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ORIGINAL ARTICLE

Classification of the conductance of moisture through wood cell components

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Abstract This study aimed to clarify the conductance of moisture through wood cell components. Moisture diffusion coefficients were determined from three models (Stamm, Siau, and Kang et al.) and cell wall, pit, and ray dimensions were experimentally observed in a wood specimen. Fractions of moisture diffusing along each path in each of the models were analyzed. As moisture content decreased, the fraction of water diffusing as bound water through cell walls in tangential and longitudinal directions decreased while water vapor diffusion through lumens and pits became more dominant. Diffusion coefficients predicted by each model were compared with experimental values. Although predicted values differed from experimental values, predicted trends for diffusion rate dependence on moisture content were similar to the experimental results. In particular, the models of Stamm and Kang et al., which consider moisture transport through rays and pits, show a very consistent trend for transverse diffusion, which is always faster radially than tangentially. Input of more accurate dimensions of cell walls and cavities into the models should result in more reliable values, closer to the experimentally determined diffusion coefficients.

Keywords Diffusion model · Diffusion coefficient · Conductance of moisture · Separation of variables

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Introduction

Movement of bound water and water vapor in wood below the fiber saturation point is an important phenomenon that transforms the physical and mechanical properties of wood and influences its chemical processing. Stamm [1] divided the moisture movement into bound water diffusion and water vapor diffusion, and estimated the directional moisture diffusion rates in wood based on a theoretical approach that considered that the diffusion paths depended on the shape and dimensions of cell wall and openings. Siau [2, 3] simplified Stamm's model by neglecting water vapor passing through the openings. Kang et al. [4] proposed a modified model considering the openings of pits and rays.

The paths for movement of bound water and water vapor in wood are segregated into the connected cell wall, and fiber cavity + cell wall, and fiber cavity + pits combinations [5]. Water molecules are diffused through these paths by the moisture concentration gradient. Most water vapor is condensed and transformed into bound water when it passes through the amorphous region in the cell wall, and the bound water then moves along the cell wall. When the bound water arrives at the next cell lumen, it turns into vapor, and the vapor moves to the next cell wall. The diffusion rate of water vapor in a narrow path like a pit pore is lower than it is in cell lumen. The proportion of water passing through each of the paths depends on the water resistance of each wood cell wall structure [5, 6]. Stamm [1], Siau [2, 3], and Kang et al. [4] proposed models of moisture movement by analogy with resistive electrical circuits.

Many pits on the radial section of the tracheids play a major role in water movement in the tangential direction. The number of pits per tracheid varies from 50 to 300 in earlywood [7]. Panshin and de Zeeuw [8] reported that the fractional volumetric compositions of longitudinal tracheids, longitudinal resin canals, and wood rays in white pine, whose anatomical properties are similar to Korean pine, are 93, 1, and 6 %, respectively. This is a typical composition for softwood. Because the rays occupy a relatively small fraction of the volume of softwoods, the roles of rays are sometimes neglected when composing a diffusion model to simplify the diffusion path. However, if the contributions of rays are neglected in modeling, it is hard to explain the observation that moisture movement in the radial direction is faster than in the tangential direction. Banks [9] found the radial permeability of *Pinus sylvestris* is greater than its tangential permeability.

Methods for determining the diffusion coefficient using Fick's second law have been developed in various ways. With some assumptions—that the driving force causing moisture movement is a moisture concentration gradient, and that the diffusion coefficient is constant in any moisture concentration range—a general solution of Fick's second law can be obtained by the separation of variables method [10–12]. The other general solution of Fick's second law can be obtained by the transformation method; this solution can be expressed as an error function [10–15].

This study was carried out to predict the moisture conductance using the models of Stamm, Siau, and Kang et al. with actual dimensions of cell walls, pits and rays. The proportions of water passing through each path in the three models were analyzed. The effectiveness of the theoretical models in estimating the diffusion coefficient in the unsteady state was examined by comparing the predicted diffusion coefficients with experimental results.

Materials and methods

Prediction of moisture diffusion coefficient (conductance) using three different diffusion models (Stamm, Siau, and Kang et al.)

Stamm [1] proposed an electrical circuit model to approximate the moisture transfer rate in wood in the hygroscopic range (Fig. 1b). The electrical model is composed of four resistances, which represent resistance to moisture movement: R_1, resistance across the cell wall; R_2, resistance of lumen; R_3, resistance of pits or rays; and R_4, resistance along the cell wall (Fig. 1a). In general wood, the value of R_4 is larger than total resistance resulting from the series connection of R_1–R_3 (which are connected in parallel) and R_2. Because water vapor moves relatively fast in the lumen, the value of R_2 is much smaller than resistance resulting from the parallel connection of R_1 and R_3.

