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Combined effects of sorption hysteresis and its temperature dependency on wood materials and building enclosures-part II: Hygrothermal modeling

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A B S T R A C T

Hygroscopic materials such as wood and wood based materials have been widely used as insulation and surface moisture buffering materials due to their low thermal conductivity and high moisture capacity. And their hygrothermal performance is mainly dependent on the moisture properties, such as sorption isotherm and water vapor permeability etc. Instead of a univalued function of relative humidity, sorption isotherm of wood materials is not only affected by sorption history, but also temperature dependent. This work is devoted to a better understanding of the effects of temperature dependent sorption hysteresis on moisture transport in wood and wood based materials under ambient temperature and relative humidity variations through experimental investigations and numerical modeling. In part I, the formulated hygrothermal model based on local thermodynamic equilibrium assumption and Frandsen's hysteresis model are experimentally validated. In this part, the effects of sorption hysteresis and its temperature dependency are investigated under several dynamic conditions through numerical modeling. Hysteresis should be taken into account in determining the moisture buffering capacity, and temperature dependency should be considered to investigate the RH variation in the material when it is subjected to drastic temperature fluctuation. Then heat and moisture transport through a roof assembly under natural climate conditions is further modelled to show the effects of temperature dependent sorption hysteresis in practical applications.

1. Introduction

Indoor air humidity is an important parameter to determine the perceived indoor air quality (IAQ) [1] and occupants' thermal comfort [2]. It also plays a role in the durability of building materials and components. High humidity may cause moisture condensation, mold growth, insulation failure and material degradation etc. [3]. In building physics, for the issues of energy conservation and avoiding moisture related problems in building components and enclosures, understanding heat and moisture storage and transport phenomena in building materials and enclosures is of crucial importance. Hygroscopic materials, such as wood and wood based materials, have an ability to adsorb and desorb moisture with the variations of surrounding conditions. This characteristic has been utilized in building physics to attenuate the moisture variations and moderate the indoor thermal environment [4–6]. Therefore, sorption isotherm is an important hygric property of building materials for hygrothermal modeling.

Hameury [7,8] studied the moisture buffering capacity of heavy timber structures which were directly exposed to an indoor climate. The simulation results showed that the buffering capacity of a massive timber structure depends on the air exchange rate and the effective wood wall area. The damping of the variation of indoor air relative humidity is especially appreciable at the low ventilation rates with sufficiently large surface area. Osanyintola and Simonson [9] studied the potential of hygroscopic materials (spruce plywood) to reduce energy consumption in buildings; they found that in hot and humid climates, applying hygroscopic materials has a promising energy saving of HVAC systems, with a reduction of energy

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consumption for heating and cooling up to 5% and 30% respectively. Moon et al. [10] investigated the effect of moisture transport on energy efficiency, thermal comfort and mold growth risks in residential building based on hygrothermal modeling. They stated that the moisture buffering effect could significantly reduce the amplitude of relative humidity fluctuations during all seasons. Barclay et al. [11] investigated the hygrothermal performance of buildings with walls constructed with hemp-lime. The whole building simulation indicated that including moisture transport has a large influence on indoor relative humidity, however little influence on overall heating and cooling energy demand.

During the last decades, there is an increasing interest in moisture buffering of hygroscopic materials in both scientific investigations and practical applications [12–14]. The moisture buffering performance at a room level may be influenced by many factors, such as material property, local climate, moisture loading profiles [15] and room factors corresponding to specific applications etc. [3,7,16–18]. From material property point of view, the buffering effect mainly depends on the moisture capacity (sorption isotherm) and vapor permeability [15]. And also many investigations have been carried out for material characterization, e.g. Refs. [19,20]. However, for most of the works, sorption hysteresis of the moisture storage curve is not taken into consideration.

Since last few decades, many computerized hygrothermal modeling tools for heat, air and moisture transfer simulation in building elements have been developed, such as WUFI [21], MATCH [22], MOIST [23] etc. Among them, only a few models consider the effect of sorption hysteresis (e.g., MATCH), while the others assume that the influence of sorption hysteresis on the hygrothermal behavior of material is marginal [24–26]. Omitting the effect of hysteresis on moisture transport appears to be a suitable approach in many situations, however, it is not the case for some building materials, such as wood fiber boards etc. [27].

