

CORRELATION OF LOBLOLLY PINE DRYING RATES AT HIGH TEMPERATURE

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ABSTRACT

A correlation of drying rates based on the physics of drying has been developed for plantation-grown loblolly pine at high temperatures. Flat-sawn boards, 8 ft in length, 4 in. in width, and in three thicknesses, 1, 1.5, and 2 in., were studied. At high moisture content, heat transfer is the controlling mechanism, and the predicted drying rate is a function of the air velocity and wet-bulb depression. At low moisture content, the predicted drying rate is a function of the dry-bulb temperature and the moisture content. No systematic variation in drying rate could be attributed to juvenile wood, rings per inch, or the presence of knots. The correlation is valid at dry-bulb temperatures from 180 F to 270 F, wet-bulb temperatures from 140 F to 200 F, and air velocities from 700 to 1,900 ft/min. This correlation can be used for modeling the effect of kiln operating parameters on the final moisture content variation and temperature drop across the load.

Keywords: Wood drying, high-temperature drying, southern pine, kiln modeling, rates of drying.

NOMENCLATURE

Az^p, Bz^q	asymptotes in Eq. (1)
C_p	gas heat capacity (Btu/lb/F)
D_0	constant in Arrhenius expression (ft/sec ²)
D_T	bound water diffusion coefficient at temperature T (ft/sec ²)
F_m	moisture flux (lb/ft ² /h)
F_{cr}	moisture flux during constant rate period (lb/ft ² /h)
f_v	factor for velocity (dimensionless)
H_D	activation energy (Btu/lb mole)
k	thermal conductivity (Btu/h/ft/F)
ℓ	board thickness (ft)
M_c	current moisture content (percentage dry basis)
M_e	equilibrium moisture content (percentage dry basis)
M_i	initial moisture content (percentage dry basis)
n	constant in Eq. (1) or Eq. (2), variable in Eq. (8)

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R	gas constant (1.987 Btu/lb mole/R)
S_0	constant in slope relationship (lb/ft ² /h/%)
S_T	slope of flux versus moisture content line (lb/ft ² /h/%)
t	time (h)
T	temperature (R)
T_d	dry-bulb temperature (F)
T_w	wet-bulb temperature (F)
v	air velocity (ft/min)
z	independent variable in Eq. (1)
y	dependent variable in Eq. (1)
<u>Greek</u>	
ρ_d	dry wood density (lb/ft ³) green volume basis
ρ_g	gas density (lb/ft ³)

INTRODUCTION

High-temperature drying has been recognized as a method to dry lumber that results in lower production costs, greater throughput, and improved energy efficiency over conventional drying (Rosen 1979). The most significant implementation of this method has been in the southern pine industry. As higher temperatures are used, drying times decrease; but it is more difficult to dry to the desired moisture content and to minimize board-to-board moisture variability. Fundamental drying information is needed to address this problem.

Given a southern pine board at a known moisture content, in air at a known dry-bulb temperature, wet-bulb temperature, and air velocity, one needs to know how fast it will dry. With this information, a model can then be developed to generate the moisture distribution as a function of time within a kiln charge. Combining the moisture model with prior knowledge of degrade and cost as a function of moisture content, optimum kiln performance can be achieved. The objectives of this study were to determine what wood-related and kiln-related variables affect the rate of moisture removal from plantation-grown southern pine and to establish a correlation that can be used to predict the drying rate of individual boards under commercial drying conditions.

The source of the southern pine lumber was an intensively managed plantation. Single 1-, 1.5-, and 2-in. boards were dried at dry-bulb temperatures, T_d , ranging from 180 F to 270 F, wet-bulb temperatures, T_w , from 140 F to 200 F, and air velocities, v , from 677 to 1,889 ft/min. Based on the weight loss of the boards with time, the drying fluxes (lb/ft²/h) are correlated as a function of dry-bulb temperature, wet-bulb temperature, air velocity, and board moisture content. The correlation allows a constant rate period to exist at a high moisture content. As the moisture content approaches the equilibrium moisture content (EMC), the drying rate is linearly proportional to the difference between the moisture content and the EMC. By correlating the flux, thickness is eliminated as a variable in the correlation.

