follows [8,15] :

$$\psi_T \frac{\partial T}{\partial t} + \psi_b \frac{\partial b}{\partial t} = \nabla\left[\delta_{p,mat}\nabla\left(bp_{v,sat}\right)\right] - \rho_a \cdot 0{,}622\frac{v_a}{p_0}\cdot\nabla\left[bp_{v,sat}\right] + \nabla\left[D_l^b\nabla b\right] + \nabla\left[D_l^T\nabla T\right]$$

$$\begin{aligned}&\left[\rho_0 C_{p,0} + C_{p,l}\left(T\psi_T + w - T_{ref}\psi_T\right)\right]\cdot\frac{\partial T}{\partial t} + C_{p,l}\psi_b\cdot\left(T - T_{ref}\right)\cdot\frac{\partial b}{\partial t} = \nabla\left[\lambda\nabla T\right] - C_{p,a}\rho_a v_a\nabla T\\ &+ \rho_a\cdot 0{,}622\frac{v_a}{p_0}\left(C_{p,v}T_{ref} - L_v\right)\cdot\nabla\left(bp_{v,sat}\right) - C_{p,v}\rho_a v_a\cdot\frac{0{,}622}{p_0}\nabla\left(bp_{v,sat}T\right) + \left(L_v - C_{p,v}T_{ref}\right)\cdot\nabla\left[\delta_{p,mat}\nabla\left(bp_{v,sat}\right)\right]\\ &+ C_{p,v}\nabla\left[T\delta_{p,mat}\nabla\left(bp_{v,sat}\right)\right] + C_{p,l}\nabla\left[TD_l^b\nabla b\right] + C_{p,l}\nabla\left[TD_l^T\nabla T\right] - C_{p,l}T_{ref}\nabla\left[D_l^b\nabla b\right] - C_{p,l}T_{ref}\nabla\left[D_l^T\nabla T\right]\end{aligned}$$

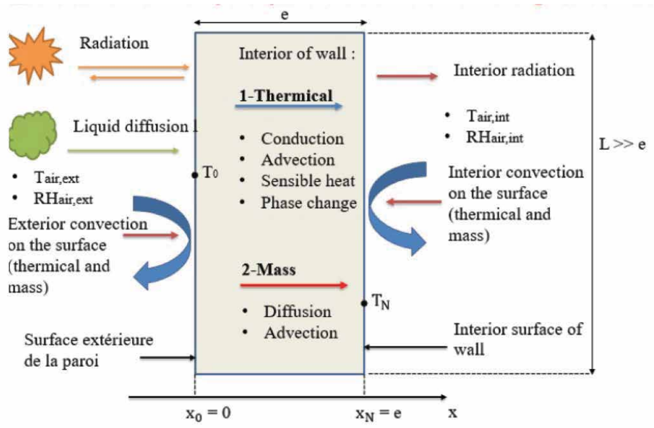

Figure 1. Schematisation phenomena of thermal and mass transfer through homogeneous wall of building envelop.

2.2 Discretisation and resoluion method of system balance equations

The previous system of equations is strongly coupled and also strongly non-linear. In order to solve this system numerically, it must first be linearised. To simplify, we have first fixed the coefficients of these equations at a temperature T0 = 303K corresponding to a relative humidity of the air circulating within the material b0 = 70%. This is because in overseas departments, humid tropical regions, the Temperature-Relative Humidity coupling retained by professionals for the dimensioning of air conditioning systems is overestimated at 32°C and 75% [16]. It should be noted that Abahri et al., 2011 [9] have already made this hypothesis to study analytically and then numerically the temperature and humidity profiles through a wooden building wall as a function of its thickness and time. Indeed, the studied material is considered as homogeneous and its thermophysical properties are assumed to be constant. Moreover, the initial distribution of moisture content and temperature in the wall is uniform. Moisture content is the potential that governs the transfer of humidity through the material.

In a second step, we discretised and applied the Euler's semi-explicit resolution method followed by the splitting method or fractional pitch. The following diagrams represent the numerical scheme of discretisation in space and in time (Figure 2) as well as the resolution methods adopted (Figure 3).

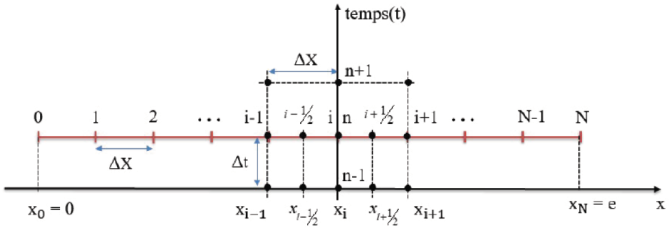

Figure 2. Representation of numerical schema in space (x) and time (t).

