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Parameter estimation of moisture diffusivity in wood by an inverse method

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Abstract This study focuses on the transfer of bound water and liquid water in wood. The moisture changes and distribution of six wood species (three softwoods and three hardwoods) were investigated in the longitudinal direction exposed to long-term moisture sorption in static environmental conditions. Most species used for the experiment reached an estimated maximum moisture content, which indicated that there might be no significant hysteresis in the capillary pressure curve due to air entrapment. The experimental data for the different samples were found to vary considerably. Using initial values obtained by the Boltzmann transformation, the Levenberg-Marquardt method was used to determine the moisture diffusivity from measured moisture content changes with time and moisture profiles. The validity was ascertained by comparing the numerical results with the corresponding experimental measurements. There was a point of discontinuity and an abrupt change in the slope of the diffusivity function around the fiber saturation point, which might slow the numerical solution process.

Key words Inverse method · Sorption · Moisture transfer · Parameter estimation · Finite volume method

Introduction

Wood is a typical hygroscopic porous material and consists of cell walls, cavities, and pits between the cell walls. Moisture in wood exists as three phases; namely, bound water,

water vapor, and free (or liquid) water. Wood is also susceptible to growth of bacteria, fungi, or algae, especially when exposed to high humidity or liquid water. Liquid water may provide a medium for diffusion of enzymes or other metabolites by which biological deterioration can be facilitated. The deterioration of decayed wood may be accelerated by physical and chemical damage. The durability of wood in building largely depends on moisture conditions. For traditional post and beam wooden structures, moisture content is kept below the fiber saturation point (FSP) during general use. However, wooden columns may be directly exposed to rainfall and come into direct contact with liquid water. In addition, moisture may enter structures by condensation, runoff from roof and facade, and by capillary action of groundwater. Therefore, simulation of moisture transport in wood under set environmental conditions should be valuable for predicting susceptibility to biological decay.

Liquid water uptake of porous materials is called imbibition or absorption in hydrology and building physics. In the case of hygroscopic porous materials such as wood, however, the more general term might be sorption. Because the moisture content of exterior wood is in an air-dried condition, moisture changes in wood in contact with liquid water involves transport of bound water, water vapor, and liquid water during sorption. As a consequence, most models use Fick's law to model bound water and water vapor for the hygroscopic region that is below the FSP. Darcy's law is used for free-water transport for the nonhygroscopic region that is over the FSP. The heat and moisture transfer coefficients of wood in the hygroscopic range, under the FSP, were reviewed by Kang et al.^{1,2} To model moisture sorption including in the over-hygroscopic range, liquid transport parameters such as capillary pressure and intrinsic and relative permeability are required. The experimental data are very limited.² A considerable number of experimental and theoretical studies have been conducted on moisture transport in wood drying. However, most such models contain at least one adjustable parameter, which must be determined by an experiment. The relevant heat and mass transfer coefficients are necessary for the simulation whose

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accuracy depends mainly on the input coefficients. Information relating to moisture transport properties is limited and insufficient, especially for the simulation of the sorption process in wood.

Moisture diffusivity can be estimated from moisture changes with time and transient moisture content profiles at a given time by inverse methods: (1) the Boltzmann transformation method (BTM), (2) the moisture gradient method (MGM), and (3) the optimization method (OM). By using the BTM, Koponen³ investigated diffusion coefficients of wood in drying over both hygroscopic and over-hygroscopic ranges under isothermal conditions. Diffusion coefficients increased with increasing moisture content up to the FSP and then decreased in the nonhygroscopic region. By using the MGM and the gradient in water potential as the driving force, Cloutier and Fortin⁴ investigated the moisture transport coefficient of wood during drying under nonisothermal conditions in which it increased exponentially with moisture content. Hukka⁵ calculated the moisture diffusion coefficient below the FSP from the measured development of the internal moisture profiles during drying by the conjugate gradient method of the OM. Due to hysteresis between drying and sorption, these results are readily applicable to the wood sorption process. However, there has been little investigation concerning the measurement and modeling of moisture sorption in wood in which the moisture content increased from low to high.⁶⁻⁹

Descamps¹⁰ reported that the optimization method with a spline function performs better than the BTM or MGM because it does not use the derivative of a moisture profile. However, the optimization methods have some serious limitations and different initial settings can lead to different optimization results. Sometimes the functions become over-parameterized and the same curve can be generated by different parameter combinations. It is also helpful to use expressions with parameters that can be directly obtained from the experiments. The goodness-of-fit depends on a good guess of initial parameters.