MATERIAL ACQUISITION

Material from plantation-grown trees best represents southern pine lumber to be produced in the future. Therefore, logs were obtained from a 28-year-old, intensively managed, loblolly pine (*Pinus taeda* L.) plantation. Planting density

was initially 750 trees per acre. Thinning to 285 trees per acre occurred at age 14, and to 140 trees per acre at age 22. The plantation was fertilized at age 20. Logs were cut 34 ft in length, end-coated, and shipped from North Carolina to the USDA Forest Service, Forest Products Laboratory, in Madison, Wisconsin. The logs were from 10 to 16 in. in diameter at the base and from 4 to 9 in. in diameter at the top. Processing was done during the cold weather of March to minimize spoilage that would raise the permeability of the material.

Upon arriving in Madison, each log was bucked into four 8-ft bolts. The 10 growth rings nearest the pith were marked with orange paint on the upper transverse face of the bolt and with green paint on the lower. These markings were later used to estimate the percentage of juvenile wood in each board. Ten growth rings from the pith were selected because most of the change in properties as a result of age occurs within that zone (Bendtsen and Senft 1986). The 8-ft bolts were then cant-sawn into boards of three thicknesses, 1.25, 1.75, and 2.25 in., all 4 in. in width. With the pattern of cant sawing, most boards were flat-grained. As much as possible, the bolts were sawn so that boards of each thickness would come randomly from the inside or outside of the bolt and from bolts of all diameters. Each board was numbered so that it could be traced to a specific position in the tree and site in the plantation. All the recovered boards, other than those with wane and logging damage, were used in the drying runs. Thus, the test material was representative of industrial practice.

Specific gravity ranged from 0.36 to 0.57, with an average of 0.44. Moisture content ranged from 90 to 180% with an average of 130%. Ring count ranged from 2 to 6 rings per inch with an average of 3.5 rings per inch. Juvenile wood ranged from 0 to 100% with an average of 34% and a median of 50%. The number of knots per board ranged from 0 to 9, with an average number and size of 3 and 1.2 in. (area basis), respectively. This was less than 1% of the drying surface. Almost no heartwood was present in the lumber, which is characteristic of plantation-grown southern pine.

The boards were divided into 44 groups of nine boards, each containing three boards of each thickness. Care was taken to ensure that no one tree or bolt from a tree was overrepresented in any group. Also, the percentage of juvenile wood was kept as uniform as possible by placing in each group two boards of each thickness that contained a large percentage of juvenile wood and one board of each thickness that had little or no juvenile wood. After sorting, each group was wrapped in plastic for freezer storage at 0 F.

DRYING EXPERIMENTS

A laboratory dry kiln was modified so that nine boards could be dried simultaneously as a differential bed (Fig. 1). Special baffling and a screen were installed to provide a slight pressure drop that produced a uniform airflow through all of the sticker spaces. The standard deviation for air velocity was 100 ft/min (40 observations). Racks were constructed of rails and short, 0.75-in.-thick stickers (Fig. 1). These racks acted as cradles to hold the boards during drying. The rails were thick enough so that after a board dried, the top of the board was flush with the top of the rails. The racks were 9.75 in. wide by 8 ft long with the stickers placed at 2-ft intervals. The space inside of the racks where the boards were held was 4.5 in. wide. These racks made stacking and handling easier and, more

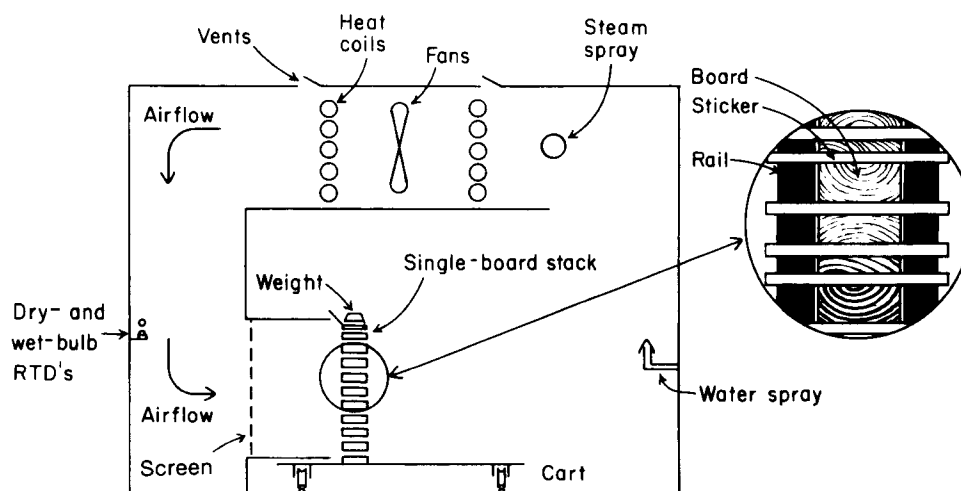


FIG. 1. Diagram showing modified laboratory kiln with baffle and rack locations. The rails were permanently attached to the stickers upon which they rested. Several dummy boards were located above and below the nine experimental boards in the single-board differential stack. (RTD is resistance temperature detector.) (ML89 5683)

importantly, helped to minimize heat transfer to the vertical faces of the lumber. Thus, the drying closely resembled a board at the interior of a package rather than the edge. The dryer set points were monitored and maintained by a computer system using resistance temperature detectors.