It is observed from measurement that all the sorption isotherms lie on or in between the main ad- and desorption branches [28,29]. Therefore, for building material exposed to natural conditions, its sorption process actually follows the intermediate scanning curves running through the space delineated by the main ad- and desorption curves with the diurnal and seasonal variations of relative humidity. These scanning curves will limit the slope of the sorption isotherm curve, and the effective moisture capacity of the material will be significantly reduced [30]. Kwiatkowski et al. [31] studied the sorption hysteresis effect of gypsum on indoor air humidity and energy demand; they stated that for gypsum, the impact of hysteresis is limited but still perceptible at building scale. The relative difference of moisture content of the indoor air between models with sorption hysteresis and with merely ad- or desorption isotherm of gypsum can reach as much as 22.5%. Even if the mean curve of ad- and desorption isotherms is adopted, for strongly dynamic variations of the boundary conditions, the hysteresis effect of gypsum is also significant [26]. Compared to gypsum, wood materials have a more pronounced hysteresis loop; much more significant effect of sorption hysteresis is expected [17]. Salin [32,33] clearly argued that there is a need to include hysteresis phenomenon in future drying models, as well as in models for the interaction of climate and wood in building environment. Time [25,34] stated that a better agreement between measurements and calculations of moisture content in wood can be obtained if hysteresis is considered than if only a mean sorption isotherm is used, when wood material is exposed to cyclic step variations of relative humidity. Rode and Clorius [35] indicated that taking hysteresis into account will lead to a reduction of the effective moisture capacity for short-term moisture variations.

However, contrary arguments about the significance of hysteresis also exist in literature [36]. According to Pedersen [37], the influence of hysteresis is dependent on the cyclic steps of the boundary conditions and the purpose of the simulation. He stated that hysteresis is worthwhile considering when the short-term dynamic moisture response of a material is of interest; however, for long-term behavior of building construction, the mean curve of ad- and desorption isotherms can be used and daily variations resulting from the intermediate scanning curves may not be relevant. Roels et al. [38] argued that it is more important to have a good expression of sorption isotherm than to model hysteresis. Carmeliet et al. [39] stated that hysteresis has a limited influence on the moisture buffering capacity of wood (oak) when it is placed in a room as hygroscopically active material, and they attributed the limited influence to the minor differences in moisture capacity between the main adsorption, desorption and hysteretic scanning curves. However, according to Time [25,34] and Svennberg [30], the intermediate scanning curves significantly reduce the moisture capacity.

Besides, the sorption process in wood material is also affected by temperature. On the whole, studies on temperature effects, on hysteresis effects or on the combined effects of temperature and hysteresis are rather scarce in literature [40]. Most of these works in literature dealing with temperature effect focused on the temperature dependency of the main sorption isotherms. Pedersen's model [22] and Frandsen's model [41] have been used by other authors to study hysteresis effect [26,39,42–46], but all these works didn't take temperature effect on sorption isotherms into account; while other investigations on the effect of temperature dependency neglected the sorption hysteresis [47–49]. To the authors' knowledge, there are only two papers [35,50] which attempted to study the combined effect of temperature-dependent sorption and sorption hysteresis for hygrothermal modeling. And the temperature effect on intermediate scanning curves is assumed to be implicitly included during the derivation process from the temperature-dependent main sorption curves. More recently, Aït Oumeziane et al. [40] investigated the joint effects of hysteresis and temperature dependence on sorption processes in hemp concrete, but only focused on sorption models without transport equations.

In the two papers dealing with temperature-dependent hysteresis in hygrothermal modeling [35,50], either the transport model is incomplete or it has too many model parameters which need to be experimentally determined: In Ref. [35], a temperature dependent moisture capacity was considered in the coupled transport equation; however, the thermal moisture capacity (defined as the partial derivative of moisture content with respect to temperature) was not taken into account, which makes this model not completely suitable for considering the effect of temperature variation. Without this term, the relative humidity variation can't be correctly updated, especially under such conditions: temperature varies under constant relative humidity or temperature variation is more significant than relative humidity variation. While Frandsen [50] formulated a non-Fickian moisture transport model based on activated bound water diffusion and activated water vapor diffusion; and a temperature dependent hysteresis model was implemented to determine the equilibrium bound water concentration in the sorption reaction rate function. Since the sorption rate coefficient is also a complicated function of proximity to equilibrium and relative humidity, which requires additional experimental efforts to determine, this multi-Fickian model is very cumbersome for practical use in building physics.

As stated above, studies in literature give inconsistent points of view on the significance of sorption hysteresis; i.e. the answer is still open whether hysteresis needs to be considered. Additionally, it is still not clear how to model the combined effects of sorption hysteresis and its temperature dependency accurately. Therefore, these issues need to be further investigated. In this paper, by virtue of the validated hygrothermal model in a companion paper (Part I: