NUMERICAL STUDIES OF THE HYGROTHERMAL BEHAVIOUR OF A HEMP CONCRETE WALL: DIMENSIONLESS STUDY OF THE TRANSFER EQUATIONS

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Abstract

Many studies have been devoted to modelling hygrothermal transfers through plant concrete walls subjected to external variations in temperature and relative humidity. On the other hand, there is a lack of knowledge in research related to the impact of green concrete on the energy performance of the building, taking into account the comfort conditions in the living environment. This work focuses on a theoretical study of the HAM system (steam, liquid and air). A phenomenological model, which has already been developed by many researchers, describes the coupled transfer of heat, air and moisture through porous walls. One of the difficulties in using this model lies in identifying the many parameters characterizing the hygrothermal properties of the material. The purpose of this work is to reduce the number of these parameters and optimize the system through a dimensionless analysis. In addition, an improvement of the HAM model has been implemented. This approach is based on a sensitivity study, as well as the evaluation of the effect of gas pressure on coupled heat and mass transfers. A comparison between the numerical results and the literature was then carried out to validate the proposed analytical model.

Keywords:

Vegetable concrete; Hygrothermal transfer; HAM; Energy impact; Comfort, Dimensionless study.

1 INTRODUCTION

Over the past decades, a variety of digital models of heat, humidity and air storage as well as transfer to building components (called HAM) have been discussed. With the development of building materials, these models allow the numerical modelling of complex cases with good accuracy and much faster than before. For this reason, a good understanding of the mechanisms of hygrothermal transfer and its response to climatic stresses as well as the correct choice of building materials will be a key to influencing energy consumption while maintaining comfort conditions in the building. The classical models are based on fluid mechanics and diffusion law - Fick, Darcy (mass) and Fourier (heat). In these models, transfers are consequences of some "driving forces" resulting from potential gradients. Study HAM transfers simultaneously, many combinations of driving forces could be used. Three of them are widely accepted: temperature gradient T[K], relative humidity gradient ΔH[%], air pressure gradient ΔPa[Pa]. One of the difficulties in using this model lies in identifying the many parameters characterizing the hygrothermal properties of the material. In addition, an analytical approach dedicated to the optimization of the HAM system through a dimensionless analysis. This work is based on a sensitivity study, as well as the evaluation of the effect of gas pressure on coupled heat and mass transfers.

2 PRESENTATION OF THE HAM MODEL

The study of coupled heat and mass transfers in porous media has been a concern for several researchers. Indeed, the literature proposes different models of coupled heat and moisture transfer in porous materials. The question of choosing the appropriate transfer potential remains a point of discussion for several researchers in the scientific community regardless of the transfer engines adopted (water content, vapour pressure, chemical potential, temperature, liquid pressure, capillary pressure) ... For the humidity variable, mass transfer can be described by several potentials (vapour pressure, total water pressure, capillary pressure) This term can be used under several physical states... Some models neglect the presence of water vapour and consider that the liquid phase. Other authors only consider the diffusion of water vapour without taking into account water condensation. The differences between the models studied in the literature lie mainly in the choice of the transfer motor and the formulation of the equivalent moisture transfer equations [Funk & Wakili 2007]. The difference appears in particular in the consideration of gas pressure. The choice of transfer motors is not always so obvious, since water content is not a state variable in the sense of thermodynamics. In particular, it is not continuous at the boundary between two different materials, and has a distribution in a heterogeneous environment. However, according to the experts it was agreed to introduce steam pressure as a transfer engine in the field of construction.

2.1 Hypothesis adopted

- In order to simplify the modelling of coupled heat, air and humidity transfer phenomena, the following assumptions have been adopted:
- At any point on the unsaturated porous continuum, the different phases: solid, liquid and gaseous are in local thermodynamic equilibrium.
- The solid medium is non-deformable and homogeneous within it.
- The gas phase obeys the law of perfect gases.
- Radiation heat transfer is negligible.
- The transfer of moisture under the effect of gravityis negligible.
- The transfer of moisture under the effect of gravityis negligible.

