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Combined bound water and water vapour diffusion of Norway spruce and European beech in and between the principal anatomical directions

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Abstract

The combined bound water and water vapour diffusion of wood is of great interest in the field of building physics. Due to swelling stresses, the steady-state-determined diffusion coefficient clearly differs from the unsteady-state-determined diffusion coefficient. In this study, both diffusion coefficients and the water vapour resistance factor of Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.) were investigated for the principal anatomical directions (radial, tangential and longitudinal) and in 15° steps between these directions. The values were determined with the cup method as the basic principle. The unsteady-state-determined diffusion coefficient is, independent of the direction, about half that of the steady-state-determined diffusion coefficient. Both diffusion coefficients are about two to three times higher for spruce than for beech. They are up to 12 times higher in the longitudinal direction than perpendicular to the grain for spruce, and up to 15 times higher for beech. With increasing moisture content, the diffusion coefficients exponentially increase. The water vapour resistance factor shows converse values to the diffusion coefficients.

Keywords: beech; bound water diffusion; cup method; sorption; spruce; water vapour diffusion; water vapour resistance factor.

Introduction

Wood and wood composites are renewable materials produced with a low grey energy input. They are increasingly important in civil engineering. For example, novel wood-based wall constructions made of solid wood (such as cross laminated timber or wooden walls connected with dowels or nails) are currently being developed (Joščák et al. 2010). For

wood as an anisotropic and hygroscopic material, accurate knowledge of the moisture flux in and also between the principal anatomical directions is important for precise structural-physical calculations and for numerical modelling. Wood in wall constructions and wood-based panels can be aligned with different grain and ring angles, for example, in the novel product ‘DendroLight’ (Hofstetter et al. 2009).

Three types of moisture flux are conceivable in wood. Above the fibre saturation point (FSP), the flux is mainly effected by free water. Below the FSP, diffusion processes occur under the combined participation of bound water and water vapour: the former takes place within the cell walls and the latter within the cell lumens via pit openings. The ratio of these diffusion types strongly depends on the moisture content (MC), temperature, species, and the anatomical direction. Diverse authors have attempted to investigate both diffusion processes separately (Stamm 1959; Stamm 1960a; Stamm 1960b; Mouchot et al. 2006). This knowledge found acceptance in numerous diffusion models based on the cellular wood structure (Choong 1965; Siau 1995; Frandsen et al. 2007; Kang et al. 2008; Eitelberger and Hofstetter 2010; Hozjan and Svensson 2011).

The effective diffusion (i.e., the combined diffusion of bound water and water vapour) is of primary interest for physical calculation in wood buildings. To this purpose, two methods are established: the cup method and the sorption method (Olek 2003). The cup method according to ISO 12572 (2001) is used to measure the steady-state (SS) moisture transport in wood according to Fick’s first law. The sorption method determines the diffusion coefficient at unsteady-state (US) conditions according to Fick’s second law. Unfortunately, the results of the two methods can differ up to a factor of 10 (Wadsö 1993; Pfriem 2006), especially due to swelling stresses (Comstock 1963).

Hence, for calculations in the field of building physics, both diffusion coefficients are required. The SS-determined diffusion coefficient is useful to calculate the moisture gradient through external walls and the risk of condensation. The US-determined diffusion coefficient is required to describe short-term water storage and loss and the penetration depth at alternating indoor climates.

Water diffusion coefficients were frequently described in the last six decades for various woods. However, the data were obtained with different methods and are not always free of contradictions. While water diffusion in the principal wood directions is better studied, experimental data for off-axis diffusion (between the main directions) are not available from literature, though the influence of the grain angle on

mechanical wood properties was determined by Hankinson (1921).

In this study, Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.) are in focus; the diffusion coefficients were revisited for the combined diffusion of bound water and water vapour, at SS and US conditions. For a better reliability, both diffusion coefficients were determined on the same specimens. Moreover, the water vapour resistance factor was also investigated. To take the anisotropic characteristics of wood into account, measurements were carried out not only in the three principal directions, radial (R), tangential (T), and longitudinal (L), but also between them in 15° steps. The main focus was laid on these off-axis directions.

Material and methods

Material

Cylindrical samples (diameter 140 mm, thickness 20 mm) of adult wood from European beech and Norway spruce were tested. Beech was cut from one stem and spruce from two stems from the region of Zurich. Thereby, the direction of the sample thickness corresponded to the investigated anatomical direction. Water vapour resistance and combined water vapour and bound water diffusion were determined in the three principal anatomical directions (R, T, and L) and between them in 15° steps so that a total of 18 directions were considered. Three specimens per species, direction and climate (see below) were tested.

Experimental setup

Water vapour resistance was determined according to ISO 12572 (2001) under 'dry cup' and 'wet cup' conditions. Here, the water vapour flow through a specimen, which is exposed to two different partial vapour pressures inside and outside the cup, is tested. The ambient air was conditioned to 20°C and 65% relative humidity (RH), whereas, within the cup, a desiccant with almost 0% RH for the 'dry cup' tests and desalinated water with almost 100% RH for the 'wet cup' tests were used. Additionally, 'dry cup' and 'wet cup' tests at drier ambient air conditions (20°C and 35% RH) were carried out for the specimens with the diffusion direction oriented perpendicular to the grain.

The specimens were first stored at 20°C/65% RH or 20°C/35% RH, respectively, until they reached equilibrium moisture content (EMC). For the tests (Figure 1), they were then put on top of a glass vessel filled up to 20 mm under the brim with either a desiccant (silica gel) or totally desalinated water. The specimens were laterally sealed with a tight-fitting circular rubber band. To measure the water sorption, from which the diffusion coefficient at US conditions was calculated, the specimens were weighed at defined intervals (by detaching the rubber band from the specimen) until they finally reached the EMC of the differentiating climate. Thereafter, the diffusion and water vapour resistance was measured at SS conditions, at which the vessels with the specimens were weighed five times with an interval of at least one day between two weighings.

Determination of the water vapour resistance

The water vapour resistance factor was calculated according to Annex G of ISO 12572 (2001) taking into account the thickness of the air layer in the test cup between the base of the specimen and

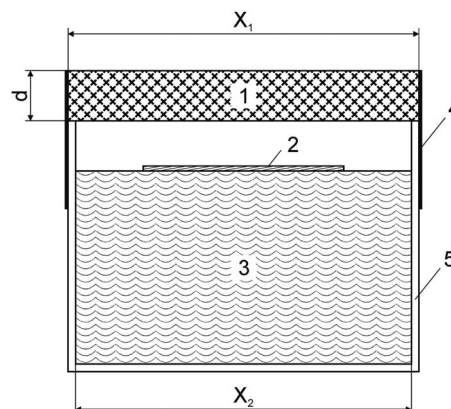


Figure 1 Test assembly for the 'dry cup' and 'wet cup' tests. 1, specimen with X_1 and X_2 as the upper and lower exposed area and with thickness d ; 2, wood chip (used in 'dry cup' tests); 3, desiccant/desalinated water; 4, rubber band; 5, glass vessel.

the desiccant or the desalinated water (Sonderegger and Niemz 2009):

$$\mu = \frac{\delta_a}{d} \cdot \left(\frac{A \cdot \Delta p_v}{G} - \frac{d_a}{\delta_a} \right) \quad (1)$$

where μ is the water vapour resistance factor (-), δ_a the water vapour permeability of air with respect to the partial vapour pressure ($\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$), d the mean thickness of the specimen (m), A the circular area of the specimen (m^2), Δp_v the water vapour pressure difference across the specimen (Pa), G the water vapour flow rate through the specimen (kg s^{-1}), and d_a the thickness of the air layer in the test cup between the base of the specimen and the desiccant or the desalinated water (m).

Determination of the diffusion coefficient at steady-state conditions

The diffusion coefficient derived from the water vapour permeability at SS conditions according to ISO 12572 (2001) was determined according to Siau (1995):

$$D_{SS} = \frac{\delta_p \cdot p_o \cdot V}{w_o} \cdot \frac{\partial H}{\partial M} \quad (2)$$

where D_{SS} is the diffusion coefficient at steady-state conditions ($\text{m}^2 \text{s}^{-1}$), δ_p ($= \delta_a / \mu$) the water vapour permeability with respect to the partial vapour pressure ($\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$), p_o the saturated water vapour pressure (Pa), V the volume of the specimen at standard climatic conditions (m^3), w_o the oven-dry mass of the specimen (kg), ∂H the difference of RH (%), and ∂M the difference of MC (%). For Eq. (2), a MC of 30% was assumed for both wood species at 100% RH.

Determination of the diffusion coefficient at unsteady-state conditions

According to Klopfer (1974) it is possible to determine a water absorption coefficient below FSP for the combined bound water and water vapour diffusion analogously to the capillary water absorption of liquid water (ISO 15148 2002). By neglecting the mass of water vapour, the absorption is carried out solely as bound water:

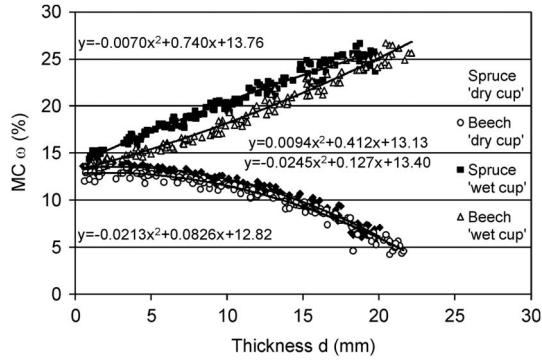


Figure 2 Distribution of MC ω over specimen thickness d at final conditions after the cup tests [according to Zwicker (2008), modified].

$$A_{bw} = \frac{\Delta m}{A \cdot \sqrt{t}} \quad (3)$$

where A_{bw} is the water absorption coefficient of bound water ($\text{kg m}^{-2} \text{s}^{-0.5}$), Δm the mass gain (kg), A the face area (m^2), and t the time (s).

From the water absorption coefficient, the diffusion coefficient at US conditions can be derived under the assumption that the diffusion coefficient is almost constant (Klopfner 1974):

$$D_{US} = \left(\frac{A_{bw}}{1.128 \cdot \Delta c} \right)^2 \quad (4)$$

where D_{US} is the diffusion coefficient of bound water diffusion ($\text{m}^2 \text{s}^{-1}$), Δc the water concentration difference (kg m^{-3}) and 1.128 is equal to $(4/\pi)^{0.5}$. Thereby, Eq. 4, converted and applied to water sorption of two opposing faces, corresponds to the calculation of

the diffusion coefficient by Teischinger (1987) according to Comstock (1963) and Stamm (1964).

For 'wet cup' conditions, the gradient of the water concentration through the specimen was assumed to be nearly linear as observed by Zwicker (2008) and shown in Figure 2. Therefore, Δc was determined by doubling the differences of the mean water concentration at initial and final conditions (Sonderegger and Niemz 2011) as follows:

$$\Delta c = 2 \cdot (c_{end} - c_{begin}) \quad (5)$$

where c_{end} is the water concentration of the specimen at the end of the experiment (kg m^{-3}) and c_{begin} the water concentration at the beginning of the experiment (kg m^{-3}), at conditions of 20°C/65% RH and 20°C/35% RH, respectively.

For dry cup conditions, a cumulative decrease of the water concentration through the specimen is visible (Figure 2). Therefore, a wood chip approximately 80 mm × 20 mm × 2 mm, was put onto the silica gel during the experiment (Figure 1). Its water concentration ($c_{wood,chip}$) measured at the end of the tests was the data used as the lower water concentration in:

$$\Delta c = c_{begin} - c_{wood,chip} \quad (6)$$

Results and discussion

Water vapour resistance

The water vapour resistance factors μ and their interactions between the principal anatomical directions and correlated by polynomial functions are presented in Figures 3 and 4 and Table 1, while the moisture-dependent data correlated by exponential functions are presented in Figure 5 and Table 2.

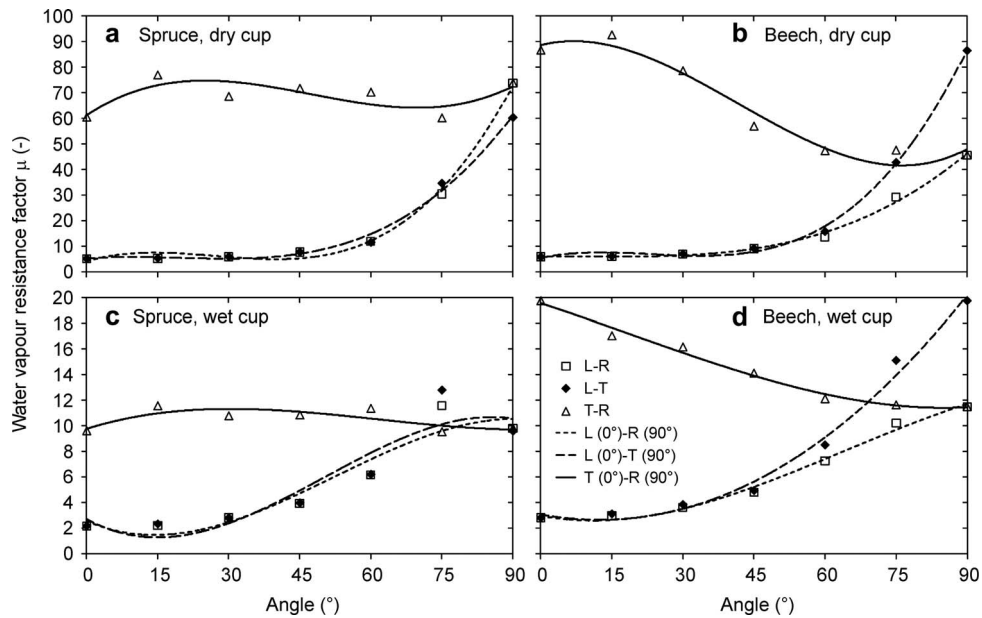


Figure 3 Water vapour resistance factor μ in and between the principal anatomical directions of Norway spruce (a, c) and European beech (b, d) at 'dry cup' (20°C/65% RH to desiccant) and 'wet cup' conditions (20°C/65% RH to desalinated water). R, radial; T, tangential; L, longitudinal; symbols, measured data; lines, calculated values.

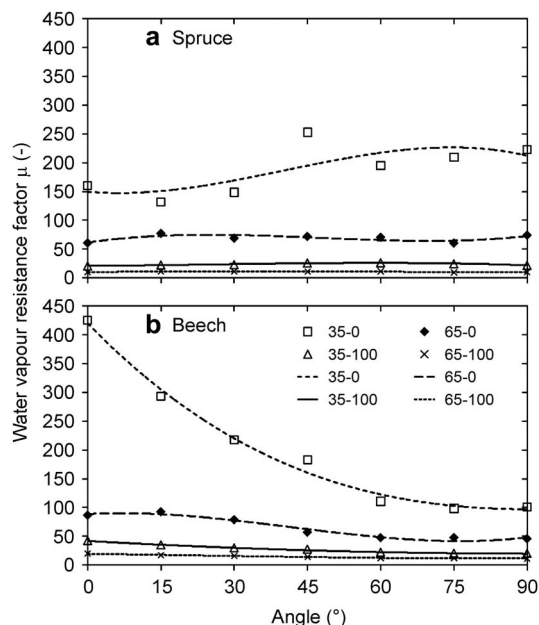


Figure 4 Water vapour resistance factor μ of Norway spruce (a) and European beech (b) perpendicular to the grain between the tangential (0°) and the radial (90°) directions at different cup conditions. 35-0 and 65-0 = $20^\circ\text{C}/35\%$ RH and $20^\circ\text{C}/65\%$ RH to desiccant, respectively; 35-100 and 65-100 = $20^\circ\text{C}/35\%$ RH and $20^\circ\text{C}/65\%$ RH to desalinated water, respectively; symbols, measured data; lines, calculated values.

Figure 3 shows μ in and between the three principal anatomical directions for spruce and beech. The trend between two principal directions was determined as a polynomial function of third order. Thereby, according to Bodig and Jayne (1993), the angles between the L direction and the directions perpendicular to the grain correspond to the grain

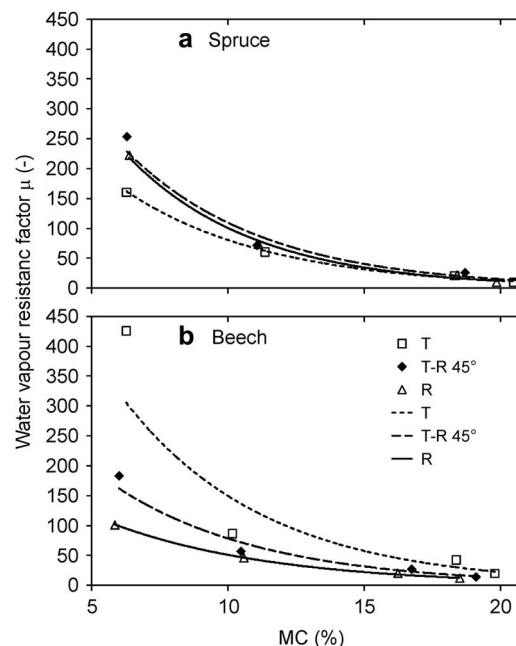


Figure 5 Water vapour resistance factor μ of Norway spruce (a) and European beech (b) perpendicular to the grain, in the tangential (T) and the radial (R) direction and at an angle of 45° between these directions (T-R 45°), depending on MC.

angle ($L=0^\circ$ and R and T = 90°) and the angles between the T and the R direction to the ring angle (T = 0° and R = 90°).

For spruce, the trends are almost congruent between the L and T and the L and R direction. In contrast, values of μ for beech increase to a greater extent from the L to the T than to the R direction, most noticeably at grain angles of 75° and 90° . At 'wet cup' conditions, μ increases for both species above a grain angle of 15° . At 'dry cup' conditions

Table 1 Parameters of the polynomial function $\mu = A + B \cdot x + C \cdot x^2 + D \cdot x^3$ describing the water vapour resistance factor μ (-) between the principal anatomical directions.

Wood species	Condition (RH in %)	Diffusion direction	A	B	C	D	R ²
Norway spruce, dry cup	65-0	L (0°)-R (90°)	4.18	0.532	$-2.51 \cdot 10^{-2}$	$3.07 \cdot 10^{-4}$	0.995
	65-0	L (0°)-T (90°)	5.24	0.141	$-9.77 \cdot 10^{-3}$	$1.68 \cdot 10^{-4}$	0.99
	65-0	T (0°)-R (90°)	61.3	1.23	$-3.34 \cdot 10^{-2}$	$2.35 \cdot 10^{-4}$	0.61
	35-0	T (0°)-R (90°)	150	-0.743	$6.16 \cdot 10^{-2}$	$-5.07 \cdot 10^{-4}$	0.55
Norway spruce, wet cup	65-100	L (0°)-R (90°)	2.57	-0.162	$6.53 \cdot 10^{-3}$	$-4.16 \cdot 10^{-5}$	0.92
	65-100	L (0°)-T (90°)	2.72	-0.204	$8.04 \cdot 10^{-3}$	$-5.33 \cdot 10^{-5}$	0.87
	65-100	T (0°)-R (90°)	9.77	0.115	$-2.51 \cdot 10^{-3}$	$1.36 \cdot 10^{-5}$	0.62
	35-100	T (0°)-R (90°)	20.6	0.0656	$2.30 \cdot 10^{-3}$	$-3.21 \cdot 10^{-5}$	0.94
European beech, dry cup	65-0	L (0°)-R (90°)	6.11	0.0163	$-2.57 \cdot 10^{-3}$	$8.16 \cdot 10^{-5}$	0.99
	65-0	L (0°)-T (90°)	5.51	0.377	$-2.02 \cdot 10^{-2}$	$2.90 \cdot 10^{-4}$	0.998
	65-0	T (0°)-R (90°)	88.7	0.460	$-3.63 \cdot 10^{-2}$	$2.91 \cdot 10^{-4}$	0.96
	35-0	T (0°)-R (90°)	420	-8.71	$7.39 \cdot 10^{-2}$	$-1.89 \cdot 10^{-4}$	0.99
European beech, wet cup	65-100	L (0°)-R (90°)	2.98	-0.0710	$3.51 \cdot 10^{-3}$	$-1.83 \cdot 10^{-5}$	0.99
	65-100	L (0°)-T (90°)	3.08	-0.0667	$2.64 \cdot 10^{-3}$	$2.38 \cdot 10^{-6}$	0.99
	65-100	T (0°)-R (90°)	19.6	-0.122	$-5.26 \cdot 10^{-4}$	$9.76 \cdot 10^{-6}$	0.99
	35-100	T (0°)-R (90°)	41.9	-0.474	$2.52 \cdot 10^{-3}$	$-1.14 \cdot 10^{-7}$	0.99

x, angle between the directions in degrees; L, longitudinal; R, radial; T, tangential; R², coefficient of determination.

Table 2 Parameters of the exponential function $\mu = A \cdot e^{B \cdot \omega}$ describing the water vapour resistance factor μ (-) depending on MC ω (%).

Wood species	Diffusion direction	A	B	R ²
Norway spruce	T	526	-0.188	0.99
	T – R (45°)	798	-0.199	0.97
	R	854	-0.214	0.98
European beech	T	1012	-0.191	0.90
	T – R (45°)	482	-0.182	0.97
	R	270	-0.167	0.99

T, tangential; R, radial; T–R (45°), angle of 45° between R and T; R², coefficient of determination.

a clear increase of μ was only found above a grain angle of 60°.

Figure 4 illustrates μ in and between the T and the R directions at different cup conditions. In the T direction, μ of beech is up to four times higher than in the R direction and decreases up to about 60° with increasing ring angle. The differences between the T and the R directions are greater for dry than for wet cup conditions. These values are in good accordance with measurements by Vanek and Teischinger (1989); however, they are contradictory to results of Kiessl and Möller (1989), who quoted literature data from different sources, where the values in R direction are higher than in the T direction both for dry-cup and wet-cup tests. In contrast to beech, μ of spruce is either equal for both directions or higher in the R than in the T direction. The polynomial function depending on the ring angle shows a clearly lower coefficient of determination (Table 1). Higher μ values for spruce in the R than in the T direction are also stated by diverse authors for wet conditions (Kiessl and Möller 1989, Vanek and Teischinger 1989, Zillig et al. 2007). In

contrast to our results, this ratio is partly reversed at low MC (Vanek and Teischinger 1989, Zillig et al. 2007).

As presented in Figure 5, μ decreases exponentially with increasing MC. The highest values and the greatest decrease were found for beech in the T direction, as already stated by Vanek and Teischinger (1989). For spruce, the values in the R direction are similar to the values at a ring angle of 45° and they are both higher than in the T direction up to about 18% MC.

Combined bound water and water vapour diffusion

Figures 6–11 show diffusion coefficients for the combined bound water and water vapour diffusion at SS (D_{SS}) and US conditions (D_{US}) in and between the principal anatomical directions of the two species with the corresponding polynomial and exponential function parameters in Tables 3 and 4.

In all directions, D_{SS} is about two to three times higher for spruce than for beech, in agreement with the results of Mouchot et al. (2006). In the L direction, it is up to 12 times higher than perpendicular to the grain for spruce, and up to 15 times higher for beech. Similar mean diffusion coefficient ratios between the principal directions are described by Olek et al. (2005) for beech, although the absolute values are about twice as high due to the higher measuring temperature. In contrast, Mouchot et al. (2006) measured up to 36 times higher values in the L direction than perpendicular to the grain. This may be due to the different test conditions. The relatively low differences of the data between the L direction and those perpendicular to the grain correspond well with the model of Kang et al. (2008), who integrated water vapour diffusion through pits and rays into the classical diffusion model of Stamm (1960b) and Choong (1965) in Siau (1995). While D_{SS} is equal under dry and wet conditions in the L

