THE INFLUENCE OF EXTERNAL RESISTANCE ON MOISTURE ADSORPTION RATES IN WOOD

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ABSTRACT

Dry specimens of black walnut and silver maple, end- or side-coated to restrict moisture movement to the radial or longitudinal direction, were subjected to adsorption at 97% relative humidity at 25 C. The specimens of 0.7-, 1.6-, and 2.7-cm thickness were moved through humid air at velocities of 0.4 to 11.7 m/s by rotating them on carrousels at various speeds to determine the influence of external resistance on moisture adsorption rates. Adsorption rates were considerably increased by increasing the wood velocity through the air up to 3 m/s, but the benefits of increasing wood velocity to increase adsorption were reduced above this velocity. The relative importance of external resistance to moisture movement in wood increased as wood thickness and/or velocity decreased, and was greater for longitudinal than for radial flow.

Keywords: *Juglans nigra, Acer saccharinum,* diffusion, air velocity, moisture, adsorption.

NOMENCLATURE

a —half thickness, cm.
D —diffusion coefficient reflecting internal resistance, cm^2/s.
D′ —apparent diffusion coefficient, cm^2/s.
$\bar{E}$ —fraction moisture gain.
F_{er}—fraction of total resistance due to external resistance.
H —s/a, cm^{-1}
S —surface emission coefficient, cm/s.
t —time, h.
$t_{0.5}$—time at $\bar{E} = 0.5$, h.

INTRODUCTION

The migration of moisture between wood and humid air is controlled by two resistances: the external resistance, which includes the resistance of the air boundary layer adjacent to the wood surface, and the internal resistance, which is the resistance of the wood structure itself. Factors influencing internal resistance, usually quantified in terms of a diffusion coefficient, have been studied in considerable detail in the literature (Stamm 1964, Ch. 23; Siau 1971, Ch. 6); whereas few studies have been directed at examining variables affecting external resistance.

Martley (1926) and Ogura and Umehara (1957) recognized that external resistance influenced moisture movement through wood. They accounted for this resistance by empirically adding an "equivalent thickness" of wood in the direction of moisture flow. Choong and Skaar (1969, 1972) provided a method for quantitatively separating internal and external resistance to moisture sorption in wood. Their analysis was an approximation to the analytical solution of the unsteady-state diffusion equation for unidirectional flow in a plane sheet assuming surface

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evaporation (Crank 1956, p. 56). Accordingly, Choong and Skaar (1972) showed that:

$$\frac{t_{0.5}D}{a^2} = 0.20 + \frac{0.7}{Ha}, \tag{1}$$

where $t_{0.5}$ was the half-sorption time or the time when half of the moisture to be adsorbed or desorbed by the wood was complete, a was the half thickness of the wood in the direction of moisture movement, D was the diffusion coefficient that reflected internal resistance, and H equaled S/D, where S was the surface emission coefficient that reflected external resistance. If D′ is defined as the apparent diffusion coefficient calculated by assuming no external resistance, i.e., $Ha = \infty$, then

$$a/D' = a/D + 3.5/S. \tag{2}$$

A plot of a/D' versus a will yield 1/D as the slope and 3.5/S as the intercept. Using a different approach, Hart (1977) described external resistance in terms of a temperature or vapor pressure difference between the ambient air and wood surface. He evaluated an effective surface moisture content, which was coupled with a finite-difference solution to the Fickian diffusion equation.

External resistance can be reduced by increasing the air velocity across the surface of the wood and thus decreasing the thickness of the boundary layer near the air-wood interface. Drying rates of green lumber have been shown to increase with increased air circulation (Kollman and Schneider 1960; Salamon and McIntyre 1969; Steinhagen 1974; Torgeson 1957), but the benefits decreased as moisture content decreased and finally were not measurable. Moisture content below which air velocity does not influence drying depends on wood species, and is lower for thin boards, mild temperatures, and low initial moisture content (Kollman and Schneider 1960). Mackay (1971) showed that the flux through the wood in a diffusion cell, used by many researchers to evaluate diffusion coefficients for wood, was proportional to stirrer speed, thus confirming that external factors can influence the rate of moisture movement through wood at moisture contents below the fiber saturation point.