2.2 Equations constituting the coupled transfers

First, the mass and energy conservation equations are described for all phases considered. Then they are defined according to the transfer engines given by: water content, temperature and total pressure. The energy and mass balance equations for each phase are established. The equation the energy balance balance of the liquid phase (1), the balance of the liquid phase (2), the dry air balance (3), are defined by the following local formulations:

$$C_p \rho_s \frac{\partial T}{\partial t} = -div(j_q) \quad (1)$$

$$\frac{\partial u}{\partial t} = -div(j_l + j_v) \quad (2)$$

$$\frac{\partial u_a}{\partial t} = -div(j_a) \quad (3)$$

With,

-j_q[J /m^{2}s]: heat flow density

- j_a[kg/m^{2}s]: the mass flow density of dry air

- j_v[kg/m^{2}s]:the mass flow density of the water vapour

- u [*kg/m*^{3}] : total water content (liquid and water vapour)

- j_l[*kg/m*^{2}*s*]: the mass flow density of the liquid phase

-u_a[*kg/m*^{3}]: the dry air content

- *T* [*K*]: temperature

According to the work of [Crausse et al, 1996] heat transfer is attributed to three forms: The purely conductive transfer given by Fourier's law, the convective transfer of sensitive heat by liquid and vapour flows and the transfer of latent heat carried by vapour. The heat flux density is therefore expressed by:

$$j_q = -\lambda \nabla T + h_l j_l + h_v j_v \quad (5)$$

Here,

h_l [J/kg] is the mass enthalpy of liquid water,

h_v [J/kg] is the mass enthalpy of steam water,

λ[w/m K] is the thermal conductivity.

Finally, the mass and energy balances reflecting the coupled transfers of heat, air and humidity for multilayer walls are represented in equation (6). The equation system in question is a strongly coupled partial differential equation system with non-linear input parameters, highly dependent on the hygrothermal state of the material.

$$\begin{cases} C_p \rho_s \dfrac{\partial T}{\partial t} = div(\lambda \nabla T + \alpha\, \nabla P_v + \gamma \nabla P) \\ \qquad + L_v\, \rho_s \sigma\, C_m \dfrac{\partial P_v}{\partial t} \\ C_a \frac{\partial P}{\partial t} = div(\, K_f \nabla P) \\ C_m \rho_s \dfrac{\partial P_v}{\partial t} = div[K_m \nabla P_v + K_T\, \nabla T + K_f \nabla P] \end{cases} \quad (6)$$

Cm	Moisture storage capacity
Km	Total moisture permeability [kg/(m.s.Pa)]
K_T	Hydraulic conductivity due to a gradient of temperature [$kg/(m{\cdot}s\ {\cdot}K)$]
K_f	Total infiltration coefficient [$kg/(m\ {\cdot}s\ {\cdot}Pa)$]
Ca	The capacity of the humid air and the capacity of the humid air [s^2/m^2]
λ	Thermal conductivity [$W/(m^2K)$]
Cp	Specific heat [$J/(kg{\cdot}K)$]
Lv	Latent heat of phase change [J/kg]
ρ	Density mass [$kg/m3$]
σ	Phase change criteria
ε	the thermogradient coefficient

3 SIMPLIFICATION OF THE HAM MODEL

Indeed, a parametric study was developed in our work to evaluate the influence of each of these parameters on hygrothermal transfers in a hemp concrete wall. A kind of sensitivity study was adopted, consisting in evaluating the hygrothermal transfers by eliminating each of the parameters characterizing the hygrothermal properties of the material and then making the comparison with the adopted HAM model (6). This approach has been adopted in order to address the most important factors during the transfer processes. For this reason, a numerical study was carried out by Comsol multiphase to carry out this comparison. This justification was assured was made in three points of a 36 cm thick hemp concrete wall for 3 months.

