Water Vapour Sorption and Moisture Transport in and Across Fibre Direction of Wood

Alexander Murr (✉ alexander.murr@gmx.at)

Universität Innsbruck: Universitat Innsbruck <https://orcid.org/0000-0003-3874-9220>

Research Article

Keywords: Water vapour sorption, Sorption kinetics, Moisture transport , Diffusion, Water vapour transport, Wood

Posted Date: December 1st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1054651/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Version of Record: A version of this preprint was published at Cellulose on March 30th, 2022. See the published version at <https://doi.org/10.1007/s10570-022-04520-x>.

Water vapour sorption and moisture transport in and across fibre direction of wood

Alexander Murr

Received: date / Accepted: date

Abstract Water vapour sorption experiments are frequently used to characterise the absorption and desorption of water in wood during transient conditions in relative humidity. When interpreting such experiments, it is still unclear to what extent the resulting time-dependent change of sample mass (i.e. sorption kinetics) is influenced by moisture transport, sorption and sorption related processes. To evaluate the impact of water vapour diffusion under such transient conditions, this study investigates the sorption kinetics of small wood samples with different lengths of transport pathways in and across fibre direction. For this purpose, water vapour sorption experiments on Norway spruce (*Picea abies*) samples were performed under identical climatic conditions at ambient air pressure and ambient standard temperature. The results showed that sample thickness has an impact on the sorption kinetics along the whole tested range of relative humidity. Differences between the sorption kinetics for samples in and across fibre direction were considerable at low relative humidity, indicating the relevance of water vapour diffusion through the lumen-pit-ray system. In contrast at high relative humidity, differences between the sorption kinetics for samples in and across fibre direction started to disappear while the impact of sample thickness was still considerable. Therefore, it seems as if an additional or modified process that depends on the number of sorption sites becomes relevant at an increased moisture content of wood. This process, as well as the increasing uptake and release of water across fibre direction, should be further investigated to gain a better understanding of the absorption and desorption of water in wood.

Keywords Water vapour sorption · Sorption kinetics · Moisture transport · Diffusion · Water vapour transport · Wood

A. Murr
Unit of Material Technology, University of Innsbruck
Technikerstraße 13, 6020 Innsbruck, Austria
E-mail: alexander.murr@gmx.at
ORCID: 0000-0003-3874-9220

1 Introduction

Wood is a hygroscopic material and capable to absorb large amounts of moisture from the surrounding air. Since many physical properties depend on the moisture content of wood (MC), a change of relative humidity (RH) in the surrounding air causes a corresponding change in the physical properties of wood (Niemz 1993). To characterise the behaviour of wood and to identify the relevant processes during such non-stationary (i.e. transient) conditions, experimental investigations are often realised under transient conditions in RH (Christensen and Kelsey 1959; Christensen and Hergt 1969; Rosen 1978; Avramidis and Siau 1987; Wadsö 1994b; Hill et al. 2010; Eitelberger and Svensson 2012). According to the wide spread of dynamic vapour sorption devices, water vapour sorption experiments are frequently used for this purpose (Xie et al. 2011; Himmel and Mai 2015; Glass et al. 2017; Murr and Lackner 2018). Sample material is exposed to a well-defined change in RH and the resulting time-dependent change of sample mass (i.e. sorption kinetics¹) is measured by weighting the sample. Consequently, this method provides direct information on the uptake and release of H₂O-molecules (hereinafter referred to as water). The interpretation of water vapour sorption experiments is though not trivial since moisture transport, sorption and sorption related processes are strongly coupled and might affect the measured sorption kinetics (Thybring et al. 2019). This raises the question of what kind of information can be extracted from the sorption kinetics of water vapour sorption experiments. Therefore, the processes that restrict the uptake and release of water in wood during a transient change of RH need to be identified. As water vapour has to be transported to and through the lumen-pit-ray system prior to getting bound on/in the cell wall and prior to any sorption related processes are initiated (e.g. release of binding energy, swelling, reorganisation of wood polymers), water vapour transport should be of particular importance for the initial sorption kinetics (see Fig. 1).

To avoid an overemphasis of water vapour diffusion through the lumen-pit-ray system, small or thin samples are often preferred in experimental investigations. Several studies have investigated the water vapour sorption behaviour of small wood samples but only a few analysed the impact of sample thickness or anatomical orientation on the measured sorption kinetics. Christensen and Kelsey (1959) compared the absorption kinetics between two 1 mm thick samples in longitudinal and tangential direction (i.e. in and across fibre direction) and a 40 μ m thick microtomed sample in tangential direction of Klinki pine (*Araucaria hunsteinii*) and found slightly faster sorption kinetics for the microtomed sample but no significant differences between the 1 mm samples. In contrast, Thybring et al. (2019) mentioned about a study on Mountain ash

¹ There is a variety of expressions which are used synonymously for the time-dependent change of sample mass during water vapour sorption experiments in wood science: sorption kinetics, absorption/adsorption and desorption kinetics, kinetics, temporal mass change, sorption rates, absorption/adsorption and desorption rates, or rates. In this work the term sorption kinetics as well as absorption and desorption kinetics will be used.

Fig. 1 Simplified illustration of the involved processes when wood is exposed to a change of relative humidity. Figure a indicates the transport of water vapour to the sample surface and through the lumen-pit-ray system. Figure b shows the concomitant processes in the cell wall of wood.

71 (*Eucalyptus regnans*) done by Christensen (1960), where the absorption kinet-
 72 ics between samples with a thickness between $20\ \mu\text{m}$ and $3\ \text{mm}$ in tangential
 73 direction were considerable different at low RH, while differences at high RH
 74 were not appreciable. However, Wadsö (1994b) compared the absorption ki-
 75 netics of various soft- and hardwoods with a thickness between $3.8\ \text{mm}$ and
 76 $22.8\ \text{mm}$ (in longitudinal, tangential and radial direction) and found differ-
 77 ences in the initial sorption kinetics at mid to high RH. Similarly, Nopens
 78 et al. (2019) have found differences in the absorption and desorption kinetics
 79 for samples with a thickness between $1\ \text{mm}$ and $20\ \text{mm}$ (in longitudinal direc-
 80 tion) of Scots pine (*Pinus sylvestris*) and European beech (*Fagus sylvatica*).
 81 Further, a comparison of microtomed and cut Norway spruce wood (*Picea*
 82 *abies*) with a thickness of $25\ \mu\text{m}$ and $0.5\ \text{mm}$ in longitudinal direction showed
 83 significant differences in the absorption kinetics at low RH (Murr and Lackner
 84 2018). Similar to the different experimental observations, a variety of differ-
 85 ent approaches to model the moisture transport in wood can be found in the
 86 literature. Some authors have used a coupled transport model, where water
 87 vapour and bound water (i.e. water within the cell wall) were described by a
 88 separate diffusion equation (Krabbenhof and Damkilde 2004; Frandsen et al.
 89 2007; Eitelberger et al. 2011; Konopka and Kaliske 2018). Diffusion coefficients
 90 for water vapour were given to be (almost) constant while the diffusion coef-
 91 ficients for bound water were described by exponentially increasing functions
 92 with MC. A simplification of the coupled approach was given by Hozjan and
 93 Svensson (2011), where the bound water diffusion was shown by a theoretic-
 94 al analysis to be negligible, particularly at low RH (see also Eitelberger and
 95 Svensson 2012). On the contrary, other authors have neglected the transport
 96 of water vapour and instead used a diffusion equation for the transport of
 97 bound water combined with a certain boundary condition for the flux (Olek
 98 et al. 2011). Using an inverse analysis, a non-monotonic behaviour for the
 99 diffusion coefficients as well as differences in the diffusion coefficients between

absorption and desorption were found with this model. In addition, a combined transport approach has been used, where water vapour and bound water were treated together with a single diffusion equation (Time 1998; Florisson et al. 2020). With this approach, an increase of diffusion coefficients with MC across fibre direction was frequently reported, while diffusion coefficients in fibre direction were given to decrease with MC (Droin-Josserand et al. 1989; Jakiela et al. 2008; Kang et al. 2008). Consequently, there seems to be no consensus on whether moisture transport - compared to sorption and sorption related processes - can be neglected in water vapour sorption experiments on small wood samples under ambient conditions.

