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Temperature dependence of sorption isotherm of hygroscopic building materials. Part 1: Experimental evidence and modeling

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ABSTRACT

The knowledge of sorption isotherm is of high importance when evaluating the performance and the durability of building envelope. Whereas the influence of hysteresis was often investigated, less attention has been paid to the influence of temperature. In the present paper, a specific experimental protocol is defined to investigate the influence of temperature on relative humidity variations within three building materials (Autoclaved Aerated Concrete, wood fiber insulation and hemp concrete). The measurements are analyzed in terms of a hygrometric coefficient κ [%r.h./°C], defined as the maximal relative humidity amplitude against the maximal temperature amplitude, and are compared to three modeling approaches: temperature dependent sorption model, Kelvin equation and Clausius-Clapeyron equation. Discussions show that the third approach is relevant and that it can be used to evaluate effortless the isosteric heat of sorption and the temperature dependence of the sorption isotherm.

1. Introduction

In building made of hygroscopic materials, excess moisture has several effects on the energy performance, indoor air quality (mold growth, increase of VOC emission) and durability (physical, chemical and biological damages) [1]. Therefore, numerous models were developed to predict moisture level over time and space in building materials and envelopes [2,3]. However, reliable experimental data are required to validate these models. Recently, Tada and Watanabe [4], Roels et al. [5] or Phillipson et al. [6] propose an overview of current techniques of moisture measurements in building materials. For instance, transient moisture content profiles can be determined in a non-destructive way by several techniques like gamma-ray attenuation technique [7], X-ray or neutron radiography [8,9] or NMR technique [10,11]. These techniques provide continuous information with a good spatial resolution; however, they require specific and expansive equipment and are not feasible to use in-situ. On the other hand, a common and relative cheap alternative for in-situ assessment of internal moisture state relies on the local measurement of internal relative humidity (RH) by using embedded relative humidity sensors in drilled holes [12,13]. This technique has been widely used to monitor building walls [14,15]. However, making a hole into a sample has an effect on its behavior in terms of building physics. First, internal RH of a material must be rather defined as the RH of the gaseous phase around the porous material, characterized by a pore network filled with an interstitial liquid phase [16]. Nevertheless, the time characteristics of the heat and mass transfer are much lower in the gaseous phase than within the porous material (some seconds compared with some minutes or hours). Consequently, the gaseous phase can be assumed in instantaneous equilibrium with the porous material and its hygrothermal response depends mainly on the variation of boundary conditions with the porous material. Second, Granja et al. [12] analyzed the measuring procedure regarding, among others, the type of RH sensor (home-made vs. commercial and calibration issue), the size of the embedment body into which the RH sensor

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Table 1
Estimated BET and GAB coefficients of the investigated materials.

	BET		GAB			Temperature
	$w_{m,BET}$	C_{BET}	$w_{m,GAB}$	C_{GAB}	k_{GAB}	
AAC	0.0064	77.77	0.0094	80	0.73	25 °C
WFI	0.0314	7.44	0.0569	3	0.77	20 °C
HC	0.0152	11.17	0.0165	10	0.925	23 °C

is inserted or the existence of interface materials (e.g. membranes) between the sample and the embedded sensor. Their results show that there is almost no variability in the RH measurement regarding the above-mentioned parameters.

Last, the RH measurement in hygroscopic building materials should be analyzed regarding the building physics. For instance, the effect of change of external relative humidity on internal RH measurement is relative straightforward [14,15]. On the other hand, the effect of changes in temperature on RH is particularly intriguing: indeed, RH tends to decrease with increasing temperature in the atmosphere, while it tends to increase in the drilled hole [17–28]. This temperature effect was observed at different scale (small sample or wall) and for different temperature variations (temperature step, diurnal cycle or solar radiation). Furthermore, it is more significant for organic building materials than mineral one and the correlation between temperature and RH measurements depends on the RH level within the material. This effect is generally attributed to the temperature dependence of the sorption curve [29–35] and evaluated by considering the temperature dependence of liquid water density and surface tension in Kelvin equation [36]. However, Radjy et al. [20] and Grasley and Lange [21] underline that Kelvin equation fails in predicting the temperature effect.

