ONE- AND TWO-DIMENSIONAL MOISTURE PROFILES IN RED OAK[1]

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ABSTRACT

Differential moisture losses during the early stages of drying are critical to the development of stresses that result in checking and associated degrade. This research was conducted to determine the shape of the moisture profiles in flat sawn red oak (*Quercus* sp.) under several different conditions early in drying. In addition, both one- and two-dimensional profiles were compared graphically and statistically to determine if moisture loss from the narrow (nearly radial) surfaces was significant. The results indicate that the moisture profiles are continuous and nearly parabolic after one day of drying under mild or severe conditions. The one- and two-dimensional profiles were essentially the same when compared both graphically and statistically, which indicates that moisture losses from the narrow faces can be neglected when developing drying models for flat sawn red oak having a width at least four times its thickness.

Keywords: Moisture gradients, moisture profiles, drying, red oak.

INTRODUCTION

Early in drying, wood shrinks differentially due to moisture gradients between the surfaces and the interior. The differential shrinkage results in stresses that cause most drying defects. Thus, one key to understanding drying behavior and improving drying processes is understanding moisture movement and the development of the moisture profiles that are basic to the magnitude and distribution of drying stresses. Studies such as those of McMillen (1955) have shown that the maximum stresses in the outer layers of wood develop during the first few days of drying. However, the associated moisture profiles have not been well established, constraining analysis that could lead to more economical drying procedures.

The purpose of this research was to determine whether the moisture profiles during the first four days of drying were smooth continuous curves having well-defined shapes. A secondary goal was to compare the differences between one- and two-dimensional moisture profiles to ascertain if drying models using one-dimensional profiles are adequate.

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As part of a larger study of mass transfer and stress development in red oak (*Quercus* sp.), both one- and two-dimensional moisture profiles were measured in essentially flat-sawn boards under various conditions. One-dimensional moisture loss occurs with drying from the board (nearly tangential) surfaces, and two-dimensional loss occurs with drying from both the narrow and broad faces.

BACKGROUND

Figure 1a, taken from Hawley (1931), shows profiles that are based on the assumption that diffusion is the only cause of moisture loss. The profiles represent the moisture content values at various points within the board and assume that drying has not occurred from the "wet line" inward to the center of the board. The result is a profile with a discontinuity at fiber saturation.

In Fig. 1b, the profiles illustrate moisture loss under the combined mechanisms of diffusion and liquid moisture movement. In this case, moisture movement in the wood occurs from the interior as well as from the exterior surfaces. The result is a well-defined, continuous profile without a discontinuity and with a shape that approaches a parabola.

A number of researchers have verified that the profiles in Fig. 1b predominate in the middle and latter stages of drying. Stamm (1946) measured the drying profile of Sitka spruce after several hours at moderate temperatures and extremely low relative humidity. The profile was clearly parabolic. McMillen (1955), using red oak under mild drying conditions, traced the moisture loss from the fifth day of drying onward. The profiles were smooth continuous curves. In a subsequent paper, he reported the moisture gradients of different temperatures. Under mild conditions, such as those used to dry red oak commercially, the parabolic profiles were shown about 2.5 days into the drying process (McMillen 1956). Bai and Garrahan (1984) reported parabolic profiles in preheated (steamed) white birch after one day of drying and in red pine after 2.5 days. Simpson (1976) compared the moisture gradients of both steamed and upsteamed red oak and found that the profiles of the unsteamed oak had an inflection point at about fiber saturation. The inflection point disappeared when the wood was steamed before drying. Other studies, such as those of Hann (1964) and Stevens (1972), have discussed parabolic profile development under high temperature, press drying conditions.

The literature has not, however, frequently addressed the rationale for neglecting moisture loss from the narrow surfaces of flat sawn boards when modeling the drying process. The well-known fact that flat sawn lumber dries more quickly than quarter sawn wood is generally attributed to the moisture transport properties of the rays. Siau (1984) states that the radial and tangential diffusion coefficients are nearly equal and suggests that diffusion in the tangential direction can be neglected if the ratio of width to thickness is greater than about seven. Simpson (1973) observed that the rate of diffusion through the ray tissue was clearly greater than in the surrounding tissue. Although these examples underscore the importance of the rays as conduits for the transport of liquids and gasses, it is not clear whether moisture loss from the narrow surfaces can be neglected early in the drying process. A typical flat sawn board has a number of cell openings on the narrow surfaces that may lose moisture quickly during the early stages of drying and cause appreciable changes in moisture content.