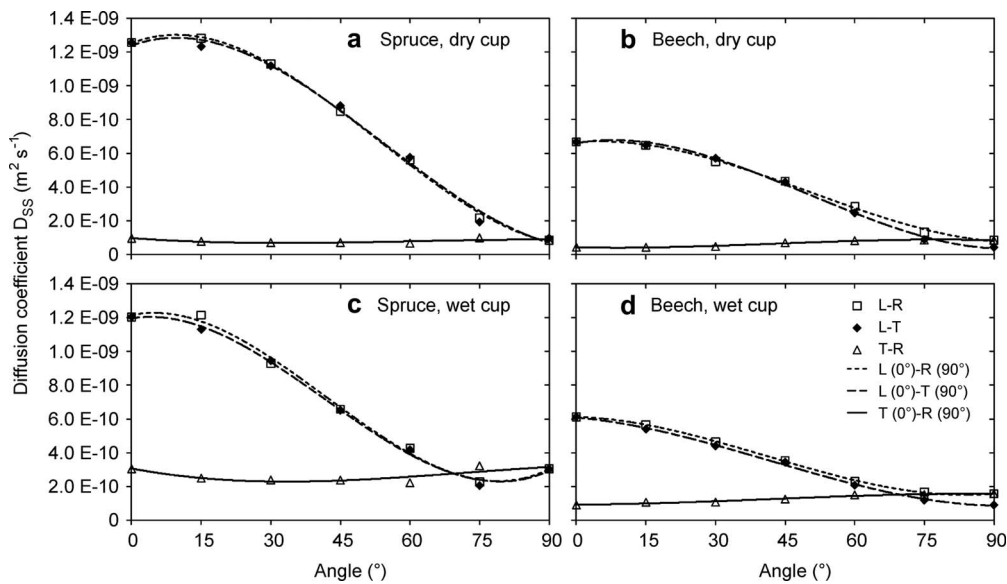


Figure 6 Steady-state-determined diffusion coefficient D_{SS} in and between the principal anatomical directions of Norway spruce (a, c) and European beech (b, d) at ‘dry cup’ (20°C/65% RH to desiccant) and ‘wet cup’ conditions (20°C/65% RH to desalinated water). R, radial; T, tangential; L, longitudinal; symbols, measured data; lines, calculated values.

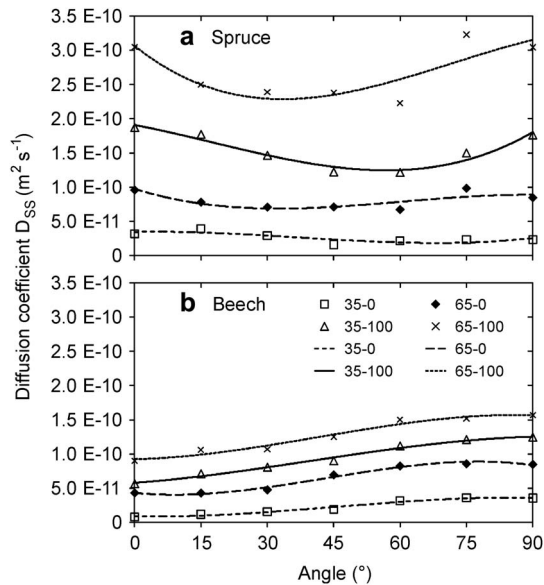


Figure 7 Steady-state-determined diffusion coefficient D_{SS} of Norway spruce (a) and European beech (b) perpendicular to the grain between the tangential (0°) and the radial (90°) directions at different cup conditions. 35–0 and 65–0 = $20^\circ\text{C}/35\%$ RH and $20^\circ\text{C}/65\%$ RH to desiccant, respectively; 35–100 and 65–100 = $20^\circ\text{C}/35\%$ RH and $20^\circ\text{C}/65\%$ RH to desalinated water, respectively; symbols, measured data; lines, calculated values.

direction it is, perpendicular to the grain, twice as high for beech and thrice as high for spruce in wet conditions compared to dry conditions (Figure 6).

Perpendicular to the grain (Figure 7), a clear increase of D_{SS} with increasing ring angle was found for beech at all considered conditions. For spruce, in contrast, a clear cor-

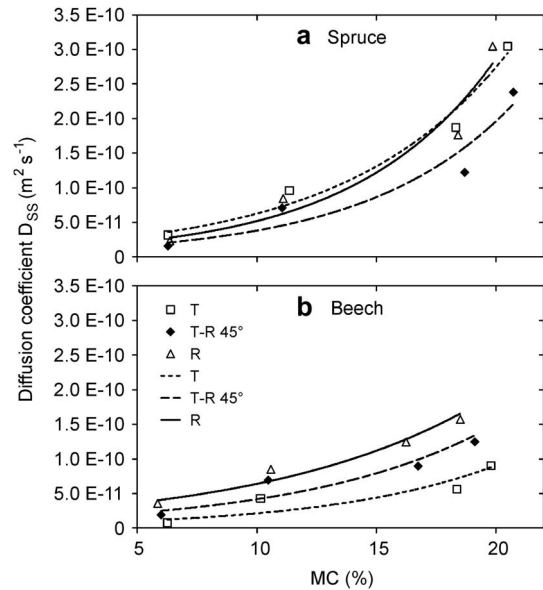


Figure 8 Steady-state-determined diffusion coefficient D_{SS} of Norway spruce (a) and European beech (b) perpendicular to the grain, in the tangential (T) and the radial (R) direction and at an angle of 45° between these directions (T–R 45°), depending on MC.

relation between D_{SS} and the ring angle is missing; at wet conditions the lowest values were found between ring angles of 30° and 60° . This can be attributed to the different anatomical composition of the two species and resembles their thermal conductivity behaviour perpendicular to the grain (Sonderegger et al. 2011). Koc et al. (2003) also determined only small differences between the T and R diffusion for spruce with, averaged over the whole MC range, moderately higher values in the T than in the R direction.

