NUMERICAL AND EXPERIMENTAL INVESTIGATION OF HEAT AND MASS TRANSFER WITHIN BIO-BASED MATERIAL

by

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In this paper, the coupled heat and mass transfer within porous media has been studies. First, the studied materials have been characterized experimentally and than evaluated their thermal properties, namely thermal conductivity and specific heat in different states (dry-wet). The hygroscopic properties, namely water vapour permeability, water vapour sorption. At second time, we present and validate the mathematical model describing heat and mass transfer within bio-based materials, by the confrontation with the experimental results. The materials properties obtained from the characterisation part are used as model's input parameters. Moreover, a test facility is mounted in the laboratory in order to compare the numerical and experimental data. The founded results show a good concordance between the simulated and measured data. According to this results the mathematical model of Philip and de Vries gives a good prediction of hygrothermal behaviour of bio-based material. This model will allow us to save money and time of the experimental part in the future.

Key words: *bio-based materials, heat and mass transfer, modelling, experimental, characterization, hemp concrete, fibre wood*

Introduction

Nowadays, the buildings sector is the largest energy-consuming sector, accounting for over one-third of final energy consumption globally and an equally important source of CO_2 emissions [1]. The energy consumed by the building depends on various factors, among those we mention the buildings materials [2, 3], the housing design and the HVAC systems [4]. For an innovative and efficient solution, the bio-based materials appear to be promising [5]. Where they have various benefits in building envelope renovation and new buildings construction [6]. The major advantage of using the bio-based materials is their good thermal insulating properties [7, 8]. In addition, they procure high moisture buffing capacity and a good balance between low mass and storage capacity [9, 10].

The phenomenon of moisture sorption by the building materials, it may have caused materials quality degradation as (thermal insulation, mechanical resistance *etc.*) [11]. Particularly, at the condensation case, humidity has a great influence on the building thermal performance related to the HVAC system consumption [12]. To deal with the moisture issues within the materials building, it is essential to study the coupled heat and mass transfer. We carried out a full methodology, which consists first on the characterizing studied materials, the hygro-

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thermal properties are used in the modelling part. The numerical work is based on the model of Philip and de Vries [13], where is implemented in Comsol Multiphysics© [14]. This software is adapted to solve the PDE.

Bio-Based materials studied

Hemp concrete

Hemp concrete is a composite porous material and one of the most materials using in buildings construction as insulation material. Hemp concrete is obtained by mixing lime based, water and vegetal particles called hemp, which is a plant of the cannabis family. The hemp is a particular plant due to its stem size and its fibres nature. The hemp concrete present high porosity where the capillaries diameters range between 10 and 40 μm, which is depends on the formulation essentially. The density of hemp concrete can varies between 200 and 600 kg/m^3. Concerning the hygrothermal and mechanical characteristics of hemp concrete, they have already a wide range of variety. Several works carried out in order to obtain the hemp concrete properties, we can mention the works of Collet and Pretot [15] and Elfordy *et al.* [7]. Other works are performed to investigate the hygrothermal performance of hemp concrete as the works of Tran *et al.* [16] and Maalouf *et al.* [2]. Figure 1(a) shows the hemp concrete sample tested in laboratory.

Flax wool

Flax wool is a raw material originally from vegetal plants, used in many application, as textile industry, in building construction as insulation material. The flax wool material has several advantages as their high specific mechanical properties Chafei *et al.* [17]. Thereby, in the durability context, flax wool presents a low environmental impact Claramunt *et al.* [18]. On the other hand, less work regarding the hygrothermal characteristics and material properties can be found. So, series of tests are carried out in order to get the hygrothermal characteristics of flax wool material. Figure 1(c) shows a sample of the studied flax wool insulation material.

Wood fibre

Wood fibers is considered as bio-based material used as building's insulation. Wood fibre is made essentially from wood, which representing a high hygroscopic properties. Wood fibre allows moderation of ambient relative humidity (RH), as it has been demonstrated by Rafidiarison *et al.* [19]. Several authors in their work focus on wood fibre properties, and attempts to characterize the material, in the literature we found the works: Vololonirina *et al.* [20] and Limam *et al.* [21]. To achieve more accuracy, a series of tests are carried out in the laboratory

Figure 1. Bio-based studied materials hemp concrete (a), wood fibre (b), and flax wool (c)
(*for color image see journal web site*)

in order to get the thermal and hygroscopic characterisation. Figure 1(b) represents the sample of wood fibre studied in laboratory.

