EFFECT OF HARDWOOD VESSELS ON LONGITUDINAL MOISTURE DIFFUSION[1]

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ABSTRACT

The hypothesis that the longitudinal moisture content profile follows the shape of the sorption isotherm under steady-state diffusion condition was confirmed. This phenomenon was explained in terms of the unrestricted flow of water vapor from the lumen of one vessel element to the lumen of the next vessel element. Despite the assumed high vapor transport efficiency of the vessels, other cell types were believed to contribute substantially to longitudinal moisture movement. The diffusion coefficients of three different hardwood species were found to vary with moisture content.

Keywords: Moisture diffusion, hardwood vessels, sorption isotherm, red oak, American elm, sweetgum.

INTRODUCTION

The presence of vessel elements is a definitive characteristic of hardwoods. Vessels are tubelike structures with long length (continuous length 1.0–1.5 m, element length 0.3–1.5 mm) and are known to affect permeability in the fiber direction (Siau 1995). Compared to softwood tracheids, hardwood vessels with diameters from 20 μm to over 300 μm are quite permeable to water if they are not occluded. The flow resistance due to the perforation plates is relatively small because these openings are much larger than those between the microfibrillar stands in the margo of softwood membranes (Panshin and de Zeeuw 1980). On the contrary, flow resistances in other hardwood cells are relatively high because fluids, in going from cell to cell, have to pass through very minute openings in the pit membranes.

The internal structure of hardwoods suggests that the vessel elements are also important passageways for longitudinal moisture diffusion. If the vessels are not blocked by ty-

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loses and deposits, moisture can move by diffusion in the lumina by a mechanism similar to the intergas diffusion of water vapor in air. Thus, in the steady-state condition, the relative humidity (RH) inside the vessels should change linearly with distance in the longitudinal direction; whereas in the other cells, moisture diffusion is hindered because of the small openings in those wood elements. Accordingly, the moisture content profile in hardwoods should follow the shape of the sorption isotherm since the moisture inside the vessel wall readily reaches equilibrium with the linearly varying RH. In such a case, the longitudinal diffusion coefficient can be derived readily if the flux data are known.

In this study, preliminary results of steady-state experiments are presented to: (a) support the hypothesis that the longitudinal moisture content profile is in the shape of the sorption isotherm due to the influence of vessel elements; (b) determine the efficiency of moisture diffusion in other hardwood cell types relative to the vessels; and (c) derive a longitudinal diffusion coefficient profile.

EXPERIMENTAL PROCEDURE

Sapwood boards of three species [red oak (*Quercus falcata* Michx.), American elm (*Ulmus americana* L.), and sweetgum (*Liquidambar styraciflua* L.)] were obtained from a local sawmill. For each species, three samples with a 1.8-cm-square cross section were prepared; two of them 5 cm long and one of them 2 cm long. The samples were placed inside a desiccator filled with water and subjected to a vacuum of 75 kPa for about an hour, then released to atmospheric pressure twice a day for two days to fill the samples with water. The dimensions and weights of the 2-cm samples were measured in the green condition and after oven-drying at 103°C, to determine the green specific gravity and volumetric shrinkage coefficients. The surfaces of the 5-cm samples were blotted with paper towels, then three coats of Dow's Saran F-120 were applied on the four longitudinal surfaces of each sample

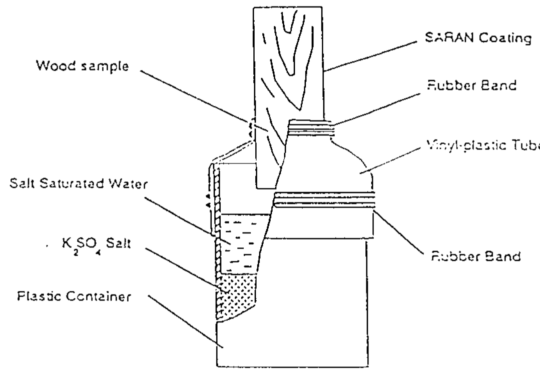

FIG. 1. Schematic diagram of the vapor cup system.

to ensure that moisture flow could occur only in the fiber direction. Six small plastic containers, 5 cm in height and 2.8-cm inner diameter, were used as diffusion cups. Potassium sulfate salt (K_2SO_4) controlled the internal RH of the cup to a nominal value of 96%. Each wood sample was inserted into the plastic container through a flexible vinyl-plastic tube as shown in Fig. 1. The vinyl-plastic tube was able to provide a tight fit between the sample and the container. In addition, two rubber bands were wrapped, one around the sample and the other around the container to prevent moisture leakage. The initial water level in the container was adjusted so that the distance between the surface of the water and the bottom of the sample was about 0.6 cm.