The purpose of this study was to investigate the moisture change and distribution of six wood species (three softwoods and three hardwoods) in the longitudinal direction when exposed to long-term moisture sorption. Based on a transport model of sorption, diffusivities of bound water and free water covering the whole moisture range needed in the simulation of wood is determined by using the inverse method. In this study, the initial settings obtained by the Boltzmann transformation method are used and compared for accuracy. Validity is ascertained by comparing the numerical results with the corresponding experimental measurements.

Theory

Moisture transfer model

Multiphase heat and mass transfer models that considered moisture content, air, and energy conservation were developed by several researchers. If the gas pressure in wood is

assumed to be constant, the mass transfer model can be converted to the diffusion equation:

$$\frac{\partial m}{\partial t} = \nabla \cdot [(D_w + \overline{D_v + D_B}) \nabla m] \quad (1)$$

where m is the moisture content based on the dry weight of wood, D_w is the liquid water diffusivity, D_v is the water vapor diffusivity, and D_B is the bound water diffusivity.

The liquid water diffusivity (D_w) over the hygroscopic range can be expressed by using the generalized Darcy's law:

$$D_w = -\frac{\rho_w k_{rw} K_w}{\rho_0 v_w} \frac{\partial P_c}{\partial S} \frac{\partial S}{\partial m} \quad \forall m > m_{FSP} \quad (2)$$

where ρ_0 is dry wood density, ρ_w is liquid water density, k_{rw} is relative water permeability, K_w is intrinsic water permeability, v_w is dynamic viscosity of liquid water, P_c is capillary pressure, and S is liquid water saturation.

The combined diffusion coefficient (D_{bc}) under the isothermal condition is expressed in different equations depending on the models.²

$$D_{bc} = \overline{D_v + D_{BL}} = p\sqrt{\phi}D_v + \frac{\sqrt{\phi}(\sqrt{\phi} - p)(L + 1 - \sqrt{\phi})\rho_c D_{BL}}{1 - \sqrt{\phi} + L\rho_c D_{BL}/D_v} + (1 - \phi)\rho_c D_{BL} \quad m \leq m_{FSP} \quad (3)$$

where p is the ratio of an effective pit opening area to end wall area; L is the ratio of fiber length to an effective diameter, D_v is the diffusivity of water vapor in air, D_B is the diffusivity of bound water in the cell wall, ϕ is the porosity or void fraction, and ρ_c is the cell wall density.

The porosity of wood may be calculated from wood and cell wall density using Eq. 4, assuming that the density of bound water is equal to the water density, the oven-dry cell wall density is 1540 kg/m³, and the pore volume remains constant with the moisture changes.¹¹

$$\phi = 1 - \frac{\rho_0}{1540} = 1 - \frac{1000 \times G_0}{1540} \quad (4)$$

The bound water diffusion coefficient in the longitudinal direction c can be estimated from transverse one,

$$D_{BT} = 7 \times 10^{-6} \exp[-(38500 - 29000m)/RT] \quad (5)$$

$$D_{BL} = 2.5 \times D_{BT} \quad (6)$$

and the water vapor diffusion coefficient is

$$D_v = D_{av} \frac{0.018 p_{vs}}{\rho_c^m RT} \frac{\partial h}{\partial m} \quad (7)$$

$$D_{av} = 2.2 \times 10^{-5} \left(\frac{1.013 \cdot 10^5}{P} \right) \left(\frac{T}{273} \right)^{1.75} \quad (8)$$

where R is the universal gas constant (8.314 J/mol K), T is temperature in Kelvin, p_{vs} is saturated vapor pressure, h is relative humidity, and P is total pressure of air and water vapor.

According to Siau,¹¹ Eq. 3 may be expressed in simplified form.

$$D_{bc} = \frac{\phi}{1-\phi} \frac{D_v D_{BL}}{D_{BL} + (1-\sqrt{\phi})D_v/L} \quad (9)$$

The maximum possible moisture content of wood can be predicted theoretically if the cell cavities remain constant in size during moisture sorption and m_{FSP} is known.

$$m_{\max} = m_{FSP} + \frac{\phi}{G_0} \quad (10)$$

where the fiber saturation point of wood m_{FSP} is usually assumed to be 0.3 and G_0 is the dry specific gravity of wood.