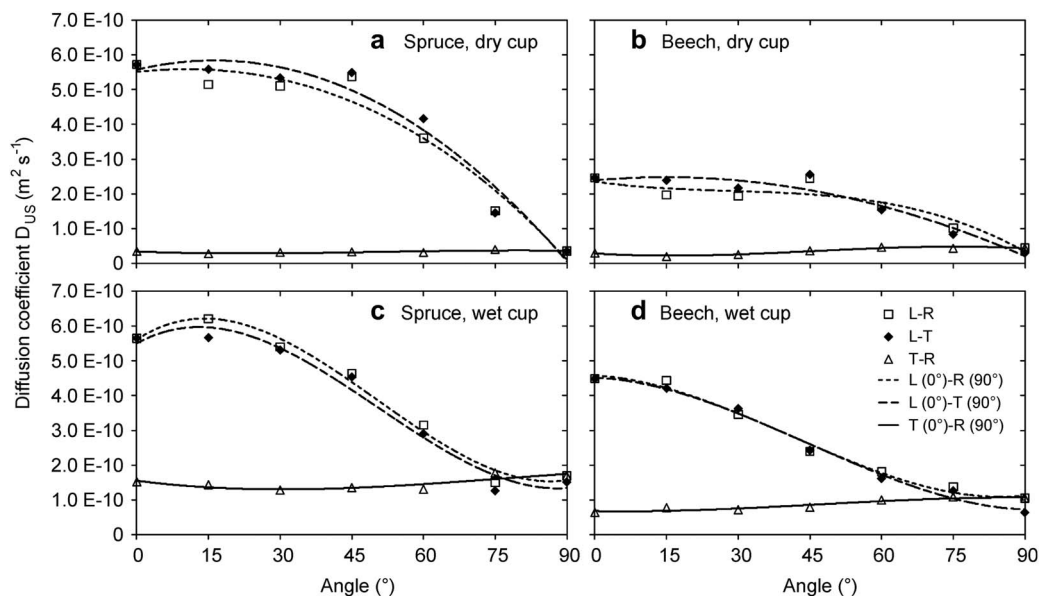


Figure 9 Unsteady-state-determined diffusion coefficient D_{US} in and between the principal anatomical directions of Norway spruce (a, c) and European beech (b, d) at ‘dry cup’ ($20^\circ\text{C}/65\%$ RH to desiccant) and ‘wet cup’ conditions ($20^\circ\text{C}/65\%$ RH to desalinated water). R, radial; T, tangential; L, longitudinal; symbols, measured data; lines, calculated values.

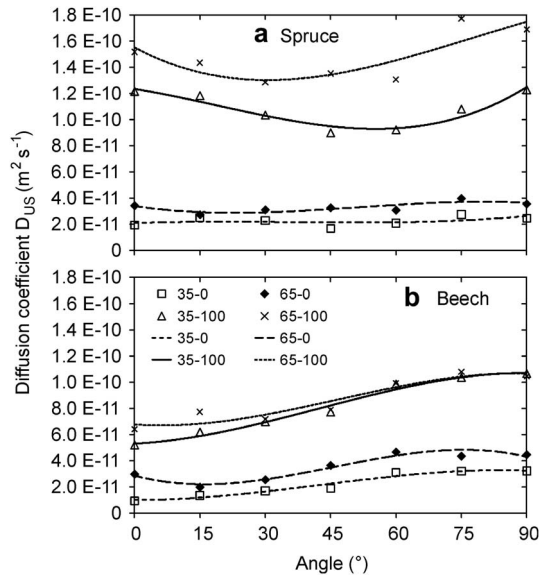


Figure 10 Unsteady-state-determined diffusion coefficient D_{US} of Norway spruce (a) and European beech (b) perpendicular to the grain between the tangential (0°) and the radial (90°) directions at different cup conditions. 35–0 and 65–0 = $20^\circ C/35\%$ RH and $20^\circ C/65\%$ RH to desiccant, respectively; 35–100 and 65–100 = $20^\circ C/35\%$ RH and $20^\circ C/65\%$ RH to desalinated water, respectively; symbols, measured data; lines, calculated values.

D_{US} shows similar tendencies to D_{SS} , but is averaged over all directions about half as high (Figures 6 and 9). The differences between D_{SS} and D_{US} are smaller for the specimens that were initially conditioned at $20^\circ C$ and 35% RH than at 65% RH, so that D_{SS} and D_{US} for beech at a differentiating climate from 35% RH to 0% RH are almost equal (Figures 7 and 10). In contrast, Wadsö (1993) and Pfriem (2006) show clearly higher differences with a factor of about 10 between D_{US} and D_{SS} , which can be attributed to their modified method (simultaneous diffusion from two opposite sides of the specimen), which is clearly more influenced by the specimen thickness (Teischinger 1987). Additionally, D_{US} is influenced by the MC difference of the experiment, which was already stated by Christensen and Kelsey (1959). The very low data by Pfriem et al. (2010) may be ascribed to the above-mentioned influences.

Moisture dependency of diffusion

Both diffusion coefficients, D_{SS} and D_{US} , increase with increasing MC. This dependency can be described as an approximate exponential function (Stamm 1959; Stamm 1960b; Klopfer 1974; Olek et al. 2005; Mannes et al. 2009; Sonderegger et al. 2010). However, when complex (e.g., multiscale) models are used to describe diffusion properties, the dependency from the MC is more complicated (e.g., Kang et al. 2008, Eitelberger and Hofstetter 2010). Figures 8 and 11 show the relationship between diffusion coefficients and MC for the R and T directions and for a ring angle of 45° , whereas the calculated parameters of the corresponding exponential functions are listed in Table 4. Both diffusion

coefficients, D_{SS} and D_{US} , show similar tendencies. The exponential increase with increasing MC highly correlates with the measured data. The correlation is higher for US than for SS diffusion and also higher for spruce than for beech. While the diffusion coefficients for beech increase from the T direction over a ring angle of 45° to the R direction, they are almost congruent in the T and R directions for spruce but (as already stated) clearly lower at a ring angle of 45° .

Eq. 4 is only valid for constant diffusion coefficients. Therefore, if the diffusion coefficients increase with increasing MC, as the measurements revealed for spruce and beech, the calculated diffusion coefficient is overestimated for adsorption and underestimated for desorption, although in theory, they should be identical (Klopfer 1974; Crank 1994). In contrast, Comstock (1963) and Teischinger (1987), for example, measured higher values for desorption than for adsorption. According to Comstock (1963), this can be attributed to compression stresses during adsorption and tension stresses during desorption that influence the diffusion process.

