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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]:

$$p_{vs} = 610 \exp\left(\frac{17.6(T-273)}{T-30}\right). \quad (7)$$

2.5. Conservation equations for vapor, air, cell wall water, and energy

The macroscopic balance equation for the vapor phase includes the vapor flux (Eq. (1)) and the moisture exchange rate term (Eq. (3)), which combine to give:

$$\frac{\partial n \rho_v}{\partial t} = -\frac{\partial n J_v}{\partial x} + \xi, \quad (8)$$

where n is the relative cell space volume or porosity and t is time. A similar balance equation for dry air can be formulated, without the source term on the right-hand side:

$$\frac{\partial n \rho_a}{\partial t} = -\frac{\partial J_a}{\partial x}. \quad (9)$$

In absence of a liquid water flux, the cell wall moisture conservation equation depends only on the moisture exchange term:

$$\frac{\partial \rho_{mat} w}{\partial t} = -\xi. \quad (10)$$

The energy balance equation is composed of the heat flux (Eq. (2)) and the evaporation enthalpy:

$$\frac{\partial \rho_{mat} c T}{\partial t} + \frac{\partial Q}{\partial x} = -\xi \frac{H_v}{M_v}, \quad (11)$$

where c is the heat capacity of the material and H_v the evaporation enthalpy.

Substitution of fluxes and constitutive relations in Eqs. (8)–(11) results in conservation equations for the vapor phase, air phase, cell wall moisture, and energy respectively as:

$$\begin{aligned} \frac{1}{T} \frac{\partial p_v}{\partial t} + \frac{\partial}{\partial x} \left[\frac{1}{T} \left(\frac{D p_v M_a}{p_v M_v + p_a M_a} - \frac{k}{\mu} p_v \right) \frac{\partial p_a}{\partial x} - \frac{1}{T} \left(\frac{D p_a M_v}{p_v M_v + p_a M_a} + \frac{k}{\mu} p_a \right) \frac{\partial p_v}{\partial x} \right] \\ = \frac{R}{M_v n} \left(w - w_{eq} \left(\frac{p_v}{p_{vs}}, T \right) \right) + \frac{p_v}{T^2} \frac{\partial T}{\partial t}, \end{aligned} \quad (12)$$

$$\begin{aligned} \frac{1}{T} \frac{\partial p_a}{\partial t} + \frac{\partial}{\partial x} \left[\frac{1}{T} \left(\frac{D p_a M_v}{p_v M_v + p_a M_a} - \frac{k}{\mu} p_a \right) \frac{\partial p_v}{\partial x} \right. \\ \left. - \frac{1}{T} \left(\frac{D p_v M_a}{p_v M_v + p_a M_a} + \frac{k}{\mu} p_v \right) \frac{\partial p_a}{\partial x} \right] = \frac{p_a}{T^2} \frac{\partial T}{\partial t}, \end{aligned} \quad (13)$$

$$\rho_{mat} \frac{\partial w}{\partial t} = -\kappa s \left(w - w_{eq} \left(\frac{p_v}{p_{vs}}, T \right) \right), \quad (14)$$

$$\rho_{mat} c \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) = -\kappa s \frac{H_v}{M_v} \left(w - w_{eq} \left(\frac{p_v}{p_{vs}}, T \right) \right). \quad (15)$$

2.6. Initial and boundary conditions

We assume that, initially, the cell wall moisture is distributed evenly along the length of the sample, i.e. we have a uniform moisture content. Furthermore, the initial moisture content is the equilibrium value corresponding to the initial relative humidity h_0 . Similarly, the initial temperature distribution is uniform throughout the sample:

$$w(x, 0) = w_{eq}(h_0, T_0), \quad T(x, 0) = T_0. \quad (16)$$

Similar to the experiments, the heat source at the exposed surface is represented by a radiative heat flux, proportional to the difference in emittance temperature and surface temperature to the fourth power. The back surface is insulated to prevent heat transport, resulting in a zero temperature gradient:

Fig. 2. Schematic representation of the temperature, relative humidity, and vapor pressure distributions during one-sided radiative heating of an insulated pine cylinder. The experimental configuration is schematically shown on top. A peak in the gas pressure some distance away from the exposed surface, due to release of cell wall moisture as vapor at increased temperatures, induces flow towards both the exposed and unexposed surface. The temperature distribution determines the local saturated vapor pressure, which results in a local maximum in relative humidity. Diffusion tends to level off this peak, resulting in a diffusive vapor flux towards both the exposed and unexposed surface.

$$-\lambda \frac{\partial T}{\partial x}(0, t) = \varepsilon \sigma (T_R^4 - T^4), \quad \frac{\partial T}{\partial x}(L, t) = 0, \quad (17)$$

where ε is the emissivity coefficient of the emitting surface, σ the Stefan-Boltzmann constant, T_R the emittance temperature, and L the length of the sample.