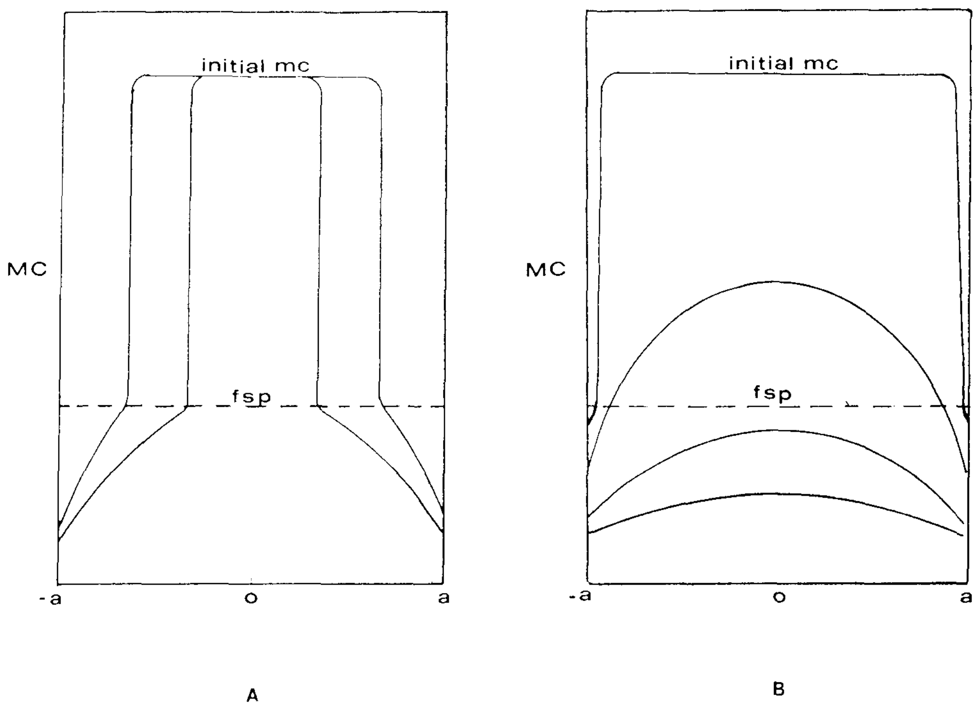


FIG. 1. Extreme examples of one-dimensional moisture movement as discussed by Hawley (1931). The surfaces are at a and-a.

METHODS AND MATERIALS

Scope of the project

One- and two-dimensional moisture profiles were determined each day for the first four days of drying at 110 F at three different relative humidity (RH) levels (85, 60 and 35% RH;) 18, 10, and 7 percent equilibrium moisture content (EMC). These conditions represent drying rates ranging from mild to severe.

EXPERIMENTAL PROCEDURE

Choice and preparation of material

A single log of red oak (*Quercus* sp.), measuring 23 inches in diameter at the small end, provided the experimental material. In order to minimize ring curvature, planks were taken from the heartwood as far distance from the pith as possible. The planks were sawn so that the rings were parallel to the broad surfaces.

The rough-sawn planks were planed to a thickness of 1.5 inches, machined to a width of 6 inches and sawn into twenty-four boards 18 inches long. The twenty-four pieces were separated into six groups of four, with each group supplying the material for the experiments at a particular drying condition. The pieces were chosen such that the boards in each group were from different planks. After machining, the wood was wrapped in plastic and kept in cold storage at 40 F to prevent drying.

Test equipment and conditions

An Aminco chamber with a capacity of approximately nine cubic feet was used to control the drying conditions. Within the chamber, four pieces were stacked on a rack that separated them by ½-inch. The air velocity was 150 ft/min, and the temperature was 110 F. The estimated maximum temperature variation was ±2 F, and the relative humidity maximum variation was about ±2%.

Test procedure

The relative humidity level was established at one of the three conditions, and four 18-inch-long samples were removed from cold storage and trimmed.

The two-dimensional samples were coated on the ends with aluminized varnish, and thin strips of plywood were tacked onto the coated areas to further seal the surfaces. The same treatment was applied to both the ends and the narrow (radial) surfaces of the one-dimensional samples.

After drying for 24 hours, a four-inch section was bandsawn from the end of each piece (Fig. 2), and the remainder was resealed and returned to the chamber. The four-inch sections were trimmed and bandsawn into a moisture content sample and three one-inch moisture gradient samples (Fig. 2). After the completion of this step, there were twelve moisture gradient and four moisture content samples.