R_3, the resistance of pits or rays, varies depending on size and number of pits (rays), and can be approximated by the permeability of wood [2]. Because Siau [3] assumed that R_3 is large, he neglected the effects of pits and rays on total diffusion rate in his model (Fig. 1c). Kang et al. [4] modified Stamm's model and considered the permeability of pits and rays (Fig. 1d).

Figure 2 shows schematic representations of the three directional diffusion models. Stamm's model and Kang's model include separate paths for tangential, radial, and longitudinal directions. In contrast, Siau assumed the shape and size of the cross wall are same as those of the side wall in the transverse diffusion model, and did not distinguish tangential diffusion from radial diffusion.

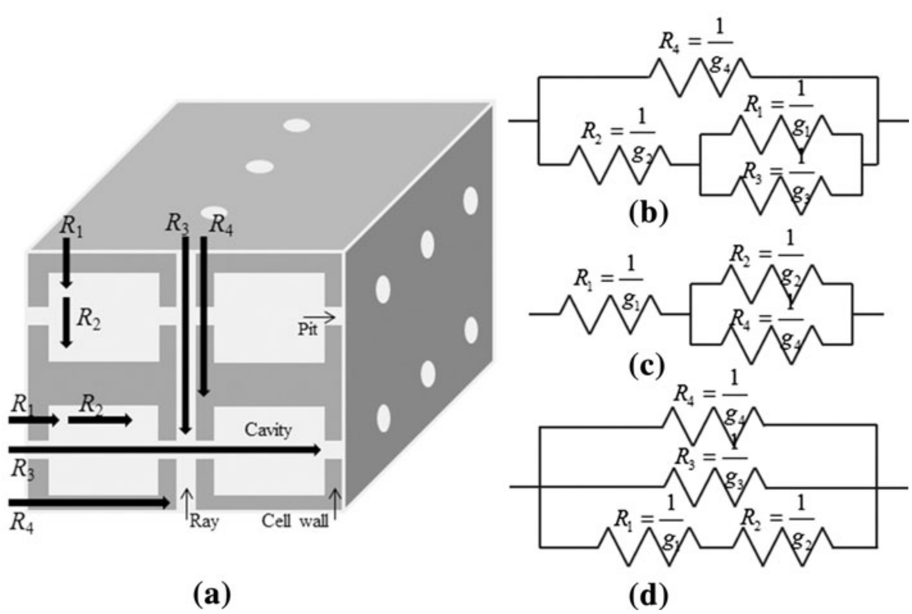

Fig. 1 Primary paths for moisture transport (**a**), and electrical circuit models (**b**–**d**) for expressing diffusion paths (**b** Stamm's model, **c** Siau's model, **d**: Kang et al.'s model; *R* resistance, *g* conductance, *1* across wall, *2* lumen, *3* cavities (pits and rays), *4* along wall)