Experimental characterisation

Thermal characterisation

The experimental set-up consists of maintaining a temperature gradient, ΔT, between two parallel flat plates, into which a sample with known thickness is positioned, fig. 2. The sample's area is greater than (200 × 200 mm), where the heat flux sensors area is 150 mm × 150 mm in order to prevent border effect. Figure 2 shows the schematic of principle heat flow method according to the standard NF EN 12667 [22]. The thermal conductivity is calculated according to the eq. (1):

$$\lambda = \frac{e\Phi}{\Delta T} \tag{1}$$

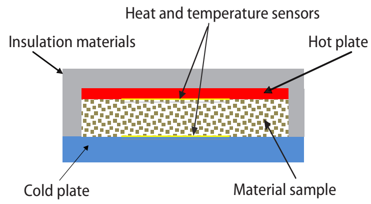

Figure 2. Principle method of thermal characterisation

where λ [Wm^{-1}K^{-1}] is the thermal conductivity, Φ [Wm^{2}] represents heat flux, and e and ΔT are the sample thickness and temperature gradient.

The test was done for the three studied materials: hemp concrete, flax wool, and wood fibre. First, the experiment is held for the dry materials, where the three tested materials are dried at constant temperature of 100 °C. The thermal conductivity and heat capacity are evaluated for the dry state. At second time, the samples are placed inside a climatic chamber, and under monitored RH. The water content is determined, while the samples are covered by waterproof screen to prevent the moisture diffusion within them. Similarly, the thermal conductivity and heat capacity are evaluated for the wet state.

Likewise for the specific heat is evaluated with the same device, only the thermal loads imposed changes. The previous system (sample and fluxmeters) are exposed to constant temperature until reaching steady-state, than we changed toward another constant temperature and waiting for the steady-state again. We assume that the sample go from initial temperature, T_{init} to final temperature T_{fin}, between these instances the sample have stored an amount of energy Q [Jm^{-2}]. In this case the heat capacity C [JK^{-1}m^{-2}] is calculated:

$$C = \frac{Q}{\Delta T} \tag{2}$$

where $\Delta T = T_{\text{fin}} - T_{\text{init}}$, and

$$Q = \int_{T_{\text{init}}}^{T_{\text{fin}}} \Delta\Phi \, \partial T$$

The specific heat c [Jkg^{-1}K^{-1}] is calculated:

$$c = \frac{C}{\rho A l} \tag{3}$$

where ρ [kgm^{-3}] and l [m^{2}] are the material density and sample thickness, respectively. The heat flux density is measured per unit area.

Isotherm water vapour sorption

Water vapour sorption is the process that relates the water content inside the material with the ambient RH, for a given temperature. The porous materials with open porosity tend to fix the air humidity, this means that the evolution of air RH leads to an increase of bulk density.

The water vapour sorption test is performed according to the discontinuous method NF EN ISO 12571 [23]. The materials samples are placed inside the climatic chamber BINDER MKFT E3.1, the ambient conditions of temperature and RH are controlled via an integrate controller. The climatic chamber has a large wide of the ambient conditions variety, where temperature range can varies between –40 °C to 60 °C, and *RH* of 10% until 98%, the uncertainties are evaluated by the supplier at 0.5 °C and 2.5 %, respectively. The water content is determined for successive stages of RH increasing then decreasing at a constant temperature 23 °C (isothermal test). For each materials type, three samples are performed, which is the minimum required by the standard [23]. The samples are weighted until reaching the steady-state. We consider that after three successive weighting during 24 hours, if the difference is lower than 0.1% of the mass, therefore the equilibrium is reached and the water content is calculated:

$$\frac{m - m_{\text{dry}}}{m_{\text{dry}}} \tag{4}$$

where m_{dry} [kg] is the mass of sample in the dry state and m [kg] is the mass sample of steady--state.

Overview

The thermal and hygroscopic characteristics of the studied materials (hemp concrete, flax wool and wood fibre) are reported tab. 1. The materials thermal conductivity, specific heat, water vapour resistance, and dry bulk density are evaluated at the dry state and at high moisture content state (wet). These characteristic are used in the modelling part. Concerning the test of vapour permeability, (dry-wet cup [24]) it requires a specific set-up and takes long time to be performed adequately. For these reasons, the water vapour permeability values of the studied materials are taken from the literature [10, 20].

Figure 3 represents the experimental isotherm of sorption, 3(a), and desorption, 3(b), curves for hemp concrete, flax wool and wood fibre, where is reported on the same figures the measured and the modelled water vapour sorption.