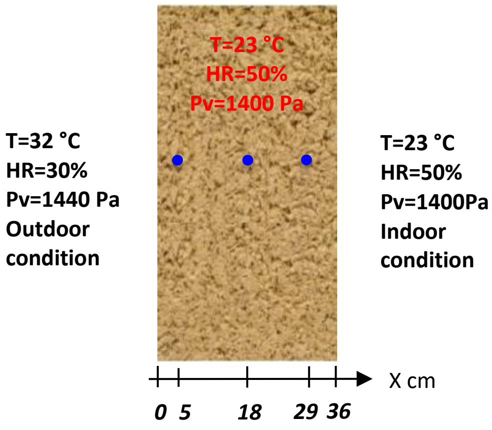
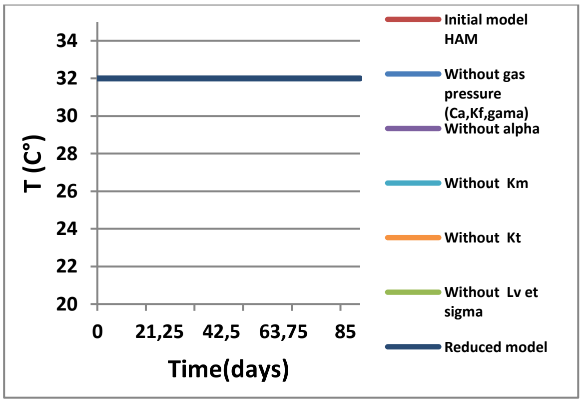
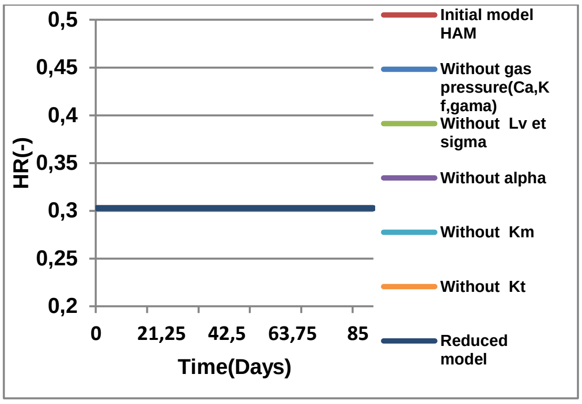


Fig.1: Boundary conditions

Starting by evaluating the contribution of gas pressure on hygrothermal transfers, the results show that gas pressure has no influence on the numerical results as well as L_v, σ, α. On the other hand, K_T has an influence when applying higher temperature gradients. Moreover, by eliminating Km which represents the total permeability in moisture, it is clear that the evolution of the vapour pressure is no longer there, hence the interest of this parameter in transfers.

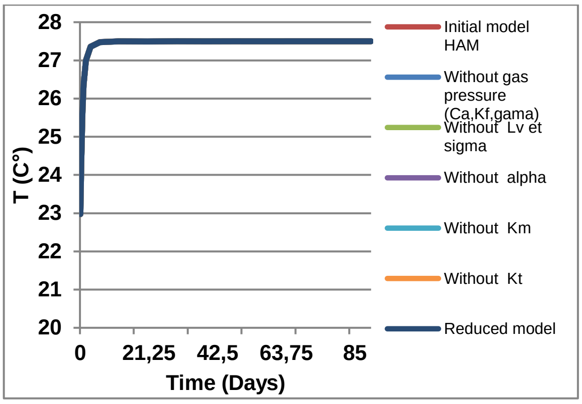


(a)

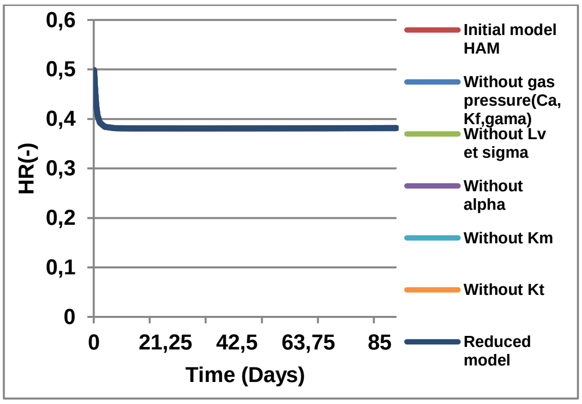


(b)

Fig.2 : (a) Temperature (b) Vapour pressure in 5 cm from inside

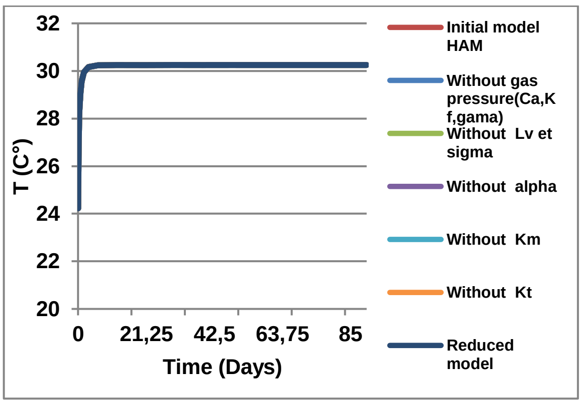


(a)

