WATER-FILLED LUMENS IN STEADY-STATE FLOW IN OAK AND POPLAR[1]

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ABSTRACT

In white oak (*Quercus alba*, L.) and yellow poplar (*Liriodendron tulipifera*, L.), steady-state moisture profiles between either 100% or 97% relative humidity and 71% relative humidity were determined by slicing samples perpendicular to the direction of moisture diffusion. Both the shape of the moisture profiles and the magnitude of the moisture contents (exceeding 40% in some oak samples) indicated the presence of water-saturated lumens in both species. Most of these saturated lumens occurred above 20% MC, but in the oak some of them evidently persisted to moisture contents well below 20%. This resulted in a moisture-content gradient that was steeper than the actual hygroscopic gradient for the oak and thus can lead to misinterpretations in comparing oak diffusion coefficients with poplar values. The presence of collapse was indicated by the presence of excessive shrinkage in some specimens of both species, particularly in one group of oak samples. This strongly supports the Tiemann theory of capillary tension collapse.

The objective of this study was to compare the steady-state diffusion coefficients of white oak heartwood (*Quercus alba* L.) and yellow poplar sapwood (*Liriodendron tulipifera* L.). Oak is a slow-drying species prone to drying defects, while poplar tends to dry rapidly and free of serious defects. In a comparison of unsteady-state drying rates of green oak and poplar, a number of factors are involved, the most important presumably being density and permeability of the wood. In steady-state comparisons, however, permeability is not expected to be an important factor since at moderate temperatures and higher humidities only a small fraction of the total moisture movement below fiber saturation is by continuous vapor flow (Stamm 1964; Choong 1965). Also, any effects of time-dependent relaxation or retardation of dimensional change that may affect unsteady-state comparisons are absent in steady-state studies (Comstock 1963). Thus, as part of an overall objective to examine factors controlling the drying rate of oak, it was decided to compare diffusion coefficients of oak and poplar under steady-state conditions to see if the difference in their densities could account for the difference in their diffusion coefficients.

Martley (1926) examined steady-state moisture profiles for radial movement in Scots pine heartwood and found that the slope of the moisture profile became progressively steeper toward the low-moisture-content face. Since the flux (F) is directly proportional to the product of the diffusion coefficient (D) and the slope of the moisture profile (dC/dX)

$$F = -D\left(\frac{dC}{dX}\right), \qquad (1)$$

then it follows that in steady state, where the flux is everywhere the same, the diffusion coefficient is inversely proportional to the moisture gradient. If the concentration (C) is expressed in grams of water per gram of wood (g/g), distance (X) in centimeters (cm) and flux in g/cm^{2}sec, then the diffusion coefficient has the dimensions g/cm sec. This may be converted to the cm^2/sec dimensions commonly employed in unsteady-state diffusion by dividing by the wood density (g/cc) (oven-dry weight/current volume basis).

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TABLE 1. *Steady-state data of Run No. 1 comparing yellow poplar and white oak moisture diffusion between 100% and 71% relative humidities at 40 C*

ID[a]	Sg[b]	Flux g × 10⁷ cm²sec	Initial thickness cm	Thickness shrinkage %	Average MC Initial %	Average MC Final %	Profile Maximum MC (%)	Regression (20-EMC) Intercept %	Regression (20-EMC) Slope %/cm	Regression (20-EMC) EMC %	Diff. coeff. g × 10⁷ cm sec	Diff. coeff. cm² sec ·10⁷
1-YP-Q	0.45	2.75	1.245	6.3	75.0	22.3	—[c]	—	—	—	—	—
2-YP-Q	0.45	2.85	1.250	5.7	83.8	22.2	36.9	28.4	−11.5	14.9	24.8	51.7
3-YP-Q	0.44	2.77	1.250	5.7	91.1	21.8	31.9	29.1	−13.7	12.9	20.2	43.0
4-YP-Q	0.44	2.71	1.242	3.9	94.8	22.3	32.6	29.4	−14.5	12.1	18.7	40.7
Average	0.44	2.78	1.247	5.4	86.2	22.2	38.8	29.0	−13.2	13.3	21.2	45.1
5-YP-F	0.46	3.71	1.242	2.3	99.2	20.0	26.6	25.6	− 8.3	15.5	44.7	95.1
6-WO-Q	0.69	1.25	1.321	3.5	37.1	20.7	25.2	30.0	−14.4	11.7	8.7	12.3
7-WO-Q	0.69	1.33	1.321	2.0	44.5	20.7	24.7	32.0	−16.0	11.3	8.3	11.9
8-WO-Q	0.69	1.27	1.318	2.7	53.6	22.9	31.3	35.0	−18.4	11.4	6.9	9.7
9-WO-Q	0.70	1.27	1.321	3.9	61.2	25.1	35.8	37.2	−19.9	11.9	6.4	8.8
Average	0.69	1.28	1.320	3.0	49.1	22.4	29.2	33.6	−17.2	11.6	7.6	10.7
10-WO-F	0.68	2.07	1.311	1.6	64.6	24.8	39.3	33.4	−16.4	12.2	12.6	18.3

[a] YP = Yellow Poplar, WO = White Oak, Q = quartersawn, F = flatsawn.
[b] Specific gravity on an oven-dry weight/green volume basis.
[c] Specimen was inadvertently destroyed.

