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On the estimation of moisture permeability and advection coefficients of a wood fibre material using the optimal experiment design approach

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ABSTRACT

This paper presents a practical application of the concept of Optimal Experiment Design (OED) for the determination of properties of porous materials with *in situ* measurements and an identification method. First, an experimental set-up was presented and used for the measurement of relative humidity within a wood fibre material submitted to single and multiple steps of relative humidity variation. Then, the application of OED enabled to plan the experimental conditions in terms of sensor positioning and boundary conditions out of 20 possible designs. The OED search was performed using the Fisher information matrix and *a priori* knowledge of the parameters. It ensures to provide the best accuracy of the identification method and thus the estimated parameter. Optimal design results have been found for single steps from the relative humidity $\phi = 10$–75%, with one sensor located at the position X between 4 and 6 cm, for the estimation of moisture permeability coefficients, while from $\phi = 75\%$ to $\phi = 33\%$, with one sensor located at $X^{\circ} = 3\ \mathrm{cm}$, for the estimation of the advection coefficient. The OED has also been applied for the identification of couples of parameters. A sample submitted to multiple relative humidity steps ($\phi = 10$–75–33–75%) with a sensor placed at $X^{\circ} = 5\ \mathrm{cm}$ was found as the best option for determining both properties with the same experiment. These OED parameters have then been used for the determination of moisture permeability and advection coefficients. The estimated moisture permeability coefficients are twice higher than the *a priori* values obtained using standard methods. The advection parameter corresponds to the mass average velocity of the order of $\mathrm{v} = 0.01\ \mathrm{mm/s}$ within the material and may play an important role on the simulation of moisture front.

1. Introduction

Heating or cooling strategies and design of building envelopes are commonly based on numerical simulations performed by hygrothermal tools such as Delphin [1], MATCH [2], MOIST [3], WUFI [4] or Umidus [5,6] or by whole-building simulation programs, used in the frame of the International Energy Agency Annex 41 [7]. Details about the mathematical models and their numerical schemes are described in [8]. Those programs are capable to simulate whole buildings considering the combined heat and moisture transfer through porous elements.

Nevertheless, porous materials have hygrothermal properties strongly dependent on moisture content - mainly highly hygroscopic materials such as wood, are commonly estimated using experimental characterisation methods. The moisture capacity is traditionally determined using the gravimetric methods (ISO 12571). Samples are weighed for different relative humidity conditions, ensured by salt solutions. For the vapour permeability, the most common measurement procedure is based on the standard (ISO 12572). It measures the mass variation of a material sample under a controlled difference of relative humidity between both sides. The vapour permeability is estimated for different relative humidity levels (dry and wet cup). For the liquid permeability, the sample is exposed to a liquid pressure gradient. The permeability is estimated by measuring the liquid flux at the equilibrium.

Even if measurements of these properties are well established and largely reported in the literature, some discrepancies can appear when comparing experimental data from *in situ* measurements to numerical model results. A material, with an initial moisture content w_0, is submitted to an adsorption phase at relative humidity ϕ_1 and then to a desorption phase at relative humidity ϕ_2. Results of the simulation underestimate the adsorption process or overestimate the desorption process. Numerous studies state similar observations. Interested readers may consult [9,10] for a preliminary introduction to this investigation.

To answer this issue, models are calibrated using *in situ*

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Nomenclature

Latin letters

a	advection coefficient [s/m]
b	volume ratio of moisture [–]
d	moisture diffusion [s]
c	moisture storage capacity [kg/m^3/Pa]
h	vapour convective transfer coefficient [s/m]
j	moisture flux [kg/(s·m^2)]
k	permeability [s]
L	length [m]
P_c	capillary pressure [Pa]
P_s	saturation pressure [Pa]
P_v	vapour pressure [Pa]
R_v	water gas constant [J/kg/K]
T	temperature [K]
v	mass average velocity [m/s]
V	volume [m^3]

