PENETRATION OF WATER INTO HARDWOODS

Howard N. Rosen

Research Chemical Engineer, Forestry Sciences Laboratory, North Central Forest Experiment Station,[1] Forest Service, U.S. Department of Agriculture, Carbondale, IL 62901

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ABSTRACT

The longitudinal penetration of water into hardwoods was studied by continuously measuring swelling and uptake in a swelling cell apparatus. Mathematical equations were developed to relate swelling, bound moisture uptake, free moisture uptake, and time of penetration. The initial stages of bound moisture uptake and free moisture uptake were each shown to be linear when plotted against the square root of time.

Bound and free moisture penetration constants were calculated from swelling and uptake data for different wood species at different temperatures. The transport of bound water by vapor and water diffusion became more important than transport by capillarity as temperature increased, or when wood species with obstructed vessels were used. The relative amount of water uptake distributed between bound moisture and free moisture was shown to change with increasing temperature.

Additional keywords: Liriodendron tulipifera, Quercus shumardii, Juglans nigra, swelling, bound moisture, free moisture, diffusion, temperature.

NOTATION

- D diffusion constant, cm^2/sec
- D_{gL} longitudinal water-vapor diffusion coefficient of gross wood, cm^2/sec
- E fraction of final moisture content
- G specific gravity at M_i
- G_S specific gravity of water
- G_w specific gravity of wood substance
- K coefficient of volumetric swelling
- L specimen thickness, cm
- M_B bound moisture uptake, percent
- M_F free moisture uptake, percent
- M_{fsp} fiber saturation point, percent
- M_m maximum moisture content, percent
- M_i initial moisture content, percent
- M_T total moisture uptake, percent
- N_B bound-moisture flux, g/cm^2-sec
- N_F free-moisture flux, g/cm^2-sec
- P_B bound-moisture penetration constant, cm^2/sec
- $\overline{P}_B$ integral bound-moisture penetration constant, cm^2/sec
- P_F free-moisture penetration constant, cm^2/sec
- $\overline{P}_F$ integral free-moisture penetration constant, cm^2/sec
- S volumetric swelling percentage relative to oven-dry conditions
- S' volumetric swelling percentage relative to initial moisture of M_i
- S_m maximum volumetric swelling percentage relative to oven-dry conditions
- S_m' maximum volumetric swelling percentage relative to M_i
- S_i volumetric swelling percentage at M_i relative to oven-dry conditions
- t time, hours
- V_L liquid volume
- V_T wood volume at oven-dry conditions
- V_w wood volume at M_i
- x distance along the wood axis, cm
- ρ_w wood density
- σ differential swelling, cm^3

INTRODUCTION

Although considerable fundamental research has been done on the drying of green wood, little work has been done on the reverse process, the addition of liquid

[1] Laboratory maintained in cooperation with Southern Illinois University.

during treatment of dried wood. As liquid penetrates wood that has been dried below the fiber saturation point (fsp), the liquid is adsorbed by the cell walls (causing swelling of the wood), as it simultaneously fills the lumens or cell cavities. Before methods can be devised to control the swelling, uptake, and distribution of liquids in wood, a mechanism must be found to explain how liquids move in wood, the proportion of liquid uptake that contributes to swelling, and the effect of temperature, wood structure, etc. on liquid movement.

The objective of this study is to investigate the simultaneous uptake and swelling as water penetrates wood that has been previously dried below the fsp. Water is the liquid used because it causes considerable dimensional change in wood and because considerable data are available in the literature concerning this liquid and its interaction with wood. Longitudinal penetration is studied because this pathway offers the least resistance. Mathematical relationships will be developed through extension of previous theory to evaluate penetration constants related to the rate of bound and free water uptake.

BACKGROUND

The movement of liquids through the capillaries in wood is a complex process. Stamm (1959, 1960) showed that for the initial stages of diffusion the bound water diffusion constant as well as the combined bound water and vapor diffusion constant could be determined by the following relationship:

$$D = \frac{\Pi L^2 E^2}{16t}, \qquad (1)$$

where L is the specimen thickness, E is the fraction of final moisture content or final swelling, t is time, and D is the diffusion constant for either bound water or combined bound water and water vapor. This relationship was shown to be valid until $E = 0.667$.