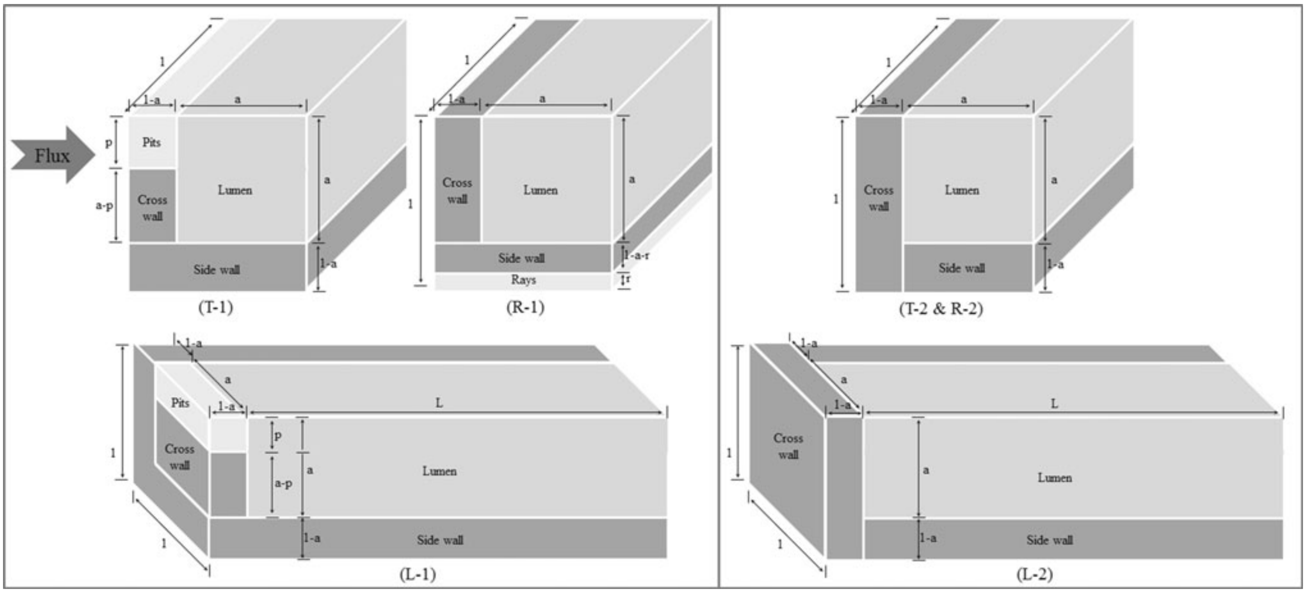

Fig. 2 Schematic representations of the three directional diffusion models: (Stamm's and Kang et al.'s (T-1, R-1, L-1), Siau's (T-2 & R-2, L-2); *a* ratio of lumens to wood cells, *p* ratio of pits to wood cells, *r* ratio of rays to wood cells, *L* ratio of fiber length to diameter of cell)

For Stamm's model (Eq. 1), Siau's model (Eq. 2), and Kang et al.'s model (Eq. 3), as shown in Fig. 1, the total resistance (R) and conductance (g) of the parallel-series models are as follows:

$$R_{\mathrm{Stamm}} = \frac{1}{\frac{1}{R_2+\frac{1}{\frac{1}{R_1}+\frac{1}{R_3}}}+\frac{1}{R_4}},\ g_{\mathrm{Stamm}} = \frac{1}{\frac{1}{g_2}+\frac{1}{g_1+g_3}}+g_4 \tag{1}$$

$$R_{\mathrm{Siau}} = R_1 + \frac{1}{\frac{1}{R_2}+\frac{1}{R_4}},\ g_{\mathrm{Siau}} = \frac{1}{\frac{1}{g_1}+\frac{1}{g_2+g_4}} \tag{2}$$

$$R_{\mathrm{Kang\,et\,al.}} = \frac{1}{\frac{1}{R_1+R_2}+\frac{1}{R_3}+\frac{1}{R_4}},\ g_{\mathrm{Kang\,et\,al.}} = \frac{1}{\frac{1}{g_1}+\frac{1}{g_2}}+g_3+g_4 \tag{3}$$

Each conductance (g) in Eqs. (1)–(3), can be defined from the thickness (l), cross-sectional area (A) and moisture diffusion coefficient (D) of the corresponding component.

$$g = D\frac{A}{l} \tag{4}$$

D is defined based on the idea that the concentration of water in wood (C) is the potential that drives diffusion. However, depending on the type of concentration that causes diffusion, for example, the concentration of water vapor in the lumen (C_{a}) or the concentration of bound water in the wood cell wall (C_{cw}), the corresponding diffusion coefficients can be expressed individually.

$$D \times \text{Concentration of water vapor in lumen} = D^{\mathrm{v}} \times \partial C_{\mathrm{cw}} = D^{\mathrm{a}} \times \partial C_{\mathrm{a}} \tag{5}$$

$$D \times \text{Concentration of bound water in wood cell wall} = D_{\mathrm{cw}}^{\mathrm{BT}} \times \partial C_{\mathrm{cw}} \tag{6}$$

where, D = moisture diffusion coefficient (m^2/s) of wood; D^{v} = diffusion coefficient (m^2/s) of water vapor in the air within in the lumens, and is associated with the difference in concentrations of bound water in the cell walls on either side of the lumen; D^{a} = diffusion coefficient of water vapor in air = $2.2 \times 10^{-5}(1.013 \times 10^5/P) \times (T/273)^{1.75}$ (m^2/s), where P is the air pressure; $D_{\mathrm{cw}}^{\mathrm{BT}}$ = transverse bound water diffusion coefficient of the cell wall (m^2/s); C = concentration of water in wood (kg/m^3); C_{cw} = concentration of bound water in the cell wall in equilibrium with the air in the lumens (kg/m^3); and C_{a} = concentration of water vapor in the lumen in equilibrium with the cell wall (kg/m^3).

It is necessary to know $\partial C_{\mathrm{a}}/\partial C_{\mathrm{cw}}$ to determine D^{v} using Eq. (5). C_{a} may be calculated from the gas law [3]:

$$pV = \frac{w}{M_{\mathrm{v}}}R^*T \tag{7}$$

where: p = partial water vapor pressure in lumens (Pa); w = mass of water vapor (kg); V = volume of air (m^3); M_{v} = molecular weight of water vapor (kg/mol);

R^* = universal gas constant (8314 m^3 Pa/(kgmol K)); and T = temperature (K).