In preparation for a drying experiment, a nine-board group was thawed and raised to room temperature. On the day prior to the start of drying, the boards were inspected and a coating of aluminum flakes suspended in spar varnish was applied to the ends and vertical faces. During the inspection, the ring count, the percentage of juvenile wood, and the number and size of the knots were recorded. On the day the drying experiment was to begin, the nine boards were planed on each face to a thickness of 1, 1.5, or 2 in. (± 0.003 in.). This was done so that thickness did not vary from board to board to affect the drying rate. Also, any surface dryness incurred in handling was removed.

To execute the experiment, each board was weighed and placed in a rack. These racks were stacked on a kiln cart, one on top of the other, in a repeated pattern of 1, 1.5, and 2 in. in thickness. Two dummy boards were placed above and four below the nine experimental boards to minimize top and bottom effects. Iron weights with a distributed load totaling 50 lb/ft² were placed on top of the racks. The racks were located on the cart so that when the cart was rolled into the kiln, the racks and boards were directly in line with the airflow. The kiln conditions were then brought back to steady-state. This took from 5 to 15 min, depending on the conditions.

The range of drying conditions used are shown in Table 1. As indicated, a full set of experiments was conducted at a velocity of 1,329 ft/min, and subsets of these were conducted at 1,889 and 667 ft/min. At 1- to 8-h time intervals, depending on the drying rate, the boards were removed from the dryer, weighed, and returned to the dryer. This took approximately 10 min. The times for the

TABLE 1. *Experimental design for 27 drying conditions.*

Wet-bulb temperature (F)	Dry-bulb temperature (F)				
	180	210	240	270	
140	LMH	M	M	LHM	Velocity ^b
	36	18	9.6	5.5	Relative humidity, %
	4.4	2.2	1.0	0.4	EMC, %
	0.1413	0.1326	0.1240	0.1156	Absolute humidity ^c
160	M	LMH	M	LMH	Velocity ^b
	62.0	32	17	10	Relative humidity, %
	7.6	3.3	1.6	0.7	EMC, %
	0.2914	0.2807	0.2701	0.2595	Absolute humidity ^c
180	(Out of range)	M	MM ^a	M	Velocity ^b
		52	29	17	Relative humidity, %
		5.3	2.5	1.1	EMC, %
		0.6417	0.6258	0.6099	Absolute humidity ^c
200	(Out of range)	LMH	M	LMH	Velocity ^b
		81	46	27	Relative humidity, %
		10.3	3.8	1.7	EMC, %
		2.280	2.241	2.202	Absolute humidity ^c

^a First and last experimental runs were done at $T_d = 240$ F, $T_w = 180$ F, and $v = 1,329$ ft/min.

^b L = 677 ft/min; M = 1,329 ft/min; H = 1,889 ft/min.

^c Pounds of water per pound of dry air.

1-in. boards to reach a constant moisture content ranged from 8 to 48 h, and the total time for a given experiment ranged from 24 to 53 h. These constant moisture contents were in good agreement with EMC values published in the Wood Handbook (Forest Products Laboratory 1987). These published EMC values were used in subsequent analyses.

The last step in the experimental procedure was to determine the oven-dry weight of each board. This was done by returning the boards to the dryer for 4 days at 225 F and then reweighing the boards.

DATA ANALYSIS

The drying flux is the weight of water transferred per unit area of board surface per unit of time (lb/ft²/h). Fluxes were calculated from the board weight change by numerical differentiation. To do this, the change in board weight was divided by the upper and lower face areas of the board divided by the length of the time interval. For analysis, this average flux was assigned to a moisture content that was determined by averaging the moisture contents at the beginning and end of the time interval.

