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Accurate numerical simulation of moisture front in porous material

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ABSTRACT

When comparing measurements to numerical simulations of moisture transfer through porous materials a rush of the experimental moisture front is commonly observed in several works shown in the literature, with transient models that consider only the diffusion process. Thus, to overcome the discrepancies between the experimental and the numerical results, this paper proposes to include the moisture advection transfer in the governing equation. To solve the advection-diffusion or the so-called convection differential equation, it is first proposed two efficient numerical schemes whose efficiencies are investigated for both linear and nonlinear cases. The first scheme, Scharfetter–Gummel, presents a Courant-Friedrichs-Lewy (CFL) condition but it is more accurate and faster than the second one, the well-known Crank–Nicolson approach. Furthermore, the Scharfetter–Gummel scheme has the advantages of being well-balanced and asymptotically preserved. Then, to conclude, results of the convective moisture transfer problem obtained by means of the Scharfetter–Gummel numerical scheme are compared to experimental data from the literature. The inclusion of an advective term in the model may clearly lead to better results than purely diffusive models.

1. Introduction

Moisture in porous building elements can affect indoor air quality, thermal comfort and energy consumption/demand. excessive level of moisture may also damage the construction quality and their durability and can lead to mould growth on the inside surface [1,2].

In order to predict those effects in buildings, moisture transfer models have been integrated in early nineties in simulation tools such as Delphin [3], MATCH [4], MOIST [5], WUFI [6], Umidus [7,8] and Blast [9]. In the frame of the International Energy Agency Annex 41, detailed models and their successful applications for accurate assessment of hygrothermal transfer in buildings have been reported [10].

1.1. Problem statement

Nevertheless, some discrepancies normally appear when comparing the results from numerical models and experimental data, as illustrated in Fig. 1. A material, with an initial moisture content w_0, is submitted to an adsorption phase at ϕ_1 and then to a desorption phase at ϕ_2. Results of the simulation under estimate the adsorption process or over estimate the desorption process. In other terms, the experimental moisture front always rushes faster than the simulation results. Numerous studies state similar observations.

In Ref. [11] four cross-laminated timber wall assemblies were studied monitoring a test wall during one year period. The boundary conditions corresponded to outside weather and fixed in time for indoor side. The panels were initially wetted and their drying behaviour were analysed. Simulations were performed with the WUFI program (based on Kunzel diffusion model [12]), using material properties based on laboratory characterisation.

In Refs. [13,14], spruce plywood and cellulose insulation were evaluated considering single-step change increase in humidity or adsorption and desorption cycle tests. The model used to compare the experimental data is based on moisture diffusion due to water vapour density or total gas pressure difference.

In Ref. [15], autoclaved and hemp concretes are used combined with various experimental designs. Data are compared with the Kunzel diffusion model [12]. The comparison reveals the same type of discrepancies, specially for the design operating four 24 h steps of temperature and relative humidity.

In Ref. [16], gypsum boards were conditioned to adsorption and

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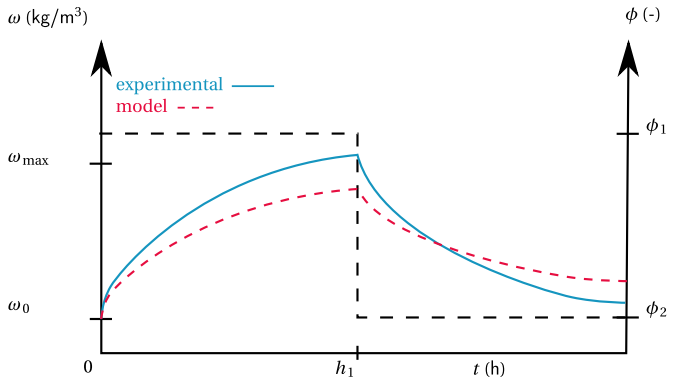

Fig. 1. Illustration of the discrepancies observed when comparing experimental data to results from numerical model of moisture transfer in porous material.

desorption cycles of $(30\% - 70\% - 30\%)$ relative humidity. The whole experiment was conducted for 48*h* under isothermal conditions. The numerical results, in terms of relative humidity, obtained with models from eight different institutions, were compared to experimental data. All the models predicted transient behaviour slower than experimental data.

In Refs. [17,18] experiments were performed in a climatic chamber with hemp concrete samples. Slow and fast cycling tests of adsorption and desorption were done. The discrepancies between experimental data and model results were reduced by considering the hysteresis of the material moisture capacity. In Ref. [19], other hygrothermal data were provided for hemp concrete and compared to a numerical model without hysteresis effect considerations. The conclusions underlined the good tendencies but nevertheless with some lack of accuracies. In Ref. [20], experiments for similar materials under climatic variations were performed. Influence of material properties and convective coefficients were investigated to reduce the discrepancies with experimental data.