However, it is difficult to measure the dry volume because the moisture content can change during measurement. Therefore, the dry specific gravity can be obtained using the moist one.

$$G_0 = \frac{G_m}{1 - mG_m} \quad (11)$$

where G_m is the specific gravity of wood based on dry weight and moist volume at moisture content m .

Numerical analysis

The equation governing isothermal moisture transfer can be obtained by substituting Eq. 3 into Eq. 1.

$$\begin{aligned} \frac{\partial m}{\partial t} &= \nabla \cdot [(D_w + D_{bc}) \nabla m] \\ &= \nabla \cdot [D \nabla m] \end{aligned} \quad (12)$$

Finite volume method

Consider the nonlinear diffusion equation as

$$\frac{\partial m}{\partial t} = \frac{\partial}{\partial x} \left[D(m) \frac{\partial m}{\partial x} \right], \quad t > 0, \quad 0 \leq x \leq L \quad (13)$$

with the initial condition

$$m(x, 0) = m_0(x), \quad 0 \leq x \leq L \quad (14)$$

and two point boundary conditions

$$\begin{aligned} D \frac{\partial m}{\partial x} \Big|_{x=L} &= h[m(L, t) - 0.05] \\ m(0, t) &= m_{\max} \end{aligned} \quad (15)$$

where h is the external convective mass transfer coefficient ($0.0001/\rho_0$).

In order to find the solution of Eq. 13 by the finite volume method, one takes some meshes

$$\Pi = \{(x_i, t_j) | 0 = t_0 < t_1 < \dots < t_N, 0 = x_0 < x_1 < \dots < x_M = L\} \quad (16)$$

and constructs an appropriate control volume corresponding to spatial nodes $\{x_i\}$.

By integrating Eq. 13 on each control volume (Fig. 1) and using the Gauss-divergence theorem, the following discrete form is obtained:

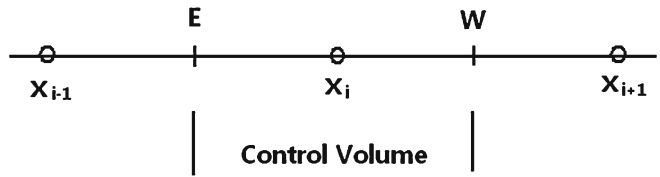


Fig. 1. Nodes and control volume

$$\frac{m_i^{j+1} - m_i^j}{\Delta t} = \sum_{f=E,W} [D(m^{j+1}) \frac{\partial m^{j+1}}{\partial x}] \cdot n_f \quad (17)$$

where superscript j is the time layer, subscript i represents nodes, and n_f is the outward normal vector at each end point of the control volume. At the end points W , the value of $D(m^{j+1})$ is given by an average value

$$D(m^{j+1})|_W = (D(m_i^{j+1}) + D(m_{i+1}^{j+1}))/2 \quad (18)$$

and the derivative is approximated numerically as in Eq. 19

$$\frac{\partial m^{j+1}}{\partial x} = \frac{m_{i+1}^{j+1} - m_i^{j+1}}{x_{i+1} - x_i} \quad (19)$$

At the $(j+1)$ -th time, Eq. 19 provides the solution $m^{(j)}$ at the (j) -th time. Hence, as shown in Eq. 17, each equation can be used to obtain m_{i-1}^{j+1} , m_i^{j+1} , and m_{i+1}^{j+1} . However, the system of equations must be nonlinear, and so Newton's iteration method has been used.

Diffusion coefficients

To adopt the generalized Darcy's law to the simulation, there is a need for an intrinsic and relative permeability as well as a capillary-liquid water relation. For the combined diffusion coefficient, the law requires information of the cell wall geometry as well as the sorption isotherm, for which there are no sufficient data until now. Therefore, two types of diffusion coefficient were assumed as follows:

First, one coefficient was proposed by the exponential function with the fourth-order polynomial, which is continuous in the whole moisture content range.

$$D = \exp(a_0 + a_1 m + a_2 m^2 + a_3 m^3) \quad (20)$$

Second, two coefficients were proposed by the exponential function with a third-degree polynomial over the hygroscopic range and a first-order polynomial in the hygroscopic range.