Initially, water vapor and cell wall moisture are in equilibrium, hence the vapor pressure is distributed evenly too. We further assume that the vapor pressure at the exposed surface remains unchanged. The back surface is completely sealed to obstruct vapor transport, resulting in a no-flux boundary condition. In combination with the absence of a temperature gradient, this results in a zero pressure gradient:

$$p_v(x, 0) = p_{veq}(w_0), \quad p_v(0, t) = p_a, \quad \frac{\partial p_v}{\partial x}(L, t) = 0. \quad (18)$$

The transport processes described in the equations above are schematically depicted in Fig. 2 in terms of temperature, relative humidity and gas pressure distributions. A rise in temperature results in an increase of the local saturated vapor pressure (see Eq. (7)). The consequential decrease in relative humidity induces the release of moisture from the cell wall as water vapor, in accordance with the source terms in Eqs. (12) and (13). Accordingly, the vapor pressure and thus the gas pressure increase, thereby inducing pressure-driven water vapor transport towards both the exposed and unexposed surfaces. This is represented by the permeability terms between the square brackets in Eqs. (12) and (13). Meanwhile, pressure-driven air transport also occurs which tends to decrease the local gas pressure. In addition to the pressure-driven water vapor transport, water vapor diffusion occurs away from the peak in relative humidity towards both the exposed and unexposed surface. The local temperature determines the local vapor saturation pressure. If vapor is transported towards regions of lower saturation pressure, the relative humidity rises. This, in turn, induces

moisture exchange with the cell wall, resulting in a rise in the local moisture content.

3. Materials and methods

3.1. Material and sample preparation

Pine wood cylinders with a diameter of 70 mm and a length of 70 mm are prepared with their axis in either one of the principal directions of wood (longitudinal, i.e. along the grain, or, perpendicular to that, combined radial/tangential). The cylinders are equilibrated at an RH of 53%, after which they are wrapped in Teflon tape and squeezed in a tight Teflon beaker to seal the sides for moisture transfer, thus creating a semi one-dimensional experiment. Holes are drilled at different distances from the exposed surface (5, 12, 20, 30, 45, and 65 mm), in which thermocouples are placed to measure the temperature during the experiment. The beakers are additionally wrapped in a layer of Rockwool® insulation material to prevent heat losses to the sides and the back surface. The beakers are then placed in the NMR setup, which is described below.

3.2. NMR setup

A home-built NMR setup is used to measure moisture content profiles of a pine cylinder, while it is exposed to a heat source on one side. The setup, schematically shown in Fig. 3, was specifically designed for performing non-isothermal moisture measurements on building materials, and will be introduced here briefly; a more extensive description can be found elsewhere [27,28].

The setup is placed inside the bore of a 1.5 T whole-body medical scanner (Gyrosan, Philips), which provides the main magnetic field during the experiments. A constant gradient of 80 mT/m in the main magnetic field is achieved with two anti-Helmholtz coils, enabling us to measure one-dimensional profiles with a spatial resolution of approximately 3 mm [27]. A birdcage coil, made from copper strips wrapped around an alumina (AlO₃) tube, is used for sending radio-frequency (RF) pulses and receiving the signal from the sample. The alumina tube is able to withstand high temperatures and provides no background signal. In order to perform quantitative measurements, the coil is equipped with an internal Faraday shield, which prevents detuning of the RF-coil induced by changes in the dielectric constant. To measure the spatial distribution of the moisture content, a Hahn spin echo with

an echo time of 300 μs is performed under a gradient at different frequencies, i.e. different slices along the length of the cylinder are excited by RF pulses and measured.

The one-sided heating of the cylinder is achieved by an array of seven 100 W halogen lamps. The reflective surfaces of the lamps are gold-plated to maximize the infrared radiative flux towards the exposed sample surface. Accordingly, the surface can be heated up quickly. The radiative temperature of the lamps is estimated based on the measured temperature increase of the sample.