Some experimental designs were also operated at the building scale. In Refs. [21,22], a wooden-frame house was instrumented. Vapour was generated during certain periods. The comparison with the numerical model was during and after those periods and some discrepancies were observed in the transient behaviour. An experimental benchmark is presented in Ref. [23], using calcium silicate boards submitted to five adsorption and desorption cycles $(50\% - 70\% - 50\%)$. The model used for comparison included two sub-models considering coupled heat and moisture transfer equations in the material and in the air within the climatic chamber.

All those studies highlighted slower transient behaviour of the results obtained by numerical models comparing to experimental data. The observations are particularly valuable for hygroscopic materials. The models are based on the coupled heat and moisture diffusion in porous materials.

1.2. Objectives of the paper

Some attempts have been done to reduce those discrepancies. Among others, in Refs. [17,18,24], the hysteresis of the sorption material capacity was considered. In Ref. [25] a non-Fickian moisture diffusion model was proposed for thermally modified wood. A possible explanation of the slower transient behaviour of the numerical results is the absence of advection transfer in the proposed model. When the advective and diffusive fluxes have the same direction, the advection mechanism increases the moisture front velocity. Hygroscopics materials such as wood fibre board, gypsum board and aerated cellular concreted have a larger air permeability, almost three orders of magnitude higher, if compared with the concrete one [26]. Some numerical models have been developed considering moisture advection [27]. However, to the knowledge of the authors, no comparison with experimental studies of adsorption/desorption cycles for building materials have been accomplished.

Thus, the objectives of this paper are basically two. First, it aims at analysing the numerical schemes to solve an advective-diffusive problem or the so-called convective moisture transfer in porous materials, represented by a model proposed in Section 2. After a brief recall of the fundamentals and objectives of numerical methods, the Crank–Nicolson and the Scharfetter–Gummel schemes are then described. The primer has been extensively used to solve advective-diffusive equation as for instance in Ref. [28]. The latter is a relatively innovative approach, despite being firstly proposed in 1969, and presents several advantages that will be discussed for both linear and nonlinear problems. Then, the second objective is to illustrate the influence of the moisture convection hypothesis on the comparison with the experimental results. Thus, in the last section, the results of the Scharfetter–Gummel scheme are compared to an isothermal experiment from Ref. [16].

2. Moisture transfer in porous materials by diffusion and advection

The physical problem involves one-dimension moisture convection through a porous material defined by the spatial domain $\Omega_x = [0, L]$. The moisture transfer occurs due to capillary migration, vapour diffusion and advection of the vapour phase. The physical problem can be formulated as the convective moisture equation [27,29–31]:

$$\frac{\partial \rho_{l+v}}{\partial t} = \frac{\partial}{\partial x}\left(k_l \frac{\partial P_c}{\partial x} + k_v \frac{\partial P_v}{\partial x}\right) - \frac{\partial}{\partial x}\left(\frac{P_v}{R_v T} v\right), \tag{1}$$

where ρ_{l+v} is the volumetric moisture content of the material, k_v and k_l, the vapour and liquid permeabilities, P_v, the vapour pressure, T, the temperature, v, the air velocity and, R_v, the water vapour gas constant. Eq. (1) can be written using the vapour pressure P_v as the driving potential. For this, we consider the physical relation, known as the Kelvin equation, between P_v and P_c:

$$P_c = R_v\, T \ln\left(\frac{P_v}{P_s(T)}\right),$$

$$\frac{\partial P_c}{\partial P_v} = \frac{R_v\, T}{P_v}.$$

Thus we have:

$$\frac{\partial P_c}{\partial x} = \frac{\partial P_c}{\partial P_v}\frac{\partial P_v}{\partial x} + \frac{\partial P_c}{\partial T}\frac{\partial T}{\partial x}.$$

The temperature remains the same at the boundaries. Even if heat transfer occurs in the material due to latent heat evaporation, the temperature variations in the material are assumed negligible. Thus, the second right-hand term vanishes and we obtain:

$$\frac{\partial P_c}{\partial x} = \frac{R_v\, T}{P_v}\frac{\partial P_v}{\partial x}.$$

In addition, we have:

$$\frac{\partial \rho_{l+v}}{\partial t} = \frac{\partial \rho_{l+v}}{\partial \phi}\frac{\partial \phi}{\partial P_v}\frac{\partial P_v}{\partial t} + \frac{\partial \rho_{l+v}}{\partial T}\frac{\partial T}{\partial t}.$$

Under isothermal conditions, the second right-hand term of the