$$\begin{aligned} D_w &= \exp(a_0 + a_1 m + a_2 m^2 + a_3 m^3) \quad \forall m > m_{FSP} \\ D_{bc} &= \exp(-b_0 - b_1 m) \quad \forall m \leq m_{FSP} \end{aligned} \quad (21)$$

Least-square method and Gauss-Newton method

Suppose that one must determine the value of the coefficient $D(m)$ by using the known experimental results of m_i^j for some i and j . Because there are four parameters a_0 , a_1 , a_2 , and a_3 , many experimental values for m_i^j are given. In this case, it is common to use the least-squares method as follows:

To find the parameters $A = [a_0, a_1, a_2, a_3]$ that minimize the objective functional, it was defined as the sum of the squares of the deviation between the measured and the predicted data on both average moisture content and a moisture profile.

$$F(A) = \sum_{j=1}^N [\bar{m}(t_j) - \bar{m}_e(t_j)]^2 + \sum_{k=1}^M [m(x_k, t_N) - m_e(x_k, t_N)]^2 \quad (22)$$

where \bar{m} and \bar{m}_e are the average moisture contents of predicted and experimental data with time t , respectively. $m_e(x_k, t_N)$ is the moisture profile of the experimental data for final time t_N and $m(x_k, t_N)$ is one of the numerical solutions for the nonlinear diffusion equation (Eq. 13) by finite volume method.

The condition necessary to minimize the function at A^* is

$$\nabla F(A^*) = 0 \quad (23)$$

Then the gradient of $F(A)$ is

$$\nabla F(A) = \sum_{i=1}^K r_i(A) \nabla r_i(A) = J(A)^T r(A) \quad (24)$$

where $r(A) = (r_1, r_2, \dots, r_K)^T$

$$\begin{aligned} r_i(A) &= \bar{m}(t_i) - \bar{m}_e(t_i) & i &= 1 \dots N \\ r_{N+k}(A) &= m(x_k, t_N) - m_e(x_k, t_N) & k &= 1 \dots M \\ K &= N + M \end{aligned}$$

and the Jacobian matrix of $r(A)$ is

$$J(A) = \begin{pmatrix} \frac{\partial r_1}{\partial a_0} & \frac{\partial r_1}{\partial a_1} & \frac{\partial r_1}{\partial a_2} & \frac{\partial r_1}{\partial a_3} \\ \frac{\partial r_2}{\partial a_0} & \frac{\partial r_2}{\partial a_1} & \frac{\partial r_2}{\partial a_2} & \frac{\partial r_2}{\partial a_3} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial r_K}{\partial a_0} & \frac{\partial r_K}{\partial a_1} & \frac{\partial r_K}{\partial a_2} & \frac{\partial r_K}{\partial a_3} \end{pmatrix} \quad (25)$$

However, this system of equations is nonlinear and difficult to compute. Hence Newton's method is used to solve this system. The original Newton's iterative formula has the form

$$A^{(k+1)} = A^{(k)} - \left[J(A^{(k)})^T J(A^{(k)}) + S(A^{(k)}) \right]^{-1} J(A^{(k)})^T r(A^{(k)}) \quad (26)$$

where Hessian $S(A)$ has the second-order derivative such as

$$S(A) = \sum_{i=1}^K r_i(x) \nabla^2 r_i(x) \quad (27)$$

However, $S(A)$ is expensive to compute and makes the system ill-conditioned. Hence, by neglecting this second-order term in Newton's method, the simplified iteration is:

$$A^{(k+1)} = A^{(k)} - \left[J(A^{(k)})^T J(A^{(k)}) \right]^{-1} J(A^{(k)})^T r(A^{(k)}) \quad (28)$$

This equation is said to be the Gauss-Newton iteration. To make the iteration well defined, it is required that the rank of the Jacobian matrix is 4. Obviously, the success of the Gauss-Newton method will depend on the importance of the neglected second-order term $S(A)$. If $S(A^*) = 0$, the Gauss-Newton method would have a quadratic convergence rate. In general, the Levenberg-Marquardt method is used to improve the numerical stability and convergence. These parameters were adjusted by the fitting procedure until the best agreement between experiment and simulation was obtained.