The object of this study was to evaluate the influence of external resistance on moisture adsorption to wood. Evaluation of the factors affecting adsorption in wood has application in better understanding the conditioning of wood, such as the conditioning in a dry kiln to relieve internal stresses or the preparation of wood specimens at a prescribed moisture content for experimentation.

METHODS AND PROCEDURES

The two species selected for the study were silver maple (*Acer saccharinum* L.) and black walnut (*Juglans nigra* L.). Four squares 5 cm × 5 cm × 80 cm along the grain were cut from green bolts of each species. To minimize structural differences, the squares were cut approximately 10 cm from the pith, one from each quadrant of the bolt. Silver maple squares contained all sapwood, whereas black walnut squares contained all heartwood. The squares were dried to approximately 6% moisture content in a controlled environment chamber at 30 C. From the dry squares, specimens for determining radial and longitudinal flow

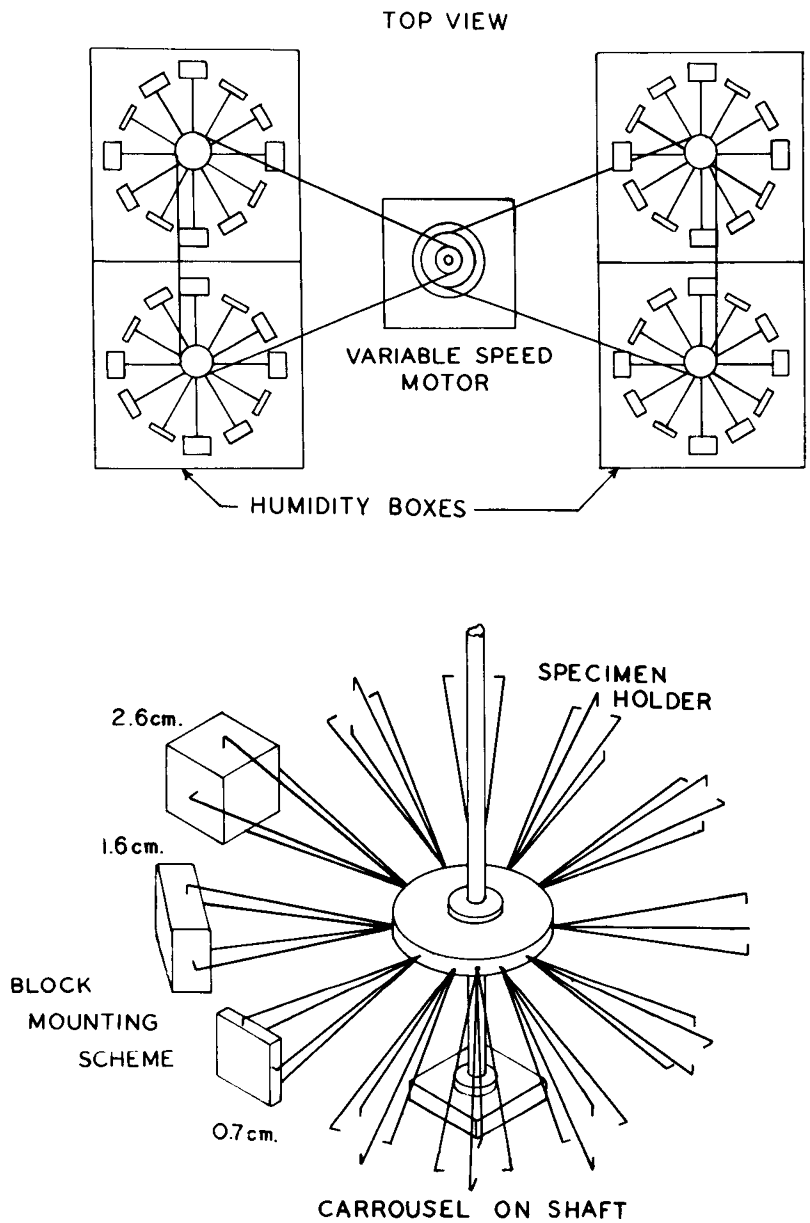

FIG. 1. Diagram of the arrangement of humidity boxes and specimens on carrousels for adsorption study (only three specimens shown on perspective sketch).

were cut on a band saw with 3.8 cm × 3.8 cm cross section and with thicknesses in the flow direction of 0.7, 1.6, and 2.6 cm. Following the procedure of Choong and Skaar (1972), the four side faces of each specimen were coated with Dow's Saran F-310 and Fisher's Sealit to insure unidirectional flow of moisture through the specimens and returned to the controlled environment chamber for several months before being used in a run.

Rather than having conditioned air blown across the specimens as had been done previously by others when studying the influence of air velocity on sorption rates, the specimens of this study were rotated on carrousels at varying speeds through the conditioned air.

Four trays, 30 cm × 8 cm × 5 cm deep, were filled to a depth of ¾ cm with saturated solutions of potassium sulfate and then placed on the bottom of four sealed cubic (50-cm sides) sorption chambers constructed of Plexiglas (Fig. 1) to maintain 97% relative humidity in the chambers. A 1.6-cm steel shaft ran through the center of each box. Pulleys of different diameter on the bottom of each shaft were connected to pulleys on a variable speed motor located between the four sorption chambers. All shafts were run simultaneously from one motor but at different speeds depending on the ratios of the pulley diameters.