Moisture gradients were determined following McMillen's (1955) method using wafers sawn parallel to the growth rings. In our experiments, eight wafers were bandsawn from alternate sides of each sample (Fig. 2). After each wafer was sawn, the wafer and sample thickness were measured to establish position and kerf thickness. The average wafer thickness was about 0.070 inch and the kerf was about 0.030 inch.

After labeling and weighing, the wafers were oven-dried and reweighed to determine their average moisture contents.

The wafer slicing experiments shown in Fig. 2 were repeated daily for four days for the one-dimensional tests, then were repeated for the two-dimensional tests. Next, the humidity conditions were changed, and the experiments were repeated at the new level. In summary, ninety-six wafers were sawn each day for a four-day period at one humidity level. Two treatments were used (one and two dimensions) and the tests were done at three levels of humidity for a total of 2,304 wafers.

RESULTS AND DISCUSSION

The daily sawing regimen resulted in twelve wafers for each of the eight positions (Fig. 2). The moisture contents of the twelve wafers were averaged, and the average was assumed to represent the moisture content at the center of the wafer.

Graphs of moisture content versus position were prepared. Two additional data points were generated by assuming that the moisture content at each surface was equal to the equilibrium moisture content. This assumption may not have been strictly valid because of boundary layer effects and the low air velocities used in these tests, but the results of the comparison were not affected. Smooth curves were drawn to connect the five data points from each side. The results are shown in Fig. 3. Although the curves are drawn so as to connect the data points from

