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Effect of Temperature-dependent Sorption Characteristics on The Hygrothermal Behavior of Hemp Concrete

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Abstract

Hemp concrete has been used more and more in building construction because hemp is a renewable plant, recyclable and does not degrade within time. Up to now, many simulation tools use the sorption isotherms that describe the relationship between relative humidity of air and the moisture content to predict the humidity in porous materials. However, the sorption capacity of material depends on temperature. The objective of this paper is to study the impact of the temperature dependency of the sorption curves on the hygrothermal behavior of a hemp concrete building envelope. Mathematical models to describe the coupled heat and mass transfer in porous materials are presented and validated against experimental data at the wall scale. The results show that taking the influence of temperature on the sorption characteristics into account is necessary for better prediction of the hygrothermal behavior of a hemp concrete wall.

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Keywords: hygrothermal behavior; temperature-dependent sorption; hemp concrete

1. Introduction

Temperature and relative humidity are important parameters influencing perceived indoor air quality and human comfort. High moisture levels can damage construction and inhabitant's health. High humidity harms materials, especially in case of condensation and it helps moulds development increasing allergic risks. Consequently, several

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researchers have studied the use of various hygroscopic materials to moderate indoor humidity levels. The material that absorbs and desorbs water vapor can be used to moderate the amplitude of indoor relative humidity and therefore to participate in the improvement of the indoor quality and energy saving ([1], [2]). Vegetal fiber materials are an interesting solution as they are eco materials and have low embodied energy. Hemp concrete is one of these materials which is more and more recommended by the eco-builders for its low environmental impact. The physical properties of hemp concrete has been measured by many authors ([3], [4]). It is highlighted that the one presents high moisture buffering capacity and a good compromise between insulation and inertia materials.

Nomenclature

Symbol	Definition	Unity
C_P	Specific heat at constant pressure	$J.kg^{-1}.K^{-1}$
D_T	Mass transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
$D_{T,v}$	Vapor phase transport coefficient associated to a temperature gradient	$m^2.s^{-1}.K^{-1}$
D_θ	Mass transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
$D_{\theta v}$	Vapor phase transport coefficient associated to a moisture content gradient	$m^2.s^{-1}$
h_M	Mass transfer convection coefficient	$m.s^{-1}$
h_T	Heat transfer convection coefficient	$W.m^{-2}.K^{-1}$
L_v	Heat of vaporization	$J.kg^{-1}$
T	Temperature	K
θ	Moisture content	$m^3.m^{-3}$
ρ_0	Mass density of dry material	$kg.m^{-3}$
ρ_l	Mass density of water	$kg.m^{-3}$
ρ_v	Mass density of vapor water	$kg.m^{-3}$
φ	Relative humidity	%

To investigate the hygrothermal behavior of building envelope, a simulation should be done because it is cheaper and more detailed than the test in situ. For this to be done, many simulation tools have been developed. Hygrothermal properties are required for all Heat, Air and Moisture transfer (HAM) models. Many models and simulation tools for predicting the hygrothermal behavior of building envelope are represented in the Annex 41 of the International Energy Agency's (IEA). For the building envelope, the main difference in HAM-transfer modeling is made by the dimension of represented phenomena and they can be classed by the granularity and complexity[†].

A detailed parametric study of hygrothermal behaviour of a wall made of hemp concrete submitted to hygrothermal shock has been carried out and showed that temperature and relative humidity variations in a wall are very sensitive to thermal properties, moisture transport coefficient and sorption isotherm [5]. Up to now, most hygrothermal tools have used the isothermal sorption curves that express the equilibrium between the moisture content and relative humidity in the representative elementary volume at a constant temperature. However, few works studied the effect of temperature on hygrothermal behaviour of building envelope ([6], [7]).

This article aims to study the effect of the temperature-dependent sorption on the prediction of hygrothermal behavior of a hemp building envelope submitted to a variation of temperature and relative humidity. First, the details for the mathematical model are shown. The models were elaborated and implemented in the Simulation Problem Analysis and Research Kernel (SPARK), which is adapted to the complex problems. Then, the simulation tools are validated with experimental results obtained from the test wall realised in our laboratory. After being validated, the effect of non-isothermal conditions on the temperature and relative humidity profiles will be discussed. In the next part, the mathematical model for the coupled heat and moisture transfer in building materials will be presented.