For application of the equation to water vapor diffusion in air, the concentration is normally expressed in terms of water vapor density (g/cc) and D will then have the dimension cm^2/sec. An equation for the calculation of the water vapor diffusion coefficient may be found in Stamm (1964, p. 437), and values of water vapor density in tables (Handbook of Chemistry and Physics, 1955). Thus, for a known flux, the vapor concentration gradient across an air space of known dimension can be readily calculated.

Stamm (1964) has also measured the bound water diffusion coefficient in the cell walls of wood and has derived a theoretical model to calculate the diffusion coefficient of softwoods in tangential flow by combining bound water and water vapor diffusion coefficients in series and parallel flow paths. Although the model more realistically depicts softwood structure, it is of interest to compare hardwood diffusion coefficients with the model.

PROCEDURE

The general procedure consisted of sealing a green disc of wood over a plastic cup containing either water or a high humidity salt solution, exposing the apparatus to a lower humidity in an environmental chamber until a steady rate of moisture loss was achieved, and then sawing a sample from each disc and slicing it parallel to the drying face to determine the moisture-content profile, or gradient, across the specimen thickness. From the flow rates and the moisture gradients, diffusion coefficients could then be calculated.

Three different runs were made. The first two runs (Tables 1 and 2) were to compare oak and poplar and included both quartersawn and flatsawn specimens. A third run (Table 3) was conducted only on quartersawn oak to evaluate the effects of freezing and boiling on the diffusion rates. In the first run, consisting of 10 cups, distilled water was used in the cups to provide a humidity approaching 100%. In the final two runs of 12 cups each, a saturated salt solution of K_2SO_4 provided a 97% RH in the cups (Schneider 1960). The cup solutions were not stirred since they were losing moisture and would thus remain saturated with salt at all times. The air space between the liquid surface and the disc surface was

TABLE 2. *Steady-state data of Run No. 2 comparing yellow poplar and white oak moisture diffusion between 97% and 71% relative humidities at 40 C*

ID[a]	Sg[b]	Flux $g \times 10^7$ / $cm^2 sec$	Initial thickness cm	Thickness shrinkage %	Average MC		Profile Maximum MC (%)	Regression (20-EMC)			Diff. coeff.	
					Initial %	Final %		Intercept %	Slope %/cm	EMC %	$g \times 10^7$ / cm sec	cm^2 / sec $\cdot 10^7$
1-YP-Q	0.41	2.60	1.245	2.9	97.7	20.2	25.4	25.4	−11.9	11.1	21.8	52.0
2-YP-Q	0.41	2.48	1.255	3.4	108.2	21.2	26.2	25.3	−10.4	12.8	23.8	56.7
3-YP-Q	0.41	2.04	1.252	6.3	107.1	21.0	26.5	28.3	−13.3	12.7	15.3	34.8
Average	0.41	2.37	1.251	4.2	104.3	20.8	26.0	26.3	−11.9	12.2	20.3	47.8
4-YP-F	0.47	2.77	1.250	0.4	59.4	18.1	22.4	23.9	− 9.3	12.3	29.8	63.4
5-YP-F	0.48	2.81	1.255	0.8	71.9	19.4	23.2	26.7	−11.4	12.4	24.6	51.2
6-YP-F	0.48	2.72	1.252	2.6	73.3	18.3	21.3	22.6	− 9.3	11.2	29.2	59.6
Average	0.48	2.77	1.252	1.3	68.2	18.6	22.3	24.4	−10.0	12.0	27.9	58.1
7-WO-Q	0.61	0.92	1.247	3.0	35.9	24.6	31.1	32.4	−17.0	11.8	5.4	8.6
8-WO-Q	0.61	1.00	1.252	2.4	45.3	24.7	36.6	34.5	−18.8	11.6	5.3	8.5
9-WO-Q	0.62	1.31	1.247	3.0	40.8	25.2	31.3	38.8	−22.8	11.2	5.8	9.1
Average	0.61	1.08	1.249	2.8	40.7	24.8	33.0	35.2	−19.5	11.5	5.5	8.7
10-WO-F	0.69	1.72	1.237	0.6	59.0	22.0	31.7	29.0	−14.4	11.3	11.9	17.2
11-WO-F	0.69	1.67	1.240	1.0	59.9	22.4	31.1	30.8	−15.9	11.2	10.5	15.0
12-WO-F	0.69	1.96	1.240	1.0	58.1	24.0	30.4	30.1	−16.5	9.8	11.9	17.0
Average	0.69	1.78	1.239	0.9	59.0	22.8	31.1	30.0	−15.6	10.8	11.4	16.4