3.3. T_2 and signal correction

During our NMR experiments, we measure the magnitude of the nuclear magnetization of protons present in a sample. In general porous media and isothermal conditions, the signal can be directly related to the moisture content of the material and a single conversion factor can be used to calibrate the obtained signal. In our experiments, however, we deal with large temperature differences over the length of the sample, which affects the measured signal twofold. The magnetization magnitude of an unchanging volume of water is inversely proportional to the absolute temperature, also known as the Curie law [28]. Hence, even though the moisture content remains equal, the obtained signal changes continuously. Furthermore, temperature influences the T_2 relaxation times of a system, which characterize the loss of magnetization after excitation in an NMR experiment (i.e. $S \sim \exp(-t_E/T_2)$). Below the fiber saturation point, i.e. the moisture content of wood in equilibrium with a relative humidity of 100%, the magnetization decay of moisture in wood can be well described by a single T_2 relaxation time [33]. Generally, the T_2 relaxation time increases with temperature [27,28]. Thence, the obtained signal after an echo time t_E will be larger at higher temperatures. Accordingly the corrected signal S_C is obtained from the collected raw signal S_R as

$$S_C = C_M(T)C_{T_2}(T)S_R, \quad (19)$$

where C_M and C_{T_2} are correction functions for the magnetization and the T_2 relaxation time respectively. C_M is proportional to the absolute temperature, which has been verified before by heating a cylindrical flask containing a 0.1 M CuSO₄ solution while measuring its signal [28]. C_{T_2} is determined on a different setup (0.78 T, for a more detailed description see [37]). A cylindrical pine sample (20 mm in diameter, 20 mm in height) is placed in a closed Teflon sample holder, additionally wrapped in Teflon tape to prevent loss of water. At different temperatures, which is achieved by placing the sample holder in the oven for a sufficiently long period of time, a CPMG sequence [38,39] is performed to determine the T_2 relaxation time.

The T_2 as a function of temperature is shown in Fig. 4a for two different samples: equilibrated with an RH of 53% and 93% respectively. The generally higher T_2 with a higher equilibration RH has been observed before [22], and is most likely due to the increased cell wall water mobility at higher moisture content. In both samples, the T_2 of the cell wall moisture increases up to a temperature of 100 °C, after which it decreases again. The corresponding total signal of the two samples (extrapolated from the measured CPMG and corrected for the decreased magnetization at higher temperatures using C_M) is shown in Fig. 4b. As can be seen, the signal increases slightly up to a temperature of 100 °C, the origin of which remains unknown to this point. Exceeding 100 °C, the signal rapidly drops to low values. Despite the vapor-tight sealing using Teflon tape, excessive vapor pressure has apparently forced out water vapor from the Teflon sample holder. This is also verified by simultaneously measuring the mass of the samples.

As can be seen from Fig. 4a, the T_2 relaxation time of the cell wall moisture is dependent on both moisture content and temperature. Hence, the T_2 correction applied to the raw experimental data is highly complex and non-linear. As a first-order approximation, we neglect the moisture content dependence of the T_2 and employ the correction corresponding to the initial conditions in the experiments (samples

Fig. 3. Schematic representation of the NMR setup used to continuously measure moisture content profiles of a cylindrical pine wood sample, while heated unilaterally by an array of halogen lamps.

Fig. 4. (a) T_2 relaxation time as a function of temperature for two pine cylinders, initially in equilibrium with a relative humidity of 53% and 93% respectively, contained in a closed sample holder. (b) The signal of the pine samples as a function of temperature, additionally corrected for the temperature-dependence of the magnetization.

equilibrated at RH = 53%). The T_2 -correction can then be expressed as $C_{T_2} = \exp(t_E/T_2(T))$, where t_E is the echo time in the NMR measurement ($t_E = 300 \mu\text{s}$) and $T_2(T)$ the free cubic spline fit to the temperature-dependent T_2 data for the sample equilibrated at an RH of 53% in Fig. 4a. We thus likely overestimate high values in moisture content. To provide an estimate of the involved error, we take the ratio of the correction factor C_{T_2} for RH = 53% and 93% at 100°C , which is approximately 1.3. Hence, the moisture content is overestimated by $\sim 30\%$ at maximum. To minimize this error, the T_2 as a function of both temperature and moisture content should be determined, which is a subject for future study. The correction to the raw experimental data applied here is qualitatively similar to cases presented by van der Heijden et al. [28] and Barakat et al. [27], where examples of the correction are shown. Additionally, moisture content distributions are normalized by the first profile to account for the decreasing sensitivity away from the center of the coil and for local inhomogeneities in the wood structure.

Several parameters influence the accuracy of moisture measurement using NMR. First of all, a small background signal contributes to the measured signal. To correct for this, the background signal is subtracted from the signal. Furthermore, the signal-to-noise ratio is improved by averaging the signal at each measurement point in space and time. The first profile, which is used to normalize subsequent profiles, is obtained using 64 measurements, all points in successive profiles are averaged 16 times to arrive at an acceptable time resolution of 3.5 minutes per profile (25 points per profile). Each measurement in turn is an average over a slice with a thickness of approximately 3 mm, which further enhances the signal-to-noise ratio. To account for the different time stamp of each measurement point, the acquired data points are linearly interpolated over time to obtain profiles at matching time stamps. Due to the high time resolution, this leads to small errors related to the sequential measurement of profile points.