The penetration of water along the fiber direction of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was observed by Stamm (1953). The swelling was shown to occur almost as fast as the water was distributed through the structure. Weight increased linearly with the square root of time up to 20% moisture content.

Stamm and Petering (1940) have suggested three steps for the uptake of a solution by wood: (1) wetting of the wood surfaces by the solution, (2) capillary rise of the solution in the capillary structure of the wood, and (3) diffusion of the solution into the cell walls of the wood. They concluded that except for the first few minutes, either capillary rise or diffusion through the cell walls controlled the rate of uptake of aqueous solutions by wood.

METHODS

Three species were used in this study—yellow poplar (*Liriodendron tulipifera*), red oak (*Quercus shumardii*), and black walnut (*Juglans nigra*). Sections 5 by 5 by 40 cm in the fiber direction were cut from the bolts of trees found locally in southern Illinois. The straight-grained and defect-free sections were kiln-dried to 8% moisture content. The square sections were then turned on a lathe into cylinders 3.6 cm in diameter and 10 cm in length along the grain. Cylindrical samples of yellow poplar heartwood (YPH), yellow poplar sapwood (YPS), red oak heartwood (ROH), and black walnut heartwood (BWH) were then stored in an environmental chamber controlled for 8% equilibrium moisture content until use in a swelling cell run.

A swelling cell described by Rosen (1973) was used to measure simultaneously and continuously the volumetric swelling and liquid uptake in the longitudinal direction of the cylindrical samples (Fig. 1). After weights and dimensions of the sample were taken, a run was started by adding water through the liquid feed tube until the level was in the range of the scale. The scale was placed on a slight tilt so that the pressure created by the head of water in the feed tube was as small as possible, approximately 4 cm. An initial reading of liquid feed and swelling (level of glycerol tube) was taken.

A valve above the liquid collection flask was open to allow liquid to run through the wood. The valve was kept open until either 2 min elapsed or the first drop came through, whichever was first, and then was closed for the duration of the run. Readings were taken several times on the first day and then one or two times a day after that until about 350 hr had passed. Air that came out of the wood sample was periodically bled from the normally closed liquid air bleed valve to make sure that the liquid displaced in the feed tube was a true value of liquid taken into the wood sample. Samples were removed at the end of a run so that the weight could be taken and the dimensions measured.

Runs were made at least in triplicate in a temperature bath controlled to 0.2 C for temperatures of 0, 25, 50, and 75 C with yellow poplar sapwood. Additional runs were made with yellow poplar sapwood at room conditions, 22 ± 2 C. The scatter of data was not significantly affected, so other runs were made at room temperature. As there was only one temperature bath, this procedure allowed runs to be made simultaneously at different temperatures. Runs were made at 22 and 75 C for black walnut and red oak, and 22 C for yellow poplar heartwood. Runs were terminated at approximately 350 hr except for the 75 C runs, which were ended at about 200 hr.

Additional experiments were run at varying humidity conditions with thin wafers of red oak heartwood, yellow poplar sapwood, and yellow poplar heartwood to determine swelling-moisture curves. The wafers, 2.5 × 2.5 × 0.3 cm in the fiber direction, were initially oven-dried before being subjected to increasing relative humidity in steps of 13, 37, 59, 76, 86, 94, and 97% at 27 C. Dimensions and weights of the wafers were taken at each increase in humidity.