An analysis of variance was done with specific gravity, percentage of juvenile wood, knot area (based on number and diameter), initial moisture content, and ring count as the dependent variables. This analysis showed good randomization of these variables between board thickness and experimental run number. However, the percentage of juvenile wood did increase slightly with board thickness, and two experimental runs had ring counts statistically different from the other 25 runs. This had no effect on the correlation as the following describes.

A number of wood-related factors may affect the drying rate of a given species. These include heartwood, specific gravity, knots, ring count, temperature, and moisture content. As a practical matter, using any of these in the flux correlation,

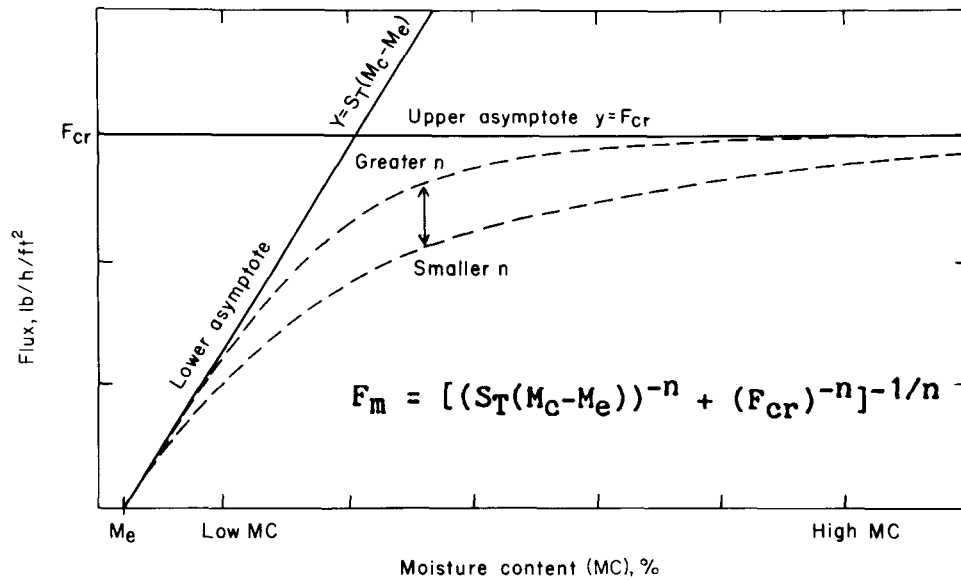


FIG. 2. A generalized form of Eq. (2) shows the two asymptotes used in the correlation. The segmented lines show the effect of n on the shape of the line between the two asymptotes. (ML89 5680)

except moisture content, would make it difficult to apply the correlation. A second analysis was done with these independent variables and the flux as the dependent variable. From this analysis, it was determined that these independent variables did not significantly affect the flux versus moisture content relationship. Other factors not considered were sticker thickness, grain orientation, and slope of grain.

CORRELATION OF THE DRYING FLUX

Churchill and Usagi (1972) presented a generalized expression for correlating rates of transfer that approach two asymptotes. Kayihan (1985) successfully applied this to wood of various geometries. The form of this expression is

$$y = [(Az^p)^{-n} + (Bz^q)^{-n}]^{-1/n} \quad (1)$$

where Az^p and Bz^q are two asymptotes and z is an independent variable.

The flux versus moisture content relationship has two asymptotes (Fig. 2). The lower asymptote is approached as the board moisture content, M_c , approaches the equilibrium moisture content, M_e . The lower asymptote can be expressed as $S_T(M_c - M_e)$, where S_T is the slope of the asymptote. The upper asymptote is the flux during the constant rate period, F_{cr} . It is independent of $M_c - M_e$. Making these substitutions for the asymptotes in Eq. (1) yields

$$F_m = \{[S_T(M_c - M_e)]^{-n} + (F_{cr})^{-n}\}^{-1/n} \quad (2)$$

as an expression for the moisture flux, F_m . As shown in Fig. 2, n will determine the shape of the curve between the upper and lower asymptotes.