In this work, we aim to reconsider the influence of the temperature on RH variations within three hygroscopic building materials differing in their nature, namely Autoclaved Aerated Concrete, Wood Fiber Insulation and Hemp Concrete. In this view, the paper is built up as follows: Section 2 presents a new set of experimental data recorded on a specific laboratory set-up. In particular, the results are discussed in terms of hygrometric coefficient κ, defined as the maximal internal RH change over the maximal internal temperature change at constant moisture content. In Section 3, the experimental results are compared to numerical results predicted by different modeling approaches evaluating the temperature dependence of sorption isotherm. Last, a reflection on defining a new protocol for evaluating more rapidly the temperature dependence of sorption isotherm is proposed in Section 4.

2. Experiments

2.1. Materials

Three building materials differing in their nature (mineral, organic or both) have been chosen for this study: Autoclaved Aerated Concrete (AAC), Wood Fiber Insulation (WFI), and Hemp Concrete (HC). Hygrothermal properties of AAC and WFI were taken from the literature [37,38] whereas HC properties were measured in the lab [14,39]. Measured sorption isotherm and their fit with BET and GAB models (see Section 3.1.1) are plotted in Fig. 1. Fitting coefficients and measurement temperature are gathered in Table 1. Note that the measurement temperature is not the same for all materials. Table 2 summarizes the density, the dry thermal conductivity and the dry vapor diffusion resistance factor. All materials are hygroscopic and permeable; AAC is less hygroscopic than HC and WFI. On the other hand, AAC and HC have similar transfer properties, while WFI presents a lower density and thermal conductivity. It should be noted that all these insulating materials are usually coated when used in building envelope.

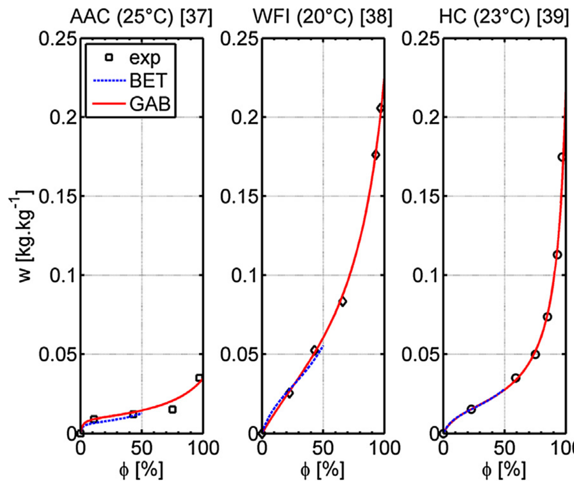

Fig. 1. Sorption isotherm of the investigated materials measured at a reference temperature and BET and GAB fitting.

Table 2
Representative hygrothermal properties of the investigated materials.

	Density [kg m^{-3}]	Thermal conductivity [W m^{-1} K^{-1}]	Dry vapor diffusion resistance factor [–]	Reference
AAC	500	0.12	10	[37]
WFI	150	0.042	6	[38]
HC	450	0.1	5	[14,39]

Table 3
Sample dimensions and sensor positions.

	Dimension (L × W × H) [mm^3]	Sensor position (from the top surface) [mm]		
		S1	S2	S3
AAC	100 × 100 × 63	9	27	48
WFI	100 × 66 × 60	8	25	44
HC	148 × 148 × 100	13	48	80

2.2. Experimental facilities and protocols

The experimental set-up used in this work was previously developed to study the moisture buffering behavior of uncoated and coated hemp concrete sample [14,15] and is adapted to investigate the influence of temperature on relative humidity variations within hygroscopic building materials. An overview of the set-up is given in Fig. 2 and essential informations are reminded hereafter.

Experiments are mainly performed on sample sealed on all surfaces except the top one with aluminum tape. The dimensions of the samples are given in Table 3: these dimensions are larger than the Representative Element Volume of each materials, but small enough so that 3D heat transfers occurring within the sample allow reaching rapidly thermal equilibrium. On the other hand, moisture may be exchanged through the open surface and 1D moisture transfer occurs within the sample. Nevertheless, since moisture transfers are slower than thermal transfers, it allows investigating the influence of temperature on sample hygric behavior.

Temperature and RH variations are monitored with three capacitive humidity sensors (Sensirion SHT 75, Staefa, Switzerland) with dimensions of 5.1 × 3 × 20 mm^3 (L × W × H) embedded in drilled holes with 8 mm in diameter. Whatever the sample, one sensor is located directly close to the top surface and two others deeper