Greek letters

β	shrinkage coefficient [–]
ϕ	relative humidity [–]
ρ	specific mass [kg/m^3]

measurements for estimating material properties to reduce the discrepancies between model predictions and real performance. For instance, in [11], liquid and vapour transfer coefficients are determined for hemp material submitted to a drying process. In [12], moisture- and temperature-dependent diffusivity and thermophysical properties are estimated using only temperature measurements under a drying process. In [13], moisture properties of a wood fibre material were estimated and so the parameter estimation problem revealed a resistance factor for vapour permeability lower than 1, which is physically unacceptable as the vapour diffusion of through the porous material cannot be faster than in the air. Physical models commonly take into account only diffusion transfer and authors conclude that other physical phenomena, such as moisture advection, might not be ignored. Therefore, this research has been conducted to estimate the moisture permeability and advection coefficients of a similar wood fibre material. First, an experimental set-up has been used, enabling to submit the material samples to several steps of relative humidity, under isothermal conditions. Temperature and relative humidity sensors have been placed within the samples.

The estimation of the unknown parameters, *e.g.*, wall thermophysical properties, based on observed data and identification methods, strongly depends on the experimental protocol and particularly on the imposed boundary conditions and on the location of the sensors. In [14], the concept of searching the Optimal Experiment Design (OED) was used to determine the best experimental conditions in terms of quantity and location of sensors, and flux imposed to the material. These conditions ensure to provide the best accuracy of the identification method and thus the estimated parameter. It was studied for the identification of hygrothermal properties of a porous material. Even though the approach was verified by solving 100 inverse problems for different experiment designs, it remained theoretical as no real experimental data nor existing facility were considered.

This research intends to go one step further. The issue is to use the methodology to determine the OED according to the existing facility. It first aims at defining the optimal boundary condition and location of the sensor to ensure an accurate solution of the parameter estimation problem. Then, experimental measurements are provided respecting the particular design and used to estimate the unknown parameters. Thus, this article is organised as follows. Next Section 2 presents the physical problem and the methodology of OED searching. Then, Section 3 describes the experimental facility used for providing measurements in a wood fibre material. In Section 4, the OED is searched according to the different possibilities for the estimation of one or several parameters. Section 5 provides an estimation of the moisture permeability and advection coefficients, given the experimental data obtained according to the OED.

2. Methodology

2.1. Physical problem and mathematical formulation

The physical problem involves one-dimension moisture convection through a porous material defined by the spatial domain $\Omega_x = [0,L]$ as shown in Fig. 1. 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 [15–17]:

$$\frac{\partial \rho_{l+v}}{\partial t} = \frac{\partial}{\partial x}(j_d + j_a), \tag{1}$$

where ρ_{l+v} is the volumetric moisture content of the material, j_d diffusion flux and j_a the advection flux. The diffusion flux can be written as:

$$j_d = k_l \frac{\partial P_c}{\partial x} + k_v \frac{\partial P_v}{\partial x},$$

where k_v and k_l, the vapour and liquid permeabilities, P_v, the vapour pressure and P_c, the capillary pressure. Eq. (1) can be rewritten 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:

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

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

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 phase change, the temperature

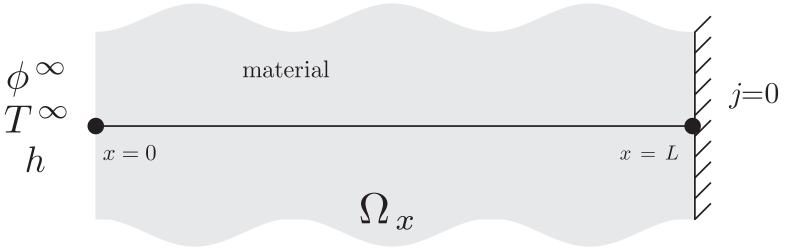

Fig. 1. Illustration of the physical problem.