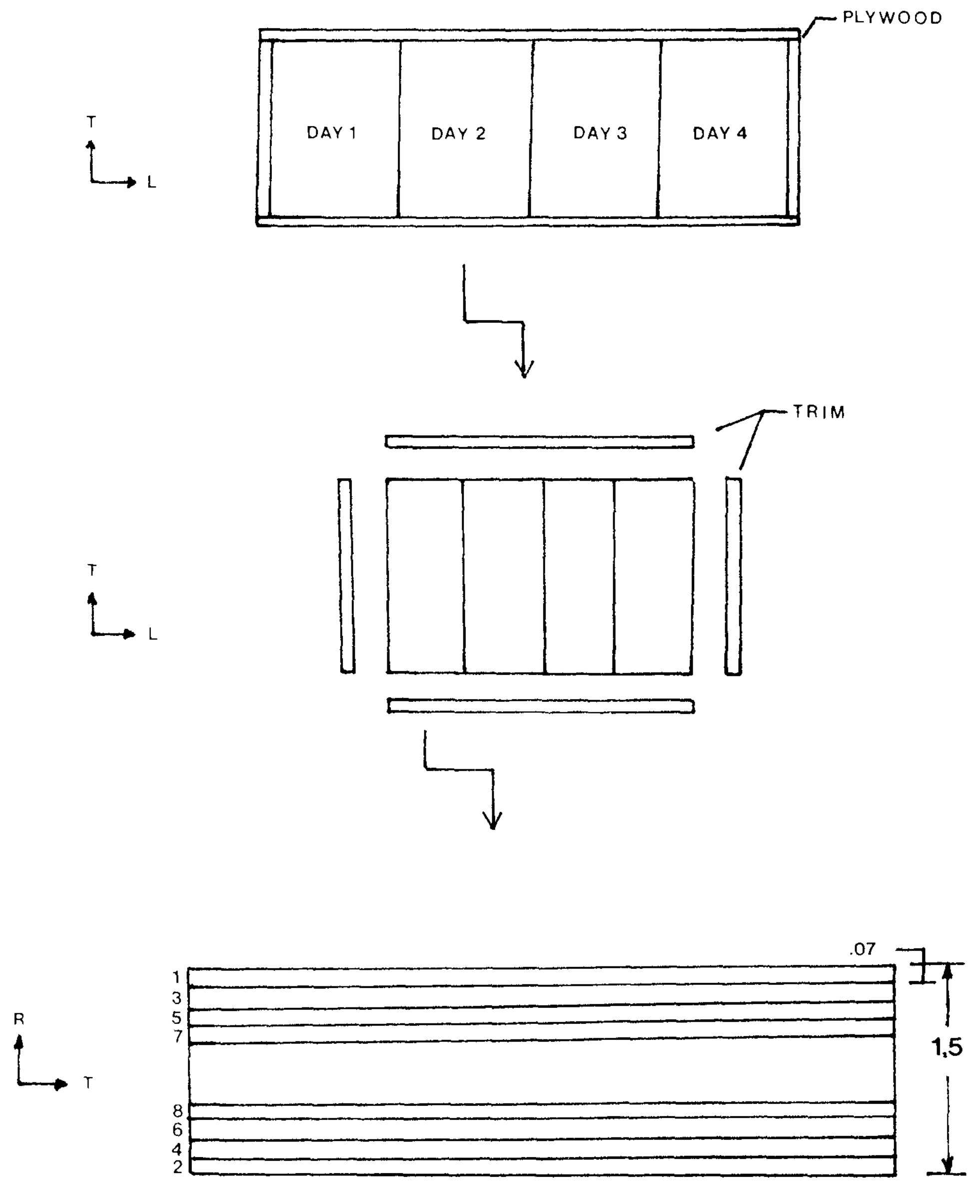


FIG. 2. Cutting diagram. Top: Each day a four-inch section was cut from each board. Middle: The section was trimmed and cut into a moisture and three one-inch samples. Bottom: the three samples were sliced into wafers about 0.07 inches thick. The small numbers refer to the cutting order. No side coating or trimming was done with the two-dimensional samples.

both sides, it should be remembered that data were taken from wafers that represented less than ½ inch from each surface of the 1½-inch-thick boards.

A regression analysis was performed for each group of five data points (e.g., one dimension, bark side, day 1, 60% RH). For convenience in analysis, the inside edge of the innermost wafer was assumed to represent position zero, and the

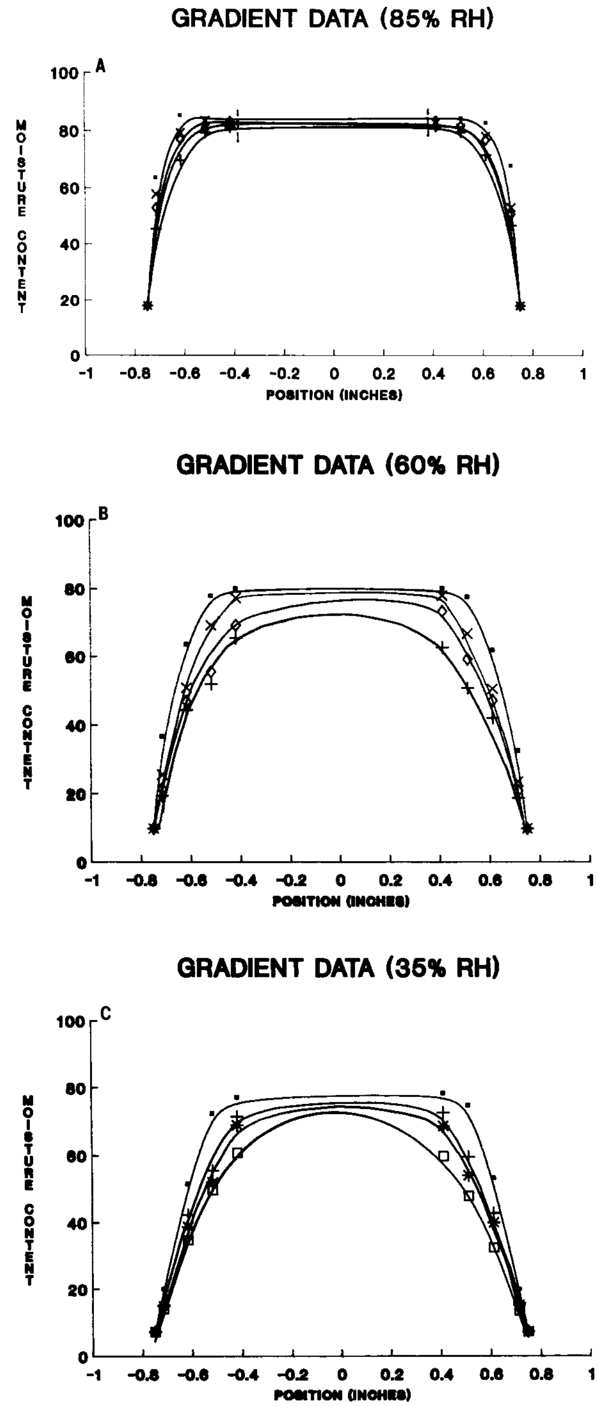


FIG. 3. (A–C). One-dimensional gradients developed during the first four days of drying. A: 85% RH. B: 60% RH. C: 35% RH. The profiles are progressive and the outer curve represents day 1. The pith side is on the right; the bark side is on the left. The curves between the vertical lines are speculative.