Since $p = p^s h$, where p^s = saturated vapor pressure (Pa); and h = relative humidity.

$$C_a = \frac{V}{w} = \frac{M_v p^s h}{R^* T}, \ \partial C_a = \frac{M_v p^s \partial h}{R^* T} \tag{8}$$

And the concentration difference can be defined by moisture content difference:

$$\Delta C_{cw} = G^m_{cw} \rho_w \Delta m, \ \partial C_{cw} = G^m_{cw} \rho_w \partial m \tag{9}$$

where G^M_{cw} = specific gravity of cell wall at moisture content m; m = moisture content; and ρ_w = water density (kg/m^3).

D^v based on C_{cw} could be defined by Eqs. (8), (9) and (5):

$$D^v = D^a \frac{\partial C_a}{\partial C_{cw}} = D^a \frac{M_v p^s}{\rho_w G^m_{cw} R^* T} \frac{\partial h}{\partial m} \tag{10}$$

It is also necessary to know $\partial C_{cw}/\partial C$ to determine D using Eq. (5). Both values are affected by porosity [3]. These values may be converted into a basis of concentration of wood by multiplying by the factor $\partial C_{cw}/\partial C$, which is the reciprocal of the volume fraction of cell wall in wood.

$$\frac{\partial C_{cw}}{\partial C} = \frac{1}{v_{cw}} = \frac{1}{1 - v^a} = \frac{1}{1 - a^2} \tag{11}$$

where: v_{cw} = volume fraction of the cell wall in wood; and v^a = volume fraction of air in wood, (related to the porosity of wood, a^2).

The porosity ($v^a = a^2$) may be calculated from the oven-dry cell-wall specific gravity (G^0_{cw}) and the moisture content. A value of 1.53 is assumed as the true value for cell wall specific gravity. Compaction of bound water is neglected. The porosity is then calculated by subtracting the volume of the cell wall and the moisture from unity [3].

$$a^2 = 1 - G\left(\frac{1}{G^0_{cw}} + m\right) \tag{12}$$

where G = specific gravity of wood.

The diffusion coefficient of bound water has been determined in a number of ways. Stamm [16] measured it in the longitudinal direction after sealing off the lumens with molten bismuth. Siau [2] converted it to the diffusion coefficient of the cell wall in the transverse direction by assuming D^{BT}_{cw} (bound water diffusion coefficient of the cell wall in the transverse directions) = D^{BL}_{cw} (bound water diffusion coefficient of the cell wall in the longitudinal direction)/2.5, and obtained an Arrhenius-type equation via least-squares fitting:

$$D^{BT}_{cw} = 7 \times 10^{-6} \exp[-(38500 - 29000\ m)/R^* T] \tag{13}$$

As mentioned above, the values of g of moisture in cell components can be calculated by substituting Eq. (11) into Eq. (4), and are given in Table 1.

Measurement of moisture diffusion coefficients in unsteady state

To determine the diffusion coefficients for Korean pine (*Pinus koraiensis*), knot-free, straight-grained specimens (Table 2) were prepared with the following dimensions [30 mm (tangential) × 30 mm (radial) × 30 mm (longitudinal)]. To determine the diffusion coefficient in the three directions, the four adjacent edge surfaces of each specimen were sealed with paraffin tape to limit moisture movement, and the two opposite surfaces of interest remained unsealed. Drying was performed at 30 °C with equilibrium moisture content conditions of 19.86, 15.71, 10.61, and 5.88 %. There were six replicates at each condition; the specific gravity of the specimens averaged 0.442, based on oven-dry weight. Air velocity was approximately 1 m/s. Average moisture content during drying was calculated from regular weighing of specimens, and final oven-drying.

Moisture diffusion coefficients in the unsteady state were determined from solutions of Fick's second law equation (Eq. 14), which were derived by the separation of variables and transformation of variables methods.

$$\frac{\partial C}{\partial t} = D \frac{\partial C^2}{\partial^2 x}, \tag{14}$$

where: x = distance in moisture movement direction (m); and t = time (s).

