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► To cite this version:

Arnaud Challansonnex, Floran Pierre, Joel Casalinho, Patrick Perre. Mass diffusivity of various building materials determined by inverse analysis of RH evolution at the back face of the sample. Eurodrying'2017, Jun 2017, Liège, Belgium. pp.19 - 21. hal-01816582

HAL Id: hal-01816582

<https://hal.science/hal-01816582>

Submitted on 15 Jun 2018

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MASS DIFFUSIVITY OF VARIOUS BUILDING MATERIALS DETERMINED BY INVERSE ANALYSIS OF RH EVOLUTION AT THE BACK FACE OF THE SAMPLE

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Abstract:

This work used a new method for the determination of the mass diffusion coefficients of hygroscopic materials [1]. The experiment consists in submitting one face of the sample to a variation in time of the relative humidity (RH) and measuring the RH on its back face. The imposed RH and temperature are measured during the test and serve as boundary conditions in a comprehensive computational code to solve heat and mass transfer in porous media. This new method was used to characterize a various building materials such as autoclave aerated concrete, plaster, massive wood or wood based materials. This paper includes the determination of sorption isotherms of the selected materials which are needed for the determination of mass diffusivity. The study also confirms that accurate values of mass diffusivity can be obtained even if sample are not at the equilibrium, which allows the characterization time to be drastically reduced.

Keywords: energy saving, mass diffusivity, relative humidity, renewable materials, sorption isotherm.

Introduction

In Europe, the building sector is responsible for the largest part of energy consumption. To limit this consumption, the thermal performances of constructions are getting more and more challenging and designers need to model physical phenomena with great accuracy. Among them, the strong influence of coupled heat and mass transfer on energy consumption is well-established [2]. This is especially true for renewable materials, which generally have a high moisture buffering effect [3]. Consequently, Building Energy Simulations (BES) models must account for coupled heat and mass transfer, which gave rise to a crucial demand of mass transfer characterisation: mass diffusivity and sorption isotherms [4].

The mass diffusion coefficient is usually determined in steady-state regime for building materials using the so-called *cup method* [5]. However, because of the alternation of day and night, materials in buildings are often in transient state which can change significantly their behaviour. To address this problem, a new method for the determination of mass diffusion

coefficients in hygroscopic materials in unsteady regime was recently proposed [1]. The principle is to submit one face of a sample to a variation in time of RH and to measure the RH on its back face. The experimental data are then analysed with a physical model by inverse analysis. The relevance of this method was discussed in this above-mentioned paper. It offers several advantages such as its simplicity and rapidity. The most demanding part in terms of material characterisation is the determination of the sorption isotherms that are needed to fill the physical code and which are anyway needed for any BES [6].

In the present work, this new method was used to characterise a set of contrasted building materials. In particular, the method was found to be effective for both mineral and lignocellulosic based materials despite their contrasted hygroscopic behaviour.

Materials and Methods

Materials

The building materials tested in this study are autoclaved aerated concrete (AAC), plaster plate (BA13) whose cardboard layer has been removed, medium density fibreboard (MDF), and two wood species, maritime pine (*Pinus pinaster*) and poplar (*Populus euroAmericana 'koster'*), both oriented in tangential direction. The choice has been made to study both mineral and lignocellulosic materials in order to have a large diversity of hygroscopic behaviour. For each material, two disk-shaped sample with a diameter of 72 mm were cut to duplicate the experimental data (Fig. 1). The mean thickness and density of these samples are presented in Table. 1. Note that the basic wood density (oven-dry mass to green volume) is indicated for wood samples. Small cuboid shape samples (less than one cm³) were cut to determine the sorption isotherms. More details about the sampling and measurement protocols can be found in [1, 7].



Table. 1. Average of density and thickness of the disk-shape samples. For poplar and maritime pine, the density value is the basic wood density

Material	Density (kg.m ⁻³)	Thickness (mm)
Autoclaved aerated concrete	664	20
Plaster	941	10.5
MDF	633	10

Maritime pine	319	9
Poplar	311	8.5

Table. 1. Average of density and thickness of the disk-shape samples. For poplar and maritime pine, the density value is the basic wood density.

Measurement of sorption isotherm

The experimental setup (Fig. 2.) is based on a magnetic suspension balance (*Rubotherm*). The principle consists in submitting the sample to a sudden step of RH under isothermal conditions. The mass variation of sample is measured over time with very high resolution (0.01 mg) and regular taring enable a very high reproducibility (± 0.02 mg). Note that because the electronic part is isolated from the sample room, tough conditions in terms of RH and temperatures can be obtained without condensation or leakage problems. More information about this experimental setup can be found in [8].