[a] YP = Yellow Poplar, WO = White Oak, Q = quartersawn, F = flatsawn.
[b] Specific gravity on an oven-dry weight/green volume basis.

about 1.5 inches but was not specifically measured. In all three runs, the environmental chamber was controlled at 40 C and 71% RH with the humidity control being monitored by periodic weighings of an open beaker of saturated $NaNO_3$ solution. The air flow in the chamber was directed by a baffle across the face of each specimen to provide an air velocity of approximately 500 ft/min.

Within a given treatment, matched discs were obtained by using a plug cutter to saw 3.6-inch-diameter discs from a ½-inch-thick planed green board. Specific gravity/moisture content samples were taken immediately adjacent to each disc. Each disc was edge-coated with neoprene and sealed with a 0.6-inch-wide rubber band to the flexible plastic cup. After periodic weighings (made on a balance in the chamber without opening the door) indicated that the steady-state condition had been attained, the discs were removed from the cups and measured; and both an average moisture content and a profile moisture-content sample were sawn out. The average MC sample was weighed, oven-dried, and again weighed to determine the average moisture content across the thickness of the disc. The profile moisture-content sample, measuring 0.5 inches across the grain and 2–2.5 inches along the grain, was sliced parallel to the drying surface by means of a heavy-duty powered paper cutter. Ten to twenty slices were generally obtained, thus giving an average slice thickness of approximately .05 inch to .02 inch. As each slice was made, it was immediately transferred to a weighing bottle to minimize moisture loss. Both the slice thickness and moisture content, the latter determined by oven-drying, were recorded so that the moisture profile across the thickness of the original disc could be determined. Since the sum of the slice thicknesses was slightly greater than the actual disc thickness, the gradients were corrected back to disc thick-

TABLE 3. *Steady-state data for Run No. 3 comparing the effects of freezing, boiling and control treatments on white oak between 97% and 71% relative humidities at 40 C*

ID[a]	Sg[b]	Flux g × 10⁷ / cm²sec	Initial thickness cm	Thickness shrinkage %	Average MC Initial %	Average MC Final %	Profile Maximum MC (%)	Regression (20-EMC) Intercept %	Regression (20-EMC) Slope %/cm	Regression (20-EMC) EMC %	Diff. coeff. g × 10⁷ / cm sec	Diff. coeff. cm²/sec · 10⁷
1-WO-F	0.61	0.88	1.262	6.8	61.6	27.6	40.3	34.6	–19.6	11.5	4.5	6.9
2-WO-F	0.62	0.77	1.270	8.8	62.7	25.5	40.8	31.4	–16.9	11.9	4.6	6.7
3-WO-F	0.62	0.79	1.275	7.1	61.5	26.0	40.8	34.6	–19.6	11.4	4.0	6.0
4-WO-F	0.62	0.92	1.252	6.1	62.1	26.7	40.0	38.5	–23.0	11.4	4.0	6.1
Average	0.62	0.84	1.265	7.2	62.0	26.4	40.5	34.8	–19.8	11.6	4.3	6.4
5-WO-B	0.65	1.00	1.273	12.2	61.5	23.1	34.5	35.1	–21.2	11.3	4.7	6.4
6-WO-B	0.63	0.94	1.262	10.5	60.0	22.6	35.2	28.4	–15.4	11.0	6.1	8.7
7-WO-B	0.63	1.15	1.270	9.8	61.6	25.1	37.3	34.2	–20.7	10.5	5.5	7.9
8-WO-B	0.63	1.00	1.260	8.7	62.1	25.7	41.3	33.2	–19.5	10.8	5.1	7.4
Average	0.64	1.02	1.266	10.3	61.3	24.1	37.1	32.7	–19.2	10.9	5.4	7.6
9-WO-C	0.62	0.79	1.267	6.9	62.6	25.6	41.5	32.3	–17.9	11.2	4.4	6.6
10-WO-C	0.64	0.80	1.275	6.4	60.3	26.2	41.9	32.0	–16.7	12.0	4.8	7.0
11-WO-C	0.62	0.97	1.270	7.2	61.5	26.1	41.0	34.0	–18.2	12.5	5.3	7.9
12-WO-C	0.64	0.79	1.285	7.1	60.2	27.7	40.7	36.4	–20.6	11.8	3.8	5.6
Average	0.63	0.84	1.274	6.9	61.2	26.4	41.3	33.7	–18.4	11.9	4.6	6.8