Materials and methods

Three species of each softwood and hardwood were selected for the experiments (Table 1). Wood samples were cut to a prismatic shape with approximate dimensions of 25 mm (width) \times 25 mm (depth) \times 200 mm (height). Four vertical sides were coated by a varnish with heavy pigments. The

Table 1. Physical properties of wood species used for the experiment

Wood species	Duration (months)	Dry density (kg/m ³)	Porosity	Maximum MC (kg/kg)		ΔMC^a
				Estimated	Measured	
Softwood						
Hemlock (<i>Tsuga heterophylla</i>)	1	485	0.69	1.71	1.80	-0.09
	2	448	0.71	1.88	2.02	-0.14
Radiata pine (<i>Pinus radiata</i>)	1	422	0.73	2.02	1.94	+0.06
	2	461	0.70	1.82	1.74	+0.08
Spruce (<i>Picea mariana</i>)	1	510	0.67	1.61	1.61	0.00
	2	500	0.68	1.65	1.69	-0.04
Hardwood						
Painted maple (<i>Acer mono</i>)	1	626	0.59	1.25	1.21	+0.04
	2	650	0.58	1.19	1.03	+0.16
Japanese elm (<i>Ulmus davidiana</i>)	1	800	0.48	0.90	0.86	+0.04
	2	686	0.55	1.11	1.03	+0.08
Horn beam (<i>Carpinus cordata</i>)	1	741	0.52	1.00	0.90	+0.10
	2	724	0.53	1.03	0.93	+0.10

MC, Moisture content

^aDifferential moisture content between estimated and measured maximum moisture content

top and bottom faces were left uncoated. The bottom surface was submerged only a few millimeters in order to avoid buildup of hydrostatic pressure. The top surface was exposed to ambient conditions. The environmental laboratory conditions were kept constant at 20°C and 40% relative humidity during the experiments (Fig. 2).

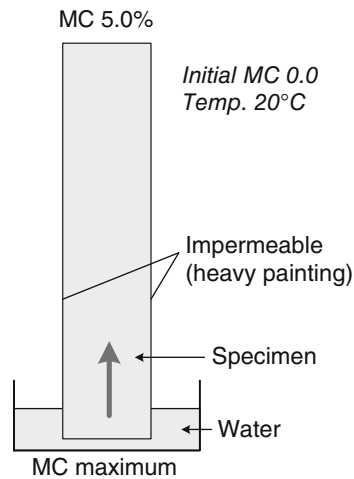
For all samples, moisture content (MC) was recorded at various time intervals. The moisture of each sample in grams was obtained by subtracting the moisture of the oven-dried samples from the moisture of the wet samples. After the absorption test, the specimen was cut consecutively into 24 to 27 pieces for measuring moisture and specific gravity distributions. The volume for the specific gravity was measured by the water immersion method after both uncoated surfaces were coated with paraffin.

Results and discussion

Maximum moisture content

The estimation of maximum MC is important in predicting the sorption process of wood accurately, which should be

Fig. 2. Schematic diagram of the moisture absorption test. MC, Moisture content



defined at the boundary conditions. Most maximum MC values estimated by using Eq. 4 were slightly higher than the measured values; hemlock was the exception. This may be due to lower FSP, air entrapment, or dead pores. The difference in hardwood was higher than in softwood. However, Eq. 4 can be used to gauge an approximate value of maximum MC.

Estimation of moisture diffusivity

Moisture content changes with time, and moisture distributions at the final stage are shown in Fig. 3. The moisture diffusivity values in Tables 2 and 3 were obtained by the Boltzmann transformation method over the whole moisture content.¹² However, the input values of b_0 and b_1 were approximated using Eq. 9.

The shape of the curve representing the dependence of diffusion coefficients with moisture content was similar in all wood, and the diffusivity decreased with moisture content until the FSP was reached and then increased. Adapting them to the moisture transfer equation (Eq. 12), the simulation results gave poor predictions for moisture content changes with time and moisture distributions. This is because the Boltzmann transformation method is valid for a semi-infinite volume and a linear correlation between moisture flux and the square root of time.

Mathematically, inverse problems belong to the class of ill-posed problems. The solution does not satisfy the general requirements of existence, uniqueness, and stability under small changes to the input data.¹³ The inverse solutions are known to be very sensitive to small changes in input data resulting from measurement and modeling errors. Therefore, to improve the numerical convergence, the initial input values of parameters obtained by the Boltzmann transformation method were used as a first approximation for the Levenberg-Marquardt method. Equation 9 for the moisture diffusivity below the FSP was used initial input values for the discontinuous model.

