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Combined effects of sorption hysteresis and its temperature dependency on wood materials and building enclosures – Part I: Measurements for model validation

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ABSTRACT

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. A heat and moisture transport model is formulated based on local thermodynamic equilibrium assumption, which includes thermal moisture capacity and a hysteresis model in [1]. To validate this model, sorption isotherms at 23 °C were measured using the static gravimetric method; and a moisture response test under dynamic boundary conditions was carried out in a climatic chamber. The simulation results show that the hygrothermal model with temperature dependency and sorption hysteresis can capture the dynamic moisture response to variable boundary conditions very well. Therefore, this model could be used to further analyze the individual and combined effects of sorption hysteresis and its temperature dependency through hygrothermal modeling in a companion paper.

1. Introduction

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 [2–4]. Therefore, sorption isotherm is an important hygric property of building materials for hygrothermal modeling.

During the last decades, many computerized hygrothermal modeling tools for heat, air and moisture transfer simulation in building elements have already been developed, such as WUFI [5], MATCH [6], MOIST [7] 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 [8–10]. 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. [11]. 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 [12]. Most of these works in literature dealing with temperature effect focused on the temperature dependency of the main sorption isotherms. Time [9] and Frandsen [13] reviewed several experimental tests on wood materials in literature. For example, Tveit [14] performed sorption isotherm measurement on spruce (*Picea abies*) at 5 °C, 25 °C and 45 °C, and implied that there is a change of 0.06–0.08 wt percent per degree (°C) in equilibrium moisture content for the reported temperature range. Choong [15]

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measured both ad- and desorption isotherms for western fir (*Abies nobilis*) at 25 °C, 32.2 °C, 40 °C and 50 °C; from his experiment, the difference in moisture content between the highest and lowest temperature is about 2–3 wt percent. Kelsey [16] measured both boundary isotherms of Klinki pine (*Araucaria hunsteinii*) at 10 °C, 25 °C, 40 °C and 55 °C. This sorption dataset has been used to study the effect of temperature dependency of sorption isotherms on hygrothermal modeling in Refs. [13,17]. More recently, Hill et al. [18] measured sorption isotherm of Sitka spruce at 14.2 °C, 24.1 °C, 33.5 °C and 43.8 °C using a dynamic vapor sorption apparatus to investigate the effect of sorption temperature upon sorption kinetics and hysteresis. To the authors' knowledge, there are nearly no sorption isotherms with associated dynamic moisture response tests which are well documented and available for model validation in literature.

In literature, sorption hysteresis and its temperature dependency are usually studied independently. To study the hysteresis effect, temperature dependency was ignored in Refs. [10,19–25]; while other investigations on the effect of temperature dependency neglected the sorption hysteresis [26–28]. To the authors' knowledge, there are only two papers [13,17] which attempted to study the combined effect of the temperature-dependent sorption and sorption hysteresis for hygrothermal modeling. However the transport model is either incomplete due to the missing of thermal moisture capacity [17] or has too many model parameters which need to be experimentally determined [13], therefore a coupled heat and moisture transport model, which takes into account sorption hysteresis and its temperature dependency, is formulated based on local thermodynamic equilibrium assumption in Ref. [1]. To provide measured data for the model validation, sorption isotherms at 23 °C and a series of intermediate scanning curves were measured. And then a dynamic moisture response test carried out in a climatic chamber was simulated to validate the hygrothermal model.

2. Materials and methods

2.1. Sorption isotherm measurement

2.1.1. Methods for determining sorption curves

The EN ISO standard 12571 [29] and ASTM standard C1498-04a [30] have stipulated two standard methods for determining the hygroscopic sorption properties of building materials: desiccator method and climatic chamber method. The main difference between these two methods is related to the accuracy of the maintained temperature and relative humidity.

1) Desiccator method

The relative humidity in the desiccators is maintained by saturated salt solutions. The desiccators are placed in a constant temperature chamber. The temperature oscillation in the desiccator is recommended to be within ±0.1 °C, and the maximum variation shall not exceed ±0.5 °C.

2) Climatic chamber method

The temperature and relative humidity in the chamber are controlled with an accuracy of ±0.5 °C, ±3% RH for the entire relative humidity range.

For the standard methods, the same samples are consecutively placed under different relative humidity until equilibrium is reached. Since the standard methods are very time-consuming, rapid methods for sorption measurements have been developed, such as sorption microbalance method [31–34].

3) Sorption balance method

The Dynamic Vapor Sorption (DVS) apparatus and IGAsorp apparatus are based on the same principle: sorption balance method. The small samples are weighed by a microbalance with a capacity of 200 mg. The relative humidity in the apparatus is maintained by mixing two constant streams of dry and water vapor saturated nitrogen gas through a flow regulator. The detailed working principle can refer to [34]. The DVS apparatus has been frequently used for sorption analyses by Hill and coauthors [18,35,36].

Peuhkuri et al. [37] compared the standard methods and sorption balance method and concluded that the choice of method and step size in relative humidity does not have any particular effect on sorption measurements, while the drying temperature used for the determination of dry mass of the samples may have a very significant effect. The sorption curves from IGAsorp apparatus showed that the size of hysteresis loop was reduced with increasing step size in relative humidity. Although the standard method takes much longer time to reach equilibrium than the sorption balance method, it however provides the possibility to measure many samples at the same time to improve the reliability of the results.

A variation of the standard desiccator method has been used at Technical University of Denmark for years [37]: *Similar samples are placed in parallel in desiccators in which certain relative humidity is maintained by different saturated salt solutions for each.* A similar method has also been adopted by Zillig [38] and Roels et al. [39]: *Similar samples are first dried and then placed in parallel in desiccators in which certain relative humidity is maintained by different saturated salt solutions for each. After equilibrium is reached, all the samples are moved to desiccators with higher or lower relative humidity consecutively.* Using this method, the main sorption isotherms and a series of intermediate scanning curves can be measured simultaneously. Therefore this method will be adopted in this work.

2.1.2. Material and sample preparations

Spruce has been widely used as a building material for a long history and its sorption isotherm has also been measured by other authors in literature. Therefore, spruce (*Picea sp.*) was chosen as the wood material for sorption measurements. The sorption measurements were carried out in the hygrothermal laboratory at Fraunhofer Institute for Building Physics (IBP), with a project No. F192.

In order to reduce the time needed to reach equilibrium, the spruce chips were used as samples for sorption measurements, see in Fig. 1.

1) The clean empty glass dishes were numbered and then dried

Fig. 1. Samples in glass dishes (left) and desiccators (right) for sorption measurement within hygroscopic range.