Each shaft rotated two carrousels placed 15 cm and 35 cm from the bottom of the chamber. As shown at the bottom of Fig. 1, a carrousel had 12 specimen holders, containing four stainless steel rods bent and pointed at the ends to grip the wood specimen. Specimens were placed in the holder so that the center of the specimens revolved in a 40-cm diameter circle. Velocity difference from front to back face of a block, calculated from the difference of the faces along the rotational axis, differed by only 13% for the thickest specimens. Each carrousel contained four replicates of three thicknesses placed in a repetitive pattern to balance the carrousel. In each chamber, the bottom carrousel contained the radial specimens and the top carrousel contained the longitudinal specimens. Ninety-six specimens were run simultaneously.

The shafts containing the carrousels were rotated at six speeds—20, 51, 90, 137, 178, and 550 rpm—which corresponded to a linear velocity of 0.43, 1.07, 1.92, 2.92, 3.80, and 11.7 m/s, respectively. The patterns of air movement across the rotated wood specimens were not the same as if air were blown across stationary specimens. Thus, velocities further mentioned in this paper will refer to linear velocities of the wood relative to the sides of the humidity box. Temperatures were controlled at 25 ± 1 C.

Specimens were weighed at intervals, approximately proportional to the square root of time and starting at 1½ h, during the course of a run until equilibrium was achieved. Two 10-cm circular access ports with removable plugs were located on the sides of each chamber to remove the specimens. Weighings required removing the specimens from the humidity box to the ambient air for less than 30 s. The motor to rotate the specimens was turned off for the 13 min required to weigh all of the 96 specimens. Specimen weight changed less than 0.02 g or 0.5% moisture content due to the interruptions for weighing. Interruption time for weighing was not counted in total adsorption time.

Humidity as measured by a dial hygrometer remained fairly close to 97% in the chambers throughout the runs, except for runs at the lowest speed of 20 rpm. For runs at carrousel speeds of 20 rpm, an increased speed of 100 rpm for 2 min followed each reading to bring the humidity in the chambers up to 97% as fast as possible. Even so, humidity slowly dropped over the first few readings to level out at 92% before achieving 97% after 10 h.

