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Effect of Temperature-Dependent Sorption Characteristics on the Hygrothermal Behavior of a Hemp Concrete Building Envelope Submitted to Real Outdoor Conditions

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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. Numerical models to describe the coupled heat and mass transfer in porous materials are presented and validated against experimental data. In addition, the effect of temperature-dependent sorption on the hygrothermal profiles of a hemp concrete wall submitted to outdoor real conditions has been conducted. 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 building envelope.

Keywords: Hygrothermal behavior; Temperature-dependent sorption; Hemp concrete.

Nomenclature

C_P	Specific heat at constant pressure	L_v	heat of vaporization
D_T	mass transport coefficient associated to a temperature gradient	T	temperature
$D_{T,v}$	vapor phase transport coefficient associated to a temperature gradient	θ	moisture content
D_θ	mass transport coefficient associated to a moisture content gradient	ρ_0	mass density of dry material
$D_{\theta v}$	vapor phase transport coefficient associated to a moisture content gradient	ρ_l	mass density of water
h_M	mass transfer convection coefficient	ρ_v	mass density of water vapor
h_T	heat transfer convection coefficient	φ	relative humidity

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 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 (Hameury 2005; Olalekan and Simonson 2006; Woloszyn *et al*.2009; Tran Le *et al*. 2010; Shea *et al*. 2013; Maalouf *et al*. 2014). 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 have been measured by many authors (Cerezo 2005; Collet *et al*. 2008; Evrard 2008; Rahim *et al*. 2015). It is highlighted that the one presents high moisture buffering capacity and a good compromise between insulation and inertia materials.

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 (Annex 41).

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 (Tran Le *et al*. 2014). 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 a building envelope (Carsten and Clorius 2004; Ait Oumeziane 2014).

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 are elaborated and implemented in the Simulation Problem Analysis and Research Kernel (SPARK), which is adapted to the complex problems (Sowell and Haves 2001;Wurtz*et al*. 2006; Mendonça *et al*. 2002;Tran Le *et al*. 2009). Then, the simulation tools are validated with experimental results obtained from the test wall realized 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 (Philip and De Vries 1957; Cunningham 1988; Bear and Bachmat. 1990; Pedersen 1992, Kunzel 1995, Mendes *et al*. 2003). 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 moisture (liquid and vapor phases) transport is used (Mendes *et al*. 2003). Forms of moisture transport depend on the pore structure as well as on the environmental conditions. The liquid phase is transported by capillarity whereas the vapor phase is due to the gradients of partial vapor pressure. With these considerations, the mass conservation equation becomes:

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

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

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

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

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 neighboring 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:

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

Where C_{Pm} is the average specific heat which takes into account the dry material specific heat and the contribution of the specific heat of liquid phase.

$$C_{Pm} = C_{P0} + C_{Pl} \frac{\rho_l}{\rho_0} \theta \tag{5}$$

λis thermal conductivity depending on moisture content. Note thatthe more porous a media is, the more the effective thermal conductivity would be on the thermal conductivity of the water content (Sadoun *et al*. 2012).

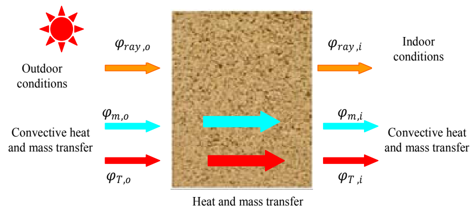

Fig. 1. Schematic representation of heat and moisture transfer through the wall.

Fig. 1 shows the boundary conditions that 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.

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

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

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 (Mendes *et al*. 2003). In this study, 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. Researchers showed that the sorption capacity of materials depends on the temperature (Carsten and Clorius 2004; Ait Oumeziane 2014; Navi and Herger 2005). 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 hygrothermal behavior for the bio-based materials is new (Carsten and Clorius 2004). Concerning the hemp concrete, Ait Ouméziane (2014) 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 (Milly 1982) and Poyet's model (Poyet and Charles 2009).

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 and Charles (2009) 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:

$$\phi_2(T_2,\theta)=\phi_1(T_1,\theta)\frac{P_{sat}(T_1)}{P_{sat}(T_2)}e^{q_{st}(\theta)\frac{M_l}{R}\left(\frac{T_2-T_1}{T_1T_2}\right)} \quad (11)$$

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 (T_1 and T_2).