The objective of this work is thus to examine the impact of water vapour diffusion through the lumen-pit-ray system on the uptake and release of water during a transient change of RH. Therefore, water vapour sorption experiments are performed on thin Norway spruce plates with a different thickness along the three main anatomical orientations (i.e. longitudinal, tangential, and radial). Experiments are carried out at ambient pressure and standard ambient temperature along a wide range of RH. The sorption kinetics between samples in fibre direction (longitudinal) and across fibre direction (tangential and radial) are compared during absorption and desorption to identify the impact of water vapour diffusion through the lumen-pit-ray system and to estimate moisture dependent changes on the transport properties. With this information the relevance of cell wall processes on the measured sorption kinetics should be estimated. However, for quantitative statements on the impact of cell wall processes on the uptake and release of water, different measurements would be necessary. The presented experimental results can be used as a state-of-the-art data for future modelling approaches and for a validation of existing transport concepts.

2 Materials and methods

2.1 Dynamic vapour sorption

All water vapour sorption experiments were carried out with the dynamic vapour sorption device SPSx-1 μ (ProUmid GmbH, Germany). The device consists of a climatic chamber, where up to 11 samples can be tested under identical pressure, temperature and RH conditions. Sample material is placed in aluminium bowls on a rotating plate and the mass of the samples is measured automatically by placing each sample bowl successively on a micro scale with a reproducibility of $\pm 10 \mu\text{g}$. Sample weighting is repeated at an 8 min interval to ensure stabilised conditions inside the climatic chamber. At the beginning and at the end of a weighting cycle (i.e. prior to the first and after the last sample was weighted), an empty reference bowl is weighted to correct the adsorption and desorption of water on the sample bowls and to correct a possible scale drift (assuming a linear drift). Relative humidity is regulated by a moistening unit using dry air (0.2 % RH; hereinafter referred to as 0 % RH) or water

142 vapour-saturated air and the two fans create a circulating flow of the water
 143 vapour-air mixture inside the climatic chamber. RH can be changed stepwise
 144 by choosing the required step-sizes for absorption or desorption. Deviations to
 145 the pre-set RH can be ensured to be below $\pm 0.5\%$ RH, except for $\text{RH} \geq 80\%$
 146 ($\pm 1\%$ RH). The integrated Peltier element ensures a constant temperature of
 147 25°C with a deviation below $\pm 0.1^\circ\text{C}$. More details on the dynamic sorption
 148 device can be found in Murr (2019).

149 2.2 Sample preparation

150 Samples were taken from the lower stem of a Norway spruce (*Picea abies*)
 151 grown in the West of Austria. A plank with a length of 1.5 m in longitudi-
 152 nal direction was cut through the centre of the stem and 136 annual rings
 153 were counted. After an initial drying phase of 7 days at ambient air, the
 154 plank was stored for 12 months in an air-conditioned room at a tempera-
 155 ture of 21°C ($\pm 3^\circ\text{C}$) and a relative humidity of 30% ($\pm 10\%$). Prior to ma-
 156 nipulation, the plank was cut to remove the inner and outer part (approx-
 157 imately 15 annual rings in each case). Thin samples were cut with a circu-
 158 lar saw using a sharp blade with alternative top bevel teeth and a positive
 159 rake angle to minimise heat production. To compare the influence of sample
 160 thickness on the sorption kinetics, several samples with a thickness between
 161 0.5 mm and 3 mm along the three anatomical orientations were cut (see Fig. 2).

Fig. 2 Anatomical orientations of wood indicated with the three arrows for the longitudinal (L), tangential (T), and radial direction (R). Samples were labelled corresponding to the direction of the surface normal of the thinnest dimension

162 Cross section was chosen to be large enough to minimise the impact of wa-
 163 ter vapour diffusion through the side surfaces (i.e. orthogonal to the sample
 164 thickness), but not too large to unnecessary slow down the time span for
 165 changing RH in the climatic chamber (Murr 2019). All samples were without
 166 any visible defects or growth irregularities and the density was determined

Table 1 Sample dimensions at MC $\approx 6\%$ and minimum sample mass after precondition phase (m_0) of used samples in the longitudinal (L), tangential (T) and radial (R) direction

Dimensions (mm x mm x mm)	Mass (mg)	Label
0.5 (L) $\times$ 21.4 (R) $\times$ 40.0 (T)	157	L_0.5mm
1.0 (L) $\times$ 20.2 (R) $\times$ 41.6 (T)	299	L_1mm
2.0 (L) $\times$ 21.0 (R) $\times$ 43.0 (T)	607	L_2mm
3.0 (L) $\times$ 20.7 (R) $\times$ 43.0 (T)	888	L_3mm
0.5 (T) $\times$ 21.2 (R) $\times$ 43.6 (L)	175	T_0.5mm
1.0 (T) $\times$ 21.2 (R) $\times$ 43.6 (L)	312	T_1mm
2.0 (T) $\times$ 22.2 (R) $\times$ 43.6 (L)	613	T_2mm
3.0 (T) $\times$ 21.6 (R) $\times$ 43.6 (L)	928	T_3mm
0.5 (R) $\times$ 21.5 (T) $\times$ 43.6 (L)	173	R_0.5mm
1.0 (R) $\times$ 21.6 (T) $\times$ 43.6 (L)	361	R_1mm
2.0 (R) $\times$ 22.1 (T) $\times$ 43.6 (L)	605	R_2mm

167 to be $370 \pm 40 \text{ kg m}^{-3}$. To measure the uptake and release of water for the
 168 various samples under identical climatic conditions, one representative slice
 169 for each thickness and anatomical orientation was chosen (see Table 1). The
 170 restriction of the investigation to one sample each was possible as pre-testings
 171 have shown identical sorption kinetics between a number of samples for each
 172 thickness and orientation, including the samples which were investigated in
 173 this study. Further, it has to be mentioned that a complete run of the mea-
 174 surement as described in Section 2.3 takes more than 6 weeks. A successive
 175 measurement of, for example, 5 samples for each thickness and orientation
 176 would therefore extend the measurement to over half a year. The sample with
 177 a thickness of 3 mm in the radial direction was omitted in this work, as the
 178 maximum number of samples to be tested at once (i.e. under identical climatic
 179 conditions) was limited to 11 samples.