A run consisted of adsorption to equilibrium at 97% relative humidity of the 96 specimens. Three runs were required to complete the study—the first with silver maple at four speeds, the second with black walnut at four speeds, and the third with black walnut and silver maple at the remaining two speeds.

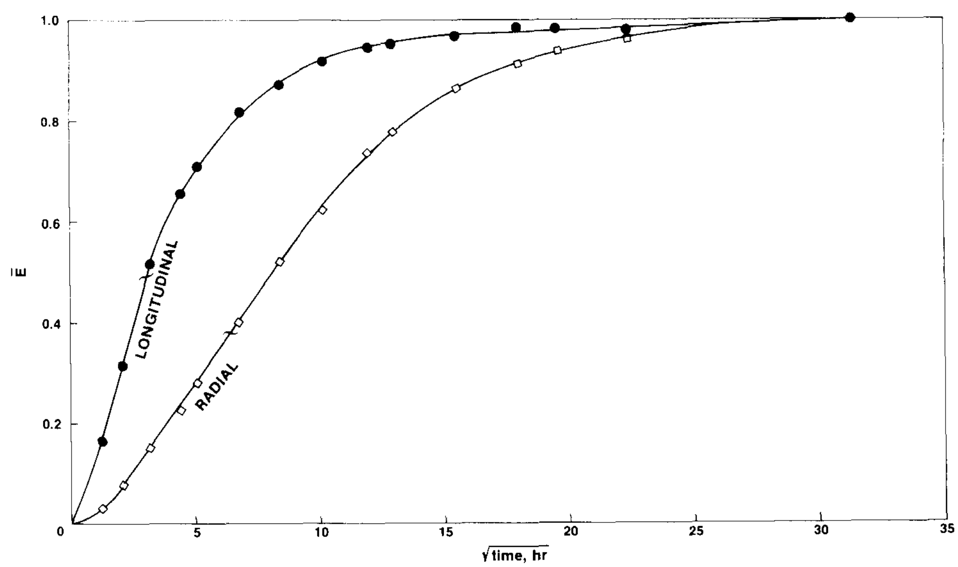

FIG. 2. The relation of Ē versus the square root of time for radial and longitudinal adsorption through 1.6 cm thick silver maple at 3.8 m/s velocity. Curly line indicates $t_{0.5}$.

Values of moisture content were determined for each weighing, and averaged for four replicates of each condition before calculating Ē, the fractional amount of moisture gained by the specimens. The following analysis has been well established in the literature for determining apparent diffusion coefficients, D′ (Comstock 1963):

$$\bar{E} = \left[\frac{4D't}{a^2}\right]^{1/2}, \qquad \bar{E} \leq 0.67. \tag{3}$$

The slope of the plot of Ē versus $\sqrt{t}$ up to Ē = 0.67 can be evaluated:

$$\text{slope} = \bar{E}/\sqrt{t}; \tag{4}$$

therefore, combining Eqs. (3) and (4),

$$D' = \frac{\pi a^2(\text{slope})^2}{4}. \tag{5}$$

Values of $t_{0.5}$ were found graphically from plots of Ē versus time, t.

RESULTS AND DISCUSSION

Plots of Ē versus $\sqrt{t}$ showed an initial lag in sorption discussed previously by others (Comstock 1963; Hart 1977; McNamara and Hart 1971). The lag was more pronounced in radial adsorption than in longitudinal adsorption (Fig. 2). Following the initial lag, the plots were linear up to E = 0.67, before smoothly approaching equilibrium at E = 1.0. Regression analysis was used to evaluate "slope" from the linear portions of the plots. The percentage of data accounted for by variation about the regression line, R^2, was greater than 96% for each of the 72 individual plots required to calculate D′S. The consistency of the plots of Ē versus $\sqrt{t}$ in this study with those in the literature demonstrates that the experimental technique of this study was adequate for determining adsorption curves for wood.

