



Moisture transport in pine wood during one-sided heating studied by NMR

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ABSTRACT

The quantification of moisture transport in heated wood is relevant to several fields, e.g. for lumber drying and processing and for fire safety risk assessment. We present non-destructive and simultaneous measurements of the moisture content and temperature distributions in pine wood during unilateral exposure to a heat source. The moisture content is measured by a nuclear magnetic resonance setup specifically built for the evaluation of moisture transport in porous materials at elevated temperatures. Temperature profiles are obtained by thermocouples placed at different distances from the exposed surface. While the temperature rises, a peak in the moisture content is formed, which travels towards the unexposed surface. The velocity of the moisture content peak depends on the principal direction in which transport occurs, as confirmed by experiments. Numerical simulations of moisture transport are performed which can qualitatively reproduce the behavior observed in experiments. Moreover, several characteristics, such as the timescale and non-linearity of the moisture peak position, are well captured. The influence of several input parameters, such as the permeability and diffusion coefficient, on the moisture peak dynamics is elaborately explored.

1. Introduction

Due to its wide availability and renewability, wood has applications in many fields. Wood has been used as a heat source, for weaponry, in creating works of art, and as a construction material for centuries. If applied correctly, wood is a highly durable material, able to stand the test of time [1]. In unfavorable conditions, however, wood can degrade biologically by e.g. fungal growth [2], or mechanically due to moisture-induced stresses. Furthermore, during fire exposure, wood degenerates by pyrolysis, which can result in the failure of a structural element. For that reason, several high-temperature performance requirements are imposed on a building component [3], e.g. on the conservation of loadbearing or insulating capacities. In fire risk assessment, it is therefore of high importance to be able to accurately predict the fire behavior of materials comprising the building component. Since moisture plays a major role in many properties of wood, the qualification and quantification of moisture transport mechanisms is essential.

Numerous modelling studies on heat and mass transfer in wood during exposure to high temperatures exist in literature [3–5]; applications are in both fire safety of wood building components [6], as well as in industrial applications, e.g. wood drying [7–12]. These models consist of coupled heat and moisture transport equations, i.e. the temperature distribution is influenced by moisture transport and vice versa. Most experimental studies on fire behavior of wood are comprised of

measurements of the temperature distribution alone [13]. Experimental studies on moisture transport in wood during fire conditions are scarce; measuring moisture content non-destructively is more complex. Moisture content meters, embedded in a wood slab in a vertical furnace, have been used before to measure moisture profiles at high temperatures by White and Schaffer [14]. The authors recognized, however, that using moisture content meters comes at the expense of large errors. Other non-destructive measurement methods are therefore preferred when measuring moisture content [15], such as neutron imaging [16,17], which, however, requires a neutron source. Another powerful technique is nuclear magnetic resonance (NMR), which has been widely applied to study moisture transport in a variety of porous materials, such as granular beds [18], fluidized bed dryers [19], building materials [20], and also wood [21,22]. Most NMR studies focus on isothermal moisture transport; performing non-isothermal measurements on porous materials requires a specialized setup, able to withstand high temperatures and equipped with a Faraday shield to allow quantitative measurement. Moreover, several materials, e.g. concrete and refractories, possess the risk of explosive spalling when heated, requiring additional safety measures. Such a custom-built NMR setup has been developed to assess the non-isothermal moisture transport in concrete [23,24], fired-clay brick [25], gypsum [26], and refractory materials [27]. Here, we will employ the setup to explore the moisture transport in wood during heating.

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The goal of this study is the simultaneous and non-destructive measurement of both moisture content and temperature in pine wood during intensive one-sided heating, simulating the initial period of a fire. Accordingly a custom-built NMR setup is used, which has been introduced before [28], in combination with inserted thermocouples. Moreover, numerical experiments with a non-isothermal moisture transport model are performed to capture basic characteristic features of moisture transport during these conditions. The theoretical framework of the numerical model will be introduced first, followed by a concise description of the experimental procedure. Experimental and numerical results are presented and discussed, and finally conclusions are drawn and an outlook is presented.

2. Theory

2.1. Microstructure

In this section, a two-phase model is formulated for the description of moisture transport in wood during non-isothermal conditions. The model shares similarities with models present in literature [5,9,29]. Since tracheid cells make up over 90% of the volume of softwood [30], we assume here that the microscopic structure of our material can be simplified to the representation given in Fig. 1 (similar to [31]). The tracheid cell consists of an air-filled cell space (typical diameter 30 μm [32]), surrounded by a cell wall (typical thickness 3 μm [32]). The cell space contains a mixture of dry air and water vapor (not measurable by NMR), whereas the cell wall contains liquid or clustered water (measurable by NMR). Moisture exchange occurs at the boundary between the cell space and the cell wall. We furthermore presume slow cell wall moisture transport compared to the water vapor flux. Hence we can neglect the influence of cell wall water transport on the overall transport of moisture [3].