180 2.3 Experimental set-up

181 Samples according to Table 1 were distributed with decreasing thickness across
 182 the 11 sample bowls, starting with the thickest (3 mm) and ending with the
 183 thinnest samples (0.5 mm). The order of anatomical orientation (i.e. the di-
 184 rection of the thinnest sample dimension) was chosen for each thickness to
 185 be longitudinal, tangential and radial. Particular attention was given to max-
 186 imise the accessibility of water vapour to the sample surface and to emphasise
 187 possible differences in the initial sorption kinetics of the various samples. This
 188 was done by mounting the thin wooden sample plates on a wire frame outside
 189 the sample bowl and parallel to the water vapour-air stream. Hence, sam-
 190 ples were exposed directly in the circulating water vapour-air stream which
 191 avoids the paths of stagnant air when samples are placed inside a sample bowl
 192 (Murr 2019). An additional wire frame was placed on the reference bowl to
 193 correct for the adsorption and desorption of water on the wire frame of the

samples. Samples were conditioned inside the climatic chamber at $T = 25^\circ\text{C}$ and 0 % RH until equilibrium condition (EC) was reached (Eq. 1). After an additional drying phase of 24 h, samples were weighted to determine the minimum sample mass m_0 (see Table 1). To measure the sorption kinetics of the various samples, RH was changed stepwise and kept constant until all samples fulfilled the EC, defined as

$$\frac{d}{dt} \left(\frac{m(t)}{m_0} \right) < 0.00017 \% \text{ min}^{-1} \quad (1)$$

evaluated in a period of 120 min. Here, $m(t)$ denotes the total sample mass and a linear regression was used for the calculation. This mass stability criterion is more than one order of magnitude lower than the most common used criterion given in Glass et al. (2017). It should be noted that the sample with the slowest sorption kinetic determined the EC and hence the time, when the next step change in RH was initiated. Samples with a faster sorption kinetic had thus an even lower EC than mentioned in Eq. 1, which might had an impact on the sorption kinetic in the following step change of RH (Christensen and Hergt 1969). Step-size in RH was chosen to $\Delta\text{RH} = 10\%$ between 0% and 90 % RH at a constant temperature of 25°C (i.e. at standard ambient temperature). An additional step to reach 94 % RH was used to provide a different starting MC for desorption at 90 % RH. After absorption was completed, a reverse order sequence of the same step-sizes in RH was used for desorption. A change of relative humidity inside the climatic chamber took between 1 and 2 min for the given experimental set-up. Only for absorption above 70 % RH and desorption below 20 % RH, step changes in relative humidity needed more time until the pre-set RH value was attained (see Fig. S5 in the *Supplementary Information*). Weighting of the samples started approximately 5 min after a step change in RH was initiated and was then repeated in an 8 min cycle until EC was reached. As mentioned by Popescu and Hill (2013), a complete run in absorption and desorption was performed in advance to reduce a possible impact of previous sorption history on the sorption kinetics.

2.4 Simulations

To simulate the diffusion of water vapour through the lumen-pit-ray structure of wood, some simplified assumption were made. The wood samples were treated as a homogeneous sheet with a thickness corresponding to Table 1. Uptake and release of water on/in the cell wall as well as the transport of moisture through the cell wall were assumed to be very fast (i.e. instantaneous). Further, processes within the cell wall and their impact on the diffusion of water vapour were not considered (e.g. a possible reduction of water vapour diffusion due to a local drop of RH caused by the release of binding energy during absorption of water on/in the cell wall). Using these simplifications and assuming a one-dimensional moisture transport through the sample, the diffusion of water

vapour in wood can be written approximately as (see e.g. Murr 2019)

$$\frac{\partial \rho_{wv}}{\partial t} = D_{\text{eff}} \cdot \frac{\partial^2 \rho_{wv}}{\partial x^2} \quad (2)$$

Here, $\rho_{wv} = \rho_{wv}(x, t)$ is the concentration of water vapour in kg m^{-3} and the effective diffusion coefficient for water vapour through wood includes the absorption and desorption of water, $D_{\text{eff}} = \frac{\xi \cdot D_a}{1 + \Delta R}$ in $\text{m}^2 \text{s}^{-1}$. D_a is the water vapour diffusion coefficient in air and ξ is a constant reduction factor for the hindered transport through the lumen-pit-ray structure. The uptake and release of water on/in the cell wall considerably reduces the diffusion of water vapour through the samples and is given by the sink factor ΔR . This factor can be calculated by the change in bound water concentration divided by the change of water vapour concentration for each step change in RH. It should be mentioned that ΔR was assumed to be constant during each step change in RH. Using Eq. 2 and an instantaneous change of water vapour on the surface of the sample, the standardised change of sample mass (Eq. 4) during a step change in RH can be evaluated as (Crank 1975)

$$\frac{\Delta m(t)}{\Delta m_{\text{max}}} = 1 - \sum_{n=0}^{\infty} \frac{8}{\pi^2 (2n+1)^2} \cdot \exp\left(-\frac{D_{\text{eff}} \cdot t \cdot \pi^2 (2n+1)^2}{d^2}\right) \quad (3)$$

where d is the thickness of the sample. To evaluate Eq. 2 under more realistic boundary conditions (i.e. the measured RH inside the measuring chamber given in Fig. S5), a simulation based on the interpolated RH values was carried out (Fig. 6b and Fig. 8). For the simulations the software *Wolfram Mathematica 12.1* was used. The reduction factor in longitudinal direction was chosen as $\xi = 0.9$ (Frandsen et al. 2007) and the water vapour diffusion coefficient in air was used as mentioned in Schirmer (1938). This results in an effective water vapour diffusion coefficient of $D_{\text{eff}} \approx 5 \cdot 10^{-9} \text{ m}^2 \text{s}^{-1}$ for the step change $0\% \rightarrow 10\% \text{ RH}$ (see Fig. 6).

2.5 Error estimation

Regarding the measurement error, the humidification process inside the climatic chamber (Murr 2019) and the variation in sample material (i.e. sample geometry and density) were identified as the main sources of error in the given experimental set-up. On the basis of pre-testings with cut samples of the same wooden plank, these errors were estimated to be below 3% of the total mass change per step.

3 Results and discussion

To compare the sorption kinetics between samples with a different sample thickness or among different step changes in RH, the time-dependent change

of sample mass was either standardised to minimum sample mass (m_0) or to the total mass change of the investigated step change in RH,

$$\frac{\Delta m(t)}{\Delta m_{max}} = \frac{m(t) - m(0)}{m(t_{max}) - m(0)} \quad (4)$$

which is sometimes termed as fractional mass change $E(t)$. For each step change the time was set to start at $t = 0$ and t_{max} refers to the time, when EC (Eq. 1) was fulfilled by the sample with the slowest sorption kinetics ($t_{max} > 1000$ min). To evaluate the sample mass at a specific time, a linear interpolation of the measured data was used. Moisture content of wood is generally a time-dependent function and was calculated on the basis of minimum sample mass, $MC(t) = (m(t) - m_0)/m_0$. In the following, desorption data were given in terms of absolute values, except for Fig. 3b, Fig. 4b and Fig. S1b in the *Supplementary Information*. The time axis was chosen to emphasise the initial sorption kinetics in the figures and is always considerably smaller than the time when EC was reached. Experimental results of the step change 90 % $\rightarrow$ 94 % RH and 94 % $\rightarrow$ 90 % RH were only shown in Fig. 9 and Fig. S4 in the *Supplementary Information*. This was done to avoid confusion, since differences in step-size have an impact on both sorption kinetics and total mass change per step (Christensen and Kelsey 1959; Murr 2019).