[a] WO = White Oak, F = frozen, B = boiled, C = control.
[b] Specific gravity on an oven-dry weight/green volume basis.

ness by multiplying by the ratio of disc thickness to the sum of the slice thicknesses. Also, since measurements of the disc diameter, which were hampered by the neoprene edge coating, indicated little change in this dimension, the specimen volume change from the green to the steady-state condition was assumed to be solely a function of the thickness shrinkage. Thus the specific gravity at the time of test was calculated from the original green volume value by multiplying by the ratio of the initial to final thickness.

Prior to its use, the green wood in Runs 1 and 2 had been stored in a freezer at approximately 10 F. However, in view of the effect of freezing on redwood (Erickson et al. 1966), there was a possibility that this storage might have affected the behavior of the wood. Thus Run No. 3 included both freezing and boiling treatments for comparison with control material. The frozen specimens were subjected to five days in a freezer at approximately 10 F. The boiled specimens were boiled in water for 30 hr and then cold-soaked for 90 hr. The control specimens were stored in plastic bags at approximately 40 F. All specimens were randomly assigned to the treatments.

RESULTS

Maximum MC As shown in Table 1, Run No. 1 consisted of five poplar sapwood and five oak heartwood specimens with four quartersawn and one flatsawn specimen of each species. When the moisture profiles were plotted, in most cases the moisture contents toward the high humidity face were much higher than expected. Although water was used in the cups, the diffusion of moisture from the water surface to the inner face of the disc insures that the average relative humidity at the disc face will be slightly lower than that at the water surface. Thus moisture contents in the mid-twenties had been anticipated, but values in the low- to mid-thirties were more commonly attained. Figure 1 shows one of the expected moisture-content profiles and one of the unexpected but more prevalent high-

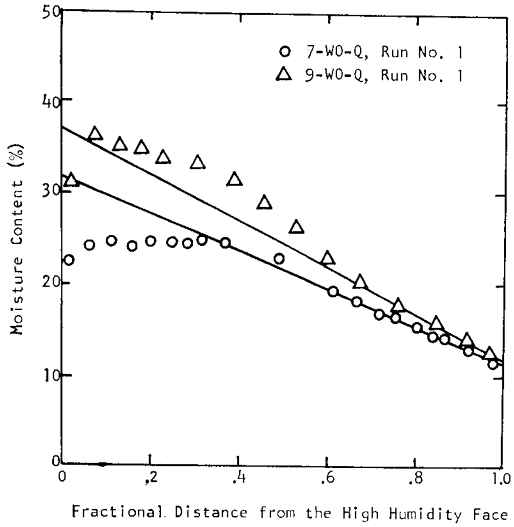

FIG. 1. Steady-state moisture profiles for 100%-71% RH for two white oak specimens with linear regressions on the data below 20% MC.

moisture-content profiles. In order to provide a tabular indication of the high moisture levels attained, the two consecutive slices showing the highest moisture content were averaged and tabulated as "Profile Maximum MC." In Table 1 it may be seen that only three of the specimens exhibited maximum moisture contents in the twenties, the flatsawn poplar and two of the quartersawn oaks. All the rest exceeded 30%. In most cases the second and third slices, rather than the first, displayed the highest moisture content, probably because of some surface drying of the discs during preparation.

The anomalous gradients are not the result of insufficient time for a steady-state gradient to be achieved. Not only had the flux attained a constant value, but the total moisture loss from each cup assembly was more than double that lost by the wood disc alone. In other words, over half of the water lost had passed through the disc from the water in the cup.

Since the available evidence (Martley 1926; Comstock 1963) indicates that, in steady-state flow, the diffusion coefficient decreases with decreasing moisture content in the bound water range, then the slope of the moisture profile should steadily increase with decreasing moisture content so that the steepest part of the profile occurs at the lowest moisture content. Such was not the case here. The profiles were consistently quite linear below 20% MC, so linear regressions were calculated for this portion. Above 20% MC, the profile should definitely fall below this regression, as does one of the data plots in Fig. 1, thus indicating a higher diffusion coefficient at higher moisture levels. But the high-moisture-content curve in Fig. 1 is totally inconsistent with the well-documented concept of higher diffusion coefficient with higher moisture content if one assumes that the moisture is *bound* water.