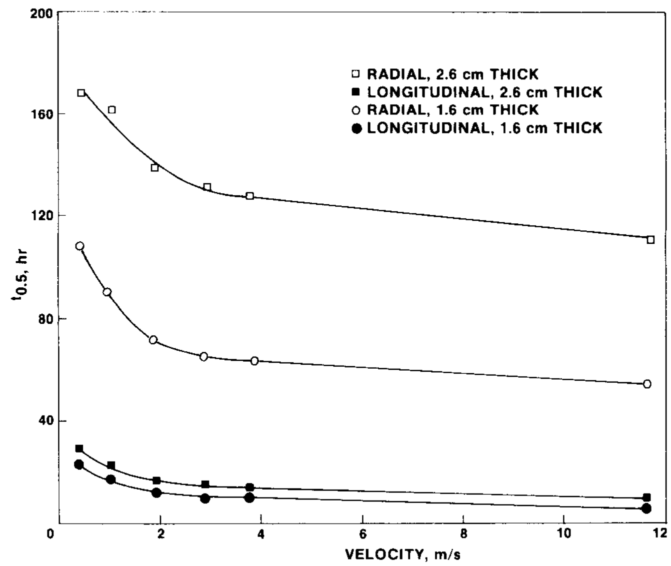

FIG. 3. The influence of velocity of the wood through humid air on the time to reach half of the total adsorption ($t_{0.5}$) in the radial and longitudinal direction of silver maple.

The primary variable influencing external resistance to adsorption was wood velocity through the air. Adsorption times decreased as velocity increased, but at a very slow rate above 3 m/s (Fig. 3). Increasing velocity was most effective in increasing apparent diffusion for thin, longitudinal specimens (Table 1).

Apparent diffusion coefficients were also affected by moisture movement direction, wood species, and thickness of specimen (Table 1). The ratio of longi-

TABLE 1. *Apparent adsorption diffusion coefficients, D', for velocities, thicknesses, species and moisture movement directions of this study.*

	D', $cm^2/s \times 10^7$					
	Longitudinal thickness			Radial thickness		
		cm			cm	
Velocity m/s	0.7	1.6	2.6	0.7	1.6	2.6
		Silver maple				
0.43	2.1	11.5	29.	2.1	4.3	6.0
1.07	5.0	19.	38.	2.3	4.7	6.7
1.92	9.4	25.	56.	3.2	5.4	7.4
2.92	10.4	31.	56.	3.5	5.7	7.6
3.80	10.9	31.	58.	3.4	5.7	7.6
11.70	38.	60.	82.	4.7	6.3	8.3
		Black walnut				
0.43	3.9	16.	25.	1.0	1.9	2.8
1.07	6.9	20.	31.	2.3	4.1	4.6
1.92	9.2	24.	37.	2.8	4.5	5.2
2.92	16.5	35.	42.	3.6	4.6	5.7
3.80	18.	38.	44.	3.8	5.3	6.6
11.70	32.	41.	48.	4.2	4.7	6.0