Diffusion coefficients were determined by solution of the unsteady state diffusion equation (Eq. 16), which was derived by the separation of variables method using the fractional change in the average moisture concentration ($\bar{E}$, Eq. 15).

$$\bar{E} = \frac{C^{average} - C^e}{C^i - C^e} = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2}{4L^2} Dt\right) \tag{15}$$

$$D = -\frac{4L^2}{\pi^2 t} \ln\left(\bar{E} \frac{\pi^2}{8}\right) \tag{16}$$

where $\bar{E}$ = fractional change in the average moisture concentration; C^i = initial moisture concentration (kg/m^3); $C^{average}$ = average moisture concentration (kg/m^3); C^e = moisture concentration of equilibrium with ambient air (kg/m^3); and L = half thickness of the specimen (m).

The other general solution of Fick's second law can be obtained by the transformation method. $\bar{E}$ becomes as shown in Eq. (17). By solving the resulting equation in terms of diffusion coefficient, Eq. (17) yields Eq. (18).

Table 1 Three directional conductance (g) values of cell components

Direction	Cross wall (g_1)	Lumen (g_2)	Pits or rays (g_3)	Side wall (g_4)
Tangential	$\frac{D_{BT}(a-p)}{(1-a)(1-a^2)}$ [a,c]	$\frac{D_v(a-p)}{a(1-a^2)}$ [a,c]	$\frac{D_v p}{(1-a)(1-a^2)}$ [a]	$\frac{D_{BT}(1-a)}{(1-a^2)}$ [a,c]
	$\frac{D_{BT}}{(1-a)(1-a^2)}$ [b]	$\frac{D_v}{1-a^2}$ [b]	$\frac{D_v p}{1-a^2}$ [c]	$\frac{D_{BT}(1-a)}{a(1-a^2)}$ [b]
Radial	$\frac{D_{BT}a}{(1-a)(1-a^2)}$ [a,c]	$\frac{D_v}{1-a^2}$ [a,b,c]	$\frac{D_v r}{1-a^2}$ [a,c]	$\frac{D_{BT}(1-a-r)}{1-a^2}$ [a,c]
	$\frac{D_{BT}}{(1-a)(1-a^2)}$ [b]			$\frac{D_{BT}(1-a)}{a(1-a^2)}$ [b]
Longitudinal	$\frac{D_{BL}a(a-p)}{(1-a)(1-a^2)}$ [a,c]	$\frac{D_v a(a-p)}{L(1-a^2)}$ [a,c]	$\frac{D_v pa}{(L+1-a)(1-a^2)}$ [a]	$\frac{D_{BL}}{(L+1-a)}$ [a,c]
	$\frac{D_{BL}a^2}{(1-a)(1-a^2)}$ [b]	$\frac{D_v a^2}{L(1-a^2)}$ [b]	$\frac{D_v pa}{(1-a)(1-a^2)}$ [c]	$\frac{D_{BL}}{L}$ [b]

[a] Stamm's model, [b] Siau's model, [c] Kang et al.'s model

Table 2 Physical properties of Korean pine specimens and test conditions

Temperature (°C)	RH (%)	Equilibrium MC (%)	Initial MC (%)	Final MC (%)	Dimension (mm)			Oven-dry specific gravity
					Length	Width	Thickness	
30	90	19.86	25.83 ± 1.36[a]	20.89 ± 0.56	30	30	30	0.442 ± 0.014
	80	15.71	20.89 ± 0.56	15.65 ± 0.15				
	60	10.61	15.65 ± 0.15	11.02 ± 0.34				
	30	5.88	11.02 ± 0.34	6.10 ± 0.21				