4. Results and discussion

4.1. Moisture content and temperature distribution

Normalized moisture content and temperature profiles during one-sided heating of a pine cylinder, with its axis in the combined radial/tangential direction, are shown in Fig. 5a and b respectively. Time between two consecutive profiles is 10 minutes. Initially, the moisture content and temperature are constant throughout the sample. After switching on the heat source, the temperature near the surface quickly

risks, resulting in steep gradients as extreme as $\sim 500^{\circ}\text{C}/\text{m}$. Meanwhile, a peak in the moisture content is formed, which travels towards the back of the sample, while the moisture content left from the peak attenuates to low values. A sharp boundary between dry material left from the peak and the peak in the moisture content itself is observed. The emergence of the moisture content peak is related to rapid release of cell wall moisture in regions with high temperatures. The resulting vapor pressure gradient induces vapor transport. In addition, diffusive vapor transport may also occur due to concentration differences. Moisture then travels as vapor towards regions of low vapor pressure or low vapor concentration, i.e. towards the surface and towards the back of the sample. Whereas the temperature near the exposed surface is high, lower temperatures towards the back of the sample cause exchange of the water vapor to cell wall moisture, which results in an increase in measurable moisture content. This increase is perceived as the peak shown in Fig. 5a.

Another representation of the same results is shown as the time-evolution of the moisture content and temperature at different distances from the exposed surface in Fig. 6a and b respectively. Closest to the surface, the normalized moisture content increases slightly before rapidly decreasing, whereas further away from the exposed surface, the moisture content increases to higher values before decreasing. The peak in moisture content occurs later in time further away from the surface, reaching higher values. A similar time-evolution was found by White and Schaffer [14] and Fredlund [3]. Meanwhile the temperature near the exposed surface quickly rises to high values. White and Schaffer [14] and Fredlund [3] found a plateau in the temperature around 100°C , which they linked to the heat associated with water evaporation. In this case, a change in the temperature increase is observed around 100°C as well, although it is less pronounced. A possible cause is the different exposure condition. In the mentioned studies, the sample is either placed in a furnace with temperatures of over 900°C [14] or exposed to much higher radiant power than in this study [3]. Furthermore, a higher initial moisture content can affect the temperature course over time due to the higher amount of energy required for evaporation.

It is well-known that the different principal directions in wood exhibit different transport characteristics. Whereas little difference is found between the radial and tangential permeability, the longitudinal permeability can be several orders of magnitude higher, depending on the wood species [40,41]. It is therefore expected that the observed moisture transport characteristics are different in case transport occurs in the longitudinal direction, as opposed to the radial/tangential

Fig. 5. (a) Normalized moisture content profiles and (b) temperature profiles during one-sided heating of a pine cylinder, with its axis in the combined radial/tangential direction. The time between consecutive profiles is 10 minutes. The position of the peak in moisture content is indicated in each temperature profile with a marker.

direction. Normalized moisture content and temperature profiles for the cylinder with its axis along the longitudinal direction are shown in Fig. 7. Time between two consecutive profiles is 5 minutes, i.e. the time resolution is higher than in Fig. 5. As can be seen when comparing Fig. 7a to Fig. 5a, the peak travels faster in the longitudinal direction, due to the higher permeability. Furthermore, the increase in temperature is more rapid in the longitudinal direction, although the profiles are qualitatively similar. The generally higher thermal conductivity in this direction, typically differing by a factor of two [42], results in a faster increase in temperature. Flatter temperature profiles are, however, expected in case of a higher thermal conductivity, which is not seen in the experimental results.

Although the timescales associated with moisture and heat transport in the different principal directions are different, the behavior is qualitatively similar. As demonstrated in Figs. 5b and 7b, in both cases the peak in moisture content travels at a constant temperature around 100 °C, which suggests similar timescales for moisture and heat transport respectively in each direction. This is elucidated by plotting the normalized signal as a function of the temperature for each distribution during the experiment in Fig. 8a and b for the combined radial/tangential and longitudinal direction respectively. For temperatures up to ~70 °C the moisture content remains equal. With a further increase in temperature, the moisture content rises towards its peak value around

100 °C, followed by a steep decrease in moisture content with increasingly higher temperature. At temperatures above ~130 °C, all moisture has been removed from the material. The figure is similar for transport in the longitudinal direction, although the rise of the moisture peak value around a temperature just below 100 °C is more noticeable.