2. Mathematical models

2.1 Heat and moisture transport in porous building materials

Mechanisms of moisture transport in a single porous building material have been extensively studied ([8], [9], [10]). Most of the models have nearly the same origin; the main difference among them is related to particular assumptions used. In this article, the model that takes into account liquid and vapor moisture transport is used [10]. Forms of moisture transport depend on the pore structure as well as on the environmental conditions. The liquid

[†] http://www.ecbcs.org/annexes/annex41.htm

phase is transported by capillarity whereas the vapor phase is due to the gradients of partial vapour pressure. With these considerations, the mass conservation equation becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial x}\left(D_\theta \frac{\partial \theta}{\partial x} \right) \quad (1)$$

with the following boundary conditions respectively for the external (x=0) and internal (x=L) surfaces of the wall:

$$-\rho_l \left(D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right)\bigg|_{x=0,e} = h_{M,e}\left(\rho_{v,a,e} - \rho_{v,s,e} \right) \quad (2)$$

$$-\rho_l \left(D_T \frac{\partial T}{\partial x} + D_\theta \frac{\partial \theta}{\partial x} \right)\bigg|_{x=L,i} = h_{M,i}\left(\rho_{v,s,i} - \rho_{v,a,i} \right) \quad (3)$$

where the subscript a represent the adjacent air and s the solid surface of the material, while the subscripts e and i correspond respectively to the external and internal neighbouring environment (a) or solid surface (s).

One dimension of the energy conservation equation with coupled temperature and moisture for a porous media is considered and the effect of the adsorption or desorption heat is added. This equation is written as:

$$\rho_0 Cp_m \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x} \right) + L_v \rho_l \left(\frac{\partial}{\partial x}\left(D_{T,v} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial x}\left(D_{\theta,v} \frac{\partial \theta}{\partial x} \right) \right) \quad (4)$$

where Cp_m is the average specific heat which takes into account the dry material specific heat and the contribution of the specific heat of liquid phase.

$$Cp_m = Cp_0 + Cp_l \frac{\rho_l}{\rho_0} \theta \quad (5)$$

λ is thermal conductivity depending on moisture content.

Boundary conditions take into account convective heat transfer, radiative heat transfer and heat associated to phase changes, as expressed in the right side of Eqs. (6) and (7) for the external and internal surfaces respectively.

$$-\lambda \frac{\partial T}{\partial x} - L_v \rho_l \left(D_{T,v} \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial \theta}{\partial x} \right)\bigg|_{x=0,e} = h_{T,e}\left(T_{a,e} - T_{s,e} \right) + L_v h_{M,e}\left(\rho_{v,a,e} - \rho_{v,s,e} \right) + \Phi_{ray,e} \quad (6)$$

$$-\lambda \frac{\partial T}{\partial x} - L_v \rho_l \left(D_{T,v} \frac{\partial T}{\partial x} + D_{\theta,v} \frac{\partial \theta}{\partial x} \right)\bigg|_{x=L,i} = h_{T,i}\left(T_{s,i} - T_{a,i} \right) + L_v h_{M,i}\left(\rho_{v,s,i} - \rho_{v,a,i} \right) + \Phi_{ray,i} \quad (7)$$

In the case lacking a data base of moisture transport coefficients, simplified models should be used. The use of simplified mathematical models has varying effects on accuracy and has been discussed in [10]. In this article, the effect of temperature gradient on moisture transport is neglected which is generally accepted. The moisture diffusion coefficient related to moisture content gradient is evaluated as:

$$D_\theta = \pi \frac{P_{vs}(T)}{\rho_l} \frac{\partial \varphi}{\partial \theta} \quad (8)$$

The equations contain several parameters that are themselves function of the state variables. The special interests of the model are the dependencies of moisture content, moisture transport coefficient, thermal conductivity etc. upon the relative humidity and temperature. This makes possible to take into account the temperature-sorption dependence into the model, which will be presented in the next sub-section.

2.2 Effect of temperature on the sorption characteristics

Up to now, many studies have been carried out to measure the general shape of the isothermal sorption characteristic. However, the physics related to the isothermal sorption curves are still disputed. The researches showed that the sorption capacity of materials depends on the temperature ([6], [7], [11]). Increasing temperature will entail that the isosteric moisture content be reached in equilibrium with a higher relative humidity. The study of its effect on the hgrothermal behavior for the bio-based materials is new [6]. Concerning the hemp concrete, Ait Ouméziane [7] showed that taking into account its influence is necessary. In this article, we use two models describing the relation between sorption characteristics at different temperatures: Milly's model [12] and Poyet's model [13].