Table 2. Diffusivities with the continuous function by the inverse method, Eq. 20

Species	Duration (months)	a_0	a_1	a_2	a_3	F	
						LM ^a	B ^b
Softwood							
Hemlock	1	-22.35	3.571	-7.875	3.849	0.161	0.777
	2	-22.37	1.880	-4.050	1.969	0.102	0.160
Radiata pine	1	-21.05	-5.596	8.226	-2.714	0.524	0.608
	2	-21.52	-6.264	8.237	-2.276	0.575	3.001
Spruce	1	-21.80	-4.354	8.995	-3.552	0.266	0.377
	2	-21.49	-6.456	8.889	-2.592	0.408	0.438
Hardwood							
Painted maple	1	-16.35	-17.63	24.09	-8.392	0.140	15.53
	2	-18.14	-14.84	28.25	-13.37	0.125	7.092
Japanese elm	1	-21.01	-4.527	7.630	0.381	0.146	0.146
	2	-21.62	-0.857	-6.190	8.955	0.361	0.469
Horn beam	1	-21.52	-3.563	-1.538	9.700	0.046	0.246
	2	-21.45	-6.995	20.57	-12.78	0.016	0.020

^aLevenberg-Marquardt method

^bBoltzmann transformation method

Fig. 3a–f. Comparison of measured and predicted average moisture content change and moisture distribution using two steps of moisture diffusivity by the Levenberg-Marquardt inverse method. **a** Hemlock, **b** radiata pine, **c** spruce, **d** painted maple, **e** Japanese elm, **f** horn beam. Measured: *filled circles*, 1 month; *open circles*, 2 months. Predicted: *solid line*, 1 month; *dotted line*, 2 months