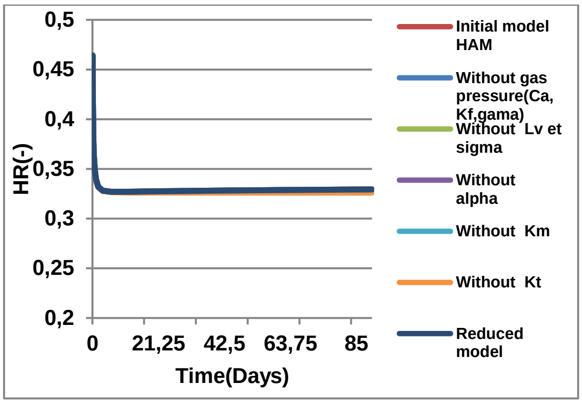


(b)

Fig.3 : (a) Temperature (b) Vapour pressure in the middle of the wall



(a)



(b)

Fig.4 : (a) Temperature (b) Vapour pressure in 7 cm from ouside

From this approach, it was possible to deduce a system of heat and mass transfer equations more reduced in number of equations and parameters. Indeed, this new system has kept the most influential parameters (Conductivity λ, calorific capacity C_p, storage capacity C_m, Km total moisture permeability, K_T hydraulic conductivity due to a temperature gradient depending on permeability).

$$c_m\rho_s\frac{\partial P_v}{\partial t} = div[K_m\nabla P_v + K_T\,\nabla T] \qquad (7)$$
$$C\rho_s\,\frac{\partial T}{\partial t} = div(\lambda\nabla T)$$

4 DIMENSIONLESS STUDY OF EQUATIONS:

Dimensionless is a procedure allowing the total removal of units from an equation by an appropriate substitution of variables, in order to simplify the parametric representation of our physical problems. We start by distinguishing the parameters and variables of the problem, and then assign for each the appropriate base units (Tab.1).

Tab.1 : Base unit

Les variables		Les paramètres	
P_v	$[M.L^{-1}.T^{-2}]$	C_m	$[M^{-1}.L.T^2]$
T	[Θ]	C_p	$[L^2.T^{-2}.Θ]$
X	[L]	K_m	[T]
T	[T]	K_T	$[M.L^{-1}.T^{-1}.Θ^{-1}]$
		λ	$[M.L.T^{-3}.Θ^{-1}]$

First, we start by normalization of the variables by dividing each by a number of scales of the same unit such that:

$\tau = \frac{t}{t_c}$; $\chi = \frac{x}{x_c}$; $\tilde{\mathcal{P}}_v = \frac{P_v}{P_{vc}}$; $\tilde\theta = \frac{T}{T_c}$

With the scale numbers:

$$t_c, x_c, P_{vc,}T_c$$

Depending on the base unit, each of the scale numbers is assigned a combination of the physical parameters of the studied material having the same base unit in our case hemp concrete Tab.2.

Tab.2: Base unit

Scale numbers	Base unit
$t_c = k_m$	$[T]$
$x_c = k_m\cdot\sqrt{\frac{\lambda}{k_T}}$	$[L]$
$P_{vc,} = \frac{1}{C_m}$	$[M.L^{-1}T^{-2}]$
$T_c = \frac{k_m}{C_m k_T}$	[Θ]

By replacing each of these variables and parameters in the system of equations (7) as follows:

$$\begin{cases} C_m\rho_s\frac{\partial(P_{vc,}\tilde{\mathcal{P}}_v)}{\partial(t_c\tau)} = K_m\frac{\partial^2(P_{vc,}\tilde{\mathcal{P}}_v)}{\partial^2(x_c.\chi)} + K_T\frac{\partial^2(T_c\,\tilde\theta)}{\partial^2(x_c.\chi)} \\ C_p\rho_s\frac{\partial(T_c\,\tilde\theta)}{\partial(t_c\tau)} = \lambda\frac{\partial^2(T_c\,\tilde\theta)}{\partial^2(x_c.\chi)} \end{cases} \qquad (8)$$

By making the necessary simplifications and replacements we obtain:

$$\frac{\partial\tilde{\mathcal{P}}_v}{\partial\tau} = \alpha\left(\frac{\partial^2\tilde{\mathcal{P}}_v}{\partial^2\chi} + \frac{\partial^2\tilde\theta}{\partial^2\chi}\right) \qquad (9)$$
$$\frac{\partial\tilde\theta}{\partial\tau} = \beta\frac{\partial^2\tilde\theta}{\partial^2\chi}$$

With:

$\alpha = \frac{K_t}{\rho_s\,C_m\lambda}$; $\beta = \frac{K_t}{\rho_s\,C_pK_m}$

5 VALIDATION NUMÉRIQUE DU MODÈLE

The hygrothermal behaviour of an uncoated hemp concrete wall (Tab.3) was studied during the [Lelievre 2015] thesis over a period of 85 days during which the temperature and relative humidity on the inside was set at the set values (23°C and 50%), while that on the outside varies according to four successive phases Fig.5. In particular, it should be noted that in order to maintain a constant vapour pressure, the instructions for the four phases must be set.