4.2. Peak in moisture content

The emergence of a peak in the moisture content was observed in the profiles displayed in Figs. 5a and 7a. This peak travels towards the unexposed surface of the sample and its value grows over time. Its occurrence is linked to the rapid moisture exchange in regions of high temperature and the consequent vapor transport to and moisture exchange in regions of lower temperature. In a later section, numerical simulations are performed to study influential parameters. Here, we will study features of this peak in moisture content in more detail.

The peak position and peak temperature over time for transport in the combined radial/tangential direction are presented in Fig. 9. As can be seen, the peak position follows a slightly non-linear course over time. This occurs in both principal directions, which is demonstrated by the time-evolution of the peak position in Fig. 10a. Two measurements have been performed in each direction. The non-linear time-evolution of the peak position can be well fitted with a power law, producing

Fig. 6. The time-evolution of (a) the normalized moisture content and (b) temperature at different distances from the exposed surface ($x = 5, 12, 20, 30, 45$, and 65 mm) in the radial/tangential sample.

Fig. 7. (a) Normalized moisture content profiles and (b) temperature profiles during one-sided heating of a pine cylinder, with its axis in the longitudinal direction. The time between consecutive profiles is 5 minutes. The position of the peak in moisture content is indicated in each temperature profile with a marker.

exponents in the range 0.67–0.82. As already observed, the peak velocity is higher in the longitudinal direction than in the radial/tangential direction. Slight differences are found between repeated measurements with different, but similarly cut samples. Nevertheless, the overall behavior is similar, with power law time-dependence of the peak position. This also becomes apparent upon a closer look at the data presented by White and Schaffer, which reveals a power law (t^b) dependence of the peak position too rather than the linear dependence reported by the authors.

Fig. 9 also elucidates that the peak temperature quickly attains a constant value around 100 °C. This occurs in both measurements in the radial/tangential direction, which is highlighted in Fig. 10b by plotting the peak position as a function of the position where the temperature is 100 °C. The values are scattered around the line $x_p = x_{100}$, which marks the agreement in position of both the peak moisture content and boiling point. A similar value (98 °C) was measured in the experiments by White and Schaffer [14]. A constant temperature at the peak position indicates that the two timescales of moisture and heat transport are of similar order. Moreover, it suggests that the pressure in the material does not reach excessive values. In other words, the permeability is sufficiently high to prevent a temperature rise above 100 °C, which can only be achieved at high pressures. For transport in the longitudinal direction we observe a peak temperature which is moderately lower than 100 °C (also observable in Fig. 8b), but slightly increases over the

Fig. 9. Peak position and temperature at the peak over time during one-sided heating of a pine cylinder, with its axis in the combined radial/tangential direction.

Fig. 8. Normalized moisture content as a function of the temperature during the experiment for the sample with its axis in the (a) combined radial/tangential and (b) longitudinal direction.

Fig. 10. (a) The peak position (x_p) as a function of time for the combined radial/tangential and longitudinal cylinders. Grey markers indicate a second measurement under identical conditions, but with a different sample. A power fit to the peak position is added in the figure. (b) The position of the peak in moisture content as a function of the position where the temperature is 100 °C ($x_{100\text{ °C}}$) for the different profiles.

course of the experiment. This is expressed by the peak position preceding the position of 100 °C in Fig. 10b, but decelerating in a later stage of the process.

4.3. Low heating rate

In isothermal drying of wood, the local moisture content decreases monotonically; a peak in the moisture content only emerges in non-isothermal conditions [3,14]. It can therefore be hypothesized that, in case of a low heating rate and thus small temperature gradients, the peak in moisture content will not appear. To verify this hypothesis, an experiment with a radial/tangential cylinder is carried out in which the heating rate is kept low to ensure small temperature gradients. The normalized moisture content profiles and temperature profiles are shown in Fig. 11. The time between profiles is 60 minutes. The large number of profiles measured indicates the larger timescale associated with this process (27 hours compared to 1–2 hours). Furthermore, the temperature gradients are considerably smaller when compared to the results in Fig. 5b. Moreover, as expected, no peak in the moisture content is observed. The slower heating rate results in a lower moisture exchange rate and thus smaller pressure gradients. Moisture transport is governed by diffusive water vapor transport towards regions of low vapor content, i.e. towards the exposed surface. At a certain moment, a

non-uniformity in the temperature increase is observed (the temperature distribution is unchanged), represented by overlapping profiles. This is caused by the stepwise elevation of the power to the halogen lamps ensuring a heat flux towards the surface to arrive at low temperature gradients and an approximately linear increase in surface temperature. At night, however, the constant heat flux resulted in an unchanged temperature distribution, which is most likely caused by heat losses towards the sides and possibly back of the sample. Consecutive elevation of the heat flux results in a temperature increase again.