Since the products might depict hysteresis behaviour, both sorption and desorption were studied: the tests were performed from 15% RH up to 75% RH in steps of 15% at 35°C for sorption. The same protocol was applied in desorption from 75% RH down to 15% RH. The oven-dry mass of each sample was determined after the experiment. For this purpose, lignocellulosic products were oven dried at 103 ($\pm 2^\circ\text{C}$) until equilibrium. Mineral materials were submitted to a flow of dry air at 35°C (dew point of -30°C) until equilibrium to avoid possible volatilisation of chemicals.



Fig. 2. Sorption isotherm device with: 1-Magnetic suspension balance; 2-Heating jacket enclosing the measuring chamber; 3-Humidity generator; 4-Shiller for temperature control.

Measurement of mass diffusivity

The measurement principle consists in submitting one face of a sample to a variation of RH and to measure the RH evolution on its back face. For this purpose, the samples are placed in an in-house sample holder (Fig. 3b) that ensures a one-dimensional transfer along the thickness. Several supports are placed inside a climatic chamber (Fig. 3a), which imposes a sudden change of relative humidity (RH) under isothermal conditions. At the back face of the sample, a sensor

measures the evolution of RH and temperature. In this study, a RH step from 40% to 60% was applied at 35°C. Additional information on this device and protocol can be found in [1].



Fig. 3. (a) General view of the experimental device (left) and (b) sample holders inside the chamber (right).

Data analysis

Sorption isotherms

The sorption data are intended to be used as input parameters in the heat and mass transfer computational code. The average value between sorption and desorption was considered here, as usually done in BES [9]. The experimental data were fitted using the GAB model (1) as its expression is able to fit the whole curve for a wide range of materials [10, 11]:

$$X = X_{12} \cdot C \cdot K \cdot RH / ((1 - K \cdot RH) \cdot (1 + (C - 1) \cdot K \cdot RH)) \quad (1)$$

with X is the moisture content and RH the relative humidity (both dimensionless)

The three model parameters were determined using the Levenberg-Marquardt least square method.

Mass diffusivity

The mass diffusivity is determined by inverse method. Contrary to the sorption isotherms, the procedure is more sophisticated as:

- The physical model involves a comprehensive set of coupled heat and mass transfer equations and a relevant computational solution,
- The actual conditions imposed at the front face of the sample are used as boundary conditions in the computational model,
- The objective function to be minimised is the difference between the recorded RH value at the back face of the sample and the computed one.

The sample characteristics (thickness, density, porosity sorption isotherm) are obviously input parameters of the code. For the minimisation procedure to work accurately, several unknown parameters are identified (diffusivity, external heat transfer coefficient, shift between RH sensors and initial moisture content). Some of these parameters just allow the objective function to be correctly minimised while the actual goal of the minimisation procedure is to determine the mass diffusivity. Additional information on the physical model and this inverse analysis can be found in [1].

Results and discussion

Fig. 4.a) is depicted the five sorption isotherms. For a better reading and because of the wide range of equilibrium moisture content (EMC), a logarithmic scale is used. The markers are the experimental points and the lines represent the fitted GAB model. The corresponding parameters can be found in table 2. As expected, lignocellulosic materials are highly hygroscopic while mineral-based materials have a very small hygroscopic domain (up to two decades smaller). Note that maritime pine, poplar and MDF have very closed sorption isotherms, because the secondary cell wall layer of lignocellulosic materials similar macromolecular composition. The content of glue in MDF is small enough to have negligible effect on the hygroscopic behaviour [13]. For all these materials, our values are in reasonable agreement with literature data [12,13,14]. Note however that mineral materials may present significant differences in hygroscopic behaviour from a product to another, depending on the manufacturing conditions.