Milly's model is based on the effect of temperature on the intrinsic properties of water to establish the sorption curves. The temperature dependent sorption characteristics are expressed as:

$$\varphi_2(\theta,T_2)=\varphi_1(\theta,T_1)e^{C_\varphi(T_2-T_1)} \quad (9)$$

$$C_\varphi=\frac{1}{\varphi}\frac{\partial\varphi}{\partial T} \quad (10)$$

However, Poyet [13] showed that this consideration is not sufficient to well predict the hygrothermal behavior of concrete. Thus, the authors propose one another model based on the differential heat of sorption, which is written as:

$$\varphi(T_2,\theta)=\varphi(T_1,\theta)\frac{P_{sat}(T_1)}{P_{sat}(T_2)}e^{q_{st}(\theta)\frac{M_l}{R}\left(\frac{T_2-T_1}{T_1T_2}\right)} \quad (11)$$

where: M_l: molar mass of water [kg.mol^{-1}]; R: ideal gas constant [J.mol^{-1} K^{-1}]; q_{st} : isosteric heat [J.kg^{-1}], which is calculated from two sorption isotherms at two different temperatures (T1 and T2).

In order to solve the previous equation system, the numerical solution is based on the finite difference technique with an implicit scheme. To solve this system of equations, we used the Simulation Problem Analysis and Research Kernel (SPARK) which is especially suited to solve efficiently differential equation systems.

3. Numerical study and experimental validation

3.1 Experiment and simulation conditions

This section concerns the validation of the numerical model by comparing the simulation results with experimental ones. For this to be done, an experimental facility has been developed at "Ecole Nationale des Travaux Publics de l'Etat (ENTPE)" in France. The experimental setup consists of an climate chamber to simulate outdoor climate conditions, a test wall and sensor for measuring the temperature and the relative humidity. More details of this facility can be found in [14]. One side of tested wall was submitted to various outdoor conditions of temperature and relative humidity using a climate chamber, while other side of the wall was in contact with the laboratory ambient where temperature and relative humidity are relatively constant. The test wall was instrumented with sensors which are connected to an acquisition system to measure the hygrothermal profiles. It consists of a hemp concrete wall with 30 cm of thickness. The wall was subjected to cyclic step-changes in relative humidity and temperature: 30°C/70% RH during 24h followed of 20°C/30% RH during 24h (see Fig. 1).

Fig. 1 *: Experimental procedure : Step-changes in relative humidity and temperature.*

Table 1: *Hygrothermal properties of hemp concrete* [4]

Density	Thermal conductivity	Specific heat capacity	Water vapor permeability
kg/m^3	W/(m.K)	J/(kg.K)	Kg/(m.s.Pa)
329	0.095	1122	2,3.10^{-11}

The hygrothermal properties of hemp concrete measured by [4] are used for the simulation. Some basic hygrothermal data of hemp concrete is given in Table 1. It is noticed here that some authors have validated their models with constant coefficients using the results of this experimental case ([5], [14]). However, the fact that a value of about 3.10^{-7} (m²/s) of mass transport coefficient associated to a moisture content gradient was used for their validations is not realistic. Therefore, this article focuses on a more completed model that takes into account the effect of the temperature-dependent sorption characteristics on the hygrothermal response of hemp concrete wall. The simulation has been realized for two following models:

- ✓ **Isoth:** Using the isothermal sorption characteristics in the simulation,
- ✓ **Non-Isoth:** Taking into account the effect of temperature on the sorption curve by using the Poyet's model or Milly's model.

In addition, to test the effect of using the different sorption curves, for each model, three cases have been considered: adsorption curve, desorption curve and mean sorption curve obtained from the average between adsorption and desorption.

In this paper, the isosteric heat adsorption of hemp concrete has been determined by using the sorption isotherms at 10° and 23°C [7]. For the both indoor and outdoor surfaces, the heat and mass transfer coefficients are 9 $W.m^{-2}.K^{-1}$ and 0.003 $m.s^{-1}$, respectively. The time step is 240 seconds and the wall was discretized into 25 nodes according to one sensitive study conducted by [15]. In order to facilitate the investigation, only the results obtained in the middle of the wall (point C) will be presented.