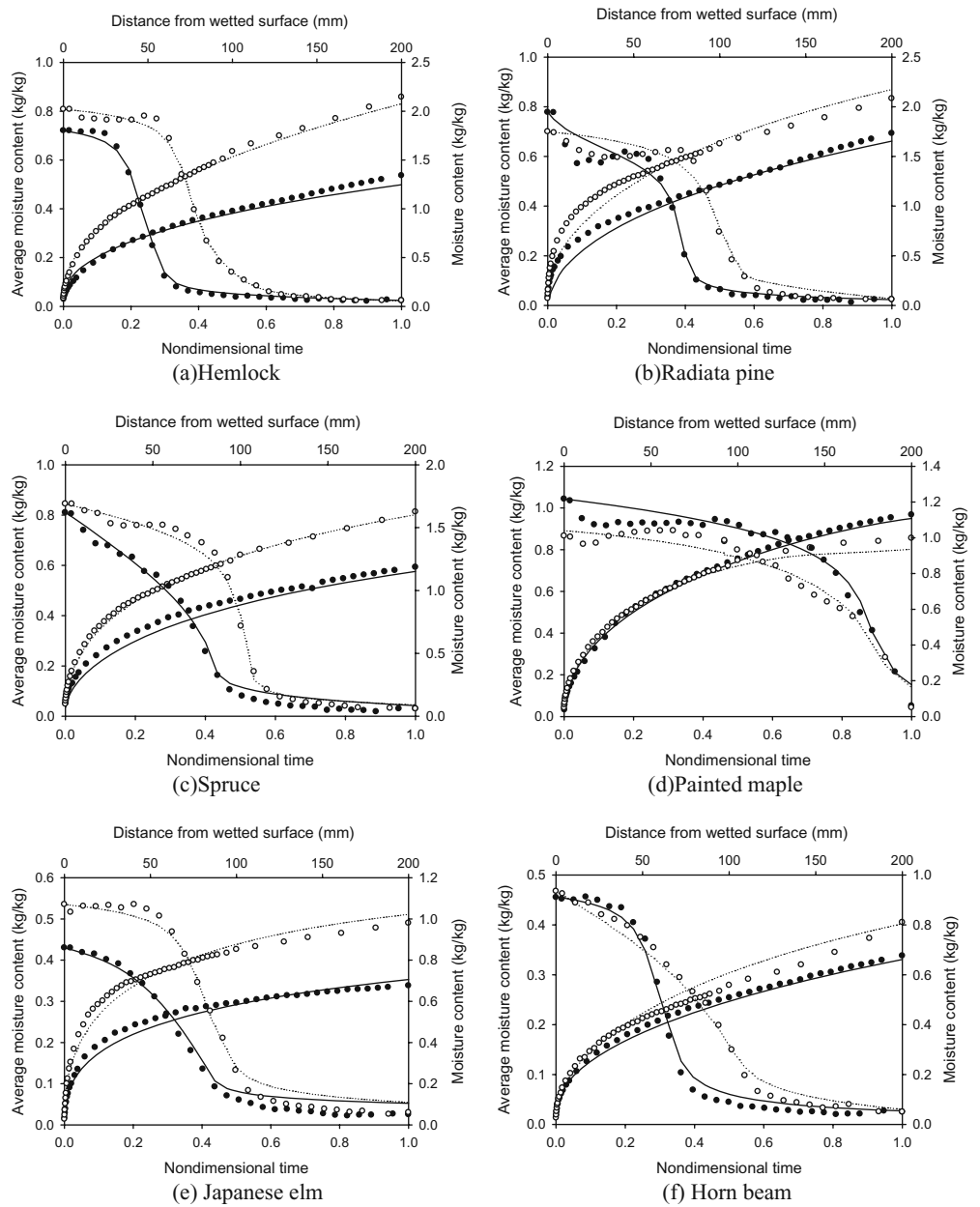
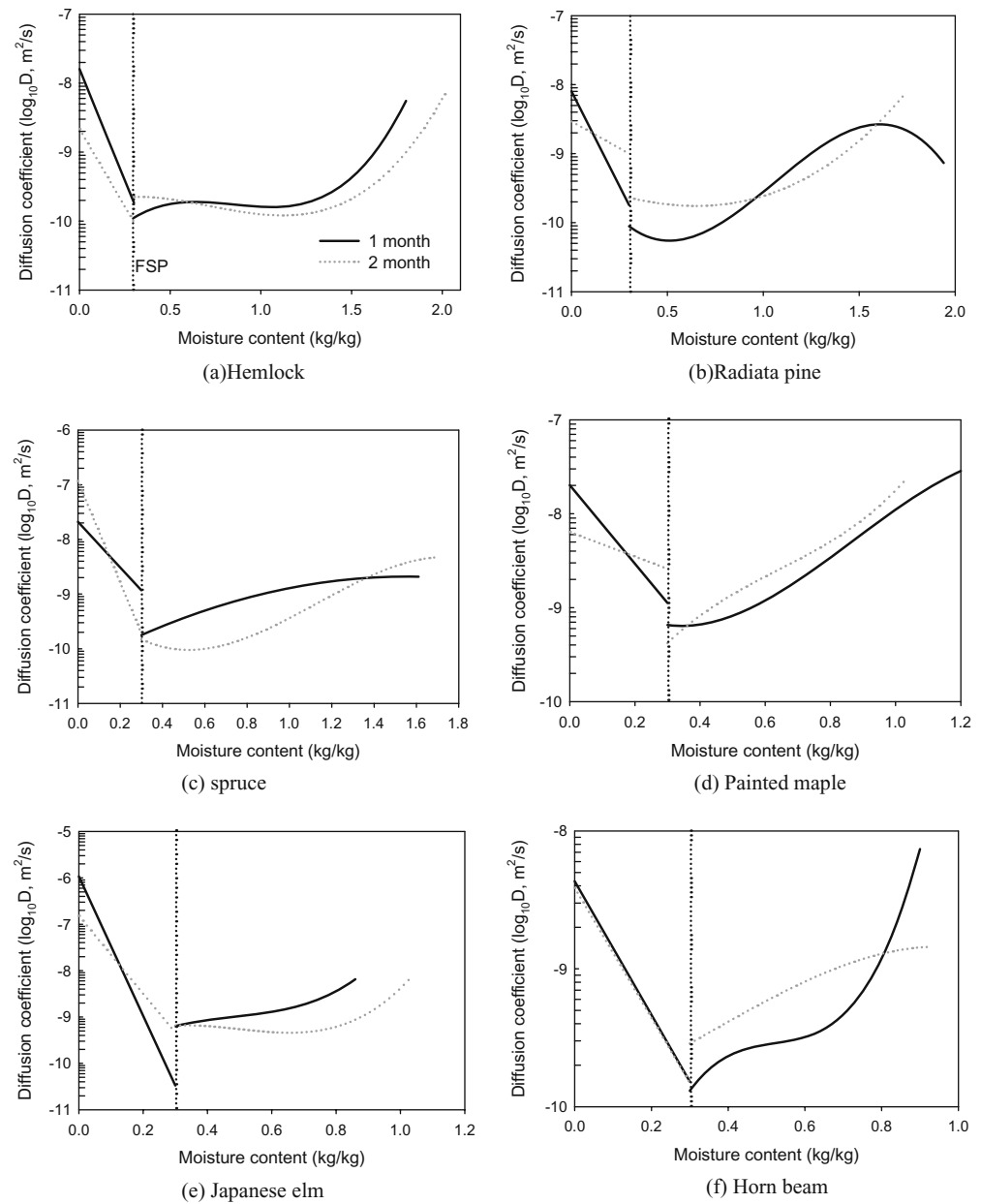