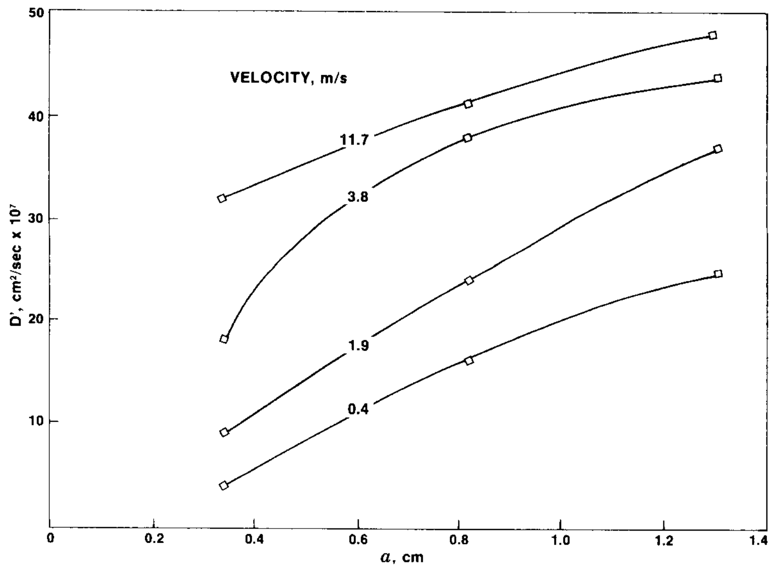

FIG. 4. The relation between D′ and a for longitudinal adsorption in black walnut at several velocities.

tudinal D′ to radial D′ varied from 1 to 10; the highest ratios were for the thick specimens at high velocities. In general, D′ was higher at the same conditions for the less dense silver maple (oven-dry specific gravity of 0.49) than for black walnut (oven-dry specific gravity of 0.58), but the opposite was sometimes true with thin specimens and at low velocity. Comparisons between the two species were confounded because initial and final moisture contents (MC) differed slightly:

	Black walnut	Silver maple
Initial MC	7.3	5.0
Final MC	22.6	24.3

The higher value of initial MC for black walnut was partially caused by a 2 C rise in the wet bulb temperature in the controlled environment chamber during storage of the black walnut, but differences in MC might also have been the result of the influence on the equilibrium MC by the differing anatomical structures of the two species. The nearly linear increase of D′ with thickness, especially at the lower velocities (Fig. 4), is consistent with similar findings in the literature (Choong and Skaar 1972; McNamara and Hart 1971; Ogura and Umehara 1957).

As predicted by Eq. 2, plots of aD′ versus a yielded a straight line with positive slope for all velocities for radial adsorption, illustrated by black walnut for several velocities (Fig. 5). The parameters D, S, and H were evaluated for radial adsorption in black walnut to quantify the importance of external resistance to moisture movement in wood (Table 2). With the exception of some deviation at 3.8 m/s velocity, S and H increased with velocity; whereas D remained constant. D was independent of velocity, as would be expected if D were related to internal resistance only. The value of 12 for Ha for the highest velocity and thickest specimen indicated that even at these extreme conditions, surface resistance sig-

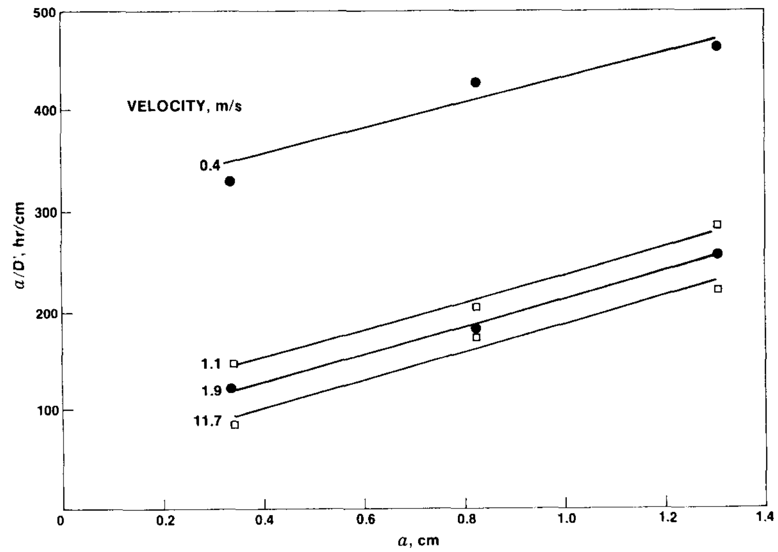

FIG. 5. Plot of a/D' versus a for radial adsorption in black walnut at several velocities.

nificantly influenced adsorption (Choong and Skaar 1972, Fig. 6). The results were similar for radial adsorption in silver maple.