3.2 Hygrothermal behavior of hemp concrete wall: Isoth model

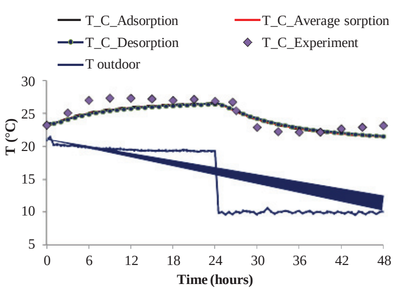

Fig. 2 : Variation of temperature at point C – Isoth model and experimental measurement

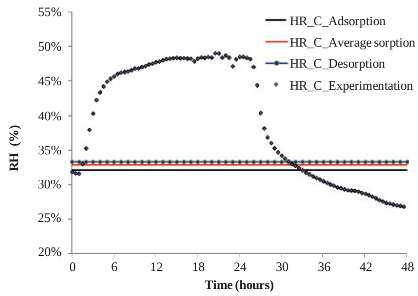

Fig. 3 : Variation of relative humidity at point C – Isoth model and experimental measurement

The comparison between the variation of temperature and relative humidity at point C obtained from the simulation using the Isoth model and the one from the experimental measurement is presented in Fig. 2 and Fig. 3 . One can observe that the variation of temperature is very similar for the three studied cases (adsorption, desorption and average curve). The model gives a quite satisfactory prediction of temperature within the wall, despite the underestimation of the maximum temperature and the overestimation of the minimum temperature. Concerning the variation of relative humidity, the computed results did not fit to the experimental ones. This should be explained by the fact that the studied model neglected the effect of temperature on the moisture sorption capacity of the material, in which increasing temperature results in increase of the relative humidity at given water content. Therefore, the dependency of sorption characteristic on temperature has been taken into account in the physical model and the result will be presented in the following subsection.

3.3 Hygrothermal behavior of hemp concrete wall: Non-Isoth model

As mentioned in the subsection 2.2, both Milly's model and Poyet's model have been used to study the impact of non-isothermal conditions on the hygrothermal behavior of hemp concrete. Because the results obtained from the Milly's model is very close to those from Isoth model, they are not depicted here. This subsection focuses only on the results obtained by using Poyet's model and the comparison between its results and experimental data are shown in Fig. 4 and Fig. 5. As can be seen from Fig. 4, the numerical results are in accordance to the experimental results. In addition, they are very close to those obtained by using the Isoth model (by comparing Fig. 4 with Fig. 2). Fig. 5 showed that compared to the final one, the Non-Isoth model results in significantly better prediction of the relative humidity variation in the tested wall.

Concerning three cases studied, the results are dependent on which the sorption curve is used for the simulations. The results calculated with the adsorption allow a better prediction of the relative humidity variation than those for the model that uses an average sorption curve between adsorption and desorption or desorption curve. The maximum difference between the computed results for the model that uses adsorption curve and the experimental ones is 3% RH. This value is small compared to the accuracy of sensor inserted in the tested wall, which is ±1.5% of RH.

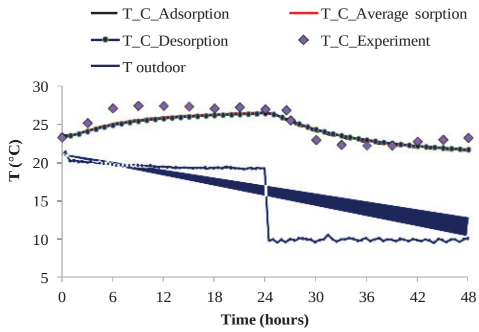

Fig. 4 *: Kinetic of the temperature in point C - Non- Isoth model and experimentation*

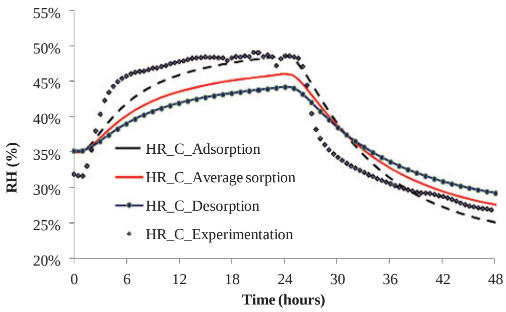

Fig. 5 *: Kinetic of the relative humidity in point C - Non- Isoth model and experimentation*

It can be drawn a conclusion that it is necessary to take into account the non-isothermal conditions on the sorption curves in order to well predict the hygrothermal behavior of the wall submitted to the dynamic conditions of temperature and relative humidity.