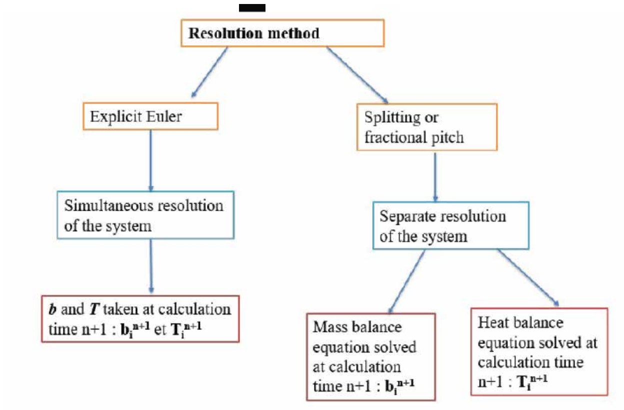

Figure 3. Methodology of resolution of equations system.

The discretisation of the system of heat and moisture transfer equations using the semi-explicit Euler method gives for the moisture transfer balance equation [17] :

$$\psi_T \cdot \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) + \psi_b \cdot \left(\frac{b_i^{n+1} - b_i^n}{\Delta t}\right) = \frac{\left(\delta_{p,mat_0} \cdot p_{v,sat} + D_{l0}^b\right)}{\Delta x^2} \cdot \left(b_{i+1}^n - 2b_i^n + b_{i-1}^n\right)$$
$$- R_1 \cdot p_{v,sat} \cdot \left(\frac{b_{i+1}^n - b_{i-1}^n}{2\Delta x}\right) + D_{l0}^T \cdot \frac{\left(T_{i+1}^n - 2T_i^n + T_{i-1}^n\right)}{\Delta x^2}$$

And for the heat transfer balance equation, we have [17]:

$$C_{mT0} \cdot \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) + C_{mb0} \cdot \left(\frac{b_i^{n+1} - b_i^n}{\Delta t}\right) = \lambda_{01} \cdot \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{\Delta x^2}\right) - C_{p,a}\rho_a v_a \cdot \left(\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta x}\right)$$
$$+ R_2 p_{v,sat} \cdot \left(\frac{b_{i+1}^n - b_{i-1}^n}{2\Delta x}\right) + R_3 \cdot \left(\frac{b_{i+1}^n - 2b_i^n + b_{i-1}^n}{\Delta x^2}\right) + R_4 \cdot \left(\frac{b_{i+1}^n \cdot T_{i+1}^n - b_{i-1}^n \cdot T_{i-1}^n}{2\Delta x}\right)$$

By following the semi-explicit Euler method with the splitting method, the two equations become respectively :

$$\psi_T \cdot \left(\frac{T_i^n - T_i^{n-1}}{\Delta t}\right) + \psi_b \cdot \left(\frac{b_i^{n+1} - b_i^n}{\Delta t}\right) = \frac{\left(\delta_{p,mat_0} \cdot p_{v,sat} + D_{l0}^b\right)}{\Delta x^2} \cdot \left(b_{i+1}^n - 2b_i^n + b_{i-1}^n\right)$$
$$- R_1 \cdot p_{v,sat} \cdot \left(\frac{b_{i+1}^n - b_{i-1}^n}{2\Delta x}\right) + D_{l0}^T \cdot \frac{\left(T_{i+1}^n - 2T_i^n + T_{i-1}^n\right)}{\Delta x^2}$$

$$C_{mT0} \cdot \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) + C_{mb0} \cdot \left(\frac{b_i^{n+1} - b_i^n}{\Delta t}\right) = \lambda_{01} \cdot \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{\Delta x^2}\right) - C_{p,a}\rho_a v_a \cdot \left(\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta x}\right),$$
$$+ R_2 p_{v,sat} \cdot \left(\frac{b_{i+1}^{n+1} - b_{i-1}^{n+1}}{2\Delta x}\right) + R_3 \cdot \left(\frac{b_{i+1}^{n+1} - 2b_i^n + b_{i-1}^{n+1}}{\Delta x^2}\right) + R_4 \cdot \left(\frac{b_{i+1}^{n+1} \cdot T_{i+1}^n - b_{i-1}^{n+1} \cdot T_{i-1}^n}{2\Delta x}\right)$$

The latter is programmed on the PYTHON software as follows :

$$\begin{cases} b^{n+1} = b^n + dt \cdot F^n\left(b^n, T^n, T^{n-1}\right) \\ T^{n+1} = T^n + dt \cdot G^n\left(b^{n+1}, b^n, T^n\right) \end{cases}$$

With Fn and Gn are square matrices.