If this excess of moisture cannot be bound water, then it must be free water. But how can free water exist at humidities substantially lower than 100%? Tiemann (1951, p. 176) supplied the answer to this when he proposed the capillary tension theory of collapse. He argued that if the lumens are saturated with water (or if any bubbles present are sufficiently small) and if the cell wall capillaries into the saturated lumen are also sufficiently small, then tensile forces sufficiently great to collapse the cell wall into the lumen may occur.

In effect, Tiemann's theory says that saturated lumens can occur at relative humidities below 100%. The data in this project indicate that they occur at moisture contents as low as 20% and possibly even lower. And 20% MC occurs approximately at 90% relative humidity (Smith 1956). For the high-moisture-content curves such as shown in Fig. 1, the data points above 20% MC exceed the linear regression on the data below 20% MC, but the bound water moisture content must be less than the regression according to the diffusion coefficient-moisture content relationship. Thus there are substantial numbers of saturated lumens above 20% MC in nearly all of the specimens in Run No. 1. Only in specimens 6 and 7 did the shapes of the moisture profiles appear reasonably normal, and they have low initial moisture contents.

In Run No. 2, where the cup humidity

was 97% rather than 100%, all of the Profile Maximum MC values for the oak slightly exceed 30% MC, but the poplar values are all in the twenties (Table 2). Relative to the linear regression, however, the quartersawn poplar were still anomalous in that the data points at high-moisture levels fell above the regression as shown in Fig. 2. Even more anomalous was Run No. 3 where the Profile Maximum MC values averaged near 40% MC. A comparison of these values with the corresponding regression intercept in Table 3 shows all but one exceeding the intercept. For a normal steady-state gradient in which the slope of the moisture profile consistently increases with decreasing moisture content, the intercept of a regression on the low-moisture-content data should be considerably higher than the highest data values. Note that in Fig. 1, no data points for specimen 9 exceed the regression intercept even though much of the data clearly falls above the regression.

Two of the three flatsawn poplar plots in Run No. 2 tended to be linear over the entire profile and in the third plot, for specimen 5, the data above 20% MC actually fell below the regression. However, the data for this specimen agree closely with the other two but the regression does not, showing a high slope and a high intercept. The final average-moisture-content values, ranging from 18.1% to 19.4%, were the lowest attained by any specimens in the entire project. Thus the flatsawn poplar closely approached the moisture profile that was expected. The fact that it fell short of a "normal" profile could well be due to the effects of growth ring density gradients rather than the presence of saturated lumens, for the flatsawn discs are sliced parallel to the growth rings and the three specimens were matched.

Regression Slope. The regression slope values for the oaks in Tables 1, 2, and 3 are consistently larger than the poplar values in Tables 1 and 2. Two possible explanations are that the oak simply has a higher equilibrium moisture content (EMC) or that it is subjected to a higher relative humidity (RH), assuming, of course, that the change in diffusion coefficient with moisture content is the same in both species.

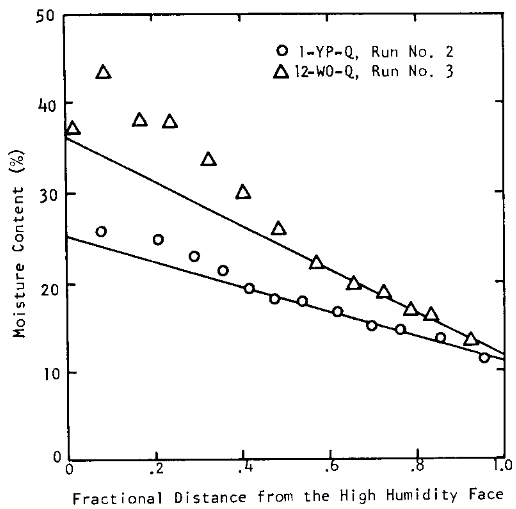

FIG. 2. Steady-state moisture profiles for 97%-71% RH for a yellow poplar and a white oak specimen with linear regressions on the data below 20% MC.

In a separate project (Kelly and Hart 1969) boiled microtomed cross sections of white oak and yellow poplar were found to exhibit essentially similar equilibrium moisture content versus relative humidity values in an adsorption-desorption study of dried specimens. Since boiling tends to remove extractives and this removal should increase the oak EMC (Nearn 1955), which is richer in extractives, then it follows that unextracted green oak would, if anything, show a lower hygroscopicity than poplar. Thus the available evidence indicates that the higher regression slopes of the oak as compared to the poplar are not a result of higher hygroscopicity.

