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Hygrothermal behavior of bio-based building materials including hysteresis effects: Experimental and numerical analyses

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ABSTRACT

Bio-based building materials such as hemp concrete have been used successfully in building construction due to their thermal and environmental properties. Since they are also hygroscopic, modeling their hygrothermal behavior is also relevant for appropriate building design. In this work, heat and moisture transfer is investigated numerically by accounting for hysteresis and phase change effects. Input physical properties and their dependency on temperature and moisture content were determined by laboratory experiments. To validate the model, two extended cyclical adsorption/desorption experiments were first performed on an instrumented hemp concrete sample. One of the tests was conducted according to the Nordtest protocol. In the third experiment, a hemp concrete wall was monitored under various boundary conditions. The comparison of numerical results with experimental data gave satisfactory results for all the experiments, regarding mean moisture variation, local temperature and relative humidity variations. Lastly, we conclude on the use of a hysteresis model for hygroscopic materials.

1. Introduction

Over the last few decades a large number of simulation works dealing with the energy efficiency of buildings have shown the positive effect of hygroscopic building materials in comparison to classical ones on building energy demand [1], on HVAC system energy consumption in dwellings [2,3] and on the indoor air quality in buildings [4]. In particular, it has been shown that moisture transfers have a great influence on the sensitivity and latent conduction loads in the building envelope and on daily indoor moisture variations. Among the numerous hygroscopic building materials available, bio-based building materials like hemp concrete are currently interesting alternative products for new building construction and for building retrofitting [5,6], since they have many environmental benefits, such as potentially very low carbon life cycles [7], interesting thermo-hydric properties including low thermal conductivity [8], and good moisture buffering capacity [9]. Tran Le [10] also showed the positive effect of hemp concrete on building energy consumption in comparison to cellular concrete. Nevertheless, whatever the hygroscopic material, moisture is adsorbed in the envelope: excessive moisture levels can affect building performance and durability, but it can also be a source of pathologies such as mould growth on the interior surface [11]. Therefore it is necessary to precisely quantify heat and moisture transfer within the materials and their interaction with the enclosed space.

To this end, numerous experiments and simulations have been performed at different scales using several methods. For instance, benchmark experiments on classical hygroscopic building materials like spruce plywood and cellulose insulation [11,12] and gypsum boards [13] were performed in a wind tunnel in the framework of IEA Annex 41. In particular, this experimental facility allows evaluating the temperature, relative humidity and moisture accumulation within materials subjected to convective boundary conditions. In order to identify more realistic flow patterns typically encountered in buildings, the hygrothermal behavior of hygroscopic building material was also investigated at the wall scale. Van Belleghem [15] proposed a good overview of these studies. All these experimental data serve as a baseline for the comparison of numerical results obtained from heat and moisture transfer models [13,14,16–18]. Generally, good agreement is found between the calculated and measured data, confirmed by sensitivity and uncertainty analyses. Nevertheless, in most simulation tools, the process of simultaneous water vapor adsorption and desorption is controlled by a single function, usually the main adsorption isotherm. However, hysteresis is observed in the sorption curves of hygroscopic building materials. Since the nature of this hysteresis is not well known, it is difficult to model. For instance, Pedersen [19] developed a simple empirical approach using weighted

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Nomenclature

Roman

a	thermal diffusivity ($m^2\ s^{-1}$)
c_p	thermal capacity ($J\ kg^{-1}\ K^{-1}$)
D	moisture diffusion coefficient ($kg\ m^{-1}\ s^{-1}$/ $kg\ m^{-1}\ s^{-1}\ K^{-1}$)
g	mass flux at the boundary ($kg\ m^{-2}$)
k	intrinsic permeability (m^2)
k_r	relative permeability (−)
h_c	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_r	radiative heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k_m	convective mass transfer coefficient ($kg\ m^{-2}\ s^{-1}$)
L_v	heat of vaporization ($J\ kg^{-1}$)
p	pressure (Pa)
q	heat flux at the boundary ($W\ m^{-2}$)
T	temperature (K)
w	moisture content ($kg\ kg^{-1}$)