4.4. Simulations

To qualitatively and quantitatively describe the observed transport processes from experiments, numerical simulations with the formulated model are performed. To this end, the balance equations (Eqs. (12)–(15)) along with initial and boundary conditions (Eqs. (16)–(18)) are implemented in Comsol and solved numerically. The input parameters are listed in Table 1. First, simulated normalized moisture content profiles and temperature profiles are compared to experimental results. After that, different values for the gas diffusion coefficient D and the permeability k are used in the simulations, so as to determine their effect on the peak dynamics. Furthermore, the influence of the

Fig. 11. (a) Normalized moisture content profiles and (b) temperature profiles for a low heating rate of a radial/tangential sample. The heating rate was controlled to have a more or less steady temperature increase over time near the surface. Time between consecutive profiles is 60 minutes.

Table 1
Parameters for numerical calculations.

Parameter	Symbol	Value
Evaporation enthalpy	H_v	44,000 J/mol
Molar mass water	M_v	0.018 kg/mol
Molar mass dry air	M_a	0.029 kg/mol
Universal gas constant	R	8.31 J/mol K
Vapor viscosity	μ_v	$2 \cdot 10^{-5}$ Pa s
Sample length	L	0.07 m
Porosity	n	0.65
Heat conductivity wood	λ	0.12 W/m K
Heat capacity wood	c	1400 J/kg K
Density wood	ρ_{mat}	470 kg/m ³
Moisture exchange rate	κ	$1.3 \cdot 10^{-3}$ kg/m ² s
Surface-to-volume ratio	s	$8.7 \cdot 10^4$ m ² /m ³
Initial temperature	T_0	293 K
Initial relative humidity	h_0	0.5
Emission temperature	T_R	1000 K

heat conductivity of the solid phase, the exposure temperature, and the initial moisture content is explored.

Simulated normalized moisture content profiles and temperature profiles for transport in the radial/tangential direction are shown in Fig. 12a and b respectively. In these simulations we have assumed values for the diffusion coefficient, permeability, and heat conductivity of 10^{-6} m²/s, 10^{-14} m², and 0.12 W/m K respectively. Experimental profiles at similar exposure times have been added to the figures for comparison. Similar to the experiments, a peak in the moisture content is formed, which travels towards the back of the sample. Although the qualitative evolution of the peak is similar, with an initially increasing peak value which eventually decreases, the moisture peak is less pronounced and will reach values of 1.4 at maximum. The discrepancy between experiments and simulations is probably caused by the overestimation of the peak moisture content in the experiments, due to the T_2 -correction of the original data. It is therefore likely that we experimentally capture the dynamics correctly, but overvalue the moisture peak. The simulated temperature profiles in Fig. 12b, however, resemble the experimental profiles adequately, despite the slight overestimation of the temperature near the exposed surface. Similar to the experiments, a small kink in the temperature profiles is observed. This kink is associated with the exchange of water from vapor to cell wall, which is accompanied by heat release thus causing distorted profiles near the peak in moisture content.

The peak position over time for diffusion coefficient values of 10^{-5} m²/s and 10^{-6} m²/s and different permeability values is shown in

Fig. 13a and b, respectively. Similar to the experimental observations in Fig. 10a, the peak position increases non-linearly over time, with power-law fitted exponents falling in the same range as experiments (0.69–0.83). As can be expected, the peak velocity is generally greater for a higher diffusion coefficient. Relatively small differences in peak displacement are observed for different permeability values (varying by four orders of magnitude), especially for high permeability values. For latter cases, the permeability is sufficiently high, such that gas diffusion of vapor and air are limiting factors for the peak displacement. This is also reflected in the peak temperature evolution shown in Fig. 14, which almost overlaps for high permeability. For a high diffusion coefficient of 10^{-5} m²/s, the peak temperature increases over time, with slightly higher values for lower permeability (see Fig. 14a). Lowering the diffusion coefficient by one order of magnitude results in a qualitatively and quantitatively different peak temperature evolution, as shown in Fig. 14b. For low permeability, the peak temperature increases to high values over time, which is accompanied by high gas pressures, as demonstrated in Fig. 15. Although the peak temperature evolution is highly dependent on the diffusion coefficient, only minor differences in the internal gas pressure are found. For high permeability, the peak temperature attains a near-constant value around 100 °C, which is in accordance with experimental observations. This constant peak temperature value corresponds to the equivalence between atmospheric pressure and saturated vapor pressure at 100 °C. For sufficiently high permeability values, a local increase in the vapor pressure at high temperatures is compensated by a decrease in dry-air pressure. This compensation prevents an increase in the total gas pressure, which is shown in Fig. 15.