To some extent the oak is subjected to a higher relative humidity on the cup side of the specimen than is the poplar since the higher poplar flux must necessarily result in a greater drop in relative humidity from the liquid surface to the inner surface of the wood disc. For 40 C and assuming barometric pressure of 760 mm, the calculated water vapor diffusion coefficient is

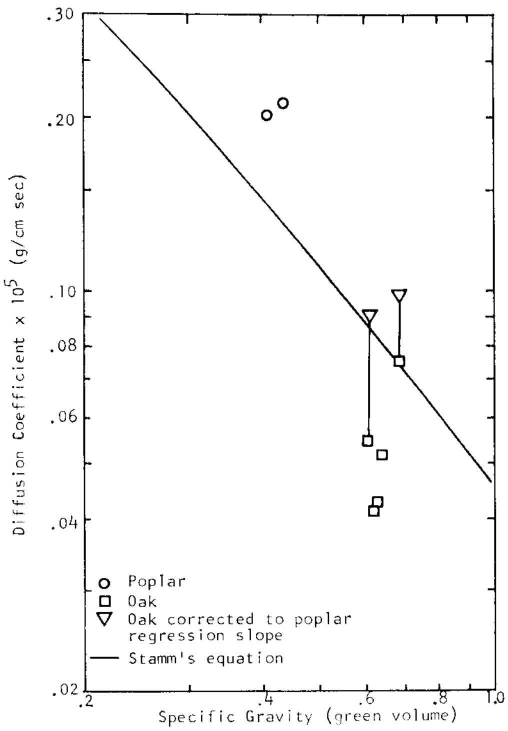

FIG. 3. Effect of specific gravity upon the comparison of the oak and poplar diffusion coefficients as compared with the theoretical effect of specific gravity calculated by Stamm's equation for softwoods (logarithm coordinates).

0.2794 cm^2/sec (Stamm 1964), the distance from the salt solution to the disc is approximately 1.5 inches and the density of saturated water vapor is 5.11 × 10^{-5} g/cc (Handbook of Chemistry and Physics 1955). Since at this temperature the ratio of water vapor densities closely approximates the ratio of their corresponding pressures, then by employing Equation (1) to calculate the vapor density drop across the air space and dividing it by the saturated density to estimate the relative humidity drop, we obtain the equation

$$RH\% = 2.67\,(\text{Flux} \times 10^7) \qquad (2)$$

to estimate the relative humidity drop across the cup air space.

According to Equation 2 the average quartersawn poplar in Table 1 was subjected to an estimated 100 – 7.4 or 92.6% RH, while in Table 2 the estimate is 97 – 6.3 or 90.7% RH and the regression slopes in Table 1 do average slightly higher than in Table 2. With the quartersawn oaks, however, the estimate for Table 1 is 96.6% RH and for Table 2 is 94.1%, but the regression slopes average less rather than more in Table 1 than in Table 2. They also average considerably more than the poplar values, even if the comparison is between the poplar in Table 1 and the oak in Table 2, where the difference in estimated relative humidity is only 1.5%. Thus there is very little likelihood that the substantially larger regression slopes of the oak as compared to the poplar can be attributed to a higher relative humidity. In fact, it seems quite unlikely that the oak regression slopes depict hygroscopic gradients alone. Instead, it appears most probable that saturated lumens persist below 20% MC in the oaks and thus inflate the moisture gradient. If so, this has an important bearing upon a comparison of their calculated diffusion coefficients.

Diffusion Coefficients. The difference in the moisture profile slopes between the poplar and oak can cause a serious misconception when one compares their diffusion coefficients (which were calculated from the regression slopes). The average values for quartersawn specimens are plotted in Fig. 3. These steady-state diffusion coefficients presumably reflect the ease with which moisture diffusion occurs. However, in this case the moisture gradients in the oak apparently do not accurately reflect the hygroscopic gradients because of the presence of free water in the saturated lumens. Thus from Table 1 the average flux ratio of quartersawn poplar to oak is 2.78/1.28 or 2.17, while the average diffusion coefficient ratio is 21.2/7.6 or 2.79. If the oak flux is adjusted to the same thickness as the poplar, the flux ratio becomes 2.78/1.35 or 2.06. By comparison, Stamm's theoretical equation for tangential flow in softwoods predicts a diffusion coefficient ratio of 13.2/7.5 g/cm sec or 1.76 at 15% MC for specific gravities of .44 and .69 as calculated from data tabulated by Choong (1965). It is interesting to note that the average oak diffusion coefficient is almost identical to the theoretical softwood value for the same density, while the poplar average substantially exceeds the corresponding theoretical value for its density. If the actual hygroscopic gradient for the oak is the same as the 13.2 value for the poplar, then the oak diffusion coefficient would be 9.9 as compared to the theoretical 7.5 value.