TABLE 1. *Regression equations determined from the moisture profile data. (x = position in inches).*

Day	RH	Side	Equation	R^2
1	85	Pith	$MC = -10{,}259.6x^3 + 5{,}010.5x^2 - 662.98x + 102.9$	0.916
		Bark	$MC = -9.762.6x^3 + 4{,}630.5x^2 - 586.7x + 99.75$	0.941
2	85	Pith	$MC = -995.3x^2 + 244.4x + 72.5$	0.886
		Bark	$MC = -1{,}105.5x^2 + 294.16x + 70.5$	0.87
3	85	Pith	$MC = -1{,}044x^2 + 262.8x + 71.1$	0.921
		Bark	$MC = -1{,}004.8x^2 + 245.5x + 72.8$	0.909
4	85	Pith	$MC = -896.5x^2 + 197.5x + 73.7$	0.936
		Bark	$MC = -864x^2 + 183.0x + 74.0$	0.935
1	60	Pith	$MC = -831.0x^2 + 138.2x + 75.5$	0.971
		Bark	$MC = -872.6x^2 + 160.98x + 74.27$	0.968
2	60	Pith	$MC = -436.9x^2 - 14.22x + 78.19$	0.889
		Bark	$MC = -503.46x^2 + 7.8x + 77.4$	0.980
3	60	Pith	$MC = -341.08x^2 - 45.9 + 74.4$	0.980
		Bark	$MC = -359.5x^2 - 23.2x + 68.98$	0.953
4	60	Pith	$MC = 31.76x^2 - 27.0x + 63.0$	0.95
		Bark	$MC = 323.86x^2 - 28.2x + 65.46$	0.972
1	35	Pith	$MC = 685.5x^2 + 60.7x + 77.57$	0.984
		Bark	$MC = 631.2x^2 + 43.7x + 71.82$	0.965
2	35	Pith	$MC = 315.2x^2 - 68.3x + 75.0$	0.972
		Bark	$MC = 263.9x^2 - 83.21x + 73.86$	0.968
3	35	Pith	$MC = 243.9x^2 - 83.26x + 71.2$	0.981
		Bark	$MC = 179.7x^2 - 109.0x + 72.19$	0.976
4	35	Pith	$MC = 154.67x^2 - 95.5x + 63.2$	0.963
		Bark	$MC = 218.4x^2 - 72.5x + 63.49$	0.974

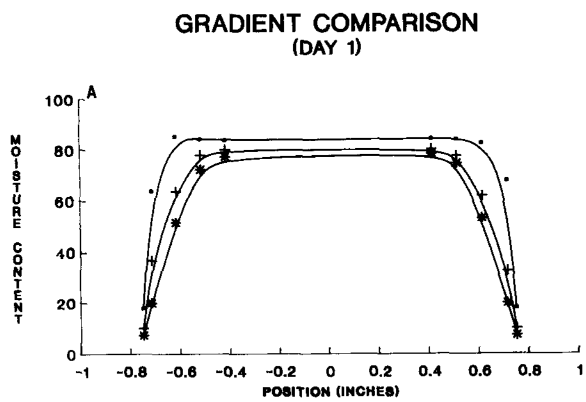
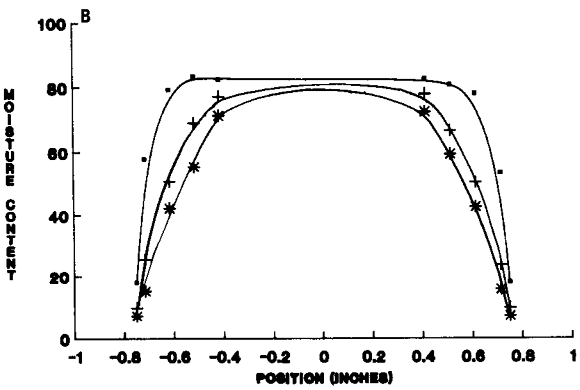
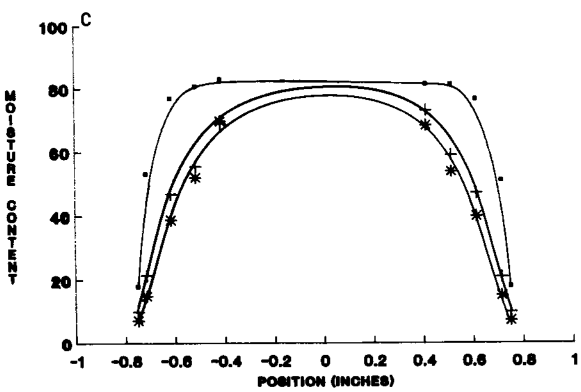


FIG. 4. (A–D). One-dimensional composite graphs of moisture profiles for each day and each condition. A: Day 1; B: Day 2; C: Day 3, D: Day 4. In each case the outer curve is the 85% RH condition and the inner curve the 35% RH condition.