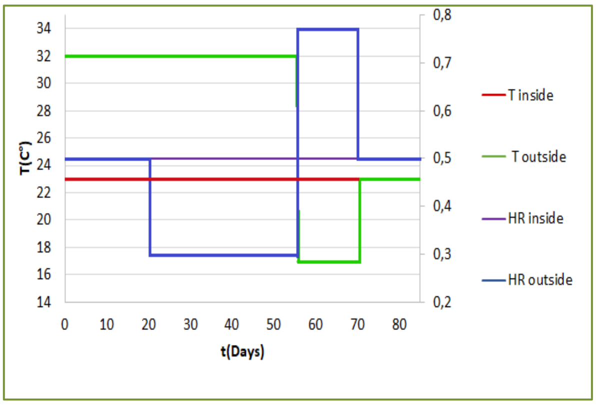


Fig.5 : Diagram of the experimental device for the uncoated hemp wall.

Tab.3: hemp concrete composition

	Chanvribat	Tradical PF70	Water
Mass composition	17%	35%	48%

A summary of the properties of hemp concrete is given in the Tab.4 :

Tab.4 : Properties of hemp concrete[Lelièvre 2015]

	ρ	λ	Cp	Ɛ	W
Hemp concrete (23°c,50%)	kg/m^3 454	W/(m.k) 0.10	(J/kg.k)m 1070	- 0,75	Kg/ m^3 55
	μ	K_T	C_m	D	
	- 5	$[kg/(m{\cdot}s{\cdot}K)]$ 1,7 10^{-11}	kg/kg.Pa 1,95. 10^{-5}	m^2/s 3. 10^{-9}	

In our case:

$\alpha = \frac{K_T}{\rho_s\, C_m \lambda}$=1,129. 10^{-8}; $\beta = \frac{K_T}{\rho_s\, C_p K_m}$= 1,211. 10^{-10};

The numerical study of the reduced model is implemented on the Comsol Multiphysics 5.6 software. a first simulation is carried out with normal mesh size and a time step of 600 s. the properties of hemp concrete are derived from the work [Leliévre 2015] table. the purpose of this approach is to validate the reduced model with the results obtained by [Leliévre 2015] the behaviours were evaluated at 5cm, 18 cm and 29 cm within the wall. The temperatures in the wall reach quasi-stationary mode during the heating phase. in addition, the simulated temperatures in the reduced model are higher than those obtained by [Leliévre 2015]. The simulated relative humidity follows the same variations as those imposed on the outside air. the relative humidity of 5 cm is reduced to a value close to the relative humidity of the inside air. However, the increase in temperature during the 55 days leads to a decrease in the water content values in the wall.

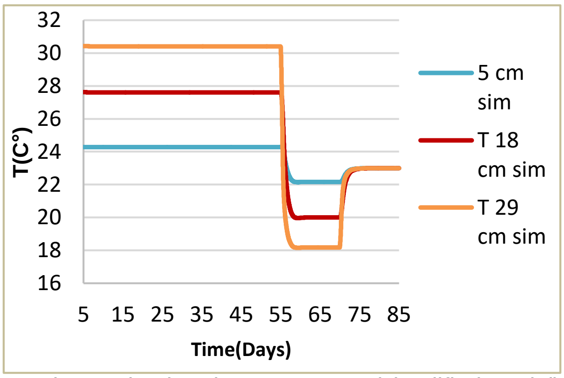


Fig.6 : Simulated temperatures (simplified model)

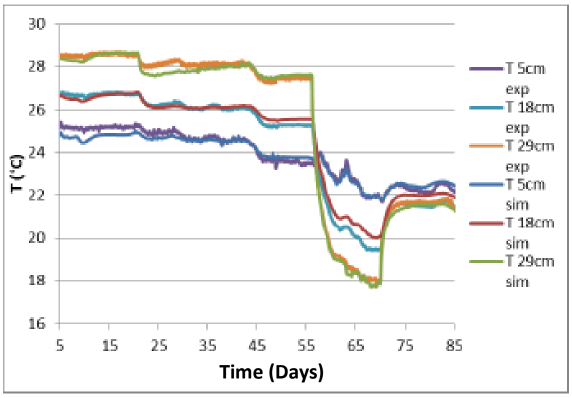


Fig.7 : Simulated and measured temperatures (Leliévre 2015)