3.1 Samples with different thickness

In fibre direction:

The absorption and desorption kinetics for samples with a thickness between 0.5 mm and 3 mm in longitudinal direction (i.e. in fibre direction) is shown for an exemplary step change in Fig. 3a,b. In both cases, differences in the sorption kinetics among the various samples can be seen particularly at the initial phase ($t \lesssim 30$ min) of the mass change. With increasing time, these differences in the sorption kinetics decrease leading to a similar increase or decrease of standardised sample mass until EC was reached (indicated by the straight dotted line). To investigate if the impact of sample thickness on the initial sorption kinetics is also present for other step changes in RH, a representation of the uptake and release of water after an arbitrary chosen evaluation time of $t_{ev} = 10$ min was used. For each step change in RH, differences in the amount of absorbed (Fig. 3c) and desorbed water (Fig. 3d) can be seen among the four tested samples. A minimum in the differences was observed in the mid range of RH, which corresponds to the smallest total mass change per step (see bars in the background of Fig. 3c,d). As the standardised mass change of the thinner samples is always faster than for the thicker ones, these results show that sample thickness has a significant impact on the initial sorption kinetics even for samples with a thickness of 1 mm and below. To investigate the impact of sample thickness on the sorption kinetics at a later phase, uptake and release of water was evaluated at $t_{ev} = 100$ min. In contrast to the initial

Fig. 3 Comparison of the absorption (left) and desorption behaviour (right) between longitudinal samples with different thickness. First row shows the sorption kinetics for a selected step change in absorption (a) and desorption (b). Middle row shows the uptake (c) and release of water (d) after 10 min for each step change in RH and the last row shows the uptake (e) and release of water (f) after 100 min. Markers were placed in the middle of each step change in RH and bars in the background show the total mass change when EC was fulfilled. The grey area indicates the range with a slow change of RH inside the measuring chamber. Error bars were omitted for a better comparability and the interpolated lines between the measured data are for illustration purposes only

phase, differences among the samples almost disappeared in the low and mid range of RH for both absorption (Fig. 3e) and desorption (Fig. 3f). Since equilibrium mass was not reached at this time (see differences between markers and bars in the background of Fig. 3e,f), the remaining mass change must be almost independent of water vapour diffusion through the lumen-pit-ray system. Hence, it seems as if processes within the cell wall are dominating the sorption kinetics of longitudinal samples in this phase. An exception is though the high range of RH, where significant differences in the uptake and release of water among the samples can be seen even after 100 min. The impact of sample thickness for samples in fibre direction lasts thus much longer in the high range of RH compared to the mid and low range of RH. For the step change 10% $\rightarrow$ 0% RH, differences among the samples were also detected after 100 min (Fig. 3f). These differences seem though to be an effect of the slow change of RH inside the measuring chamber of the used sorption device (see Section 2.3 and Fig. S5), which slows down the release of water at low RH as well as the uptake of water at high RH (see grey area in Fig. 3c-f).

Across fibre direction:

An evaluation of the absorption and desorption kinetics for samples with a thickness between 0.5 mm and 3 mm in tangential direction (i.e. across fibre direction) during an exemplary step change in RH is given in Fig. 4a,b. Differences in the sorption kinetics among the various samples can be clearly seen and the uptake and release of water is noticeable slower than for the longitudinal samples. An evaluation of the initial sorption kinetics ($t_{ev} = 10$ min) over the whole tested range of RH shows a significant impact of sample thickness on the uptake (Fig. 4c) and release of water (Fig. 4d). Hence, for tangential samples with a thickness of 3 mm and below, an even larger impact of sample thickness on the initial sorption kinetics was observed. Similar results were obtained by comparing the radial samples as shown in Fig. S1 in the *Supplementary Information*. This is contrary to the findings of Christensen (1960) reported in Thybring et al. (2019), where no differences in the sorption kinetics of tangential samples (with a thickness between 20 μ m and 3 mm) were reported above 60% RH. An investigation of the uptake (Fig. 4e) and release of water (Fig. 4f) at an evaluation time of 100 min shows further, that these differences among the tangential samples generally last longer than for the longitudinal samples. Water vapour diffusion through the lumen-pit-ray system seems thus to be more dominant (i.e. slower) across fibre direction than in fibre direction. Consequently, for investigations of sorption and sorption related processes, thin longitudinal samples are more recommended than thin tangential or radial samples as water vapour diffusion has less impact on the uptake and release of water. A fact that remains unclear is the proximity of the uptake and release of water between the 1 mm and 2 mm tangential samples in the low range of RH (Fig. 4). An explanation based on an additional transport path for water vapour through the not sealed side surface of the tangential samples seems to be improbably, as the large differences between the sorption kinet-

Fig. 4 Comparison of the absorption (left) and desorption behaviour (right) between tangential samples with different thickness. First row shows the sorption kinetics for a selected step change in absorption (a) and desorption (b). Middle row shows the uptake (d) and release of water (d) after 10 min for each step change in RH and the last row shows the uptake (e) and release of water (f) after 100 min. Markers were placed in the middle of each step change in RH and bars in the background show the total mass change when EC was fulfilled. The grey area indicates the range with a slow change of RH inside the measuring chamber. Error bars were omitted for a better comparability and the interpolated lines between the measured data are for illustration purposes only

ics of the 2 mm and 3 mm samples do not support this possibility. The radial samples showed a similar effect, although the proximity of the 1 mm and 2 mm sample was less pronounced (see Fig. S1 in the *Supplementary Information*).

3.2 Samples with different anatomical orientation

Low range of RH:

Investigating the differences between the sorption kinetics of samples in and across fibre direction at low RH, longitudinal samples show a considerable faster absorption (Fig. 5a) and desorption kinetics (Fig. 5b) than the tangential samples.

Fig. 5 Comparison of the sorption kinetics between samples with a different thickness in the longitudinal (blue) and tangential (red) direction in the low range of RH. Absorption kinetics (0% → 10% RH) are shown left (a,c) and desorption kinetics (20% → 10% RH) right (b,d). Error bars were omitted for a better comparability and the interpolated lines are for illustration purposes only

For both orientations, thicker samples show a slower standardised mass change than the thinner samples, which is indicated by the arrows for each anatomical orientation. Similar results were obtained with the radial samples as shown in Fig. S2 in the *Supplementary Information*. To evaluate if diffusion of water vapour through the lumen-pit-ray system has a significant contribution on the sorption kinetics, an illustration over $\sqrt{t/d^2}$ was used. For a sheet diffusion process with an instantaneous change of RH at the surface of the sheet (Eq. 3), this illustration leads to an identical mass change for each thickness (Fig. 6a)

(see also Crank 1975). However, if the measured change of RH in the measuring chamber is used as a boundary condition at the sample surface (see Fig. S5a in the *Supplementary Information*), differences in the mass change become apparent (Fig. 6b). Analysing the measured sorption kinetics in the $\sqrt{t}/d^2$ representation, differences among the samples with different thickness can be seen for both orientations (Fig. 5c,d). The thinner samples seem to be delayed in their sorption kinetics while with increasing thickness samples tend towards identical kinetics. Comparing the measured mass change of the longitudinal samples with the simulated solution for the sheet diffusion process, a certain similarity can be seen (cf. Fig. 5c and Fig. 6b). This indicates that water vapour supply and water vapour diffusion through the lumen-pit-ray system do have a considerable impact on the uptake and release of water for thin wood samples at low RH. Based on these results it seems as if processes within the cell wall have a smaller impact on the sorption kinetics in this range of RH.