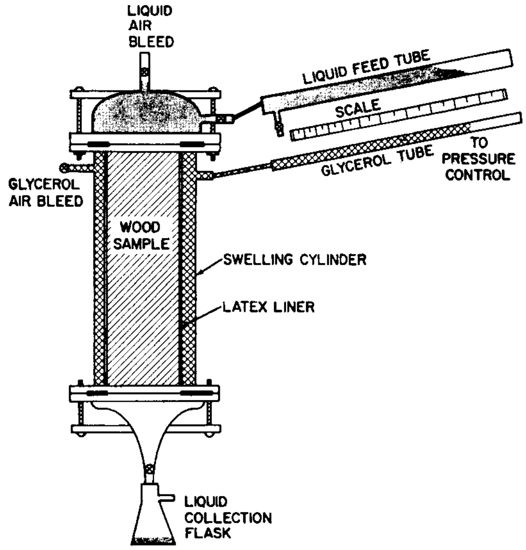

FIG. 1. Swelling cell assembly; the shaded areas are filled with penetrating liquid and the cross-hatched areas are filled with glycerol, which is displaced when the wood cylinder swells.

GENERAL EQUATIONS

According to the theory to be tested, water brought into contact with one surface of a wood specimen dried below the fsp will penetrate the wood fibers by diffusion, by capillarity, and, if the water is above the wood surface, by gravity. The water that penetrates the wood expressed on a percentage weight of water per weight of dry wood basis (total moisture uptake), M_T, can be proportioned into bound moisture uptake, M_B, and free moisture uptake, M_F:

$$M_T = M_F + M_B \; . \qquad (2)$$

The bound moisture uptake is the water that is absorbed by the cell walls, and the free moisture uptake is the water that fills the lumens or cavities of the cell.

As the water moves along a distance x from the surface ($x = 0$) toward the dry end of the wood ($x = L$), bound and free moisture simultaneously fills the wood structure. The amounts of free and bound moisture at a particular distance from the wood surface will change as time increases. Water reaching a differential element, dx, is assumed to satisfy the cell-wall requirements for bound moisture before filling the cavity with free water. Justification for this assumption is provided by Stamm (1953), who showed that wood that had been evacuated prior to soaking swelled several orders of magnitude faster than wood penetrated naturally. He showed that wood swelled almost as fast as water was distributed through the structure.

Although bound moisture is commonly thought to be transferred by cell wall and vapor diffusion, it can also be transferred by free moisture movement. Since free water is instantaneously incorporated into the cell wall, the free moisture must necessarily lag behind the bound moisture.

The uptake of bound moisture will therefore be that moisture adsorbed by the wood structure from the initial moisture content, M_i, to the fiber saturation point, M_{fsp}, and the uptake of free moisture will be that moisture from M_{fsp} to the maximum moisture content, M_m. In some cases the initial moisture content will be above the fsp. In this case, there is no bound moisture uptake ($M_B = 0$), and M_F is that free water from M_i (which is above M_{fsp}) to M_m.

Fick's first law of diffusion states that the mass flux (rate of transfer per unit area) is directly proportional to the concentration gradient. If, in using Fick's Law to develop the mathematical relationships, the volume change of wood with a change in moisture content is neglected, as is done in the literature for wood-moisture studies (Comstock 1963; Moschler and Martin 1968; and Hart 1964), then Fick's Law can be modified such that the mass flux is directly proportional to the moisture content gradient.

Although the penetration of water into wood is not completely a diffusional process, bound and free moisture gradients do occur in the wood structure. Fick's concepts are therefore applied to the penetration of water into wood. The bound moisture flux, N_B, and the free moisture flux, N_F, are assumed to occur simultaneously. The equations for the unidirectional cases are:

$$N_B = \frac{-P_B G \rho_w}{100} \frac{dM_B}{dx} \qquad (3)$$

$$N_F = \frac{-P_F G \rho_w}{100} \frac{dM_F}{dx}, \qquad (4)$$

where G is the specific gravity of the wood, ρ_w is the density of water, P_B is the bound moisture penetration constant, and P_F is the free moisture penetration constant. The initial moisture is assumed to be uniform throughout the sample. The constants P_B and P_F are used to gauge the penetration rate and are not to be confused with diffusion constants.