Equation (2) was fitted to the data obtained at each experimental condition using a nonlinear least squares regression. This gave the set of S_T , F_{cr} , and n values

TABLE 2. *Drying coefficients F_{cr} , S_T , and n for all experimental conditions.^a*

Wet-bulb temperature (F)	Velocity (ft/min)	Constant rate flux, F_{cr} (lb/h/ft ²) at various dry-bulb temperatures (F)				Slope $\times 1,000$ (lb/ft ² /h/%) at various dry-bulb temperatures (F)				Power, n at various dry-bulb temperatures (F)			
		180	210	240	270	180	210	240	270	180	210	240	270
140	677	0.166	—	—	0.382	1.9	—	—	7.1	3.5	—	—	4.8
	1,329	0.212	0.360	0.390	0.467	2.3	4.1	5.7	8.5	4.8	3.5	5.8	8.0
	1,889	0.263	—	—	0.547	2.5	—	—	8.9	7.8	—	—	10.0
160	677	—	0.209	—	0.432	—	2.9	—	7.8	—	3.5	—	2.9
	1,329	0.156	0.287	0.406	0.502	1.9	3.4	6.0	8.7	1.9	3.5	3.5	8.9
	1,889	—	0.315	—	0.566	—	3.4	—	9.7	—	5.2	—	6.3
180	677	—	—	—	—	—	—	—	—	—	—	—	—
	1,329	—	0.170	0.315	0.438	—	3.0	5.4	7.3	—	3.4	7.0	10.0
	1,889	—	—	—	—	—	—	—	—	—	—	—	—
200	677	—	0.072	—	0.323	—	1.7	—	7.1	—	1.4	—	4.1
	1,329	—	0.084	0.260	0.418	—	1.7	5.1	8.7	—	2.2	6.2	10.0
	1,889	—	0.097	—	0.533	—	1.6	—	9.9	—	2.6	—	5.4

^a To obtain these values, Eq. (2) was fitted to all nine boards at each condition using a least squares procedure. Values of n greater than 10 were set equal to 10.

shown in Table 2. All nine boards, three of each thickness, are represented by the S_T , F_{cr} , and n values for a given condition. The first data point for each board was not included in this analysis. The unsteady-state condition that occurred as the boards initially warmed caused the flux during the first period to be unpredictable. It was higher, lower, or similar to the other data in the constant rate period.

The following three sections show that the three parameters, F_{cr} , S_T , and n , can be predicted from the dryer conditions. The dryer conditions are T_d , $T_d - T_w$, and v .

Predicting the constant rate flux, F_{cr}

If a board is at a high enough moisture content, it will exhibit a constant rate drying period. In practice, this period may or may not be observed, depending on the warmup period, the intensity of drying, and the initial moisture content. Rapid drying, thin boards, low moisture contents, and low wood permeabilities tend to disallow the existence of a constant rate drying period.

The advantage of expressing drying in terms of a flux (lb/h/ft²) instead of the more traditional drying rate (%/h) becomes apparent during the constant rate period. During this period, when the rates of heat and mass transfer depend only on the air and surface conditions, boards of all thicknesses exhibit the same flux; however, their drying rates are inversely proportional to the thickness and specific gravity.

In the constant rate period, heat transfer controls the drying rate, and the surface of the board is at or near the wet-bulb temperature. For a given air velocity, the value of F_{cr} is approximately proportional to the temperature difference between the surface of the board and the air. All flux data for a velocity of 1,329 ft/min are plotted as a function of wet-bulb depression (Fig. 3). The relationship is not quite linear because of the heat transfer characteristics changing with air properties. Therefore, a quadratic equation was fitted to these data to obtain Eq. (3). At a

