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Technical Note

A Fickian model for temperature-dependent sorption hysteresis in hygrothermal modeling of wood materials

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ABSTRACT

The sorption isotherm is one of the most important hygric properties for modeling moisture transport in hygroscopic materials. For wood and wood based materials, the equilibrium moisture content within hygroscopic range is a function of temperature and relative humidity as well as its sorption history. The constitutive equations of the existing models in literature, which attempted to take into account temperature dependent sorption hysteresis, are either incomplete or have too many model parameters needed to be experimentally determined. As a result they are not suitable for practical applications in building physics. Therefore, a coupled heat and moisture transport model is formulated based on the classical local thermodynamic equilibrium assumption. Frandsen's hysteresis model is adopted and implemented in this Fickian model to determine the moisture capacity and thermal moisture capacity, since it avoids the needs to store the entire moisture history. The formulated hygrothermal model is numerically resolved in Modelica by virtue of a combination of storage model and flow model. For hygroscopic material with sorption hysteresis, its water vapor resistance factor has also been recalculated as a univalued function of moisture content instead of relative humidity. With different considerations for the moisture sorption isotherms, the new model provides the possibility of numerical study under different levels depending on the way to consider moisture sorption property. A simple example case is carried out to show the performance of the new model.

1. Introduction

In building physics, to avoid moisture related problems in building components and envelopes, such as moisture condensation, insulation failure and mold growth etc., coupled heat and moisture transport through building materials should be analyzed to optimize the design of building envelopes. Sorption isotherm, which depicts the equilibrium moisture content as a function of relative humidity at a constant temperature, is an important hygric property of building materials for hygrothermal modeling. For hygroscopic materials, such as wood and wood based materials, there usually exists a hysteresis loop within hygroscopic range; hence, the equilibrium moisture content in wood material is also determined by its sorption history [1]. Besides, the sorption isotherms and intermediate scanning curves of these materials are also affected by temperature [2,3]. Therefore, the equilibrium moisture content is a function of temperature, relative humidity and its sorption history. For wood material exposed to natural conditions, its sorption process actually follows the so-called intermediate scanning curves running through the space delineated by the main ad- and desorption curves with the diurnal and seasonal variations of relative humidity and temperature.

During the last few decades, many computerized hygrothermal modeling tools for modeling heat, air and moisture transfer in building elements have been developed, such as WUFI [4], MATCH [1], MOIST [5] etc. Among them, only a few models, e.g., MATCH, consider the effect of sorption hysteresis, while the others assume that the influence of sorption hysteresis on the hygrothermal behavior of material is marginal [6–8]. And the temperature dependency of sorption isotherms is often neglected; the sorption isotherms measured at 23 °C according to ISO 12571 standard [9] are also used for hygrothermal modeling at other temperatures. Therefore, the moisture capacity is frequently assumed to be only dependent on relative humidity [10–12]. However, according to [3], sorption hysteresis and temperature dependent sorption characteristics should be taken into consideration in some practical situations.

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Nomenclature

c_{pw}	specific heat capacity of liquid water, J/(kg·K)
c_s	specific heat capacity of wood in dry state, J/(kg·K)
c_v	specific heat capacity of water vapor, J/(kg·K)
D_φ	bound/liquid water conduction coefficient, kg/(m·s)
f_{ads}^{-1}	the inverse function of adsorption isotherm $w = f_{ads}(\varphi, T, \rho_s)$
Δh_v	latent heat of evaporation of water at 0 °C, 2.50×10^6 J/kg
p_s	saturated water vapor pressure, Pa
R	universal gas constant, J/(mol·K)
$s(\varphi)$	normalized moisture content
T	thermodynamic temperature, K
T_{ref}	reference temperature, 273.15 K
T_0	temperature at which thermal conductivity/water vapor permeability is measured, K
w	moisture content, kg/m^3
$w_a(\varphi)$	moisture contents on main adsorption isotherm, kg/m^3
$w_d(\varphi)$	moisture contents on main desorption isotherm, kg/m^3

Greek symbols

δ_a	water vapor permeability of air, kg/(m·s·Pa)
λ	thermal conductivity of moist wood, W/(m·K)
λ_{dry}	thermal conductivity of dry material, W/(m·K)
μ	water vapor diffusion resistance factor
ρ_s	density of wood in dry state, kg/m^3
φ	relative humidity
φ^*	equivalent relative humidity on main adsorption isotherm at T_0
τ	time, s

On the whole, studies on temperature effect, on hysteresis effect or on the combined effect of temperature and hysteresis are rather scarce in literature [13]. To the authors' knowledge, only two papers in literature attempted to consider the combined effects of sorption hysteresis and its temperature dependency [2,3], however, their moisture conservation equations are either incomplete or have too many parameters needed to be experimentally determined. In [3], a temperature dependent moisture capacity was considered in the transport equation; however, the partial derivative of moisture content to temperature (referred to as thermal moisture capacity hereafter) 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. Frandsen [2] formulated a non-Fickian (also called multi-Fickian) moisture transport model based on activated bound water diffusion and activated water vapor diffusion; 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 complex 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. To simplify the sorption rate term, Eitelberger and coauthors [14–16] established a dual-scale approach to determine it by a microscopic sub-model. Based on several assumptions, a simpler formula was derived [16], however, it still requires the microstructural parameters, such as the average of the radii of the tracheid in radial and tangential directions.

In building physics, the classical Fickian models are frequently used to study coupled heat and moisture transport in building enclosures; since the so-called non-Fickian model would require more input data. Therefore, this paper will propose a Fickian model which can be used to study the effect of temperature dependent sorption hysteresis on hygrothermal modeling in wood materials. In the first step, a hygrothermal model, which takes thermal moisture capacity into account, is formulated based on local equilibrium assumption. In the second step, the coupled equations and Frandsen's hysteresis model are implemented in Modelica. In the final step, a simple test case is conducted to show the difference between the models with different considerations of moisture sorption property.

2. Materials and methods

2.1. State of the art of the temperature effect on moisture sorption

Sorption isotherm is a discrete representation of equilibrium moisture states of a material with its surrounding environment at constant temperature and relative humidity within hygroscopic range [17]. To attain this equilibrium, the material exchanges moisture with ambient air, and this process involves heat gain (desorption) and release (adsorption), causing a change of temperature. Therefore, temperature level plays an influence on the equilibrium moisture content. To take the temperature dependence into account, many studies have been performed with emphasis on finding suitable sorption models with temperature-dependent parameters to acquire equations for the equilibrium moisture content as a function of temperature and relative humidity [18–20].

Sorption isotherms of building materials measured at different temperatures are not very extensive, especially for wood materials. Time [7] reviewed several such experimental tests on wood materials in literature. For example, Tveit [21] 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 weight percent per degree (°C) in equilibrium moisture content for the reported temperature range. Choong [22] 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 weight percent. Kelsey [23] 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 [2,3].

Most of the works in literature dealing with temperature effect focused on the temperature dependency of the main sorption isotherms. Pedersen's model [1] and Frandsen's model [24] have been used to study hysteresis effect [8,25–28], but all these works didn't take temperature effect on sorption isotherms into account; while other investigations on the effect of temperature dependency neglected sorption hysteresis [29–31]. In the two papers [2,3], which combined the temperature-dependent main sorption isotherms and sorption hysteresis for hygrothermal modeling, the temperature effect on intermediate scanning curves is assumed to be implicitly included during the derivation process from the temperature-dependent main sorption isotherms.