The unsteady-state equations derived from a mass balance on a differential element are:

$$\frac{\partial M_B}{\partial t} = \frac{\partial}{\partial x}\left(P_B \frac{\partial M_B}{\partial x}\right) \qquad (5)$$

$$\frac{\partial M_F}{\partial t} = \frac{\partial}{\partial x}\left(P_F \frac{\partial M_F}{\partial x}\right). \qquad (6)$$

Equations 5 and 6, with the appropriate boundary conditions, are similar to those used by a number of authors (Crank 1956; Stamm 1964; and Comstock 1963). The solutions for the initial stages of penetration in terms of the fraction of total moisture uptake for bound, E_B, and free, E_F, moisture are:

$$E_B = \frac{M_B}{M_{fsp} - M_i} = 2\left(\frac{\overline{P}_B t}{\pi L^2}\right)^{1/2} \qquad (7)$$

$$E_F = \frac{M_F}{M_m - M_{fsp}} = 2\left(\frac{\overline{P}_B t}{\pi L^2}\right)^{1/2}. \qquad (8)$$

The above equations assume that P_B and P_F are functions of moisture content, and thus can be defined as integral penetration constants:

$$\overline{P}_B = \frac{1}{M_{fsp} - M_i} \int_{M_i}^{M_{fsp}} P_B \, dM_B \qquad (9)$$

$$\overline{P}_F = \frac{1}{M_m - M_{fsp}} \int_{M_{fsp}}^{M_m} P_F \, dM_F \qquad (10)$$

The amount of bound moisture in the wood is reflected by the amount of swelling of the wood. Barkas (1949) has defined the differential swelling, σ, as the change in volume of the wood with a change in bound moisture content.

$$\sigma = \frac{dV}{dM_B} \times 100 . \qquad (11)$$

Both sides of Eq. 11 can be divided by the oven-dry wood volume V_T

$$K = \frac{\sigma}{V_T} = \frac{dS}{dM_B} , \qquad (12)$$

where S is the percentage swelling relative to oven-dry conditions, S_i is the swelling relative to oven-dry conditions at M_i, and K is defined as the coefficient of volumetric swelling.

Integration of Eq. 12 gives the relationship between swelling and moisture uptake:

$$S - S_i = \int_0^{M_B} K dM_B . \qquad (13)$$

Equations 7, 8, and 13 show that swelling, bound and free moisture uptake, and treatment time can be related to the physical parameters of the wood.

SPECIFIC EQUATIONS

Although the equations have been developed for relating swelling, moisture uptake, and time, more relationships must be derived to evaluate the physical parameters used in the equations.

The coefficient of volumetric swelling, K, is the slope of the volumetric swelling-moisture content curves. Since the slope of the volumetric shrinkage-moisture content curve has been shown to be linear over most of the bound-water range (Stamm 1964), a similar assumption of a linear relationship for volumetric swelling-moisture content is made. Data will be shown later to verify this assumption.

The following method was developed to evaluate K by using the physical data from the swelling cell. Since K will vary with temperature and specific gravity of the wood, a K must be evaluated independently for each run (Table 1).

Equation 13 integrates to yield:

$$K = \frac{S - S_i}{M_B} . \qquad (14)$$

A correction is made for measuring volumetric swelling relative to initial moisture contents other than oven-dry conditions:

$$S' = \frac{S - S_i}{1 + 0.01 S_i} , \qquad (15)$$

where S′ is the volumetric swelling relative to wood at initial moisture, M_i. For maximum swelling, Eq. 15 is:

$$S'_m = \frac{S_m - S_i}{1 + 0.01 S_i} , \qquad (16)$$

Combining Eq. 14 at maximum swelling (i.e., $S = S_m$ at $M_B = M_{fsp} - M_i$) and Eq. 16 gives a direct relationship between S_m' and K:

$$K = \frac{S'_m (1 + 0.01 S_i)}{M_{fsp} - M_i} . \qquad (17)$$

Since S_i is not a measured parameter in this study, an approximation for S_i is used:

$$S_i \cong K M_i . \qquad (18)$$

Equation 18 will hold if swelling is linear with moisture content from oven-dry conditions to S_i with the same slope as from S_i to S_m. Since the effect of S_i in Eq. 17 is small, the approximation of Eq. 18 can be greatly in error and have a negligible effect on the value of K. Solving for K by substituting Eq. 18 into Eq. 17 yields

$$K = \frac{S'_m}{M_{fsp} - M_i(1 + 0.01 S'_M)} . \qquad (19)$$

Values of the maximum moisture content, M_m, are calculated as follows:

$$M_m = \frac{(1 - \frac{G}{G_W} + 0.01 S'_m) G_S \times 100}{G} , \qquad (20)$$

where G is the specific gravity of the wood based on M_i, G_w is the specific gravity of the wood substance determined in water (1.53) and G_S is the specific gravity of the water.

The total moisture uptake, M_T, can be determined from:

$$M_T = \frac{V_L G_L}{V_W G} \times 100 , \qquad (21)$$

TABLE 1. *Penetration data*[a]

Run	Temperature °C	S_m percent	M_m%	K	$\bar{P}_B$ cm ^{2}/sec x 10^4	$\bar{P}_F$ cm ^{2}/sec x 10^7
			Yellow poplar sapwood (G = 0.49)			
1	0	10.7	152	0.432	1.00	3.73
2	0	10.5	165	0.413	1.76	6.53
3	0	10.9	148	0.421	1.02	0.97
4	22	11.6	167	0.509	9.65	102.00
5	22	11.8	158	0.519	4.02	119.00
6	25	14.0	146	0.625	5.16	111.00
7	25	12.5	164	0.564	2.53	73.00
8	25	12.0	163	0.540	7.15	80.00
9	50	12.6	169	0.615	5.45	147.00
10	50	12.4	174	0.607	5.40	101.00
11	50	14.0	146	0.676	5.59	121.00
12	75	12.1	169	0.695	3.87	212.00
13	75	11.8	173	0.659	4.54	557.00
14	75	11.8	173	0.659	3.28	376.00
15	75	10.2	164	0.591	1.89	160.00
			Yellow poplar heartwood (G = 0.43)			
16	22	10.3	204	0.368	0.23	1.07
17	22	9.6	190	0.360	2.32	--
18	22	9.8	190	0.352	0.11	2.61
19	22	10.5	186	0.395	1.33	2.03
			Red oak heartwood (G = 0.74)			
20	22	14.0	93	0.694	0.293	13.90
21	22	15.7	85	0.700	0.353	29.60
22	22	14.5	90	0.692	1.20	30.50
23	75	18.4	101	1.09	1.70	229.00
24	75	18.9	97	1.08	4.94	276.00
25	75	20.9	95	1.25	46.1	329.00
26	75	20.5	91	1.20	19.3	375.00
			Black walnut heartwood (G = 0.54)			
27	22	10.0	146	0.435	0.119	7.46
28	22	11.0	144	0.471	0.213	6.95
29	22	9.9	134	0.434	0.201	10.40
30	22	11.7	146	0.538	0.242	7.00
31	22	10.8	140	0.495	0.296	11.90
32	75	13.9	140	0.761	0.272	5.10
33	75	13.5	134	0.760	0.262	3.93
34	75	14.6	126	0.822	0.199	--

a/ Samples averaged 8% initial moisture content.

where V_w is the initial volume of the wood at M_i and V_L is the volume of inlet water.

Volumetric changes in the samples are measured directly from the glycerol tube at different time intervals. Swelling relative to M_i is:

$$S' = \frac{\Delta V_w}{V_w} \times 100 \; , \qquad (22)$$

where ΔV_w is the volume of glycerol displaced, which is equal to the change in wood volume.

The bound moisture uptake is determined from the swelling measurements. Combination of Eqs. 14, 15, and 18 yields the relationship relating bound moisture uptake to swelling:

$$M_B = \frac{S' \; (1 + 0.01 \; KM_i)}{K} \; . \qquad (23)$$