Greek

ε	emissivity (−)
η	dynamic viscosity ($m^2\ s^{-1}$)
θ	sorption capacity ($kg\ kg^{-1}$)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	vapor resistance coefficient (−)
π_a	vapor permeability of air ($kg\ m^{-1}\ s^{-1}\ Pa^{-1}$)
ρ	density ($kg\ m^{-3}$)
φ	relative humidity (−)

Subscripts

ad	adsorption
air	air
c	capillary
des	desorption
hys	hysteresis
l	liquid
mat	material
ref	reference
sat	saturation
surf	surface
v	vapor

capacity values, which was successfully applied by Carmeliet [20] and Kwiatkowski [18] in the field of building physics. Although Pedersen's model is easy to use, it has no physical meaning and does not account for micro-structural properties, such as sorption site distribution and accessibility. These phenomena are considered in hysteresis models based on the independent domain theory, which was originally presented by Preisach [21] and further developed by Everett [22] and Mualem [23]. In particular, the independent domain theory is simplified through a similarity hypothesis [23] and Mualem's model requires only two measured main isotherm curves for determining a function P_d of pore water blockage against air entry and predicting the scanning curves [24]. This model was extensively used in the field of building physics [16,20,25–27]. On the one hand, its numerical implementation is still arduous whatever the hysteresis model used; on the other hand, previous studies showed that using a hysteresis model leads to better agreement with benchmark experiments [16,18]. Furthermore, such models may be useful when the moisture buffering potential of hygroscopic building material is investigated [28,29].

Although common hygroscopic building materials have been investigated extensively, fewer works have focused on bio-based building materials in general and on hemp concrete in particular. These studies dealt with experiments [9,30], modeling [10,31,32] or both [33–36], and with two types of material: precast and sprayed hemp concrete. At the material scale, Maalouf et al. [35], Dubois et al. [36] and Aït Ouméziane [32] calibrated their models against only mean moisture content variations measured during moisture buffering experiments performed according to the Nordtest protocol. Nevertheless, Dubois et al. [36] considered moisture transfer using an effective vapor diffusion coefficient and neglected hysteresis, contrary to Maalouf et al. [35] and Aït Ouméziane [32]. At the wall scale [30,32–34], no perfect match has been found to date between numerical results and experimental data: in Samri's thesis [33], the infiltration of embedded sensors caused uncertainties in the relative humidity measurement within the wall, whereas Aït Ouméziane [32] succeeded in validating Künzel's model accounting for hysteresis of the sorption curves by performing isothermal tests on a prefabricated hemp concrete wall, but failed when non-isothermal conditions were investigated. Lastly, most of these works were devoted to precast hemp concrete and less to sprayed hemp concrete, although they present different thermo-physical properties [37,38].

In this work, we study heat and moisture transfer within sprayed hemp concrete experimentally and numerically. To achieve this, a model accounting for phase change effects is presented and hysteresis is investigated using two sub-models: the empirical model of Pedersen [19] and the phenomenological model of Mualem [24] (Section 2). Great attention is paid to the input parameters of the model, and the dependency of hygrothermal properties on temperature and moisture content is evaluated experimentally (Section 3). In Sections 4 and 5, the performance and accuracy of the model is evaluated against experimental data obtained from three different tests, namely two extended cyclical adsorption/desorption tests performed at the material scale (Section 4) and one non-isothermal experiment performed at the wall scale (Section 5). All the comparisons are confirmed by sensitivity analyses.

2. Mathematical model

2.1. Energy and moisture conservation equations

The modeling of heat and moisture transport processes in open porous material was dealt with in the main theories of Philip and De Vries [39], Luikov [40] and Whitaker [41] and adapted to building components under the following usual assumptions [19,42,43]:

- Porous material is regarded as continuous, homogeneous, stabilized (e.g. no chemical reactions) and non-deformable (e.g. no shrinkage);
- Local thermodynamic equilibrium is assumed at every point of the material;
- The effect of gravity is negligible and total gas pressure is constant, equal to the atmospheric pressure;
- No air transfer occurs;
- No liquid transfer due to thermal gradients occurs;
- Moisture storage is independent of temperature;
- The temperatures remain well below the boiling temperature of water.

Several models describing heat and moisture transfer in building components have been developed on this basis, but they differ in the choice of state variable and driving potential [44]. In the present work, temperature T and relative humidity φ are used since both these parameters vary continuously when multi-layered components are considered [45].