Further decreasing the diffusion coefficient by one order of magnitude results in a more rapid attainment of the constant peak temperature of 100 °C for sufficiently high permeability. This, however, is accompanied by a substantial decrease in peak value, and a complete absence of a moisture content peak for even higher diffusion coefficients. Only a combination of low diffusion coefficient and low permeability produces a moisture peak, the temperature of which, however, increases over time. Moreover, the implemented values for the diffusion coefficient are in the same range as reported and used in literature [5,9,40]. We can therefore conclude that the diffusion coefficient should be in the approximate range of $5 \cdot 10^{-7}$ to $5 \cdot 10^{-6}$ m²/s.

In the experiments, differences in the moisture peak dynamics were observed for the different sample configurations. These differences were attributed to the varying transport properties in the principal transport directions. The permeability in the longitudinal direction compared to the transverse directions is generally several orders of

Fig. 12. Simulated (a) normalized moisture content profiles and (b) temperature profiles for transport in the radial/tangential direction ($D = 10^{-6}$ m²/s, $k = 10^{-14}$ m², $\lambda = 0.12$ W/m K). Time between profiles is 20 minutes, total simulation time is 2 hours. For illustrative purposes, experimental profiles at matching time stamps are shown as dashed lines.

Fig. 13. Peak position over time for (a) $D = 10^{-5} \text{ m}^2/\text{s}$ and (b) $D = 10^{-6} \text{ m}^2/\text{s}$ and different permeability values.

Fig. 14. Temperature at peak position over time for (a) $D = 10^{-5} \text{ m}^2/\text{s}$ and (b) $D = 10^{-6} \text{ m}^2/\text{s}$ and different permeability values.

Fig. 15. Maximum gas pressure over time for $D = 10^{-5} \text{ m}^2/\text{s}$ and $D = 10^{-6} \text{ m}^2/\text{s}$ and different permeability values.

magnitude higher [34], although a wide range of values is reported in literature [3,5,9,40,43]. It can therefore also be hypothesized that the diffusion coefficient in this direction is higher, since gas diffusion is obstructed by the solid structure to a lesser extent. The enhanced

moisture peak displacement in the longitudinal direction is therefore probably a consequence of a higher permeability in conjunction with a higher diffusion coefficient. The latter observation is also in agreement with the slightly increasing peak temperature in this direction.

Not only the moisture transport properties are direction-dependent, but also the thermal conductivity varies with the principal direction. Generally, the conductivity has twice the value in the longitudinal direction compared to the transverse directions [40]. The influence of doubling the thermal conductivity on the moisture peak dynamics is shown in Fig. 16. Due to enhanced heat transfer, the displacement of the moisture peak is marginally accelerated. Furthermore, the moisture peak displacement becomes more linear, which is accompanied by a reduction in moisture peak value due to smaller thermal gradients. For even higher thermal conductivities, temperature gradients decrease which are accompanied by a complete disappearance of the moisture content peak.

The peak position and peak temperature over time for two different heating rates (different emittance temperatures T_R) are shown in Fig. 17a and b respectively. As can be seen, the peak displacement is substantially enhanced when exposed to higher heating power. Moreover, the peak temperature increases for higher T_R , especially for low permeability. During these conditions, the temperature increase is rapid relative to the system's ability to equilibrate pressure differences, resulting in high pressures and high peak temperatures. For sufficiently high permeability, however, the peak temperature attains a near-constant value around 100 °C, similar to lower heating power. This

Fig. 16. (a) Peak position and (b) temperature at peak position over time for $D = 10^{-6} \text{ m}^2/\text{s}$ and different permeability values, for two different heat conductivities λ .

indicates that the permeability is high enough to prevent a large increase in total gas pressure near the moisture peak. From this we can conclude that the peak displacement is mainly governed by the external heating conditions, whereas the peak temperature and hence the internally generated pressure is more profoundly influenced by the permeability.

A different initial equilibrium relative humidity h_0 can influence the moisture peak dynamics. The initial cell wall water content decreases with a decrease in h_0 , hence the reduced water exchange results in a faster movement of the moisture peak. The effect is, however, rather small, as demonstrated in Fig. 18. A larger influence is expected for high h_0 , i.e. for high initial moisture content, even more so if the cell wall moisture content approaches saturation. In this case, the vapor pressure during heating eventually surpasses the saturated vapor pressure, which should be accompanied by condensation of vapor in the cell space. Our model, however, does not account for the presence of liquid water in the cell space. To simulate these conditions, the model should be extended to incorporate liquid water.