Modelling heat and mass transfer

Generality

Mechanisms of heat and mass transport within porous material have been extensively investigated in the literature. Several models described the simultaneous heat and mass transfer, the most popular ones are Philip and de Vries model [13] Luikov [25] and Whitaker [26]. These models have been developed on the bases and principles of heat and mass conservation, Fourier's law for heat conduction, Fick's and Darcy's law for the gas and fluid diffusion, respectively. The particularity between these models is the choice of driving potentials like the partial pressure, RH, and water content for the single layer. The model of Philip and de Vries [13] is taken as the basic model for our numerical simulation to predict the hygrothermal behaviour of wood fibre material.

Table 1. Materials properties tested in laboratory

Materials	Thermal conductivity [$Wm^{-1}K^{-1}$]		Heat capacity [$JK^{-1}kg^{-1}$]		Water vapour resistance [–]		Dry bulk density [kgm^{-3}]
State	Dry	Wet	Dry	Wet	Dry	Wet	
Hemp concrete	0.073	0.096	815	1464	13.9*	5.32*	369
Flax wool	0.04	0.065	1443	2538	–	–	40
Wood fibre	0.044	0.062	1202	1795	6**	4**	152

* [10], ** [20]

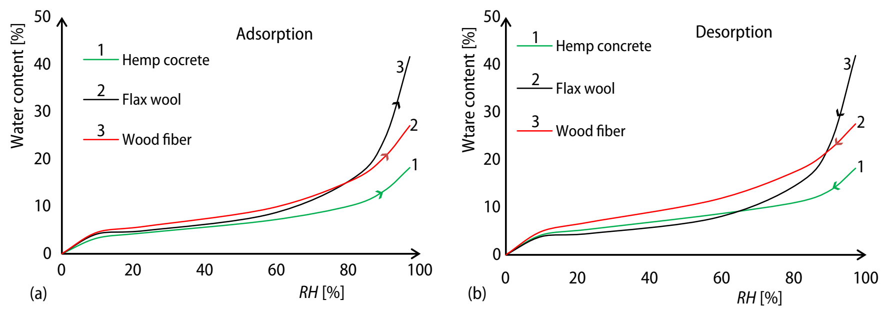

Figure 3. Water vapour sorption (a) and desorption (b) of hemp concrete, flax wool, and wood fibre

Philip and de Vries model

Philip and De Vries model [13] takes into account the moisture transport under two phases (liquid and vapour). It assumes that the vapour phase moves under a gradient of partial vapour pressure and the water phase moves under capillarity. With these considerations the balance of mass and heat equations becomes:

$$\frac{\partial \theta}{\partial t} = (D_\theta \nabla \theta) + (D_T \nabla T) \tag{5}$$

$$\rho_0 C p_m \frac{\partial T}{\partial t} = (\lambda \nabla T) + \rho_l L_v (D_{T,v} \nabla T) + \rho_l L_v (D_{\theta,v} \nabla \theta) \tag{6}$$

where θ [$kgkg^{-1}$] is the water content, T [K] – the temperature, D_T [$m^2s^{-1}K^{-1}$] and D_θ [m^2s^{-1}] – are, respectively, the mass transport coefficients associated to temperature and moisture content gradient.

The associated boundary conditions of mass and heat transfer are represented by:

$$\rho_l (D_\theta \nabla \theta + D_T \nabla T) = h_{m,i,e} (\rho_{v,a,i,e} - \rho_{v,s,i,e}) \tag{7}$$

$$-\lambda \nabla T - \rho_l L_v D_{T,v} \nabla T + \rho_l L_v \nabla \theta = h_{T,i,e} (T_{a,e} - T_{s,e}) + \rho_l L_v (\rho_{v,a,e} - \rho_{v,s,e}) + \Phi_{\mathrm{rad},i,e} \tag{8}$$

where $h_{m,i,e}$ [ms^{-1}] and $h_{T,i,e}$ [$Wm^{-2}K^{-1}$] are the convective mass and heat coefficient from external and internal side, respectively, $\rho_{v,e,i}$ [kgm^{-3}] – the air density, while the subscripts e and i correspond, respectively, to the external and internal side, neighbouring environment, a, air or solid surfacem, s, $\Phi_{\mathrm{rad},e,i}$ – a radiation term [Wm^{-2}].

Experimental facility and model validation

In order to validate the mathematical model, represented by the eqs. (5) and (6), and reproducing the boundary conditions given by eqs. (7) and (8), the following experimental device is performed.