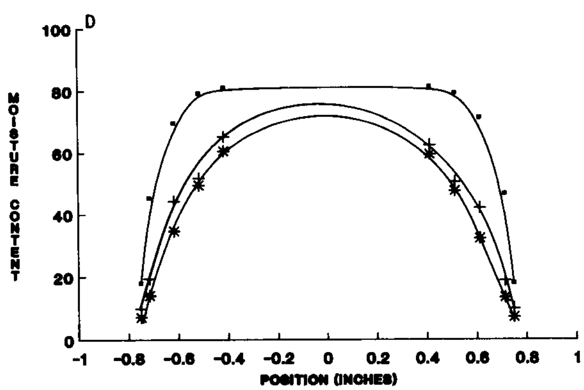
GRADIENT COMPARISON
(DAY 2)



GRADIENT COMPARISON
(DAY 3)



GRADIENT COMPARISON
(DAY 4)



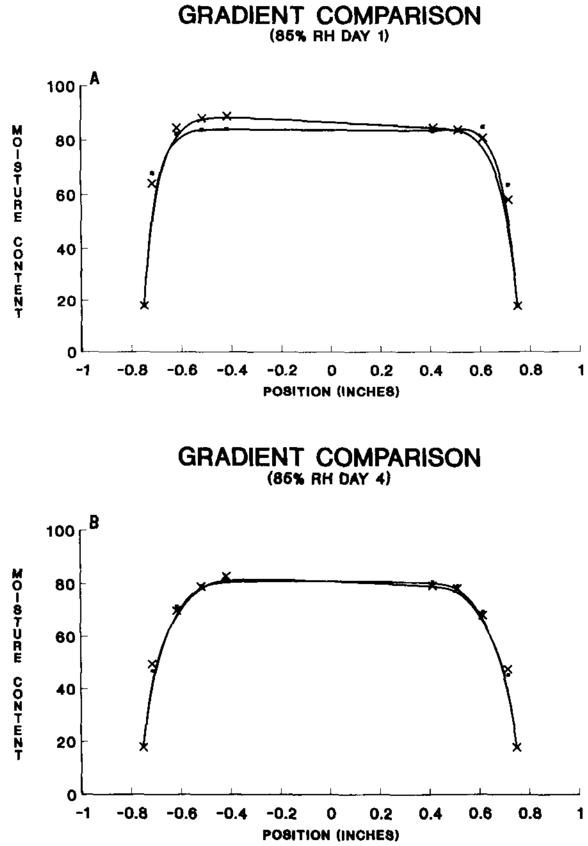


FIG. 5. (A–B). A comparison of the one- and two-dimensional moisture profiles for days 1 and 4 at the 85% RH condition. The pith side is at the left, the bark side at the right. The X indicates the two-dimensional profile.

surfaces of the wood were located 0.370 inches from this position. The results of the analysis are shown in Table 1.

Composite graphs were prepared to show the effect of the drying conditions (Fig. 4). Each profile represents one day of drying at a particular relative humidity condition.

Although the term "parabolic" is strictly reserved for a curve that is represented by a specific mathematical function, we will use the term to describe the general shape of the measured profiles. Figure 3 clearly shows that the measured profiles are nearly parabolic within the first 24 hours of drying. In all cases the profiles are smooth, with no obvious discontinuities that would occur if pure diffusion were the sole mechanism for moisture movement. The generally parabolic profile is supported by the equations in Table 1, which are second-order in nearly all cases. The only profile that does not clearly approach a parabolic shape is the curve developed during the first day of drying at the highest relative humidity condition (Fig. 3A). In this case, the curve flattens considerably about 0.300 inches from each surface, which suggests that little or no drying occurred from the interior of the board. The fact that very little drying occurred after 1 day may be attrib-

TABLE 2. *Results of the curve comparison test described in the text. The only significant differences occur on the pith side while drying at the 35% relative humidity condition.*

RH (%)	Drying time (hours)	Side	F*	Significant difference
85	24	Pith	1.157	No
85	24	Bark	0.741	No
85	48	Pith	1.398	No
85	48	Bark	0.203	No
85	72	Pith	0.634	No
85	72	Bark	0.022	No
85	96	Pith	0.201	No
85	96	Bark	0.201	No
60	24	Pith	0.184	No
60	24	Bark	0.935	No
60	48	Pith	0.322	No
60	48	Bark	0.889	No
60	72	Pith	0.646	No
60	72	Bark	0.089	No
60	96	Pith	2.114	No
60	96	Bark	0.448	No
35	24	Pith	6.31	Yes
35	24	Bark	1.36	No
35	48	Pith	3.33	Yes
35	48	Bark	1.94	No
35	72	Pith	9.88	Yes
35	72	Bark	1.74	No
35	96	Pith	7.23	Yes
35	96	Bark	0.812	No

* $F_{0.05} = 2.68$.

utable to the time required to heat the samples and remove condensate that developed when the cold samples were placed in the warm, humid drying chamber.