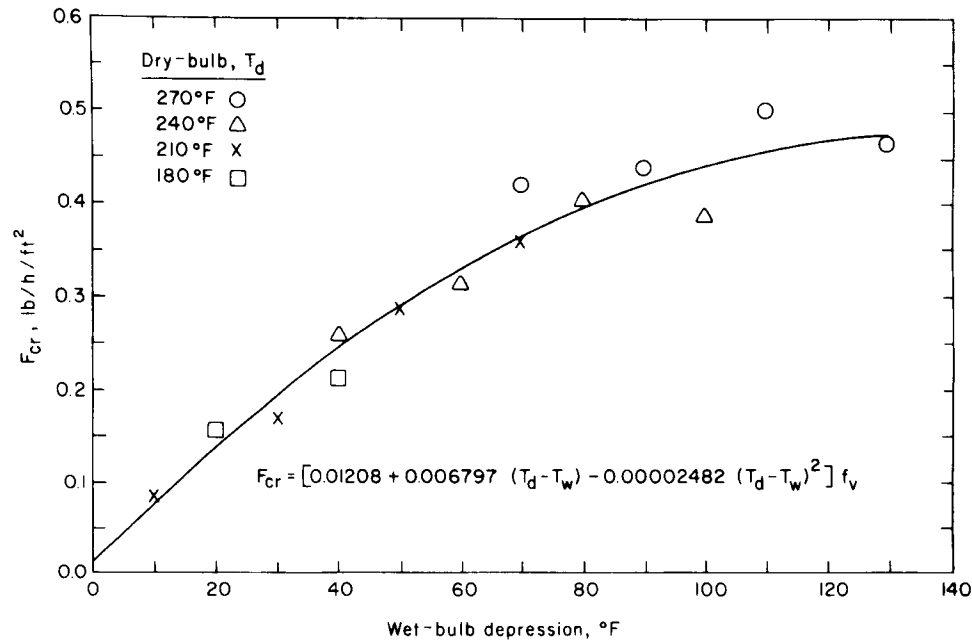


FIG. 3. The dependence of the constant rate flux, F_{cr} , on the wet-bulb depression for a constant air velocity of 1,329 ft/min. (ML89 5682)

velocity of 1,329 ft/min, the velocity correction factor, f_v , is equal to unity (Fig. 3).

$$F_{cr} = [0.01208 + 0.006797(T_d - T_w) - 0.00002482(T_d - T_w)^2]f_v \quad (3)$$

For changes in flux with velocity as shown in Table 2, f_v was obtained using the following equation.

$$\begin{aligned} f_v &= (v/1,329)^{0.3} & (v < 1,329) \\ f_v &= (v/1,329)^{0.5} & (v > 1,329) \end{aligned} \quad (4)$$

The exponents 0.3 and 0.5 were selected so that Eq. (3) would fit the data for the low and high velocities, respectively. Within the limits of the data, the empirical form of Eq. (4) accounts for the observed effect. The fractional power is typical of the published heat transfer relationships.

It may be more appropriate to incorporate the Reynolds and Prandtl numbers into this analysis, therefore accounting for changes in gas velocity, density, viscosity, heat capacity, and thermal conductivity. However, when F_{cr} (Table 2) was fitted using various heat transfer relationships incorporating dimensionless groups, at best only 87% of the total variation was explained, while Eq. (3) accounts for 95% of the total variation. In addition, Eq. (3) requires significantly less computation than the conventional heat transfer correlations.

At some drying conditions, for example, with a dry-bulb temperature of 270 F and a wet-bulb temperature of 140 F, a constant rate drying period did not occur during the experiments. In these cases, F_{cr} may be higher than the experimentally

observed value, F_m ; however, when the correlation is applied at moisture contents within the experimental range, fluxes lower than F_{cr} are predicted, which correspond to the observed fluxes.

Predicting the slope, S_T

As the moisture content approaches the EMC, the exact shape of the function relating flux and moisture content depends on the mechanisms by which moisture is being transferred from the interior of the wood to the surface. If the slope of the flux versus moisture content relationship decreases as the EMC is approached, diffusion is indicated. An increasing slope indicates capillarity. A constant slope implies that a combination of diffusion and capillarity are occurring (Thodos 1943). For southern pine wood at high temperatures, a constant slope, or a straight line such as the lower asymptote in Fig. 2, is observed. At the EMC, the flux is zero.

The slope of the lower asymptote, S_T , depends on the rate of moisture movement to the surface of the board. If one assumes that bound water diffusion is the primary mechanism, then the rate depends on the diffusion coefficient. Because the diffusion coefficient is a function of temperature, a relationship for S_T can be developed in which temperature is the only independent variable.

According to Treybal (1980), diffusion through polymers is an activated process that follows a temperature-dependent, Arrhenius-type expression

$$D_T = D_0 \exp(-H_D/RT) \quad (5)$$

where H_D is the activation energy, R the gas constant, T the absolute temperature, and D_0 a constant. If the slope of the line, S_T , is proportional to the diffusion coefficient, D_T , then by substituting S for D in Eq. (5), we obtain

$$S_T = S_0 \exp(-H_D/RT) \quad (6)$$

Equation (6) now expresses the slope of the lower asymptote as a function of temperature and two constants, H_D and S_0 . These constants will be obtained from the experimental data.