4. Conclusions

This article focuses on the development and use of a numerical model that takes into account the effect of temperature on the sorption characteristics in the transient modeling of coupled heat and mass transfer in porous materials. In order for this to be done, two models (Isoth and Non-isoth that uses the approaches proposed by Milly and Poyet) have been carried out and implemented in the simulation environment SPARK which is suited to solve efficiently differential equation systems. The numerical results were then compared to the experimental ones. The results showed that taking the influence of temperature on the sorption curves into account is necessary for better prediction of the hygrothermal behavior of a hemp concrete wall. Both Isoth and Non-isoth models predicted well the variation of temperature. However, only Non-isoth model that uses the Poyet's approach is adapted to study the variation of the relative humidity in the wall.

References

[1] Olalekan FO, Simonson CJ. Moisture buffering capacity of hygroscopic building materials: Experimental facilities and energy impact, Energy and Building, vol. 38, pp. 1270-1282, 2006.
[2] Tran Le AD, Malouf C, Mai, TH, Wurtz E, Collet F. Transient hygrothermal behaviour of a hemp concrete building envelope, Energy Build, vol. 42, pp. 1797-1806, 2010.
[3] Rahim M, Douzane O, Tran Le AD, Promis G, Laidoudi B, Crigny A, Dupre B, Langlet T. Characterization of flax lime and hemp lime concretes: Hygric properties and moisture buffer capacity, Energy Build, vol. 88, pp. 91-99, 2015.
[4] Collet F, Bart M, Serres L, Miriel J. Porous structure and water vapour sorption of hemp-based materials, Constr. Build. Mater, vol. 22, pp. 1271-1280, 2008.
[5] Tran Le AD, Maalouf C, Douzane O, Lahoche L, Mai TH, Lachi M, Langlet T. Effect of simulation parameters on the hygrothermal behaviour of a wall and a room made of hemp-lime concrete, International Journal of Mathematical Models and Methods, vol. 8, pp. 521-528, 2014.
[6] Carsten R, Clorius CO. Modeling of moisture transport in wood with hysteresis and temperaturedependent sorption characteristics, in Performance of Exterior Envelopes of Whole Buildings IX: International Conference, Clearwater, Florida, 2004.
[7] Ait Oumeziane Y. Evaluation des performances hygrothermiques d'une paroi par simulation numérique: application aux parois en béton de chanvre, Thèse de doctorat, INSA de Rennes, 2014.
[8] Philip JR, De Vries DA. Moisture movement in porous materials under temperature gradients, Trans. Am. Geophys. Union, Vols. 222-232, no. 2, 1957.
[9] Kunzel M. Simultaneous heat and moisture transport in building components, Fraunhofer Institute of building physics, 1995.
[10] Mendes N, Winkelmann FC, Lamberts R, Philippi PC. Moisture effects on conduction loads, Energy and Buildings, vol. 35, no. 7, pp. 631-644, 2003.
[11] Navi P, Herger F. Comportement thermohydromécanique du bois : applications technologiques et dans les structures, PPUR Suisse, 2005.
[12] Milly PCD. Moisture and heat transport in hysteretic, inhomogeneous porous media: a matric head-based formulation and a numerical model, Water Resources Research, vol. 18, pp. 489-498, 1982.
[13] Poyet S, Charles S. Temperature dependence of the sorption isotherms of cemented based materials: heat of sorption and Clausius-Clapeyron formula, Cement and Concrete Research, vol. 39, no. 11, pp. 1060-1067, 2009.
[14] Samri D. Analyse physique et caractérisation hygrothermique des matériaux de construction : approche expérimentale et modélisation numérique, Thèse ENTPE de Lyon, France, 2008.
[15] Tran Le AD, Maalouf C, Mendonça KC, Mai TH, Wurtz E. Study of moisture transfer in a double-layered wall with imperfect thermal and hydraulic contact resistances, Journal of Building Performance Simulation, vol. 2, no. 4, pp. 251-266, 2009.