Although the curves shown in Fig. 3 are generally parabolic, the profiles that developed from day to day were quite different. The two major effects are seen most clearly in Fig. 4.

The first, and most obvious, effect is that the moisture loss is proportional to the ambient relative humidity. In all cases, the moisture loss becomes more pronounced each day, and the magnitude of the loss increases as the relative humidity decreases.

A more subtle effect of the drying conditions can be seen most clearly in Figs. 4C and D. The three curves in each figure were developed at 80, 60, and 35% RH (EMCs of 18, 10, and 7%). These figures demonstrate that the EMC differences are a better indicator of drying rate than are relative humidity differences. Although the profiles from the 10 and 7% EMC conditions are quite close to one another, they differ greatly from the 18% EMC profile even though the RH differences are about the same in all cases.

Another effect, most clearly seen in Figs. 4B and C, is the gradual daily drop and leveling of the profiles. This reduction in the steepness of the moisture gradients is probably the result of liquid water movement within the wood. As the gradient is reduced, the drying stress levels would also be reduced and the moisture loss rate would decrease. The effect would become increasingly important as the

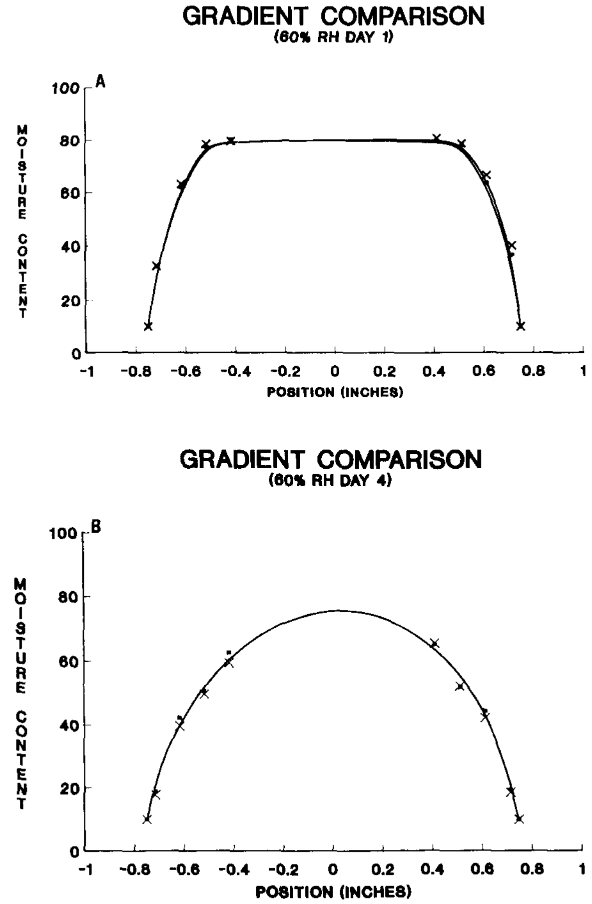


FIG. 6. (A–B). A comparison of the one- and two-dimensional moisture profiles for days 1 and 4 at the 60% RH condition. The pith side is at the left, the bark side at the right. The X indicates the two-dimensional profile.

air velocity was increased above the relatively slow 150 ft/min used for these tests.

The data from the one-and two-dimensional gradients were graphically compared by drawing the one-dimensional curves and superimposing the two-dimensional profiles. Typical results are shown in Figs. 5 through 7.

Apparently, little difference exists between the one- and two-dimensional profiles. In both cases the profiles are nearly parabolic, and the pattern is beginning to develop within the first 24 hours of drying. The profiles remained essentially parabolic and were closely matched during the entire test period. In several cases, the drying patterns between the pith and bark sides were slightly asymmetrical (e.g., Fig. 5A, B). However, the asymmetry is not consistent and is apparently not related to any preferential drying effect from the bark or pith sides of the wood.