Fig. 6 Solutions for diffusion in a plane sheet with different thickness to simulate the water vapour diffusion in the longitudinal direction. Instantaneous (a) and the measured change of RH inside the measuring chamber (b) were used as boundary conditions at the surface

High range of RH:

In the high range of RH, the sorption kinetics of samples in longitudinal and tangential direction show a remarkable similarity during absorption (Fig. 7a) and particularly during desorption (Fig. 7b). For absorption, an identical uptake of water can be observed for the 0.5 mm samples while with increasing thickness the differences between the longitudinal and tangential samples increase. In contrast for desorption, the release of water is identical for the 0.5 mm samples as well as for the 1 mm samples and only slight differences were found for the thicker samples. A similar trend was observed between the longitudinal and radial samples (Fig. S3 in the *Supplementary Information*). Therefore, the sorption kinetics between samples in and across fibre direction seems to be more similar for desorption, but this appears to be related to the moisture content of the wood samples (see Section *Transition low to high range of RH*). A fact that was not expected is the difference in the sorption kinetics among samples with a different thickness. Even though the anatomical orientation is less relevant for the uptake and release of water at high RH,

Fig. 7 Comparison of the sorption kinetics between samples with a different thickness in the longitudinal (blue) and tangential (red) direction in the high range of RH. Absorption kinetics (80% → 90% RH) are shown left (a,c) and desorption kinetics (90% → 80% RH) right (b,d). Error bars were omitted for a better comparability and the interpolated lines are for illustration purposes only

sample thickness still has a considerable impact. Pre-testings on another sample set of the same wooden plank with the same step changes in RH confirmed this results. Furthermore, experiments with a step-size in relative humidity of $\Delta RH = 30\%$ led to similar results. To evaluate if a diffusion process through the sample thickness can explain these differences, a representation of the sorption kinetics over $\sqrt{t/d^2}$ was used. As shown in Fig. 7c and Fig. 7d, both the shape of the sorption kinetics as well as the differences among the samples deviate considerably from the simulated water vapour diffusion behaviour given in Fig. 6b. This deviation also becomes evident when comparing the measured desorption kinetics (Fig. 7b) with a corresponding simulated solution for a plane sheet diffusion process using an arbitrary chosen high and a low diffusion coefficient. With a high diffusion coefficient, differences between the four samples occur mainly in the fast rising initial phase, and these differences decrease rapidly with increasing time (Fig. 8a). In contrast, with a low diffusion coefficient, differences between the four samples occur from the slow rising initial phase to long measurement times and these differences decrease slowly with increasing time (Fig. 8b). Both cases differ from the measured desorption kinetics (Fig. 7b), which is characterised by a rapid rising initial phase followed by a slowly rising later phase. Hence, it seems as if processes within the cell wall have a larger impact on the sorption kinetics in the high range of RH. These results are supported by other investigations in the literature, where the deviation of the measured sorption kinetics from a

426 simple moisture diffusion process was frequently mentioned as a non-Fickian
 427 behaviour (Wadsö 1994a; Krabbenhoft and Damkilde 2004; Olek et al. 2005;
 428 Himmel and Mai 2016). However, as sample thickness was shown to have a
 429 considerable impact on the sorption kinetics, the uptake and release of water
 430 cannot solely depend on processes within the cell wall of wood. Hence, either
 431 a barrier for the moisture transport or a process that depends on the sam-
 432 ple mass but not on the sample orientation (i.e. a dependence on the number
 433 of sorption sites) seems to be relevant in the high range of RH. Thermal ef-
 434 fects, a boundary layer, or an additional or modified moisture transport might
 435 be possible candidates for this process. Future experiments should thus com-
 436 pare the sorption kinetics of chemically modified samples (see e.g. Thybring
 437 and Fredriksson 2021 and references therein) or of samples with different dry
 438 densities to investigate the impact of sorption sites on the absorption and
 439 desorption of water in the high range of RH. It should be mentioned that
 440 with increasing sample thickness diffusion processes become more dominant
 441 as their characteristic time scales with the square of the thickness ($t \sim d^2$).
 442 As a result, the uptake and release of water in thicker samples should be
 443 increasingly dominated by diffusion (e.g. water vapour diffusion through the
 444 lumen-pit-ray system). This might explain the increasing differences in the
 445 sorption kinetics between samples in and across fibre direction with increasing
 446 thickness (see Fig. 7a,b and Fig. S3a,b in the *Supplementary Information*).

Fig. 8 Simulated solutions for diffusion in a plane sheet with different sheet thickness for a high (a) and low (b) diffusion coefficient. Arrows indicate the impact of increasing sheet thickness and boundary conditions are chosen corresponding to desorption at high RH

447 *Transition low to high range of RH:*

448

449 The sorption kinetics of thin wood samples in and across fibre direction differ
 450 significantly between the low and high range of RH. Hence, there seems to
 451 be at least one transition in the processes which dominate the uptake and
 452 release of water in thin wood samples. To allow such a transition between
 453 two or more processes to happen, either the characteristic times of the in-
 454 volved processes or their relative amplitudes (or both) have to change with
 455 increasing RH. As the uptake and release of water depends on moisture trans-
 456 port, sorption and sorption related processes, the slowest of the involved pro-

cesses will dominate the sorption kinetics. This fact has to be considered in all types of experiments under transient conditions in RH (e.g. measuring the heat of sorption or swelling). To investigate the transition between the low and high range of RH, the ratio between the mass change of the tangential and longitudinal samples ($\Delta m_T / \Delta m_L$) for each sample thickness was used. Evaluation time for the ratio was chosen to $t_{ev} = 10$ min to capture particularly the initial phase of the sorption kinetics. If $\Delta m_T / \Delta m_L < 1$, the uptake and release of water for the tangential sample is slower than for the longitudinal sample. In the case of $\Delta m_T / \Delta m_L = 1$, the uptake and release of water is identical for both samples. The fact that a similar initial mass change between the samples ensures a similar sorption kinetics until EC is reached is supported by the measurements of this study (see e.g. Fig. 7). Figure 9 shows the four mass change ratios along the moisture content of wood.

Fig. 9 Initial mass change ratio between tangential and longitudinal samples during absorption (★) and desorption (◆) for a sample thickness of 0.5 mm (a), 1 mm (b), 2 mm (c), and 3 mm (d). Grey area indicates the range with a similar sorption kinetic between the tangential and longitudinal samples

For each sample thickness a continuous increase of the ratio $\Delta m_T / \Delta m_L$ can be seen. These results indicate a continuous transition in the processes which dominate the initial sorption kinetics between the low and high range of RH. Since for each thickness the ratio $\Delta m_T / \Delta m_L$ between absorption and desorption is similar, the processes involved in this transition must be independent on the uptake and release of water. Similar results were obtained for the ratio

between the radial and longitudinal samples (Fig. S4 in the *Supplementary Information*). Consequently, processes which are different between absorption and desorption seem to have a minor impact on the initial sorption kinetics. Further, moisture content of wood seems to be an appropriate parameter for the transition as in a representation over RH differences between absorption and desorption were observed. This appears plausible as changes in wood properties (and thus in the involved processes) should depend mainly on the state of the material instead on the surrounding conditions (see e.g. Niemz 1993). Comparing the four mass change ratios among each other, an increase of the ratio with decreasing sample thickness can be seen. This seems reasonable, as in the limiting case of a sample thickness close to the cell wall thickness water vapour diffusion through the lumen-pit-ray system can be omitted and should lead to a similar sorption kinetics between the anatomical orientations. In contrast, with increasing sample thickness water vapour diffusion through the lumen-pit-ray system will get more dominant since the characteristic time for a diffusion process increases proportionally to the square of the sample thickness. An evaluation of the mass change ratio at a later time led also to an increase of $\Delta m_T / \Delta m_L$. This supports the findings that water vapour diffusion across fibre direction has a considerable impact on the measured sorption kinetics even after the initial phase. It should be mentioned that along with a later evaluation time differences between the mass change ratio during absorption and desorption emerged. This indicates that processes which are different between absorption and desorption have a larger impact on the sorption kinetics at the later phase.