From Table 2 it is even more apparent than in Table 1 that a simple comparison of diffusion coefficients can be misleading. For the quartersawn specimens, the average flux ratio of poplar to oak is 2.37/1.08 or 2.19, while the average diffusion coefficient ratio is 20.3/5.5 or 3.69. Stamm's equation gives a diffusion coefficient ratio of 14.1/8.8 or 1.60. But if the actual hygroscopic gradient in the oak is the same as the 11.9 average value of the poplar, then the oak diffusion coefficient would agree almost exactly with the theoretical softwood value. The poplar exceeds the theoretical value by virtually the same amount as in the first run. The oak values obtained by using the poplar hygroscopic gradients (regression slopes) are also shown in Fig. 3.

If, because of more comparable relative humidity boundary conditions, the comparison is made between the quartersawn poplar of Table 1 and the quartersawn oak of Table 2, the results are similar. In this case the poplar to oak flux ratio is 2.78/1.08 or 2.57, while the diffusion coefficient ratio is 21.2/5.5 or 3.85. Stamm's equation gives a ratio of 13.2/8.84 or 1.49 for the corresponding specific gravity values of .44 and .61.

In summary, the ease of moisture diffusion in poplar exceeds that in oak by a somewhat greater amount than predicted from Stamm's model for softwoods, but the difference is not nearly so great as a simple comparison of the diffusion coefficients would indicate. This results from the oak moisture slopes' apparently being inflated by the presence of saturated lumens in the 20%–12% MC range.

From Table 3 it appears that the oak diffusion coefficient is increased by the boiling treatment. This was not caused by any change in the regression slope but rather by an increase of about 20% in the flux as compared to the frozen and the control specimens. Partial removal of extractives which bulk the cell wall would be expected to increase the rate of cell-wall diffusion at high relative humidities. This is not necessarily inconsistent with results by Stamm (1959), who found that in adsorption from the dry state, extracted redwood exhibited a lower diffusion coefficient than did unextracted redwood. Extractives generally replace the bound water held at the higher relative humidities (Nearn 1955), and it seems probable that these extractives would not facilitate moisture diffusion as well as would the water whose place they take. But at lower relative humidities this water would not be in the cell wall anyway, so it is a comparison of extractives versus no extractives. In this case the extractives apparently serve to keep the cell wall more swollen and thereby facilitate diffusion at low relative humidities.

Swelling Pressure. In addition to the steady-state measurements in Run No. 3, six small specimens of matched material of approximately 20 g green weight and 60% initial moisture content were sealed in a desiccator over saturated K_2SO_4 to determine the equilibrium moisture content at 97% relative humidity. After 48 days, when periodic weighings indicated they were at equilibrium, the specimens were oven-dried, and the moisture contents were found to range from 52.5% to 56.6%. This is in good agreement with the 63% fiber saturation indicated by electrical measurements on green swamp oak by Stamm (1964, p. 365). He attributed this response to the presence of completely filled fiber cavities. Although the 52–56% range of the small specimens is quite a bit higher than the 40% MC attained in the steady-state discs, it must be remembered that the relative humidity at the face of the disc was lower than at the surface of the salt solution. For a flux of 0.84×10^{-7}, which both the frozen and control specimens in Table 3 averaged, Equation 2 gives a relative humidity drop of 2.24%. Thus the small EMC specimens were exposed to a 97% RH, while the inner face of the disc was exposed to an estimated 94.76% RH. Furthermore, the swelling pressure equation (Tarkow and Turner 1958) for the situation of a saturated lumen in equilibrium with a relative vapor pressure (RH%/100) of less than unity is

$$P = 20{,}952\,(-\ln p), \qquad (3)$$

where P is the swelling pressure (tension) in psi, and $\ln p$ is the natural logarithm of the relative vapor pressure. Now, the point is that 97% RH gives 638 psi, while 94.76% RH gives 1,131 psi, a difference of almost 500 psi. This, then, accounts for the difference between the 54% moisture content of the EMC specimens and the 40% attained by the discs. It is primarily a difference in the amount of free water in saturated lumen as controlled by capillary tension rather than a difference in the amount of bound water in the cell walls. In addition, as previously pointed out, the highest moisture content in the disc generally occurred not at the disc surface but just to the inside of it so the relative humidity at that depth would be still lower. Furthermore, the lower average Profile Maximum MC for the boiled specimens in Run No. 3 may have resulted in some part from the higher flux causing a lower relative humidity on the disc face (an estimated 94.28% for the 1.02 flux value) and a corresponding higher capillary tension of 1,232 psi as compared to the 1,131 psi estimated for the frozen and control specimens.