To determine if the profile differences were statistically different, a curve comparison test was performed (Kmenta 1971). For each group of five data points, a

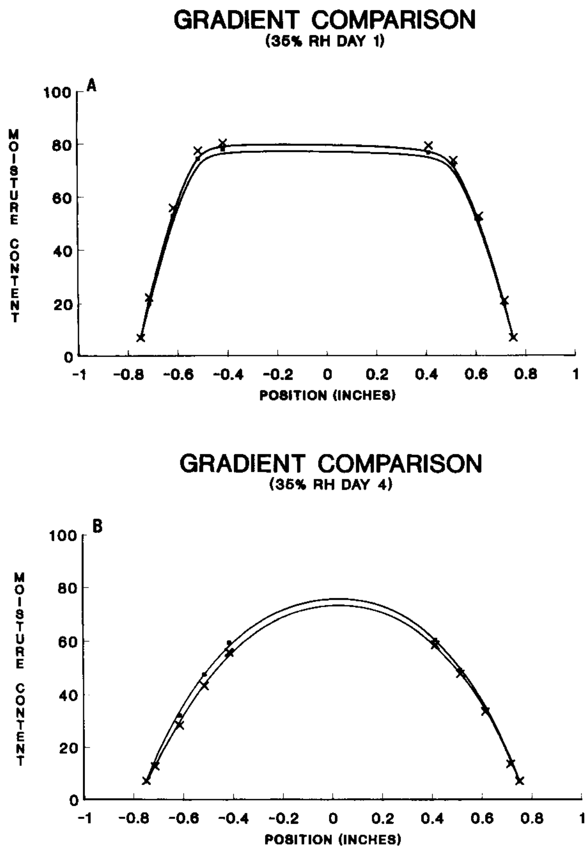


FIG. 7. (A–B). A comparison of the one- and two-dimensional moisture profiles for days 1 and 4 at the 35% RH condition. The pith side is at the left, the bark side at the right. The X indicates the two-dimensional profile.

least squares regression was done (e.g., one dimension, pith side, day 1, 35% RH). Next, the one- and two-dimensional daily data from each side were combined for each condition (a total of 10 data points), and another least squares analysis was done.

The regression of the individual data sets yields two equations of the form:

$$Y_1 = b_0 + b_1X + b_2X^2 \qquad \text{(one dimension)}$$
$$Y_2 = c_0 + c_1X + c_2X^2 \qquad \text{(two dimension)}$$

The combined regression yields a third equation of the form:

$$Y_3 = d_0 + d_1X + d_2X^2 \qquad \text{(combined)}$$

We wish to test the hypothesis that $b_i = c_i$ for $i = 0, 1, 2, \ldots$ etc. If the hypothesis were not rejected, the two curves are considered statistically equivalent and the data could be combined to produce a usable equation. To test for equivalence, an *F-test* is performed using the sums of squares error (SSE) from the individual and combined data sets as follows:

$$F = \frac{(SSE_0 - SSE_1 - SSE_2)/3}{(SSE_1 + SSE_2)/(n + m - 6)}$$

where SSE_0 is the combined sum of squares error, SSE_1 is the SSE from the one-dimensional data set, SSE_2 is the SSE from the two-dimensional data set, m and n are the number of data points in the one- and two-dimensional data sets, respectively.

The results of the curve comparison test are shown in Table 2.

In nearly all cases, the results confirm that the drying patterns are not statistically different. This result suggests that moisture movement from the narrow face of a flat-sawn board is minimal early in drying and that this moisture loss can be neglected when modeling the drying process.

There were four cases in which the curves were significantly different (35% RH, day 1–4, pith side). The reasons for the difference are not clear, but the differences may be the result of the test used to determine significance. The curve comparison test determines if the coefficients of the one- and two-dimensional regression equations are the same. A significant difference may be more indicative of the tests sensitivity than to major differences in drying rates. The significantly difference may also result from stress differences between the pith and bark sides under these severe drying conditions. Further research is required to determine if the effect is genuine.

CONCLUSIONS

The moisture profiles that developed in red oak were continuous and generally parabolic within 24 hours of the commencement of drying. The same patterns were observed under both mild and severe conditions. As drying progressed, the profiles remained parabolic, but the gradients became less steep. Since the gradient steepness is related to the magnitude of the drying stresses, it is probable that the maximum stresses occur early in drying very close to the surface of the wood.

After graphically and statistically comparing both one- and two-dimensional moisture profiles under various conditions, we conclude that moisture loss from the narrow faces of flat-sawn boards early in the drying of red oak is minimal. This conclusion generally coincides with the commonly held theory of how oak dries as described by Bois (1977) and others. Therefore, when modeling the red oak drying process, one-dimensional models in which moisture loss is assumed to occur from the tangential surfaces appear to be reasonable and to reflect accurately the early stages of the drying process. Since this comparison is based on flat-sawn material that is four times as wide as it was thick, the conclusion should not be extended to material with a smaller ratio of width to thickness.

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