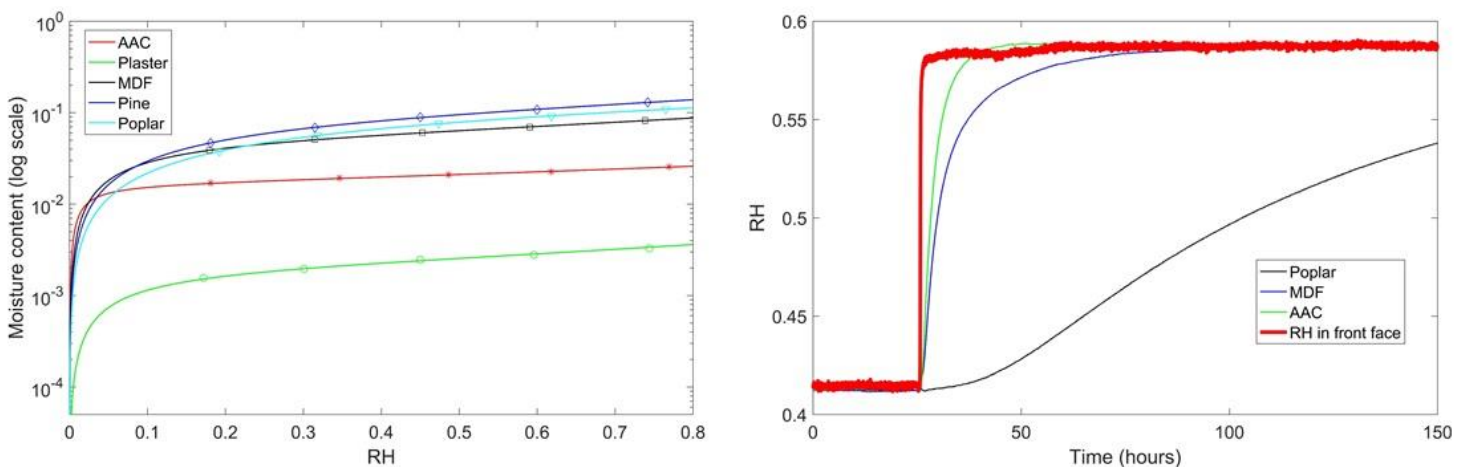


Fig. 4. (a) All different isotherms identified with G.A.B. model (left) and (b) evolution of the RH at the back face for some contrasted materials(right).

Fig. 4.b) proposes some examples of the evolution of the RH value at the back face of the sample, which shows the great difference of time constant among materials. The identified values of the dimensionless diffusivity f confirm this wide range (Table 2). The results obtained for AAC are in good agreement with the literature data and the residue between experimental and simulation is excellent. In the case of plaster, the mass diffusion coefficient seems to be larger than literature data even though the residue is also quite good. This is likely to be due to

the difference between steady-state and dynamic determination. This is an important issue to be addressed in material characterisation, specifically in building materials: most routine characterisation protocols work in steady-state while materials are mostly in dynamic regimes while in-use. Additional tests using the cup method are in progress in our lab to further investigate this point. Mass diffusion coefficient obtained for lignocellulosic materials are in reasonable agreement with literature data.

Materials	Sorption isotherms			Reduced diffusivity (f)	
	Parameters of G.A.B. model			Sample 1	Sample 2
	$X_{12} (.10^3)$	C	K ($.10^2$)		
Autoclaved aerated concrete	16.59	143	46.11	0.095	0.091
Plaster	1.986	19.26	58.48	0.46	0.67
MDF	49.69	13.54	55.24	0.090	0.095
Maritime pine	101.2	7.37	49.34	0.0027	0.0028
Poplar	110.1	6.121	36.82	0.0042	0.0065

Table. 2. The complete set of material data determined in the present work.

Some materials present very long diffusion time constants and thus can take a long time to reach the equilibrium. For example, poplar took more than 400 hours to be considered as in equilibrium. Table 3 shows the reduced diffusivity obtained for maritime pine when using only one part of the experimental data: 50; 150; 300 and 500 hours after the RH stepwise (500 hours corresponding to the whole set of data). The error on the mass diffusivity consider the value determined with the full data set as reference value. When using only the first 50 hours after the RH step, the error is only 7.5% which is quite remarkable as this duration is just 10 % of 500 hours. This result confirms that this back-face method is able to characterise the mass diffusivity without the need to wait for the equilibrium [1].

Time of identification	50 hours	150 hours	300 hours	500 hours
Reduced mass diffusivity($\times 10^2$)	0.4606	0.4179	0.4088	0.4284
Relative error	7.5 %	2.4 %	4.5 %	0 %

Table. 3. Identified values of the reduced diffusivity and corresponding relative error obtained for poplar when the identification use on a subset of the experimental data, limited to a certain time after the RH stepwise.

Conclusion

This work exploits a new method to determine the mass diffusion coefficient in dynamic regime using the RH evolution at the back face of the sample. Different building materials have been characterised. Some important conclusions can be drawn from this work:

- This new method works well for materials with very contrasted hygroscopic behaviours,
- A comprehensive data set is proposed for 5 building materials,
- The determination of the mass diffusion coefficient is possible at much shorter times than the time required to reach equilibrium, which is a large advantage for slow diffusive materials.

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