Finally, the normalized moisture content profiles and temperature profiles for a low heating rate, comparable to the one used in the experiment, are shown in Fig. 19. To this end, the sample surface temperature is derived from the experimental data and supplied to the model. Similar to the experimental results, the moisture content decreases monotonically near the exposed surface, with a minor increase near the unexposed back. The simulated temperature profiles exhibit

smaller gradients, i.e. the distributions are more leveled compared to the experimental profiles. This is an indication that we either overestimate the heat conductivity, or that heat losses to the side of the cylinder are more significant during slow heating. The latter is more probable since lowering the heat conductivity results in more non-linear temperature distributions, which is qualitatively different from the nearly linear experimental distributions shown in Fig. 11b. Despite the discrepancies, the agreement in overall timescale of the processes is acceptable, with simulated normalized moisture content distributions comparable to experimental results.

5. Conclusions and outlook

We have demonstrated the possibility to assess moisture transport in pine wood at elevated temperatures using NMR. The non-destructive nature of NMR enables us to measure moisture profiles continuously while controlling the heating rate at the exposed surface. A constant heat flux at the exposed surface, imposed by the radiance of gold-coated halogen lamps, results in steep temperature gradients near the surface. Cell wall moisture is released and transported as water vapor. The vapor travels towards regions of lower pressure, i.e. both towards the exposed surface, where the sample dries, and towards the back surface. Near the back surface, the lower temperatures result in exchange of water vapor into cell wall moisture and thus a local increase in the measurable moisture content. Consequentially, a peak in the moisture

Fig. 17. (a) Peak position and (b) temperature at peak position over time for $D = 10^{-6} \text{ m}^2/\text{s}$ and different permeability values, for two different emittance temperatures T_R .

Fig. 18. (a) Peak position and (b) temperature at peak position over time for $D = 10^{-6} \text{ m}^2/\text{s}$ and different permeability values, for different initial equilibrium relative humidity ($h_0 = 0.25$ and $h_0 = 0.5$).

content is formed, which travels towards the back surface while increasing in intensity. Owing to the direction-dependent transport properties of wood, this peak velocity is higher in the longitudinal direction than in the radial/tangential direction. The temperature at this peak is nearly constant at 100 °C, suggesting the absence of high pressures required for reaching higher temperatures brought about by a sufficiently high permeability. For low heating rates, temperature gradients are considerably lower. Hence the pressure buildup is minor. Water vapor transport towards the back surface is not dominant and therefore no peak in the moisture content is observed. In addition, the whole process is appreciably slower, covering 27 hours instead of two.

Numerical experiments have been performed with a two-phase model comprising moisture being present as cell wall water or as vapor. Moisture transport takes place solely as water vapor, moisture exchange between air and cell wall results in an increase or decrease of the NMR-measurable moisture content in the cell wall. This relatively simple model can phenomenologically and qualitatively explain the observed processes occurring during the heating of pine wood, despite quantitative deviations. Characteristic features of the transport behavior, such as the non-linearity and timescale of the moisture content peak displacement, are well captured in the model. The influence of several input parameters has been explored. For sufficiently high permeability values and adequately chosen diffusion coefficient values, the peak temperature attains a constant value around 100 °C, similar to

experimental observations. This constant peak temperature value is coupled to the equivalence between atmospheric pressure and saturated vapor pressure at 100 °C. A decrease in the local air pressure compensates the increase in the vapor pressure at high temperatures, thereby preventing an increase in the total gas pressure. Furthermore, the higher peak displacement velocity in the longitudinal direction is most probably caused by a higher permeability in conjunction with a moderately higher diffusion coefficient.

In the present study, samples had the same initial condition. An interesting extension of this study is the assessment of the influence of the initial moisture content on the moisture transport behavior. Ultimately, the non-isothermal drying behavior of water-saturated samples can be assessed, which is expected to be completely different from the behavior found in this study. Liquid moisture transport plays a substantial role, not only in the moisture distribution but also in heat convection and through its significant influence on the heat capacity of the system as a whole. Moreover, the pressure can rise to much higher values due to the smaller volume available for water vapor.

Furthermore, we have seen that the heating rate of the exposed surface influences the moisture transport both qualitatively and quantitatively. We have, however, only considered the two extremes of high and low heating rate. A more detailed study of the effect of the heating rate can help identify different drying behaviors based on dominating processes. Finally, the study of different wood species is expected to

Fig. 19. (a) Normalized moisture content profiles and (b) temperature profiles for a simulation of transport in the radial/tangential direction, with a low heating rate. The time between profiles is 60 minutes, total simulation time is 27 hours.

deepen the understanding of moisture transport mechanisms at elevated temperatures in wood.

Conflict of interest

The authors declared that there is no conflict of interest.

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