Table 3. Diffusivities with two step functions by the inverse method, Eq. 21

Species	Duration (months)	a_0	a_1	a_2	a_3	b_0	b_1	F		
								LM	B ^a	
Softwood	Hemlock	1	-24.83	9.567	-11.99	4.706	17.95	14.87	0.042	0.320
		2	-22.58	2.552	-5.179	2.407	19.95	10.35	0.056	10.22
Radiata pine	1	-20.32	-14.49	18.70	-5.887	18.64	12.66	0.272	2.055	
	2	-21.59	-2.453	1.298	0.610	19.65	3.574	0.333	4.873	
Spruce	1	-23.76	4.817	-1.515	-0.014	17.68	9.609	0.118	0.192	
	2	-20.27	-11.93	14.85	-4.384	15.96	21.40	0.059	0.664	
Hardwood	Painted maple	1	-19.55	-10.29	18.67	-7.152	17.72	9.629	0.114	1.475
		2	-25.12	16.79	-19.86	10.34	18.87	3.010	0.078	8.431
Japanese elm	1	-24.09	17.41	-32.35	22.32	13.74	34.61	0.064	0.115	
	2	-23.18	14.72	-33.27	22.41	15.69	19.33	0.078	0.901	
Horn beam	1	-29.98	44.12	-82.70	52.86	19.26	11.15	0.028	0.153	
	2	-22.93	2.491	3.353	-3.284	19.37	10.86	0.037	0.330	

^aEquation 9 below the fiber saturation point and Boltzmann transformation method in nonhygroscopic range

Fig. 4a–f. Apparent moisture diffusivity over whole moisture content predicted by the Levenberg-Marquardt inverse method. **a** Hemlock, **b** radiata pine, **c** spruce, **d** painted maple, **e** Japanese elm, **f** horn beam. *FSP*, Fiber saturation point



Comparing Tables 2 and 3, the discontinuous diffusivity model (Eq. 21) gave better prediction of the development of the internal moisture distributions in wood during sorption than the continuous model (Eq. 20). Using the discontinuous diffusivity of Table 3, the simulation results are represented by solid lines in Fig. 3.

This study shows that there is a distinctive hygroscopic zone in wood, although both experimental and model-based determination of phase-separated transport properties is still one of the most disputed issues in moisture transport analysis.¹⁴ For liquid water sorption simulation, moisture diffusivity should be separated into hygroscopic and nonhygroscopic zones and two step functions of diffusivity should be used rather than an effective diffusivity to improve the simulation results.

As shown in Fig. 4, the moisture diffusivity decreased with increasing moisture content until the FSP was reached

and it increased in the nonhygroscopic range, which agrees with other studies.^{7,11,15} For most species, the order of magnitude of moisture diffusivity lies within the range of 10^{-8} to 10^{-10} m²/s.

Conclusions

Using the Levenberg-Marquardt inverse technique, two diffusion models to predict moisture change with time and moisture distribution have been investigated for liquid water sorption. The moisture-dependent diffusivity was considered as a continuous function over the whole moisture range, while this coefficient was discontinuous at the fiber saturation point. The initial input values of parameters by the Boltzmann transformation method were used to

improve the numerical convergence as a first approximation for the Levenberg-Marquardt method. Comparing the calculated moisture changes and profiles with experimental values, it is apparent that the discontinuous model using the parameters obtained by the inverse method is able to predict the development of the internal moisture distributions in wood during liquid water sorption. The results of this study should be useful in studying the process of sorption for exterior wood such as columns and dipping methods used for preservation treatments.

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