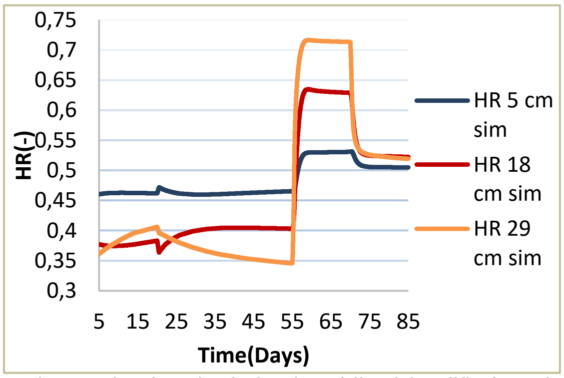


Fig.8 : Simulated relative humidity (simplified model)

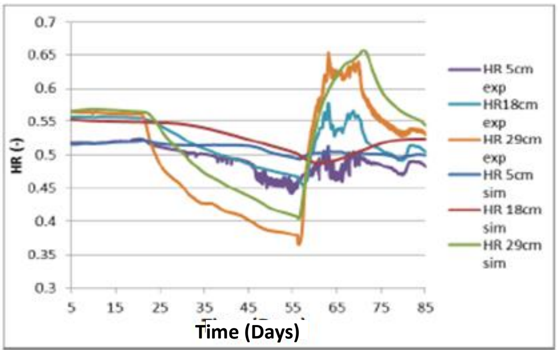


Fig.9 : Simulated and measured relative humidity [Leliévre 2015]

The temperature and relative humidity profiles simulated in the case of the simplified model are plotted in Fig 6 and 8 compared to the results obtained during the [Leliévre 2015] work, fig 7 and 9.

The simulated temperatures are higher than the values measured and simulated by [Leliévre 2015] for the first 55 days 18 cm and 29 cm. On the other hand, at 5 cm the temperature values are close to those of [Leliévre 2015] the temperature profiles are linear, which shows that the influence of the water content on the thermal conductivity is negligible in the studied domain. for mass transfers, the relative humidities able to reproduce the imposed external variations and they are higher than those obtained by [Leliévre 2015], which indicates an overestimation of the water transport in the wall.

6 CONCLUSION

Hemp concrete is a material that is increasingly recommended in new construction. This lime / hemp compound has many advantages, including its low environmental impact throughout its life cycle. This material is highly hygroscopic due to its high porosity, which gives it a good insulating capacity and the ability to moderate the living environment in relative humidity. However, contact with an uncontrolled environment can have a significant impact on the main characteristics. Transfers through the wall are also influenced by boundary conditions. In addition, a simplification of the HAM model was implemented through a sensitivity study, the objective of this work is therefore to study hygrothermal transfer phenomena at the wall scale using the simplified model obtained.This hygrothermal system was implemented in the Comsol multiphysics software and subsequently confronted with experimental and numerical results carried out in a controlled environment as part of the thesis work of [Leliévre,2015],which is likely to reproduce the phenomena of hygrothermal transfer as well as the interactions between atmosphere and wall.

7 REFERENCES

[Funk & Wakili,2007], Funk.M, Wakili.K «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):273-294,2007.

[CRAUSSE,1996] CRAUSSE P., LAURENT J.P. & PERRIN B. “INFLUENCE DES PHENOMENES D’HYSTERESIS SUR LES PROPRIETES HYDRIQUES DE MATERIAUX POREUX : COMPARAISON DE DEUX MODELES DE SIMULATION DU COMPORTEMENT THERMOHYDRIQUE DE PAROIS DE BATIMENT”. REVUE GENERALE DE THERMIQUE, 35(410), PP.95-106,1996.

[LELIEVRE,2015] LELIEVRE.D,2015 “SIMULATION NUMERIQUE DES TRANSFERTS DE CHALEUR ET D’HUMIDITE DANS UNE PAROI MULTICOUCHE DE BATIMENT EN MATERIAUX BIOSOURCES” THESE ,2015.

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