2.2. Moisture, air, and heat flux

In the experiments, the configuration of the samples is such that transport occurs in only one direction, i.e. in either the longitudinal or along a combined radial/tangential direction of the wood (see Fig. 1). Moisture and heat transport can therefore be treated as one-dimensional processes. Along the transport direction, transport of dry air and vapor is induced by a gradient in the total gas pressure p_g . Furthermore, differences in air and vapor mass fraction concentration (ρ_a/ρ_g or ρ_v/ρ_g) cause diffusive transport of the respective species. Accordingly, the flux of dry air and vapor J can be expressed as:

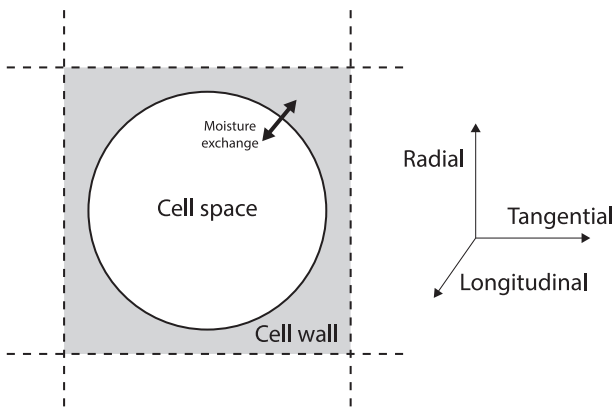


Fig. 1. Schematic microstructure (a tracheid cell) of pine wood used in our model. Longitudinal transport occurs perpendicular to the figure, radial/tangential transport takes place in-plane.

$$J_i = -\rho_i \frac{k}{\mu} \frac{\partial p_g}{\partial x} - D_g \rho_g \frac{\partial}{\partial x} \left(\frac{\rho_i}{\rho_g} \right), \quad i = v, a, \quad (1)$$

where ρ_a and ρ_g are the concentration of dry air and vapor respectively, k the gas permeability of the material, μ the gas viscosity, x the distance from the exposed surface in the transport direction (longitudinal or radial/tangential), D_g the gas diffusion coefficient, and ρ_g the total gas concentration ($\rho_g = \rho_a + \rho_v$).

In the experiments, one surface of the sample will be exposed to a constant heat source. Consequentially, one-dimensional heat transport occurs towards the opposite, unexposed surface. We assume that, in the absence of cell wall water flow and the water vapor density being too low to contribute to convective heat transfer, the heat flux Q will consist of a conductive term only:

$$Q = -\lambda \frac{\partial T}{\partial x}, \quad (2)$$

where λ is the heat conductivity of the material and T the temperature.

2.3. Coupling between water vapor and cell wall moisture

As mentioned before, we presume slow cell wall moisture transport compared to the water vapor flux. The NMR-measurable cell wall moisture content can therefore only change due to moisture exchange with the vapor in the cell space. We assume the exchange rate ξ to be proportional to the difference between actual and equilibrium cell wall moisture content w_{eq} [kg/kg]:

$$\xi = \kappa s (w - w_{eq}), \quad (3)$$

where w is the mass-based cell wall moisture content, κ the moisture exchange rate constant, and s the specific surface area for moisture exchange. A crude approximation of the exchange rate constant κ is introduced here as $\kappa = D_{cw} \rho_{mat} / d_{cw}$, where D_{cw} is the cell wall moisture diffusion coefficient [33], ρ_{mat} the wood density, and d_{cw} the typical cell wall thickness.

2.4. Constitutive relations

To couple the vapor concentration to vapor pressure and to temperature, we assume that the dry air and water vapor behave as ideal gasses, so that we have:

$$\rho_i = \frac{p_i M_i}{RT}, \quad i = v, a, \quad (4)$$

where p_a and p_v are the pressures of the air and vapor phases respectively ($p_g = p_a + p_v$), M_v and M_a are the molar masses of water and dry air respectively, and R is the gas constant. The relation between the equilibrium moisture content w_{eq} and the relative humidity h (the ratio of the vapor pressure over the saturated vapor pressure, i.e. $h = p_v/p_{vs}$) can be expressed using a temperature-dependent sorption curve for wood [30,34,35]:

$$w_{eq}(h, T) = \frac{a_1}{1 + a_2 \left(\frac{1}{h} - 1 \right)^{\frac{a_3}{3}}}, \quad (5)$$

with the temperature-dependent variables:

$$\begin{aligned} a_1 &= -5.90 \cdot 10^{-7} T^2 - 9.73 \cdot 10^{-5} T + 0.40, \\ a_2 &= -2.18 \cdot 10^{-6} T^2 - 0.02 T - 2.69, \\ a_3 &= 2.06 \cdot 10^{-6} T^2 - 1.67 \cdot 10^{-3} T + 2.29. \end{aligned} \quad (6)$$

The sorption curve predicts a decrease in the sorption capacity of the wood with an increase in temperature.

Since the relative humidity is the ratio of the vapor pressure over the saturated vapor pressure, we need an expression to describe the temperature-dependence of the saturated vapor pressure. To this end, the Magnus equation is used as an approximation [36]:

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