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. MODEL 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 a 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 (Samri 2008). One side of tested wall was submitted tovarious 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: 20°C/50% RH during 24h followed of 10°C/80% RH during 24h; 40°C/45% RH during 24h and finally finished with 20°C/50% during 24h (see Fig.).

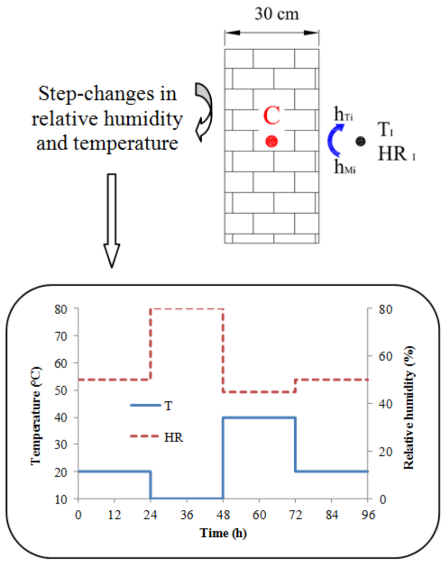

Fig. 2. Experimental procedure: Step-changes in relative humidity and temperature.

Table 1Hygrothermal properties of hemp concrete (AitOumeziane, 2014)

Density	Thermal conductivity	Specific heat capacity	Water vapor permeability
kg/m^3	W/(m.K)	J/(kg.K)	Kg/(m.s.Pa)
320	0.091	1250	1.10^{-10}

The hygrothermal properties of hemp concrete measured by (Ait Oumeziane, 2014) 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 (Tran Le *et al*., 2014; Samri, 2008). 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
- 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 (AitOumeziane, 2014). 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 (Tran Le*et al*. 2009). In order to facilitate the investigation, only the results obtained in the middle of the wall (point C) will be presented.

3.2 Isothermal hygrothermal behavior of hemp concrete wall: Isoth model

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. and

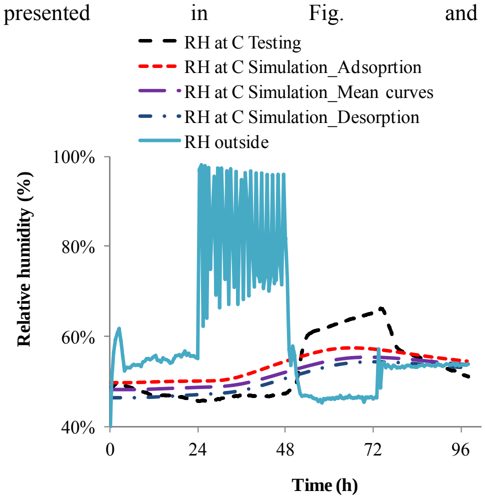

Fig..

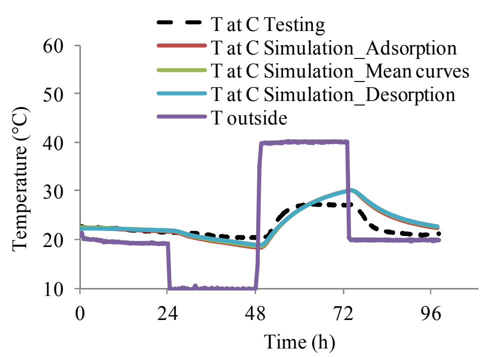

Fig. 3.Variation of temperature at point C – Isoth model and experimental measurement.

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 some discrepancy between experimental and predicted values. Concerning the variation of relative humidity, the computed results did not fit to the experimental one. 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.

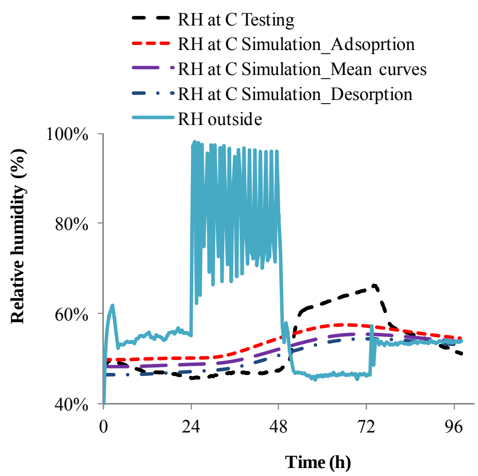

Fig. 4. Variation of relative humidity at point C – Isoth model and experimental measurement.