Boundary conditions are applied to the outer and inner surfaces of the insulation material. On the one hand, the Dirichlet boundary conditions consist in imposing at the initial moment on the external surface of the material; a temperature Tini = 330K corresponding to a relative humidity bini = 20% of the air circulating within the material. On the other hand, the Neumann boundary conditions consist in considering that the derivatives of the temperature and relative humidity flows are null on the inner surface of the material, according to the order of arrival of the heat flow.

2.3 Input data of model

Different hygrothermal parameters are required before using the numerical model on materials produced locally in the humid tropical climate (raw banana and coconut leaves). These parameters are summarised in the following table :

Table 1. Different data of model

Input parameter of the model	symbols	Units
Thermal conductivity of material	λ	W.m^{-1}.K^{-1}
Specific heat (air, material, water vapor, water liquid)	$C_{p,a}$; $C_{p,0}$; $C_{p,v}$; $C_{p,l}$	J.kg^{-1}.K^{-1}
Coefficient of resistance to vapor diffusion	μ_0 et $\mu(b)$	-
Permeability of material at the vapor	$\delta_{p,mat}$	kg.m^{-1}.Pa^{-1}.s^{-1}
Volume mass (air and material)	ρ_a et ρ_0	kg.m^{-3}
Latent heat of vaporization	L_v	J.kg^{-1}
Atmospheric pressure	P_0	Pa
Molar mass (water and air)	M_l et M_a	kg.mol^{-1}
Water content	w	kg.m^{-3}
Permeability of air	$\delta_{p,a}$	kg.m^{-1}.Pa^{-1}.s^{-1}
Pressure of saturation	$P_{v,sat}$	Pa

Different hygrothermal parameter necessaries before using straw banana or coco are summarised in the following table:

Table 2. Different hygrothermal parameter necessaries before using straw banana and coco

Hygrothermal parameter	symbols	Method of determination
Permeability banana straw on air	$\delta_{p,mat}$	Cup method
Coefficient of resistance of banana straw to water vapor diffusion in dry state (low humidity)	μ_0	Dry cup method
Coefficient of resistance of banana straw to water vapor diffusion in wet state (high humidity)	$\mu(b)$	Humid cup method
Specific heat of banana straw	$C_{p,0}$	Formulas
Water content of banana straw	w	Formulas
Hydraulic conductivity	K_l	Darcy's law
Pressure exercised on two faces of banana straw sample	P_1 and P_2	Sensors of pressure

Given the absence of these data in the literature on banana and coconut leaves, we have subsequently used those of other well referenced biosourced materials.

Table 3. Example of Hygrothermal properties for cork. [18]

Input parameter of model	Values
Thermal conductivity	0,06 à 0,11 W.m^{-1}.K^{-1}
Specific heat	1560 J.kg^{-1}.K^{-1}
Coefficient of resistance to vapor diffusion	10 (dry) and 5 (humid)
Volume mass	20 à 400 kg.m^{-3}

Table 4. Example of Hygrothermal properties for wood [19,20]

Input parameter of model	Values
Thermal conductivity	0,1 à 0,65 W.m^{-1}.K^{-1}
Specific heat	1280 à 2500 J.kg^{-1}.K^{-1}
Coefficient of resistance to vapor diffusion	72 (dry) and 18 (humid)
Volume mass	370 à 430 kg.m^{-3}

3.0 RESULTS OF REALISED TEST FOR THE VALIDATION OF NUMERICAL MODEL AND DISCUSSION

Numerical simulation tests were carried out on materials whose properties are known in the literature. The results of the tests presented in this paragraph concern wood and cork with the hygrothermal properties mentioned in this paper (see tables 3 and 4).

- Profile for the temperature and relative humidity in the cork of 10cm of thickness.