3.3 Moisture transport across fibre direction:

To evaluate if moisture transport properties change with MC, the initial uptake and release of water between the low and high range of RH was compared. Absorption at low RH and desorption at high RH were used to avoid the ranges with a slow change of RH of the sorption device (see Section 2.3). As shown in Table 2, the initial mass change ($t_{ev} = 10$ min) for the thinnest sample in longitudinal direction is smaller at high RH compared to low RH. A similar behaviour was observed for the thicker samples (cf. Fig. 3c,d). Hence, either the moisture transport decreases noticeable with increasing MC², or sorption and sorption related processes have to increase in characteristic time and/or in relative amplitude. In contrast to the samples in fibre direction, samples across fibre direction were shown to have a larger initial mass change at high RH compared to low RH (see Table 2). Again, a similar behaviour was observed for the thicker samples (cf. Fig. 4c,d and Fig. S1c,d in the *Supplementary Information*). Based on the fact that at low MC water vapour diffusion across

² The small decrease of the water vapour diffusion coefficient in air (Schirmer 1938; VDI-Gesellschaft 2006) is too low to explain these differences between the low and high range of RH. Even the often mentioned increasing bound water diffusion inside the cell wall cannot resolve this issue, since it would rather force the opposite trend.

Table 2 Initial uptake (at low RH) and release of water (at high RH) standardised to minimum sample mass for samples with a thickness of 0.5 mm in the longitudinal (L), tangential (T) and radial (R) direction. Measurement error is below $\pm 0.06\%$

Sample	Low RH [%]	High RH [%]	Difference [%]
L	1.96	1.54	−0.42
T	0.82	1.50	+0.68
R	0.92	1.55	+0.63

fibre direction has a larger impact on the sorption kinetics than in fibre direction, these results indicate that moisture transport across fibre direction has to increase with increasing MC. Alternatively, one of the barriers which prevents the uptake and release of water across fibre direction has to decrease considerably with increasing MC. This view is supported by other investigations in the literature, where an increase of moisture transport across fibre direction was frequently mentioned (Siau 1984; Droin-Josserand et al. 1989; Krabbenhoft and Damkilde 2004). Furthermore, steady-state diffusion measurements on pine, spruce and beech samples (see Wadsö 1994b; Sonderegger et al. 2011 and references therein) as well as gas permeability measurements on several hardwoods (Choong et al. 1974) also reported about an increase of moisture transport across fibre direction with increasing MC. Sorption and sorption related processes by contrast seem to be less responsible for this significant increase, as they should have a similar impact for the three anatomical orientations. To analyse if such a significant increase of moisture transport across fibre direction can be explained with the existing concepts of a water vapour transport through the lumen-pit-ray system or a bound water transport through the cell wall of wood (see e.g. Engelund et al. 2012 and references therein), a short discussion on the two transport mechanism is given below. The coupled moisture transport will not be discussed, as a proper treatment with a coupled transport model needs an accurate information on both sorption and sorption related processes, which are still not available. Further, for a meaningful simulation a three dimensional modelling using the accurate three dimensional wood structure (e.g. using X-ray tomographic microscopy (Trtik et al. 2007)) is essential, as a one dimensional simulation cannot sufficiently capture the complex movement of moisture and the associated interaction between moisture transport, sorption and sorption related processes inside the wood samples.

Transport of water vapour:

The moisture transport through the lumen-pit-ray system of wood is usually described by a water vapour diffusion process. For this, the water vapour diffusion coefficient in air (see e.g. Schirmer 1938) is commonly used by applying a constant reduction factor for the various pathways along the three anatomical orientations (cf. Section 2.4). According to the geometrical differences,

the diffusion coefficient in longitudinal direction is given to be considerable larger than in tangential (or radial) direction, $D_{wv}^L \approx 20 \cdot D_{wv}^T$ (Krabbenhof and Damkilde 2004; Frandsen et al. 2007; Eitelberger et al. 2011). An evaluation of the water vapour diffusion coefficient in air between 0% RH and 90% RH yields a decreases of less than 3%. This slight decrease in combination with the constant reduction coefficients can neither explain the increased moisture transport across fibre direction nor the similar sorption kinetics for samples with the same thickness in the high range of RH. Similar results can be obtained when the transport of water vapour includes an instantaneous absorption and desorption of water vapour on the surface of the cell wall (see Section 2.4). This is because the effective diffusion coefficients along the three anatomical orientations are similarly reduced by the uptake and release of water. Thus, to describe an increase of moisture transport across fibre direction with the diffusion of water vapour through the lumen-pit-ray system, the tangential and radial water vapour diffusion coefficients must increase with MC. A possible mechanism for this increase might be a higher permeability of the bordered pit pairs, either by an increased permeability of the pit membrane (torus or margo) or by a movement of the pit membrane to open the pit (i.e. deaspiration of pits). This seems reasonable, since the resistance of pits to the diffusion of non-swelling gases across fibre direction was mentioned e.g. to be more than 99% for dry conifer wood (Petty 1973). The impact of pit aspiration on the gas permeability in wood is given in literature (Comstock 1970; Smith and Banks 1971; Meyer 1971), although changes of pit aspiration were only mentioned to be caused by the adhesion force of a liquid with a certain surface tension (Liese and Bauch 1967; Comstock and Côté 1968; Drive and Aberdeen 1972; Flynn 1995). Consequently, experimental studies are necessary to investigate if the position of the pit membrane or its permeability can change with increasing MC of wood. Alternatively, water vapour sorption experiments on wood samples with a different pit structure might be compared to estimate the impact of pit permeability on the increased uptake and release of water across fibre direction. In comparison to Norway spruce (*Picea abies*), northern white cedar (*Thuja occidentalis*) would be of interest, as the pit membrane hardly shows a thickened torus and the pits seem to remain more permeable at low MC (Liese and Bauch 1967; Bauch et al. 1972).