Bound water sorption

Table 5 shows the sorption coefficients of bound water in the three principal anatomical directions. Spruce has similar values for the R and the T directions at all measured humidity sectors. For beech, the sorption coefficients are higher in the R direction than in the T direction, but the difference between the coefficients of these two directions decreases with increasing RH. The values perpendicular to the grain at 35–100% RH coincide well with Teischinger's data (1987), who measured about one quarter smaller values for spruce and beech at 35–95% RH.

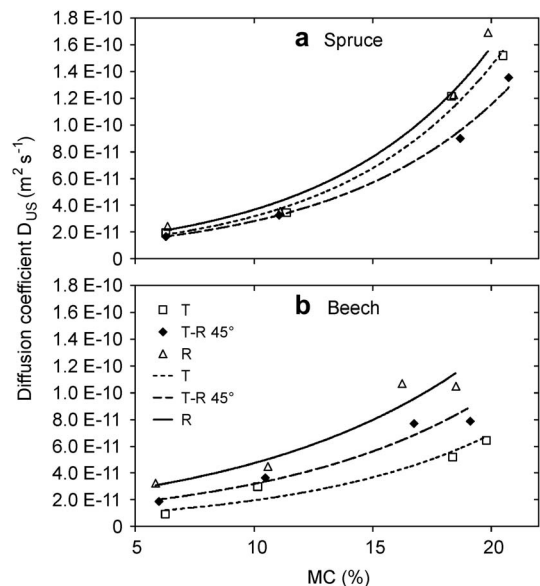


Figure 11 Unsteady-state-determined diffusion coefficient D_{US} of Norway spruce (a) and European beech (b) perpendicular to the grain, in the tangential (T) and the radial (R) direction and at an angle of 45° between these directions (T–R 45°), depending on MC.

Table 3 Parameters of the polynomial function $D=A+B \cdot x+C \cdot x^2+E \cdot x^3$ describing the steady-state-determined diffusion coefficient D_{SS} ($m^2 \cdot s^{-1}$) and the unsteady-state-determined diffusion coefficient D_{US} ($m^2 \cdot s^{-1}$) between the principal anatomical directions.

Wood species	Condition (RH in %)	Diffusion direction	Parameters of D_{SS}					Parameters of D_{US}				
			A	B	C	E	R^2	A	B	C	E	R^2
Norway spruce, dry cup	65–0	L (0°)–R (90°)	1.25 10 ⁻⁹	1.07 10 ⁻¹¹	-6.06 10 ⁻¹³	3.80 10 ⁻¹⁵	0.999	5.52 10 ⁻¹⁰	1.41 10 ⁻¹²	-6.52 10 ⁻¹⁴	-1.92 10 ⁻¹⁶	0.96
	65–0	L (0°)–T (90°)	1.24 10 ⁻⁹	1.00 10 ⁻¹¹	-5.70 10 ⁻¹³	3.49 10 ⁻¹⁵	0.99	5.57 10 ⁻¹⁰	3.28 10 ⁻¹²	-9.99 10 ⁻¹⁴	-5.11 10 ⁻¹⁷	0.96
	65–0	T (0°)–R (90°)	9.74 10 ⁻¹¹	-2.02 10 ⁻¹²	4.24 10 ⁻¹⁴	-2.34 10 ⁻¹⁶	0.67	3.39 10 ⁻¹¹	-4.99 10 ⁻¹³	1.40 10 ⁻¹⁴	-9.10 10 ⁻¹⁷	0.66
	35–0	T (0°)–R (90°)	3.45 10 ⁻¹¹	1.36 10 ⁻¹³	-1.43 10 ⁻¹⁴	1.30 10 ⁻¹⁶	0.67	2.09 10 ⁻¹¹	1.21 10 ⁻¹³	-4.21 10 ⁻¹⁵	3.93 10 ⁻¹⁷	0.26
Norway spruce, wet cup	65–100	L (0°)–R (90°)	1.22 10 ⁻⁹	5.62 10 ⁻¹²	-6.14 10 ⁻¹³	4.88 10 ⁻¹⁵	0.996	5.61 10 ⁻¹⁰	9.05 10 ⁻¹²	-3.73 10 ⁻¹³	2.47 10 ⁻¹⁵	0.99
	65–100	L (0°)–T (90°)	1.20 10 ⁻⁹	4.34 10 ⁻¹²	-5.69 10 ⁻¹³	4.55 10 ⁻¹⁵	0.997	5.51 10 ⁻¹⁰	7.57 10 ⁻¹²	-3.33 10 ⁻¹³	2.20 10 ⁻¹⁵	0.98
	65–100	T (0°)–R (90°)	3.06 10 ⁻¹⁰	-5.18 10 ⁻¹²	1.01 10 ⁻¹³	-4.71 10 ⁻¹⁶	0.73	1.55 10 ⁻¹⁰	-1.78 10 ⁻¹²	3.64 10 ⁻¹⁴	-1.58 10 ⁻¹⁶	0.72
	35–100	T (0°)–R (90°)	1.91 10 ⁻¹⁰	-1.24 10 ⁻¹²	-1.80 10 ⁻¹⁴	3.38 10 ⁻¹⁶	0.94	1.23 10 ⁻¹⁰	-5.29 10 ⁻¹³	-1.07 10 ⁻¹⁴	1.86 10 ⁻¹⁶	0.92
European beech, dry cup	65–0	L (0°)–R (90°)	6.65 10 ⁻¹⁰	2.41 10 ⁻¹²	-2.46 10 ⁻¹³	1.63 10 ⁻¹⁵	0.998	2.35 10 ⁻¹⁰	-1.99 10 ⁻¹²	5.50 10 ⁻¹⁴	-6.43 10 ⁻¹⁶	0.89
	65–0	L (0°)–T (90°)	6.60 10 ⁻¹⁰	4.64 10 ⁻¹²	-3.20 10 ⁻¹³	2.13 10 ⁻¹⁵	0.998	2.39 10 ⁻¹⁰	1.24 10 ⁻¹²	-4.22 10 ⁻¹⁴	1.63 10 ⁻¹⁷	0.93
	65–0	T (0°)–R (90°)	4.31 10 ⁻¹¹	-6.18 10 ⁻¹³	3.86 10 ⁻¹⁴	-2.97 10 ⁻¹⁶	0.98	2.87 10 ⁻¹¹	-8.91 10 ⁻¹³	3.40 10 ⁻¹⁴	-2.48 10 ⁻¹⁶	0.93
	35–0	T (0°)–R (90°)	8.79 10 ⁻¹²	-1.20 10 ⁻¹³	1.42 10 ⁻¹⁴	-1.05 10 ⁻¹⁶	0.97	1.00 10 ⁻¹¹	-1.49 10 ⁻¹⁴	1.01 10 ⁻¹⁴	-7.92 10 ⁻¹⁷	0.95
European beech, wet cup	65–100	L (0°)–R (90°)	6.12 10 ⁻¹⁰	-7.20 10 ⁻¹³	-1.80 10 ⁻¹³	1.47 10 ⁻¹⁵	0.999	4.58 10 ⁻¹⁰	-7.21 10 ⁻¹³	-1.29 10 ⁻¹³	1.04 10 ⁻¹⁵	0.99
	65–100	L (0°)–T (90°)	6.08 10 ⁻¹⁰	-2.35 10 ⁻¹²	-1.36 10 ⁻¹³	1.08 10 ⁻¹⁵	0.998	4.52 10 ⁻¹⁰	-5.92 10 ⁻¹³	-1.22 10 ⁻¹³	9.14 10 ⁻¹⁶	0.99
	65–100	T (0°)–R (90°)	9.23 10 ⁻¹¹	1.52 10 ⁻¹³	2.27 10 ⁻¹⁴	-1.82 10 ⁻¹⁶	0.97	6.78 10 ⁻¹¹	-2.42 10 ⁻¹³	2.08 10 ⁻¹⁴	-1.48 10 ⁻¹⁶	0.90
	35–100	T (0°)–R (90°)	5.78 10 ⁻¹¹	4.73 10 ⁻¹³	1.26 10 ⁻¹⁴	-1.06 10 ⁻¹⁶	0.99	5.31 10 ⁻¹¹	1.63 10 ⁻¹³	1.67 10 ⁻¹⁴	-1.31 10 ⁻¹⁶	0.98