[a] Standard deviation

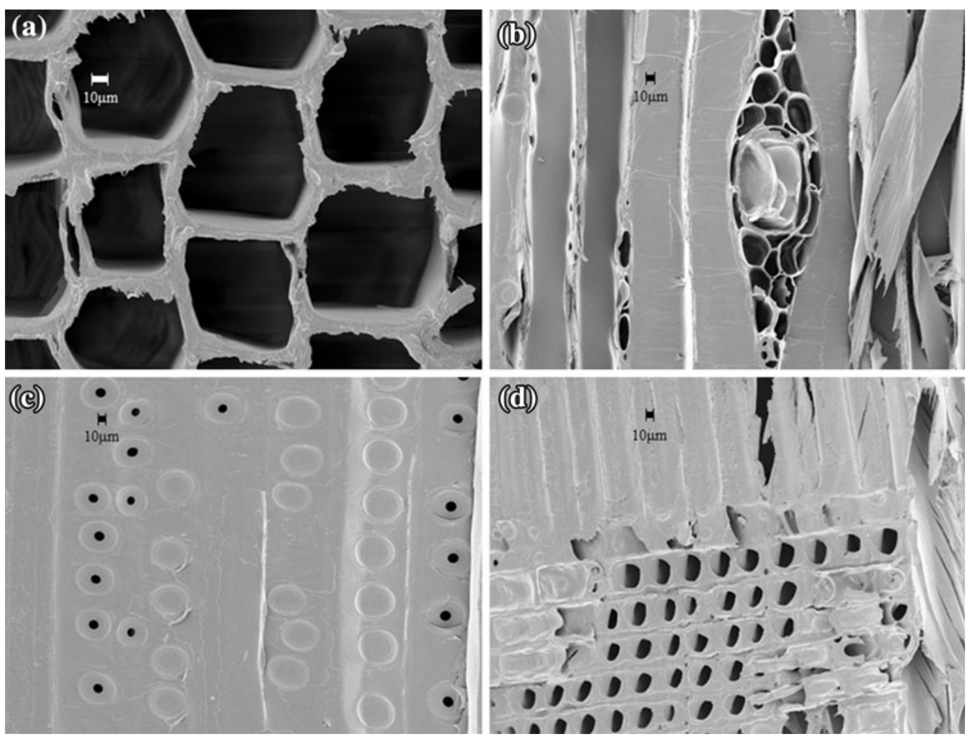

Fig. 3 SEM images of *Pinus koraiensis* (**a** diameter of tracheid, **b** numbers of pits and pores per one tracheid, **c** effective area of pit openings, and **d** length and width of ray tracheid)

$$\bar{E} = \frac{C^{\text{average}} - C^{\text{e}}}{C^{\text{i}} - C^{\text{e}}} = 1 - \frac{2}{\sqrt{\pi}}\sqrt{\frac{Dt}{L^2}} \quad (17)$$

$$D = \frac{\pi L^2}{4t}(1 - \bar{E})^2 \quad (18)$$

Results and discussion

Determination of moisture diffusion coefficient by the three diffusion models

The dimensions and numbers of tracheids and ray cells were analyzed using the SEM image in Fig. 3. The lengths of tracheids ranged from 2500 to 4000 µm, the diameters of tracheids ranged from 30 to 40 µm, the number of pits and pores per tracheid was about 85, and the effective diameter of pit openings was about 0.9 µm. Ray tracheids ranged in length between 80 and 150 µm, and in width between 15 and 25 µm. These data are similar to typical dimensions of softwood elements (tracheid length, 3500 µm; tracheid diameter, 35 µm; and effective diameter of pit openings, 0.02–4.0 µm) reported by Siau [3].

Assuming that the area of cross section perpendicular to the moisture flow direction is 1 mm^2 in the diffusion model (Fig. 2), the numbers of tracheids and pit pores are estimated as 7.48 (i.e., 93 %/0.035 mm $\times$ 93 %/3.5 mm) and 635 (i.e., 7.48 $\times$ 85), respectively, in the cross section, if the tracheid length is 3500 µm, and its average diameter is 35 µm. When the effective diameter of the openings of the pits is 1 µm, the proportion of effective area of pit openings in the cross-sectional area is 0.000499 (i.e., 635 $\times$ $(0.0005\ \mathrm{mm})^2 \times \pi$). The ratio of pits to wood cells (p) can be obtained as 0.00050 because $p \times 1 = 4.99 \times 10^{-4}$.

Because the volume fraction of ray cells is 6 %, the total area of ray cells in 1 is 0.06 mm^2. If we take the width of the ray cell as 30 µm, there are 25 ray cells within the 1 mm^2 cross-sectional area. If the length of the ray cell is 150 µm, and ray cells are connected by each of 25 pits, the proportion of effective area of pit openings in the cross section is 0.00281 (i.e., 25 $\times$ 0.15 mm $\times$ 0.03 mm $\times$ 25 $\times$ 0.001 mm). The ratio of rays to wood cells (r) can be is 0.00281, because $r \times 1 = 2.281 \times 10^{-3}$.

Figure 4 shows the tangential, radial, and longitudinal moisture diffusion coefficients that were determined by substituting an oven-dry specific gravity of 0.428, p of 0.00050, and r of 0.00281 into the equations for conductance in Table 1.