First, a sample made from wood fibre with known area of 300 × 300 mm and 80 mm of thickness is placed inside climatic chamber, however only two faces are exposed to the ambient conditions, the other face are insulated by waterproof insulation, in order to ensure a unidirectional transfer. The sample is instrumented at different positions within the depth at $x = 20$ and 40 mm with an uncertainty of ±3 mm. The fig. 4 shows the facility configuration of the test. The temperature is logged by using thermocouple sensors type K with 0.6 mm of diameter and ±0.1 °C of sensitivity. Concerning the RH, sensors type HIH-4000-003 are used with an accuracy of ±3.5% given by supplier. The wood fibre is dried and kept under the following conditions for a long period $T = 20$ °C and $RH = 50\%$, in order de get a steady initial conditions. Then, the sample is submitted to various solicitation of ambient conditions. The air temperature and RH inside climatic chamber are controlled manually. The fig. 5 represents the ambient conditions, which the material's sample is submitted.

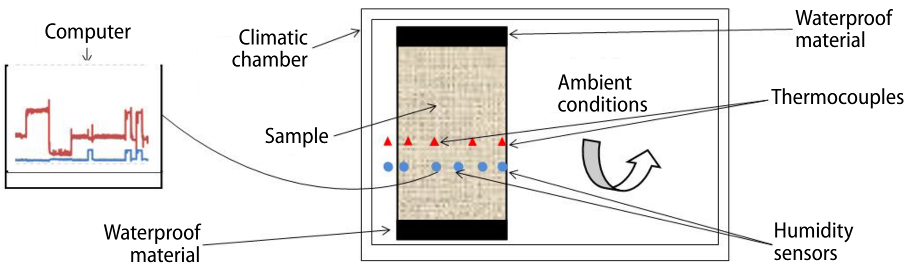

Figure 4. Test facility configuration

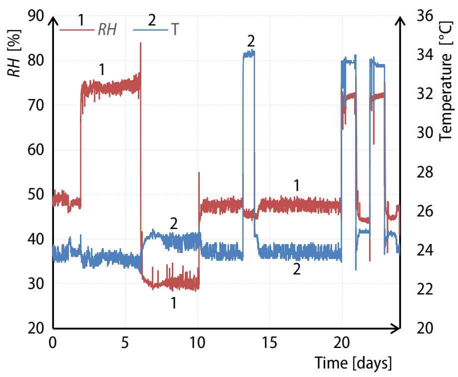

Figure 5. Ambient conditions of RH and temperature *vs.* time

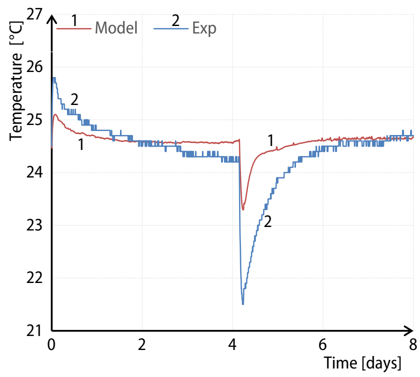

Figure 6. Experimental and modelling temperature *vs.* time at $x = 20$ mm

The aim of this configuration is to study the coupled heat and mass transfer within bio-based materials used for the insulation of building construction, we attempt to reproduce the same configuration as the reality. For this reason, the material is tested under several configurations. Among these configurations, a static loads represented by a step variation of RH and kept a constant temperature. Then the reverse case, a step variation of temperature, while keeping constant RH. The latest part consist to giving a coupled loads of temperature and relative humidity as shown is fig. 5.

Results and discussion

The modelling part is performed using Comsol Multiphysics© [10], the software is designed to solve the PDE highly coupled with high flexibility by the integrated PDE module. The model's parameters are resumed in the (section *Overview*) of this paper. The simulation is done in 2-D, with a mesh size of 1 mm and a time step of 300 second. Dirichlet boundary conditions are adopted and the logged data at the interfaces of the samples are implemented in the model.

Figure 6 represents the experimental and the modelling temperature evolution *vs.* time within the wood fibre materials at depth of 20 mm. The first case correspond to the isothermal test configuration. Despite that, we observe a peak in the temperature curve at $t = 1$ hours and at $t = 98$ hours. This can be explained by the phenomenon of latent heat liberation caused by the relative humidity gradient $RH = (50\text{-}75\%)$ at $t = 0 + \varepsilon$ (s), then at $t = 4$ days $+ \varepsilon$ (s) $RH = (75\text{-}33\%)$. This observed phenomenon demonstrates the accuracy of the model Philip and de Vries to predict the hygrothermal behavior of bio-based materials [13], moreover, the third term in the eq. (6) proves the coupled effect of the humidity on the temperature and vice versa.