Transport of bound water:

Inside the cell wall of wood, moisture transport is usually described by a diffusion process, in which water is transported through the cell wall in a bound state (see e.g. Krabbenhof and Damkilde 2004 and references therein). Bound water diffusion coefficients were given to increase exponentially with MC and the coefficient in longitudinal direction is assumed to be larger than in tangential (or radial) direction, $D_{bw}^L(MC) \approx 2.5 \cdot D_{bw}^T(MC)$ (Siau 1984). An evaluation of this bound water diffusion coefficients at 0% and 20% MC (i.e. at 0% and approximately 90% RH) gives an increase of one order of magnitude for each direction. With such an increase of the diffusion coefficients it is

difficult to justify both the similar sorption kinetics between samples of different anatomical orientation and the differences in the sorption kinetics between samples of different thickness (see Fig. 7 and Fig. S3 in the *Supplementary Information*). Though, it should be mentioned that these bound water diffusion coefficients are not necessarily correct (see e.g. Wadsö 1993b and references therein) and that the difference in the bound water diffusion coefficients has never been directly determined. However, there seems to be two major problems if bound water diffusion is used to explain the increasing uptake and release of water for samples across fibre direction. Firstly, water vapour has to be bound on the surface of the cell wall prior a transport of bound water through the cell wall is possible. Sorption and sorption related processes are thus involved and need to be fast enough to allow an additional transport path across or an alternative transport path along the cell wall of wood. As a consequence of the fast processes within the cell wall, the sorption kinetics of thin wood samples should increasingly resemble a diffusion process in the high range of RH, which contradicts the measured results and the results in literature (Avramidis and Siau 1987; Wadsö 1993a; Frandsen et al. 2007). Secondly, to provide a similar moisture transport in and across fibre direction, the combined water vapour and bound water transport has to be comparable for the corresponding anatomical orientations. As water vapour diffusion across fibre direction is considerably less than in fibre direction, the corresponding bound water diffusion coefficient has to be in a similar magnitude as the water vapour diffusion coefficient to resolve this issue. However, such high values seem to be unrealistic compared to bound water diffusion coefficients in other materials (Aldous et al. 1997; Aguerre and Suarez 2004; Wang et al. 2020). Consequently, an alternative transport mechanism should be found in which H₂O-molecules are transported through the cell wall without immediate binding to the wood polymers. One possibility could be a transport of water vapour or water clusters through the cell wall, where the H₂O-molecules interact mainly with the bound water molecules instead of with the wood polymers. Such a change in the binding behaviour of the H₂O-molecules could then possibly be associated with the strong increase in the sorption isotherms.

4 Conclusion

Water vapour sorption experiments on thin Norway spruce samples have shown that at low moisture content of wood, the initial uptake and release of water is influenced by the diffusion of water vapour through the lumen-pit-ray system. Differences in the initial sorption kinetics can thus be observed between samples with a different thickness and between samples with a different anatomical orientation (i.e. in and across fibre direction). With increasing moisture content, the results indicated an increased moisture transport across fibre direction and an increased impact of cell wall processes on the uptake and release of water. These changes might explain the similar sorption kinetics between thin samples in and across fibre direction in the high range of relative humid-

ity. However, sample thickness was shown to have a considerable impact on the uptake and release of water. Therefore, an additional or modified process must be considered at an increased moisture content of wood, which mainly depends on the sample thickness (or on the number of sorption sites) but not on the anatomical orientation. Water vapour sorption experiments with chemically modified wood or with wood of different dry density should provide further information on this process. Nevertheless, additional measurements on the sorption related processes (e.g. measuring the heat of sorption) might be necessary to correctly interpret the water vapour sorption behaviour at an increased moisture content of wood. Longitudinal samples with a thickness of less than 1 mm should be used for these measurements and the samples should be directly exposed to the water vapour-air flow. Regarding the interpretation and modelling of sorption data and other experimental investigations under transient conditions in relative humidity, the transport of moisture and the impact of sample thickness have to be considered particularly at an increased moisture content of wood.

Acknowledgements This work was partly funded by the Tiroler Wissenschaftsförderung (*Gefördert aus Mitteln des Landes Tirol*) under the grand number GZ: F.16963/5-2019. Their financial support is gratefully acknowledged. Roman Lackner is acknowledged for providing the sorption device (Unit of Material Technology, Universität Innsbruck) and Thomas Bechtold is acknowledged for reading the final version of the manuscript (Research Institute of textile chemistry and textile physics, Universität Innsbruck).

Competing interests The author has no relevant financial or non-financial interests to declare.

References

- Aguerre RJ, Suarez C (2004) Diffusion of bound water in starchy materials: Application to drying. *J Food Eng* 64(3):389–395, DOI 10.1016/j.jfoodeng.2003.11.007
- Aldous BJ, Franks F, Greer AL (1997) Diffusion of water within an amorphous carbohydrate. *J Mater Sci* 32(2):301–308, DOI 10.1023/A:1018584812561
- Avramidis S, Siau JF (1987) An investigation of the external and internal resistance to moisture diffusion in wood. *Wood Sci Technol* 21(3):249–256, DOI 10.1007/BF00351396
- Bauch J, Liese W, Schultze R (1972) The morphological variability of the bordered pit membranes in gymnosperms. *Wood Sci Technol* 6(3):165–184, DOI 10.1007/BF00351575
- Choong E, Tesoro F, Manwiller F (1974) Permeability of twenty-two small diameter hardwoods growing on southern pine sites. *Wood Fiber Sci* 6(1):91–101
- Christensen G, Hergt H (1969) Effect of Previous History on Kinetics of Sorption By Wood Cell Wall. *J Polym Sci Chem* 7(8 Pt A-1):2427–2430

- Christensen GN (1960) Kinetics of sorption of water vapour by wood. 1. The effect of sample thickness. *Aust J Appl Sci* 11(2):295–304
- Christensen GN, Kelsey KE (1959) Die Geschwindigkeit der Wasserdampfsorption durch Holz [The rate of Sorption of Water Vapour by Wood]. *Eur J Wood Wood Prod* 17(5):178–188
- Comstock GL (1970) Directional permeability of softwoods. *Wood Fiber* 1(4):283–289
- Comstock GL, Côté WA (1968) Factors affecting permeability and pit aspiration in coniferous sapwood. *Wood Sci Technol* 2(4):279–291, DOI 10.1007/BF00350274
- Crank J (1975) *The Mathematics of Diffusion*, 2nd edn. Oxford University Press
- Drive M, Aberdeen O (1972) The aspiration of bordered pits in conifer wood. *Proc R Soc London Ser B Biol Sci* 181(1065):395–406, DOI 10.1098/rspb.1972.0057
- Drain-Josserand A, Taverdet JL, Vergnaud JM (1989) Modelling the process of moisture absorption in three dimensions by wood samples of various shapes: cubic, parallelepipedic. *Wood Sci Technol* 23(3):259–271, DOI 10.1007/BF00367739
- Eitelberger J, Svensson S (2012) The Sorption Behavior of Wood Studied by Means of an Improved Cup Method. *Transp Porous Media* 92(2):321–335, DOI 10.1007/s11242-011-9905-8
- Eitelberger J, Hofstetter K, Dvinskikh SV (2011) A multi-scale approach for simulation of transient moisture transport processes in wood below the fiber saturation point. *Compos Sci Technol* 71(15):1727–1738, DOI 10.1016/j.compscitech.2011.08.004
- Engelund ET, Thygesen LG, Svensson S, Hill CAS (2012) A critical discussion of the physics of wood–water interactions. *Wood Sci Technol* 47(1):141–161, DOI 10.1007/s00226-012-0514-7
- Florisson S, Vessby J, Mmari W, Ormarsson S (2020) Three-dimensional orthotropic nonlinear transient moisture simulation for wood: analysis on the effect of scanning curves and nonlinearity. *Wood Sci Technol* 54(5):1197–1222, DOI 10.1007/s00226-020-01210-4
- Flynn KA (1995) A review of the permeability, fluid flow, and anatomy of spruce (*Picea* spp.). *Wood fiber Sci* 27(3):278–284
- Frandsen HL, Damkilde L, Svensson S (2007) A revised multi-Fickian moisture transport model to describe non-Fickian effects in wood. *Holzforschung* 61(5):563–572
- Glass SV, Boardman CR, Zelinka SL (2017) Short hold times in dynamic vapor sorption measurements mischaracterize the equilibrium moisture content of wood. *Wood Sci Technol* 51(2):243–260, DOI 10.1007/s00226-016-0883-4
- Hill CAS, Norton A, Newman G (2010) Analysis of the water vapour sorption behaviour of Sitka spruce based on the parallel exponential kinetics model. *Holzforschung* 64:469–473, DOI 10.1515/HF.2010.059
- Himmel S, Mai C (2015) Effects of acetylation and formalization on the dynamic water vapor sorption behavior of wood. *Holzforschung* 69(5):633–643,