3.3 Non-isothermal hygrothermal behavior of hemp concrete wall: Non-Isoth model

As mentioned above, 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 are 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 on the comparison between its results and experimental data which are shown in Fig. and Fig.

As can be seen from Fig., 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. with Fig.). Fig. 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. During the adsorption period, the results calculated with the adsorption curve allow a better prediction of the relative humidity variation than those for the model that uses desorption curve or an average sorption curve between adsorption and desorption. 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 equal to ±1.5% of RH.

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.

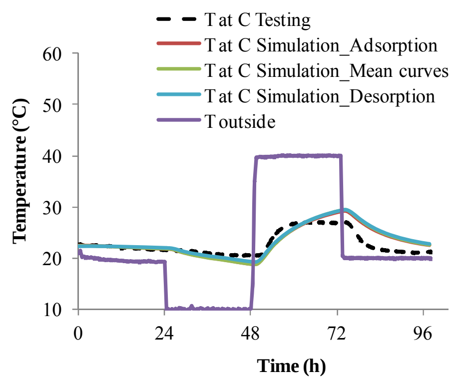

Fig. 5. Variation of temperature at point C – Non-Isoth model and experimental measurement.

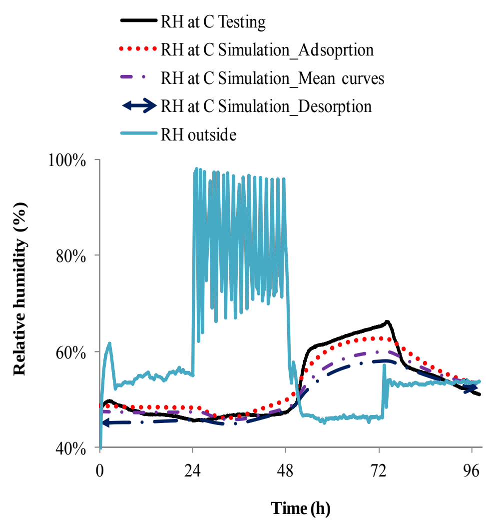

Fig. 6. Variation of relative humidity at point C – Non-Isoth model and experimental measurement.

4. HYGROTHERMAL BEHAVIOR OF A HEMP CONCRETE BUILDING ENVELOPE SUBMITTED TO REAL OUTDOOR CONDITIONS

The application case deals with the effect of temperature-dependent sorption on the prediction of hygrothermal behaviour of a hemp concrete wall submitted to outdoor real conditions. Schematic illustration of boundary conditions of studied hemp concrete wall with 30 cm of thickness is shown in

Fig. The indoor temperature and relative humidity are considered constant and equal to 25°C and 50% , respectively. The Marseille (in France) weather data is used for the outdoor condition. Simulations using Isoth and Non-isoth models are run for three months in summer. The heat transfer coefficients for the outdoor surface ($h_{T,e}$) and for indoor surface ($h_{T,i}$) are 16 W/m^2.K and 9 W/m^2.K, respectively. The mass convection coefficients were calculated by using the Lewis relation by considering the Lewis number equals to 1. The long-wave emissivity and the short-wave absorption coefficients are equal to 0.9 and 0.4. The wall is discretized into 25 nodes and the time step is 240 s.

Fig. 7. Schematic illustration of boundary conditions of studied wall.

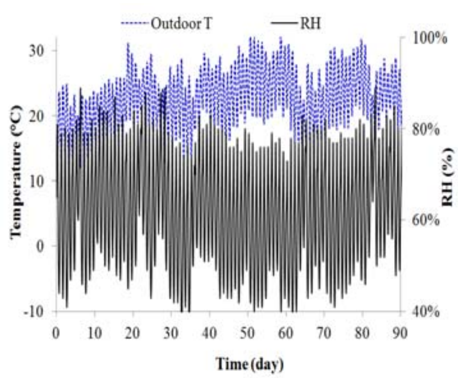

Fig. 8. Outdoor temperature and outdoor relative humidity.