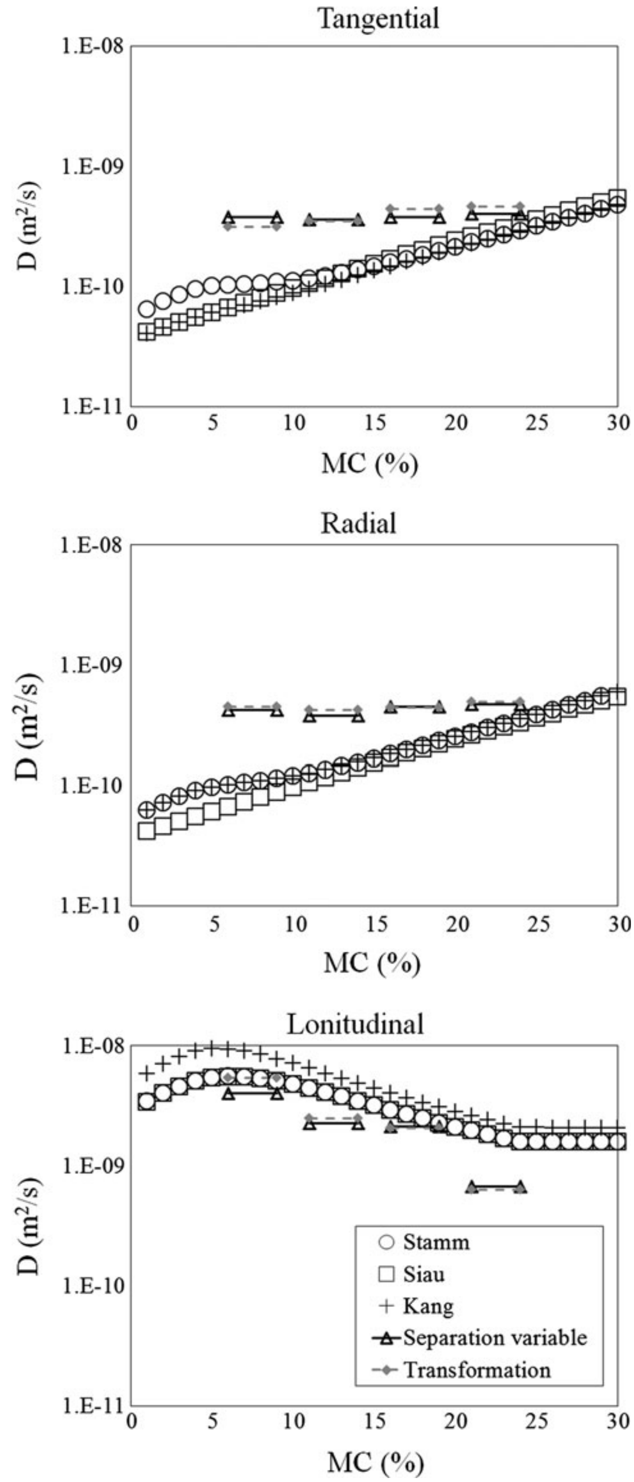

Fig. 4 Moisture diffusion coefficients (30 °C, $G = 0.428$, $p = 0.00050$, $r = 0.00281$)

Because the effects of diffusion through pit or ray openings were neglected in Siau's model, his model cannot describe tangential diffusion and radial diffusion separately—this may be a significant problem when the wood has many pit and ray cells. Both tangential and radial transverse diffusion coefficients, determined by Siau's model, decreased steadily and continuously as moisture content decreased. Meanwhile, Stamm's model and Kang et al.'s model describe the effect of pits or rays on diffusion. Transverse diffusion coefficients determined by Stamm's model and Kang et al.'s model decreased as the moisture content decreased from 30 to 10 %, in a similar way to that shown by Siau's model. However, below 10 % MC, the diffusion coefficients did not decrease, and even increased from 10 to 5 %. This result of Stamm's and Kang et al.'s models may be because these models consider the fast diffusion of water vapor passing through pits or rays at lower

MC. In particular, in Kang et al.'s model, radial diffusion coefficients were much higher than tangential diffusion coefficient below 10 % MC, so that Kang et al.'s model could reflect the effect of rays on water vapor diffusion.

In the longitudinal direction, steady increases in diffusion coefficients were seen as the moisture content decreased. Diffusion coefficients determined by Kang et al.'s model had a large variation range, twice that of other models.

Fraction of diffusion through each of the three possible paths in wood

Moisture diffusion in wood during drying can be classified into three paths: Path 1 is water vapor diffusion through the lumen, Path 2 is water vapor diffusion through the pits or rays, and Path 3 is bound water diffusion through the continuous cell wall. The conductances g_1, g_2, g_3, and g_4 of the cell components in Table 3 can be segregated: g_2 is path 1, g_3 is path 2, and the sum of g_1 and g_4 is path 3. Table 3 shows the fraction of diffusion that occurs through each of the paths at 10 % MC, 20 % MC, and 30 % MC.

As the moisture content decreases during drying, bound water diffusion through the cell wall in tangential and longitudinal directions (Path 3) decreases, and water vapor diffusion through lumens (Path 1) becomes more dominant. In both directions, the fraction of water vapor diffusion through the pits (Path 2) is below 1 %.