The diffusion cups were placed in an environmental chamber maintained at 40°C temperature, 21% RH, and 2.5 m/s air speed. At periodic intervals, they were taken out of the chamber and weighed on a balance with precision of 0.0001 g. After twenty days of drying, the water level inside the container decreased about 1 cm in height. The vinyl-plastic tube was untied and some fresh water was added to the container and the salt was stirred. After an extra three days, the drying curve showed that the steady-state condition had been reached for all three samples; then the distance between the water level and the bottom of each sample was measured. These data were used to estimate the difference between

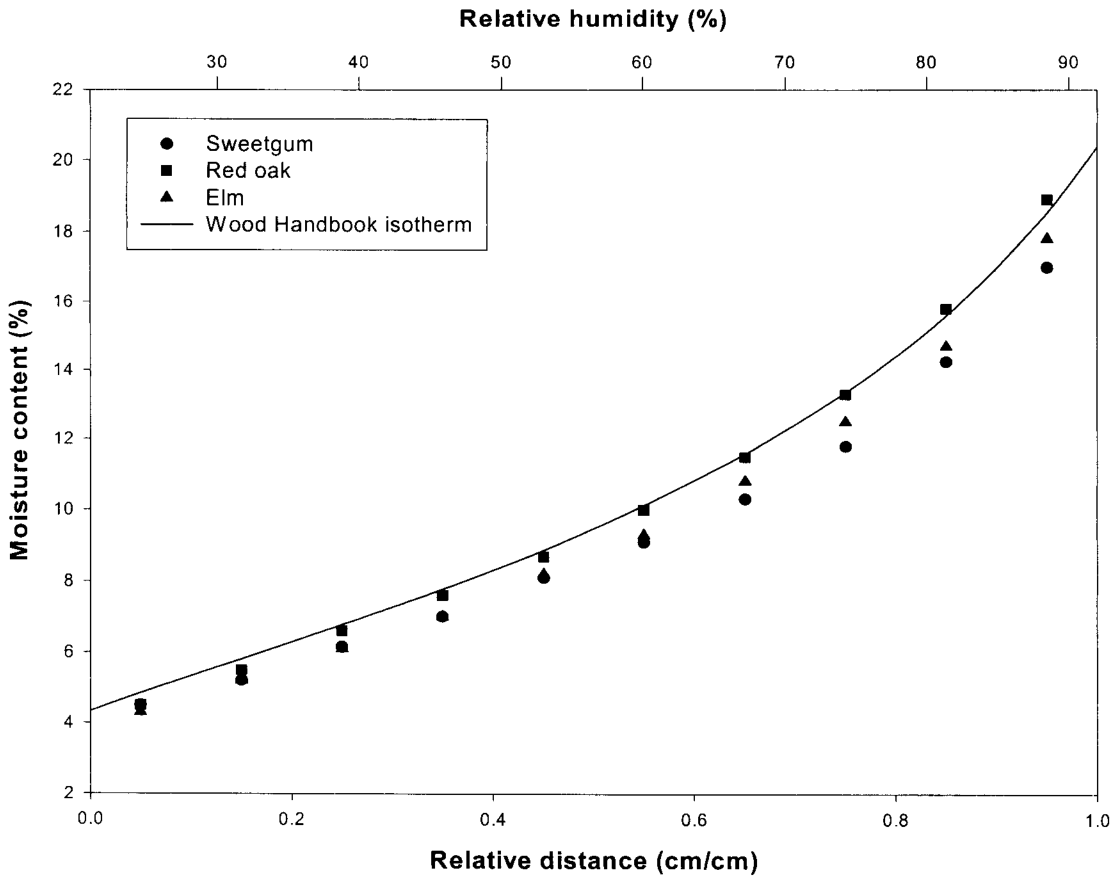

FIG. 2. Moisture content values at different locations along the length of the samples. Superimposed on the experimental data points is the single-hydrate Hailwood-Horrobin isotherm fitted by Simpson (1971) to the Wood Handbook sorption data (U.S. Forest Products Laboratory 1999).

the RH above the water surface and the bottom surface of a sample (Siau 1995).