Fig. shows the outdoor temperature and outdoor relative humidity for three months in summer in Marseille. It is noticed that during the night the outdoor temperature dropped down and the outdoor relative humidity could increase to 90 %. The solar radiation on a south-facing vertical wall is given in Fig., in which the radiation flux can reach 445 W/m². Also, the outdoor and indoor water vapor pressures were depicted in this one. Note that the direction of water vapor flow is from high vapor pressure to low vapor pressure which depends on both the relative humidity and the saturation water vapor pressure.

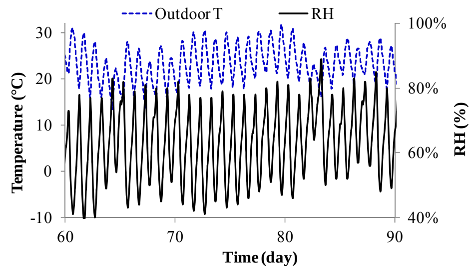

Fig. 9. Outdoor and indoor water vapor pressures and solar radiation on a south-facing vertical wall.

Fig. 10 shows the temperature distribution in the middle of the wall over a period of 5 days for clearer presentation. Firstly, it can be seen that the temperature variation in the middle of the wall is significantly dampened compared with the external

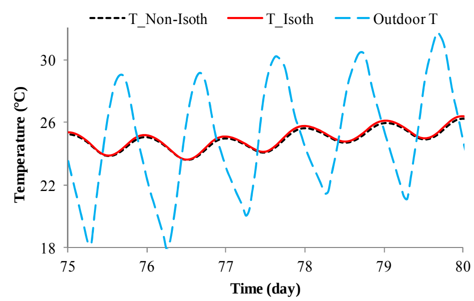

Fig. 10. Temperature distribution in the middle of the wall (x=15 cm) obtained from Isoth and Non-Isoth models.

temperature. Secondly, the results obtained from both models are very close which is in accordancewith previous results. Regarding heat-dampening ability, the temperature profile in the middle of the wall shows a reduction in amplitude of about 88% and 8 hours of time shift compared to variation of the outdoor temperature. Therefore, the use of hemp concrete contributes to avoid overheating in summer. The same conclusions have been drawn from the experimental study on a hemp concrete wall conducted by (Colinart *et al*. 2013; Collet and Pretot. 2014; Samri *et al*. 2014).

Concerning the relative humidity profile in the middle of the investigated wall, it is presented in Fig.. In contrast with the RH profile obtained from the Isoth model, the one from the Non-isoth model shows noticeable daily variation amplitude which can reach 7% of RH. The results are in accordance with the measurements conducted by Samri *et al*.(2014), in which the in situ monitoring of the hygrothermal profiles in building and a hemp concrete building envelope have been carried out. In addition, the authors confirmed that the WUFI model that not takes into account the temperature-dependent sorption cannot reproduce the variation and tendencies of the relative humidity profile in the middle of a hemp concrete wall which is submitted to real outdoor conditions. This one is in accordance with the results obtained from the Isoth model in the present study.

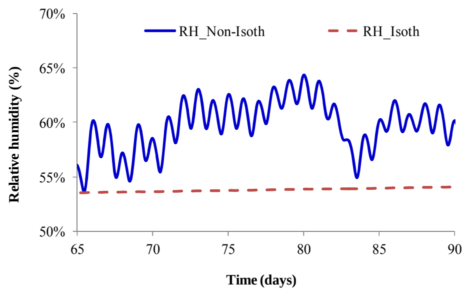

Fig. 11. Relative humidity distribution in the middle of the wall (x=15 cm) obtained from Isoth and Non-Isoth models.

CONCLUSIONS

This article focuses on the development and the 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. To validate the presented model, the numerical results were then compared to the experimental ones. Finally, the application case, which deals with a hemp concrete wall submitted to outdoor real conditions has been carried out. The results showed that taking the influence of temperature on the sorption curves into account is necessary for better prediction of the hygrothermalbehavior of a hemp concrete building envelope. 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.

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