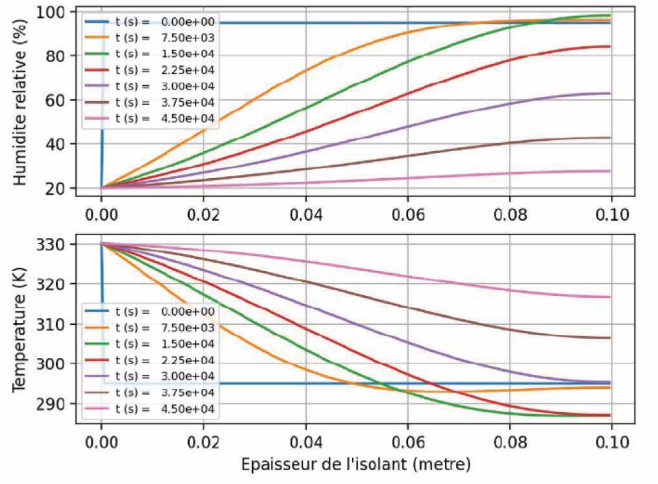

Figure 4. Graphic obtained in space (x) and time (t) for numerical simulation of system balance equation in using the data's cork.

The profiles of temperature and relative humidity are presented as a function of time and thickness of the material. Different curves are presented at different times of the simulation for t = 0 to 45000 s. For example: In the case of cork, the blue curves are curves corresponding to the instant t = 0 and x = 0, those of color correspond to 7500 s, those of green color to 15000 s, those of red color to 22500 s and the last ones of magenta color correspond to 45000 s. As the iteration time increases, the relative humidity profile shows a tendency to decrease while the temperature tends to increase. This is a normal behavior since the temperature increases when the humidity decreases. This means that the numerical model reacts well for this material.

The relative humidity profiles show that the temperature profiles increase at Dirichlet-Neumann boundary conditions as a function of time and thickness.

The profiles observed in the tested material are consistent with those in the literature [9,12].

- Profile for the temperature and relative humidity in the wood of 10 cm of thickness

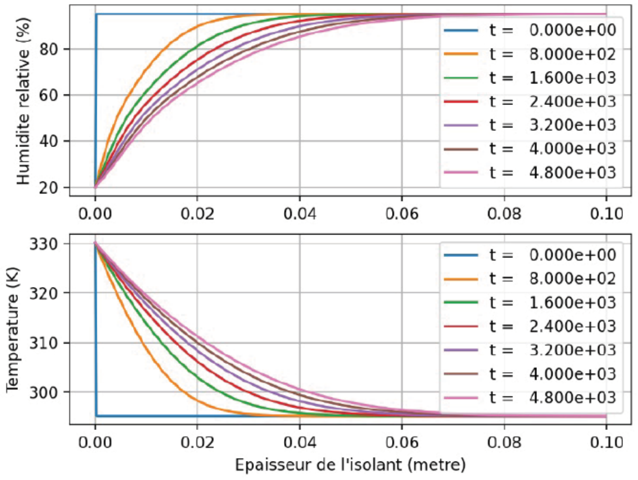

Figure 5. Graphic obtained in space (x) and time (t) for numerical simulation of system balance equation in using the data's wood.

Identically in cork, the different ones have the same colors in wood. Only the simulation times are much smaller. Temperature and humidity progress less and less within the material as they travel through the thickness as a function of time.

Moisture and temperature profiles converge and are consistent with the literature [9,12]

CONCLUSION

A system of equations modeling hygrothermal transfers through porous materials is established. The numerical model developed in this paper is applied to biosourced materials of plant origin. This model is limited to biosourced materials whose hygrothermal properties are considered constant. This model can be extended to biosourced materials at building scale by taking into account the system of equations with variable coefficients.

The results of the numerical simulation tests carried out show that the model is stable and convergent. The results obtained are compared from these tests with those of various authors in the literature in order to validate the model and the results of tests. These results are valid for the humid tropical climate characterised by a high rate of sunshine, a high temperature throughout the year (15°C to 35°C) and a relative humidity of up to 100%. Sunshine can increase the outside temperature of the building envelope by up to 60°C depending on the results of experiments carried out on the roof of a real building.

According to the results of numerical simulations obtained in the PYTHON programming, these materials can slow down heat transmission but can also increase their internal humidity level. This will generate the probability of mold growth inside the building envelope. It may be necessary to treat them and combine them with other moisture-protective materials, taking care to respect their selection criteria from the point of view of energy performance and human health before use. This would make them more effective and reduce the rate of moisture accumulation.

The disadvantages resulting from accumulation of moisture is insufficient to neglect the valorisation of insulating biosourced materials of vegetable origin taken without preliminary treatments. Their overabundance in Haïti is already a precious asset in this current context of global warming and depletion of fossil fuel resources at planetary scale. A layer of insulation using biosourced materials (banana and coconut fibers) deposited on building envelope would allow to limit the thermal contribution towards the interior of the buildings in tropical climate.

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