Each sample was removed from the diffusion cup and, after removing the Saran coating, was cut into ten equal-sized pieces along the length with a small bandsaw. Since the sawblade was very thin (0.3 mm), less than 6% of wood was lost; therefore, the effect of wood loss was neglected in determining the moisture content profiles. After cutting, each piece of wood was placed in a small plastic container with a tight cover and weighed on a top-loading balance. The dimensions of the sample were measured at both ends to allow calculation of the moisture flux. They were then oven-dried for two days before weighing. The average moisture content for each piece was calculated accordingly.

RESULTS AND DISCUSSION

The moisture content profiles along the length of the samples for the three species evaluated in this study are shown as scatter points in Fig. 2. Assuming a linearly varying relative humidity along the length of the samples, the relative humidity scale is shown as the second X-axis on the figure. The difference in RH between the saturated salt solution surface and the bottom of the samples was estimated using Eq. (6.35) of Siau (1995) and was found to be about 4%. Hence, the upper end of the relative humidity scale is only 91% to reflect this correction. Based on these relative humidity values, an isotherm was established using the single-hydrate Hailwood-Horrobin equation parameters obtained by Simpson (1971) for the Wood Handbook sorption data (U.S. Forest Products Laboratory 1999). The sorption isotherm is superimposed as the solid curve on the experimental data points in Fig. 2. It can be seen that the isotherm fits the data very well, with the absolute deviation being no more than 1.55% MC. The slight discrepancy may be due to differences in the sorption characteristics of different species that was observed by other investigators (Skaar 1988). The data indicate that for hardwoods subjected to steady-state diffusion in the longitudinal direction, the moisture content at any point in the material can be determined with reasonable accuracy simply by knowing the sorption isotherm for the wood and the boundary conditions of temperature and relative humidity.

These results support the claim by some researchers that the driving force for the movement of moisture in wood is the gradient in vapor pressure (Bramhall 1979). Notice that the moisture content profile as shown in Fig. 2 is not linear. This means that Fick's law in the form of moisture concentration gradient as the driving force is not applicable in this case. If the moisture concentration gradient form of Fick's law is used, then the diffusion coefficient is moisture content-dependent and would vary with location in the material. The variation in the diffusion coefficient D along the length of the material was evaluated using the equation:

$$D = \frac{F_h \Delta L}{30\rho_w \Delta h \dfrac{d\left(\dfrac{MG_g}{3000 - 30S_o + S_o M}\right)}{dh}} \quad (1)$$

where F_h is the experimental steady-state flux, ΔL is the length of the sample, ρ_w is the density of water, Δh is the difference in relative vapor pressure between the top and bottom surfaces of the sample, M is the percent moisture content, G_g is the specific gravity based on oven-dry mass and green volume, and S_o is the percent volumetric shrinkage from green to oven-dry condition. Equation (1) was derived by combining Eqs. (5.21), (5.22), and (5.24) of Skaar (1988) with the following equation:

$$G_M = \frac{G_g}{1 - \dfrac{S_o}{100}\left(1 - \dfrac{M}{100}\right)} \quad (2)$$

that relates the specific gravity at moisture content M (G_M) with green specific gravity (G_g) and percent volumetric shrinkage from green to oven-dry condition (S_o). The derivative of the quantity inside the bracket of Eq. (1) with respect to the relative vapor pressure h was obtained by first fitting the single-hydrate Hailwood-Horrobin equation shown below to the experimental values of moisture content and relative humidity:

$$M = \frac{1800}{W}\left(\frac{K_1K_2h}{1 + K_1K_2h} + \frac{K_2h}{1 - K_2h}\right). \quad (3)$$

The constants W, K_1, and K_2 were evaluated using nonlinear regression and their values, together with the experimental values of the parameters in Eq. (1), are shown in Table 1. By substituting Eq. (3) for M in Eq. (1), the diffusion coefficients for the three species were calculated and are presented in Fig. 3. Also included in the figure is the longitudinal diffusion coefficient obtained theoretically by Siau (1995) for softwoods with green specific gravity of 0.44 at a temperature of 40°C. All four plots are of similar shape: the diffusion coefficient initially increases, reaches a maximum, and then decreases with moisture content. The experimental longitudinal diffusion coefficient profiles peaked at a relative distance of 0.15, which corresponds to a moisture content of 5.5%. In contrast, the theoretical curve reached the maximum value at approximately 8% MC. Figure 3 also shows that the theoretical diffusion curve is of similar order of magnitude as that for red oak but is much