Shrinkage. Much of the thickness shrinkage data indicates the occurrence of collapse. Since the final average moisture content of the flatsawn poplar boards in Table 2 approached 18%, we may take this as our lowest estimate of the average bound water moisture content. If we assume shrinkage to be linear below fiber saturation and assume fiber saturation to be approximately 27 to 30%, then shrinkage to 18% should be ⅓ to ⅔ of total green-to-dry shrinkage. For poplar of 0.40 green volume specific gravity, total radial and tangential shrinkages are estimated at 4.0 and 7.1%, while for white oak at 0.60 they are 5.3 and 9.0 (Wood Handbook 1955). Thus in drying to 18%, and conservatively using 30% for fiber saturation, poplar values of 1.6 and 2.8% and oak values of 2.1 and 3.6% might be expected as maximum estimates for 0.40 and 0.60 specific gravity values, respectively. Assuming that shrinkage is directly proportional to specific gravity, these figures must be increased somewhat to adjust to the observed specific gravity values.

All of the quartersawn poplar exceeded their maximum expected shrinkage, but only one of the four flatsawn poplar shrinkages did so. Yet none of the oaks in the first two runs exhibited excessive shrinkage; but in the third run, the oak shrinkage is 1.8 to 2.7 times the maximum expected shrinkage, with the boiled specimens showing the greatest deviation. Thus it seems probable that collapse has occurred, especially in the third run oak but also to a lesser degree in all of the quartersawn poplar. Poplar is not a collapse-prone species, but in this type of steady-state treatment, many lumens may be exposed to capillary tension for much longer periods than might normally be encountered. Ellwood (1952) reports that slower drying is associated with more severe collapse so it is possible that this steady-state treatment produces collapse more readily than unsteady state drying. From the results in Table 3, it also appears that boiling in water makes oak more susceptible to collapse. However, this may be due in part to the increased flux and the resultant lower relative humidity and slightly higher capillary tension as previously pointed out.

It is difficult to explain the presence of collapse in the steady-state specimens other than by Tiemann's capillary tension theory. In unsteady-state specimens, it can be argued that the shrinking shell "squeezes" the core and produces a sufficient compression to collapse the core fibers; but in these steady-state specimens, the shrinkage compressive stress is at right angles to the thickness direction and it is difficult to see how it could produce the excessive thickness shrinkage. Because of the edge coating, the disc diameters could not be measured with great precision after steady state was achieved, but they were measured with fair accuracy and little if any shrinkage was indicated.

The capillary tension in the saturated lumens can undoubtedly reach rather high levels. Both species showed evidence of saturated lumens down to 20% MC. This corresponds to approximately 90% RH (Smith 1956) and a corresponding capillary tension of 2,212 psi (Equation 3). In the oaks, where the saturated lumens appear to persist to much lower humidities, the capillary tension must go much higher. However, the number of saturated lumens occurring below 20% MC is not great, and the data indicate that in kiln drying oak, collapse should not be a problem after the center moisture content drops below 20%.

SUMMARY

The moisture profiles attained by the steady-state specimens present virtually conclusive evidence of the occurrence of water-saturated lumens in both oak and poplar at relative humidity levels considerable below 100%. Most of these saturated lumens clearly occurred above 20% MC, which is the equilibrium moisture content at approximately 90% RH and thus corresponds to a liquid tension level of 2,212 psi. In the poplar, there was no evidence of saturated lumens occurring below this level. In the oak, however, there was strong evidence that they do occur in small numbers below the 20% MC level, for there seems to be no other explanation for the steepness of the moisture profiles below 20% MC in the oaks.

In both the poplar and the oak, the magnitude of the thickness shrinkage indicated the presence of collapse in some samples, especially in all of the specimens of oak in the last of the three runs. This strongly supports the Tiemann theory of capillary tension collapse since the presence of saturated lumens is indicated, but compression in the thickness direction caused by shrinkage appears to be absent. Since the great majority of saturated lumens occurred above 20% MC, it is unlikely that collapse occurred below this moisture level.

Freezing of white oak did not affect its behavior, but partial extraction by 30 hr of boiling in water increased the flux more than 20%, slightly reduced the occurrence of saturated lumens, and substantially increased the thickness shrinkage.

The ratio of the poplar to oak flow rates or flux values was somewhat greater than could be accounted for by the difference in wood density as predicted by Stamm's theoretical model for softwoods. This comparison would be improved by extraction of the oak. A comparison of diffusion coefficients was even worse since this ratio was inflated by the difference in the steepness of the moisture profiles of the two species.

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