- DOI 10.1515/hf-2014-0161
- Himmel S, Mai C (2016) Water vapor sorption of wood modified by acetylation and formalization - Analyzed by a sorption kinetics model and according to modeless thermodynamic considerations. *Holzforschung* 70(3):203–213, DOI 10.1515/hf-2015-0015
- Hozjan T, Svensson S (2011) Theoretical analysis of moisture transport in wood as an open porous hygroscopic material. *Holzforschung* 65:97–102, DOI 10.1515/HF.2010.122
- Jakieła S, Bratasz, Kozłowski R (2008) Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions. *Wood Sci Technol* 42(1):21–37, DOI 10.1007/s00226-007-0138-5
- Kang W, Kang CW, Chung WY, Eom CD, Yeo H (2008) The effect of openings on combined bound water and water vapor diffusion in wood. *J Wood Sci* 54(5):343–348, DOI 10.1007/s10086-008-0965-5
- Konopka D, Kaliske M (2018) Transient multi-FICKian hygro-mechanical analysis of wood. *Comput Struct* 197:12–27, DOI 10.1016/j.compstruc.2017.11.012
- Krabbenhoft K, Damkilde L (2004) A model for non-Fickian moisture transfer in wood. *Mater Struct Constr* 37(273):615–622, DOI 10.1617/14036
- Liese W, Bauch J (1967) On the Closure of Bordered Pits in Conifers Zusammenfassung. *Wood Sci Technol* 1(1):1–13
- Meyer RW (1971) Influence of pit aspiration on earlywood permeability of Douglas-Fir. *Wood Fiber Sci* 2(4):328–339
- Murr A (2019) The Relevance of Water Vapour Transport for Water Vapour Sorption Experiments on Small Wooden Samples. *Transp Porous Media* 128(2):385–404, DOI 10.1007/s11242-019-01253-7
- Murr A, Lackner R (2018) Analysis on the influence of grain size and grain layer thickness on the sorption kinetics of grained wood at low relative humidity with the use of water vapour sorption experiments. *Wood Sci Technol* 52(3):753–776, DOI 10.1007/s00226-018-1003-4
- Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. DRW-Verlag
- Nopens M, Riegler M, Hansmann C, Krause A (2019) Simultaneous change of wood mass and dimension caused by moisture dynamics. *Sci Rep* 9(1):1–11, DOI 10.1038/s41598-019-46381-8
- Olek W, Perré P, Weres J (2005) Inverse analysis of the transient bound water diffusion in wood. *Holzforschung* 59(1):38–45, DOI 10.1515/HF.2005.007
- Olek W, Perré P, Weres J (2011) Implementation of a relaxation equilibrium term in the convective boundary condition for a better representation of the transient bound water diffusion in wood. *Wood Sci Technol* 45(4):677–691, DOI 10.1007/s00226-010-0399-2
- Petty JA (1973) Diffusion of non-swelling gases through dry conifer wood. *Wood Sci Technol* 7(4):297–307, DOI 10.1007/BF00351075
- Popescu CM, Hill CA (2013) The water vapour adsorption-desorption behaviour of naturally aged *Tilia cordata* Mill. wood. *Polym Degrad Stab* 98(9):1804–1813, DOI 10.1016/j.polymdegradstab.2013.05.021

- 770 Rosen HN (1978) The Influence of External Resistance on Moisture Adsorption
771 Rates in Wood. *Wood Fiber Sci* 10(3):218–228
- 772 Schirmer R (1938) Die Diffusionszahl von Wasserdampf-Luftgemischen und
773 die Verdampfungsgeschwindigkeit. *Zeitschrift des Vereins Dtsch Ingenieure*
774 (VDI Beiheft) 6(70):170–177
- 775 Siau JF (1984) *Transport Processes in Wood*. Springer-Verlag Berlin Heidelberg
- 776 Smith D, Banks W (1971) The mechanism of flow of gases through conif-
777 erous wood. *Proc R Soc London Ser B Biol Sci* 177(1047):197–223, DOI
778 10.1098/rspb.1971.0023
- 779 Sonderegger W, Vecellio M, Zwicker P, Niemz P (2011) Combined bound water
780 and water vapour diffusion of Norway spruce and European beech in and
781 between the principal anatomical directions. *Holzforschung* 65(6):819–828,
782 DOI 10.1515/HF.2011.091
- 783 Thybring EE, Fredriksson M (2021) Wood modification as a tool to understand
784 moisture in wood. *Forests* 12(3):1–18, DOI 10.3390/f12030372
- 785 Thybring EE, Glass SV, Zelinka SL (2019) Kinetics of water vapor sorption
786 in wood cell walls: State of the art and research needs. *Forests* 10(8), DOI
787 10.3390/f10080704
- 788 Time B (1998) *Hygroscopic Moisture Transport in Wood*. Phd thesis, Norwe-
789 gian University of Science and Technology
- 790 Trtik P, Dual J, Keunecke D, Mannes D, Niemz P, Stähli P, Kaestner A, Groso
791 A, Stamparoni M (2007) 3D imaging of microstructure of spruce wood. *J*
792 *Struct Biol* 159(1):46–55, DOI 10.1016/j.jsb.2007.02.003
- 793 VDI-Gesellschaft (ed) (2006) *VDI-Wärmeatlas*, 10th edn. Springer-Verlag
794 Berlin Heidelberg
- 795 Wadsö L (1993a) Measurements of water vapour sorption in wood. *Wood Sci*
796 *Technol* 28(1):59–65, DOI 10.1007/BF00193877
- 797 Wadsö L (1993b) *Studies of Water Vapor Transport and Sorption in Wood*.
798 PhD thesis, Lund University
- 799 Wadsö L (1994a) Describing non-Fickian water-vapour sorption in wood. *J*
800 *Mater Sci* 29(9):2367–2372, DOI 10.1007/BF00363428
- 801 Wadsö L (1994b) Unsteady-state water vapor adsorption in wood: an experi-
802 mental study. *Wood fiber Sci* 26(1):36–50
- 803 Wang Q, Wang T, Lv Z, Cui M, Zhao Z, Cao X, Wei Q (2020) A Comprehensive
804 Review on Water Diffusion in Polymers Focusing on the Polymer. *Polymers*
805 (Basel) 12(1)
- 806 Xie Y, Hill CA, Jalaludin Z, Curling SF, Anandjiwala RD, Norton AJ, New-
807 man G (2011) The dynamic water vapour sorption behaviour of natural
808 fibres and kinetic analysis using the parallel exponential kinetics model. *J*
809 *Mater Sci* 46(2):479–489, DOI 10.1007/s10853-010-4935-0

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementary.pdf](#)