TABLE 1. *Values of the Hailwood-Horrobin equation parameters (equilibrium constant K_1, equilibrium constant K_2, and polymer molecular weight W), species physical properties (percent shrinkage from green to oven-dry condition S_o, specific gravity based on oven-dry mass and green volume G_g, percent volume of vessels V), and calculated parameters (experimental steady-state flux F_h, flux through cell types other than the vessels F_o, average diffusion coefficient D_{avg}, relative efficiency ϕ_o) for the three species evaluated in this study.*

Parameter	Sweetgum	Red oak	Elm
K_1	7.876	4.512	5.499
K_2	0.792	0.770	0.798
W	336.4	275.3	313.1
S_o (%)	15.9	16.0	14.5
G_g	0.44	0.50	0.45
V (%)[1]	46.2	14.6	31.1
F_h (g/cm^2 s)	1.62×10^{-6}	0.92×10^{-6}	1.59×10^{-6}
F_o (g/cm^2 s)	1.27×10^{-6}	0.73×10^{-6}	1.39×10^{-6}
D_{avg} (cm^2/s)	1.45×10^{-4}	0.62×10^{-4}	1.29×10^{-4}
ϕ_o	0.63	0.36	0.69

[1] The values of V were taken from the literature (Koch 1985).

lower than those for sweetgum and elm. By the mean value theorem, the average diffusion coefficient D_{avg} for each species, given in Table 1, was found by integrating the curves in Fig. 3 and then dividing the results by the difference between the upper and lower limits of integration. These D_{avg} values are one order of magnitude lower than those obtained by Choong et al. (1994) who used the unsteady-state method of determining the diffusion coefficient. Both studies show that the longitudinal diffusion coefficient of elm and sweetgum is about the same in magnitude and is approximately double that of red oak.

It was mentioned previously that a major assumption of this study is that longitudinal moisture diffusion in hardwoods vessels is the same as the intergas diffusion of water vapor in air. Since hardwoods are made up of other cells as well, it is instructive to evaluate the relative efficiency of these cells in allowing moisture transport by diffusion. The relative efficiency ϕ_o of cells other than vessels can be expressed as

$$\phi_o = \frac{F_o}{F} \tag{4}$$

where F_o is the flux through the other cells and F is the theoretical flux of water vapor in air. The value of F_o can be determined using the equation:

$$F_o = \frac{100F_h - FV}{100 - V} \tag{5}$$

where V is the percent volume of vessels for a given species. The values of V used in this study were taken from the literature (Koch 1985) and are reproduced in Table 1, together with the calculated values of F_o for the three species. The theoretical flux F of water vapor in air can be calculated using the following equation (Siau 1995):

$$F = D_a\frac{\Delta C_a}{\Delta L} = D_a\frac{19p_o\Delta H}{100RT\Delta L} \tag{6}$$

where D_a is the diffusion coefficient of water vapor in air, ΔC_a is the difference in the concentration of water vapor in air, ΔL is distance, 18 is the molecular mass of water in g/mol, p_o is the saturated vapor pressure, ΔH is relative humidity difference, R is the universal gas constant, and T is absolute temperature. The diffusion coefficient of water vapor in air can be estimated using the following semi-empirical equation (Siau 1995):

$$D_a = 0.22\left(\frac{101325}{P}\right)\left(\frac{T}{273.15}\right)^{1.75} \tag{7}$$

where P is total pressure of air and water vapor (Pa). The calculated F value for this study is 2.02×10^{-6} g/(cm^2 s). Substitution of the above quantities in Eq. (4) results in the values of relative efficiency ϕ_o shown in Table 1.

The results show that wood elements other than the vessels are actively involved in longitudinal moisture diffusion. Because of the low percent vessel volume in red oak, the vessels account for only 32% of the total amount of water diffusing through the wood while 68% diffuses through the other cell elements. The efficiency of the other cell types, however, is low such that the overall efficiency of the gross wood (represented by the ratio F_h/F) in allowing moisture diffusion is low as well. In