Figures 7(a) and 7(b) represent the experimental and the modelling RH evolution *vs.* time at different depths $x = 20$ and 40 mm. The RH takes a long period to reach the steady-state as expected: more than four days for the adsorption stage and two days for the desorption stage, this is due to the wood fibre hygroscopic nature. According to these observations we conclude that the material absorbs and desorbs the moisture differently. The asymmetric sorption and desorption behaviour are shown in fig. 3. By comparing the numerical and experimental works, we note that only slight difference is observed between the modelling and measurement data at depth $x = 20$ mm, fig. 7(a), in terms of amplitude and phase delay. We see clearly that the two curves, experimental and modelling have the same kinetics evolution and the same slope. A very good agreement is generally obtained between the numerical and experimental work. Concerning fig. 7(b), there is some difference between the modelling and the measured RH at $x = 40$ mm, which can be explained by the humidity infiltration and the sensor accuracy ±3.5%. Figures 8(a) and 8(b) represents the experimental and modelling RH profile within the sample at $t = 1$ and 5 days and the errors bars associated. These profiles give a good illustration for the present work.

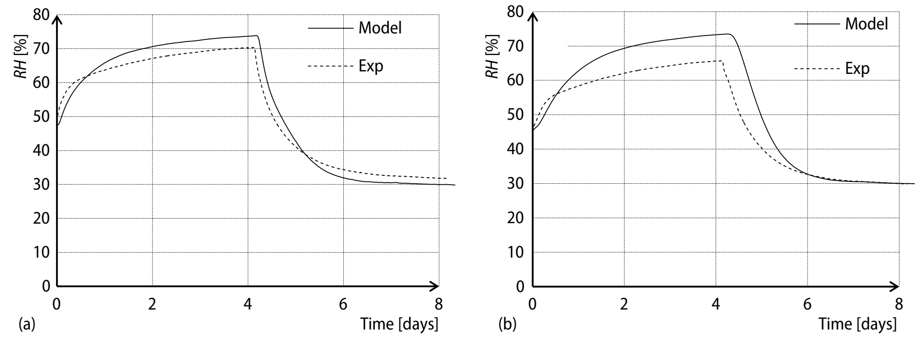

Figure 7. (a) Experimental and (b) modelling RH *vs.* time at $x = 20$ mm, 40 mm

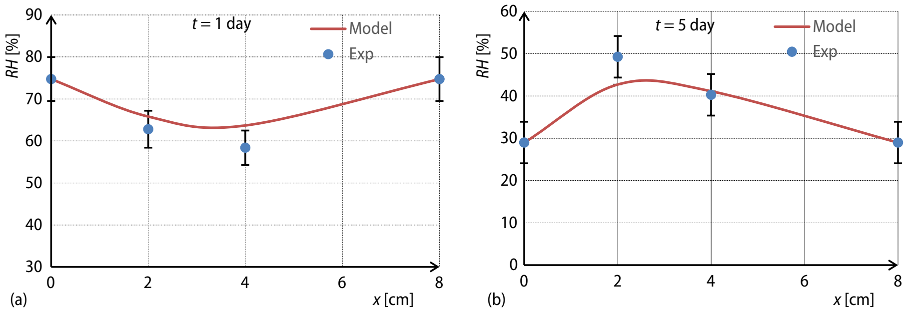

Figure 8. The (a) experimental and (b) modelling RH profile within the sample at $t = 1$ and 5 days (quasi-steady state)

Conclusion

In this paper we investigate the hygrothermal behaviour of bio-based building material, where we presented the studied materials and their origins, hemp concrete, flax wool, and fibre wood in the first time. Then we have presented a series of experimental characterization in order to obtain the hygrothermal properties of the studied materials. These characteristics are the thermal conductivity, specific heat, water vapour sorption and water vapour resistance, the hygrothermal properties deduced experimentally are summarized and used in mathematical model. The model of Philip and de Vries has been used as the based model of our numerical work, which aims to simulate and model the coupled heat and mass transfer within bio-based material. In order to validate the mathematical model, the experimental study is carried on the wood fiber material, the model's input parameters are the hygrothermal properties of wood fiber got experimentally. The sample of wood fibre was instrumented and placed inside climatic chamber, where different ambient conditions were reproduced and the wood fiber behaviour was assessed under various solicitations. The modelling and the measured data were compared and discussed.

According to these results, we can say that our mathematical model describes heat and mass transfer under certain assumptions, gives a good prediction of the hygrothermal behaviour of bio-based material, like the wood fibre insulation. The experimental device is performed by the participation of the laboratory team. As perspectives, more results are to be exploit for remaining case studies, a deep investigation in term of sensitivity of the model. Other materials with other characterisation facilities and model's improvement, example develop a hysteresis model of water vapour sorption in order to achieve more accuracy, asses the behavior of wood fiber under real ambient conditions.

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