The relative magnitude of the external and internal resistances can be calculated by the following analysis. Rearranging Eq. (1),

$$t_{0.5} = \frac{0.2a^2}{D} + \frac{0.7a}{S} \,. \tag{6}$$

The first term on the right side of Eq. (6) can be regarded as the internal contribution to the overall resistance to moisture migration and the second term as the external contribution. The fraction of the total resistance due to external resistance, F_{er}, can be calculated by dividing the external contribution by the total contribution to give:

$$F_{er} = \frac{0.7}{0.2Sa/D + 0.7} \,. \tag{7}$$

TABLE 2. *Internal and external resistance to moisture movement during radial adsorption to black walnut.*

Velocity m/s	"True" D $cm^2/s \times 10^7$	Emission coefficient S cm/s $\times 10^7$	S/D ratio H cm^{-1}	Ha (a = 1.3 cm)
0.43	7.3	12	2	2
1.07	6.9	38	5	7
1.92	7.4	47	6	8
2.92	7.1	67	10	12
3.80	8.8	65	7	10
11.70	7.0	87	13	16

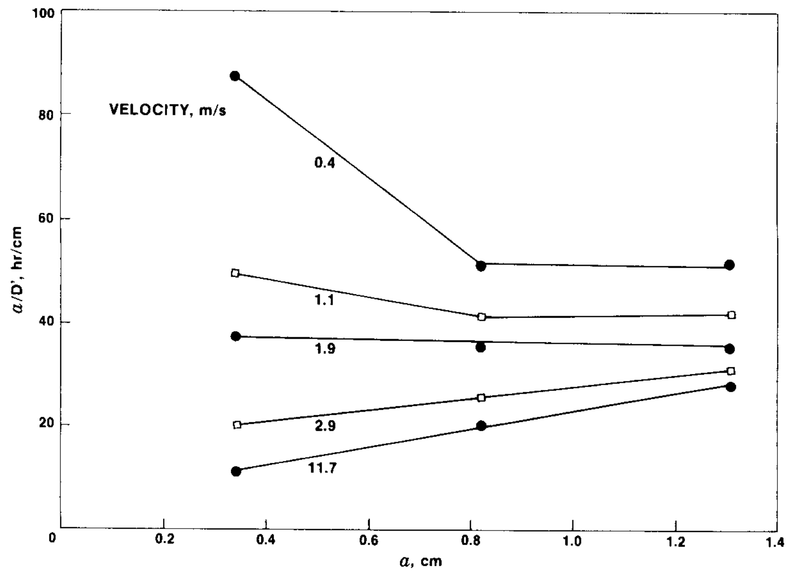

FIG. 6. Plot of a/D' versus a for longitudinal adsorption in black walnut at several velocities.

The resistance to moisture migration for thin radial sections at the lower velocities is mostly external (Table 3). As velocity is increased for all wood thicknesses, the external contribution is reduced. Even at a velocity of 11.7 m/s, external resistance is still contributing greater than 10% of the overall resistance to moisture adsorption.

The analysis for longitudinal adsorption did not follow as consistently as did the analysis for radial adsorption. Plots of a/D' versus a yielded straight lines for the higher velocities; but as velocity dropped, the plots were nonlinear and had negative slopes. As seen in Fig. 6, the plots for longitudinal adsorption in black walnut were linear with a positive slope only at velocities of 2.9 m/s and above (also true of 3.8 m/s velocity not shown in the figure). The slopes for plots for longitudinal adsorption in silver maple were negative for all but the highest velocity. D, S, H, and Ha were calculated from Eq. 2 only at those velocities where

TABLE 3. *Fraction of the total resistance due to external resistance (F_{er}) during radial adsorption in black walnut and silver maple.*