In Fig. 4, all values of S_T from Table 2 are plotted as a function of $1/T$ on semilog coordinates with T as the dry-bulb temperature R . The dry-bulb temperature was selected over the wet-bulb temperature because as the boards approach M_c , the internal board temperature will approach the dry-bulb temperature. This was confirmed by temperature measurements during the drying tests. The slope of the line in Fig. 4 is $-H_D/R$. After eliminating the three points that were well off the line, H_D and S_0 were determined to be 14,220 Btu/lb mole and 150.4 lb/ft²/h/%, respectively. This activation energy is lower than that reported by Stamm (1964), Choong (1963), and Siau (1984); however, this study is at temperatures and moisture contents higher than those of the previous work. The final equation used to predict the slope of the function relating flux versus moisture content as the moisture content approaches the EMC is

$$S_T = 150.4 \exp(-7,156.5/T) \quad (7)$$

The three points that were eliminated had been obtained at the 210 F dry-bulb and 200 F wet-bulb condition. The EMC at this condition is quite high, 10.3%.

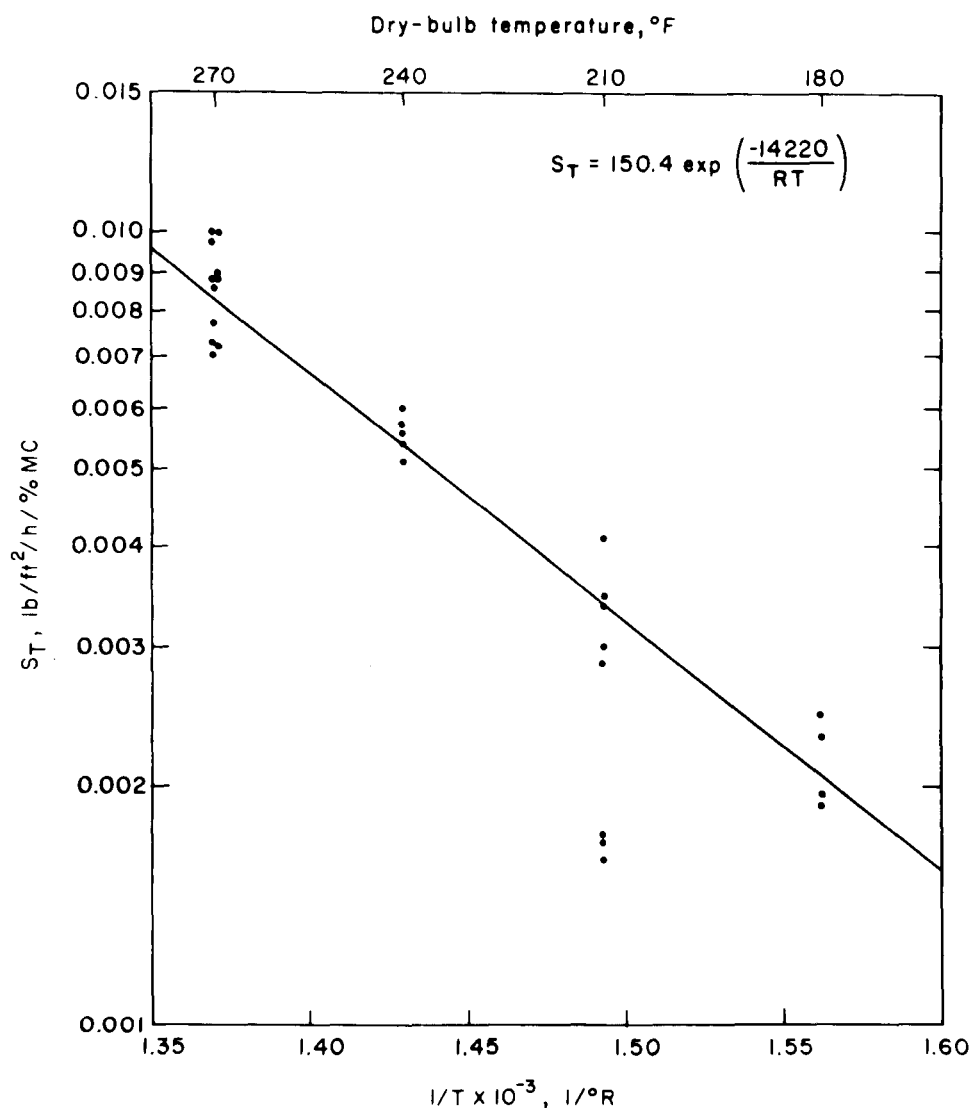


FIG. 4. S_T values from Table 2 plotted against the reciprocal of the dry-bulb temperature. (ML89 5681)

Because activation energy is a function of moisture content and temperature, eliminating these points is justified. Randomization of the experiment and careful control of the dryer make it unlikely that these three points are outliers owing to experimental error.