In Kang et al.'s model, as the moisture content decreases, the water vapor diffusion through the lumens increases more rapidly, compared with the increase seen in the other models. For this reason, the longitudinal diffusion coefficients determined by Kang et al.'s model are higher than those determined by the other models below 20 % MC (Fig. 4).

Measurement of moisture diffusion coefficients in unsteady state

Three directional moisture diffusion coefficients of Korean pine wood were experimentally determined in the unsteady state, and the results are presented in Table 4 and Fig. 4.

Table 4 shows moisture diffusion coefficients that were determined from experimental weight loss data using a numerical solution of the diffusion equation. The experimental results were not drastically different to the values determined from the models. The longitudinal diffusion coefficient is 10 times higher than that in the transverse direction, because tracheids have a decisive effect on moisture movement. These experimental results show differences with cellular orientation—the radial diffusion coefficient is approximately 20 % greater than the tangential diffusion coefficient. This result is probably the result of the contribution of the ray cells.

Figure 4 shows a comparison of experimentally determined values and the values determined by the three

Table 3 Fraction of diffusion that occurs through the three paths in wood (at 30 °C, $G = 0.428$)

	MC (%)	Path 1: g_2 (%)			Path 2: g_3 (%)			Path 3: $g_1 + g_4$ (%)		
		Stamm	Siau	Kang et al.	Stamm	Siau	Kang et al.	Stamm	Siau	Kang et al.
Tangential	10	98.841	98.956	99.082	0.292	–	0.049	0.867	1.044	0.869
	20	93.484	92.400	93.677	0.252		0.047	6.263	7.600	6.276
	30	79.573	75.861	79.699	0.198		0.040	20.229	24.139	20.261
Longitudinal	10	97.308	97.331	97.021	0.050	–	0.345	2.642	2.669	2.634
	20	82.407	82.246	82.218	0.043		0.272	17.550	17.754	17.510
	30	54.658	54.247	54.581	0.028		0.170	45.314	45.753	45.250

Table 4 Experimentally determined moisture diffusion coefficients for Korean pine

Temperature (°C)	RH (%)	Initial MC–Equilibrium MC (%)	Diffusion coefficient ($\times 10^{-10}$ m^2/s)					
			Separation of variables			Transformation		
			T	R	L	T	R	L
30	90	25.59–19.86	4.003 ± 0.147[a]	4.702 ± 0.325	6.766 ± 0.825	4.595 ± 0.081	4.922 ± 0.193	6.323 ± 0.323
	80	19.86–15.71	3.772 ± 0.485	4.483 ± 0.945	21.29 ± 0.187	4.444 ± 0.011	4.389 ± 0.017	20.57 ± 1.390
	60	15.71–10.61	3.588 ± 0.471	3.807 ± 0.589	22.61 ± 1.283	3.501 ± 0.020	4.225 ± 0.015	24.89 ± 2.559
	30	10.61–5.88	3.808 ± 0.365	4.205 ± 0.452	40.20 ± 2.191	3.163 ± 0.015	4.482 ± 0.030	53.89 ± 1.114

[a] Standard deviation

models. Longitudinal diffusion coefficient increased with decreasing MC. Transversal diffusion coefficient decreased with decreasing MC from 30 to 10 % then increased with decreasing MC from 10 to 5 %. Although the model predicted values were not the same as the experimental values, the trends in diffusion rate change with moisture content, as evaluated by the three different models, were similar to the experimental trends. The most likely reason for the differences between experimental and model values is that the p and r values used in the model in this study differed from the actual porosity of the wood specimen. Precise quantification of porosity in pits and rays is very important.

Conclusion

This study was carried out to analyze diffusion models (Stamm's, Siau's, and Kang et al.'s) and to determine the diffusion coefficients below the fiber saturation point in the tangential, radial, and longitudinal directions. To evaluate the validity of the results, the diffusion coefficients predicted by the models were compared with the experimental values. Although the model values were not the same as the experimental values, the trends in diffusion rate change with moisture content, were similar for the three models and the experimental result. In particular, Stamm's and Kang et al.'s models, which took into consideration the role of rays and pits in moisture transport, show that transverse diffusion is consistently faster in the radial direction than in the tangential direction.

The conductances of each pathway within the three models were analyzed to evaluate the fraction of diffusion that occurs through each of the three possible paths in wood. As the moisture content decreases during drying, bound water diffusion through the cell wall in tangential and longitudinal directions (Path 3: $g_1 + g_4$) decreases, and water vapor diffusion through lumens (Path 1: g_2) becomes more dominant. In both directions, water vapor diffusion through pits (Path 2: g_3) is below 2 %.

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