x, angle between the directions in degrees; L, longitudinal; R, radial; T, tangential; R^2 , coefficient of determination.

Table 4 Parameters of the exponential function $D=A \cdot e^{B \cdot \omega}$ describing the steady-state-determined diffusion coefficient D_{SS} ($m^2 s^{-1}$) and the unsteady-state-determined diffusion coefficient D_{US} ($m^2 s^{-1}$) depending on MC ω (%).

Wood species	Diffusion direction	Parameters of D_{SS}			Parameters of D_{US}		
		A	B	R^2	A	B	R^2
Norway spruce	T	$1.43 \cdot 10^{-11}$	0.148	0.97	$6.99 \cdot 10^{-12}$	0.151	0.99
	T-R (45°)	$7.44 \cdot 10^{-12}$	0.164	0.91	$6.87 \cdot 10^{-12}$	0.141	0.997
	R	$9.38 \cdot 10^{-12}$	0.171	0.95	$8.51 \cdot 10^{-12}$	0.146	0.98
European beech	T	$5.05 \cdot 10^{-12}$	0.144	0.79	$5.57 \cdot 10^{-12}$	0.126	0.89
	T-R (45°)	$1.16 \cdot 10^{-11}$	0.128	0.86	$1.03 \cdot 10^{-11}$	0.113	0.97
	R	$2.09 \cdot 10^{-11}$	0.112	0.95	$1.68 \cdot 10^{-11}$	0.104	0.95

T, tangential; R, radial; T-R (45°), angle of 45° between R and T; R^2 , coefficient of determination.

Table 5 Sorption coefficients of bound water A_{bw} according to Eq. 2 compared with literature values of water absorption by partial immersion A_w (according to ISO 15148 2002).

Wood species	Sorption direction	RH (%) sector				Literature values ^a A_w ($kg m^{-2} s^{-0.5}$)
		35–0 A_{bw} ($kg m^{-2} s^{-0.5}$)	65–0 A_{bw} ($kg m^{-2} s^{-0.5}$)	35–100 A_{bw} ($kg m^{-2} s^{-0.5}$)	65–100 A_{bw} ($kg m^{-2} s^{-0.5}$)	
Norway Spruce	R	-0.000159	-0.000282	0.000976	0.000625	0.003
Spruce	T	-0.000140	-0.000293	0.000970	0.000642	0.004
	L	–	-0.000885	–	0.000374	0.018
European Beech	R	-0.000242	-0.000498	0.001174	0.000677	0.004
Beech	T	-0.000152	-0.000441	0.001044	0.000656	0.005
	L	–	-0.001069	–	0.000677	0.059

^aWang and Niemz 2002.

R, radial; T, tangential; L, longitudinal.

The L direction shows 2 to 3 times higher values than perpendicular to the grain at the lower RH sector (65–0% RH), whereas at the higher RH sector (65–100% RH) they are equal (beech) or lower (spruce) than in the T or R directions. This is due to the fact that these test conditions have the EMC of the differentiating climate closer to the initial climate for the specimens tested in the L direction than perpendicular to the grain (Vecellio 2009).

The water absorption by partial immersion (liquid water uptake) according to Wang and Niemz (2002) shows, by comparison, values from about 3 times higher (spruce, R direction, 35–100% RH) up to 87 times higher (beech, L direction, 65–100% RH) than bound water sorption (Table 5).

Conclusions

In this study, diffusion properties were determined not only in the principal anatomical directions but also between these directions in 15° steps. Spruce and beech show clear different dependencies with regard to the anatomical directions.

Furthermore, the study points out that measurements of the SS and US diffusion coefficients of the same specimen differ by about a factor of 2. Therefore, both diffusion coefficients have to be measured for model calculations in the field of building physics. The US-determined diffusion coef-

ficient is required to describe short-term water storage at alternating indoor climates. The SS-determined diffusion coefficient should be applied for long-term and constant moisture gradients through an external wall (caused for example by a temperature gradient in the winter).

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