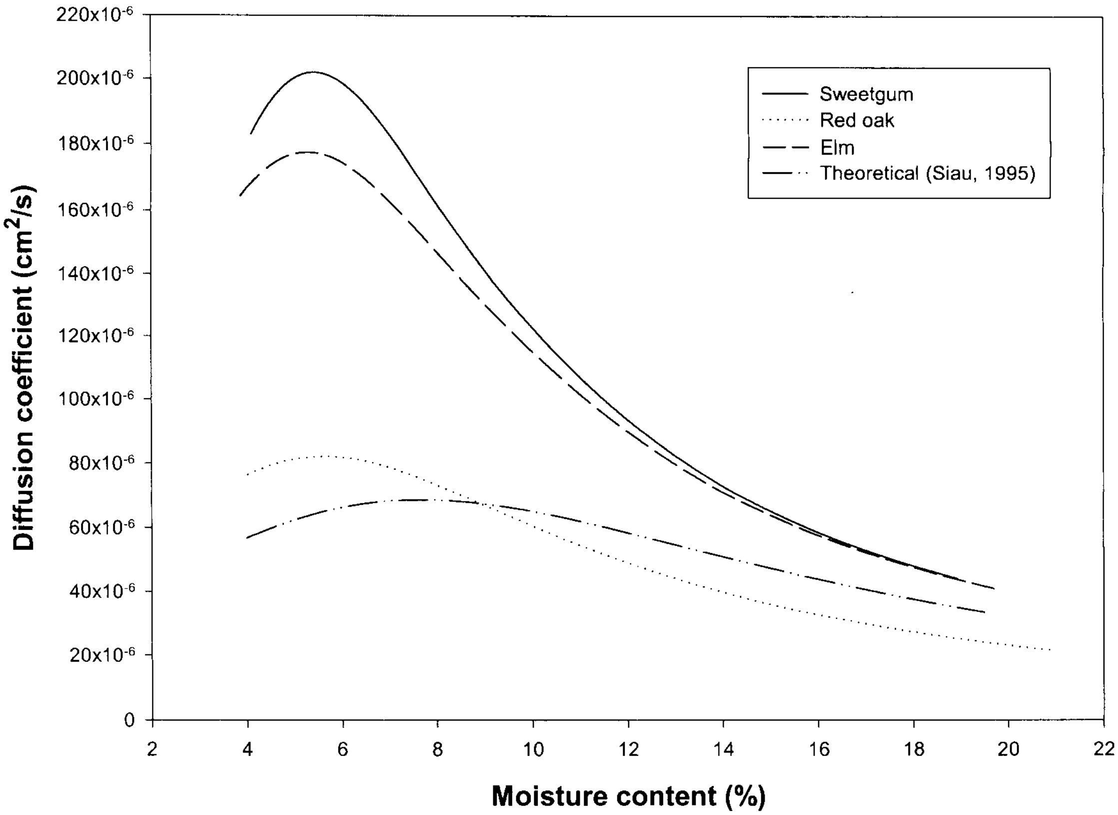

FIG. 3. Longitudinal diffusion coefficient as a function of moisture content for the three species evaluated in this study. Also shown is the theoretical longitudinal diffusion coefficient curve for softwood as obtained by Siau 1995.

the case of sweetgum and elm, the overall efficiency of the former is higher than the latter. But the fact that the percent volume of vessels in elm is only 31% compared to 46.2% for sweetgum makes the other cell types in elm more effective in allowing moisture flow by diffusion; hence, the relative efficiency ϕ_o is higher for elm than for sweetgum. In elm, 61% of the water diffused through the other cell types, while 39% diffused through the vessel lumina. In sweetgum, these values are 42% and 58%, respectively. In the calculations, it was assumed that the vessels are highly efficient. In reality some resistance due to scalariform perforation plates may be encountered in some species; therefore, we expect that the real values of ϕ_o should be higher than those obtained in this study.

CONCLUSIONS

Under steady-state conditions, the longitudinal moisture content profiles follow the shape of the sorption isotherm due to the effect of hardwood vessels. Therefore, longitudinal diffusion coefficient profiles can be derived from the Hailwood-Horribon's sorption model, using flux data. The experimental longitudinal diffusion coefficients for the three species evaluated in this study were found to vary significantly with moisture content. The calculated relative efficiencies indicate that cell types other than the vessels play a large role in the diffusion process.

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Dr. Elvin Choong, 68, longtime contributor to, and reviewer for, *Wood and Fiber Science,* passed away on Sunday, February 18, 2001 while hiking in the mountains of Honduras. Dr. Choong earned his B.S. (Forestry) at the University of Montana in 1956, his M.F. (Wood Technology) at Yale in 1958, and his Ph.D. (Wood Science) at State University of New York, College of Environmental Science and Forestry, Syracuse, in 1962. He was on the faculty at Louisiana State University since 1965, where he came from Humboldt State University. Dr. Choong published more than 150 scientific papers, many of them in this journal.

BOB YOUNGS, *Editor*