Velocity m/s	Thickness, cm: Black walnut 0.7	Black walnut 1.6	Black walnut 2.6	Silver maple 0.7	Silver maple 1.6	Silver maple 2.6
			F_{er}			
0.43	0.69	0.49	0.37	0.89	0.79	0.69
1.07	0.56	0.33	0.23	0.74	0.55	0.43
1.92	0.44	0.26	0.17	0.62	0.41	0.30
2.92	0.36	0.19	0.13	0.58	0.38	0.27
3.80	0.45	0.26	0.18	0.64	0.44	0.32
11.7	0.32	0.17	0.11	0.32	0.23	0.15

TABLE 4. *Values of D, reflecting internal diffusion in wood.*

Species and direction of diffusion	D, $cm^2/s \times 10^7$
Silver maple (oven-dry S. G. × 0.49):	
Longitudinal	137. (171.)[a]
Radial	14.1 (16.8)
Black walnut (oven-dry S. G. × 0.58):	
Longitudinal	79. (131.)
Radial	7.4 (10.5)

[a] Numbers in parentheses are theoretical values of diffusion coefficients calculated from equations derived by Siau (1971, pp. 91, 94) based on an average moisture content, $\bar{M}$, of 17.9 for silver maple and 17.5 for black walnut.

the slope of a/D′ versus a yielded a straight line with positive slope. The analysis appeared to break down for longitudinal adsorption when external resistance predominated over internal resistance.

Error was introduced in the initial stages of adsorption by specimens at 0.43 m/s velocity because the correct humidity was not maintained in the adsorption chambers. A drop from 97 to 92% relative humidity can reduce the moisture movement driving force by 30%. Apparent diffusion coefficients for the thinnest specimens were affected the most by failure to maintain proper humidity. Although this error might explain the breakdown in the analysis for separating internal and external resistance at lower velocities, other problems could have also contributed. The concept of surface emission is a convenient assumption to explain the movement of moisture from the wood surface to the surrounding air. Surface movement is actually more closely related to vapor pressure difference, which, in turn, depends on temperature as well as concentration difference. The simplifying assumptions in the analysis or a change in moisture transfer mechanism at the lower velocities, such as surface transfer proportional to some power of surface concentration (Crank 1956, p. 58), could explain the breakdown in the analysis.

Values of D, reflecting internal resistance only, were found for each species and moisture direction by averaging the D values for velocities where the slopes of a/D′ versus a were positive (Table 4). Comparison with theoretical values calculated from equations by Siau (1971, pp. 91, 94) were very good considering the assumptions in both analyses. The ratio of D/D′ (Table 5) showed that the relative contributions of external resistance to adsorption times were lower at

TABLE 5. *Ratio of D/D′ for black walnut.*

Velocity m/s	Longitudinal thickness cm 0.7	1.6	2.6	Radial thickness 0.7	1.6	2.6
0.43	20.3	4.9	3.1	7.2	3.9	2.6
1.07	11.5	3.9	2.6	3.2	1.8	1.6
1.92	8.6	3.3	2.1	2.6	1.6	1.4
2.92	4.8	2.3	1.9	2.1	1.6	1.3
3.80	4.4	2.1	1.8	1.9	1.4	1.1
11.70	2.5	1.9	1.6	1.8	1.6	1.2

higher velocities, for thicker materials, and for radial rather than longitudinal movement. Although values in Table 5 were for black walnut, the trends were the same for silver maple.

CONCLUSIONS

The movement of wood through air at moisture contents below the fiber saturation point influences the external resistance and thus moisture adsorption by the wood. The effect of wood velocity through air becomes more significant for thinner wood and for longitudinal rather than radial flow. The benefits of increasing wood velocity through air to increase adsorption rates are rapidly reduced above 3 m/s, although some benefit does occur up to 12 m/s, the highest velocity examined in this study. Since apparent diffusion coefficients are dependent on circulation rates and patterns, these rates and patterns should be recorded when specifying diffusion coefficients.

NOTES

Mention of trade names does not constitute endorsement of the products by the U.S. Dep. Agric. Forest Service. This paper was prepared by U.S. Government employees on official time and is therefore in the public domain.

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