As previously discussed, S_T should not depend on velocity; however, at high temperatures it appears to increase as the velocity increases. Because this effect was small compared to the temperature effect, it was not included in the correlation. This will make the correlation easier to apply and does not significantly hurt its predictive ability.

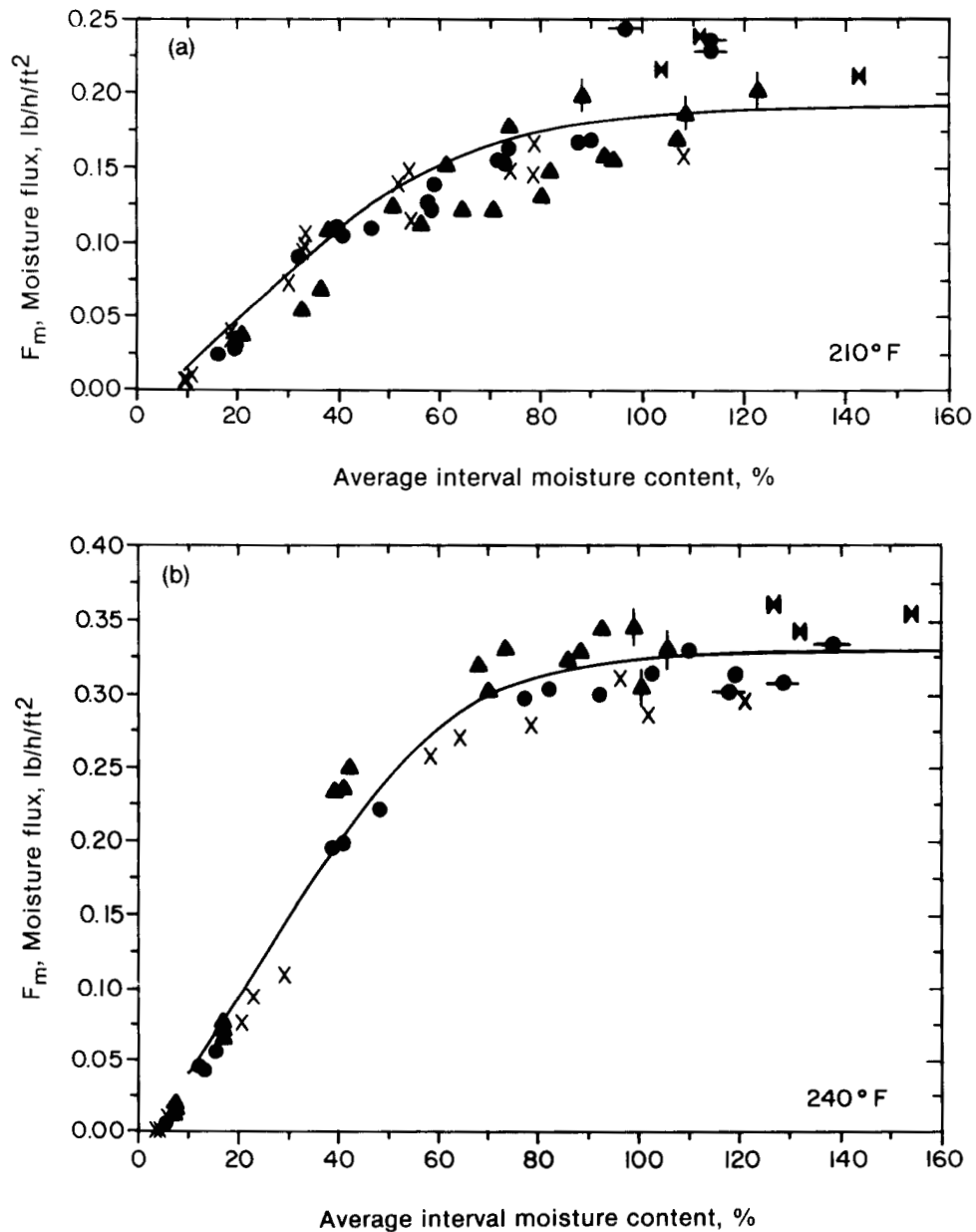


FIG. 5. Experimental data and the predicted fluxes at 1,329 ft/min, 180 F wet-bulb temperature, and (a) 210 F, (b) 240 F, and (c) 270 F dry-bulb temperatures. All three board thicknesses are plotted.

Predicting the transition variable, n

The value of n was found to be dependent upon wet-bulb depressions less than or equal to 46 F. A least squares procedure was applied to values of n in Table 2. The resulting linear equation is

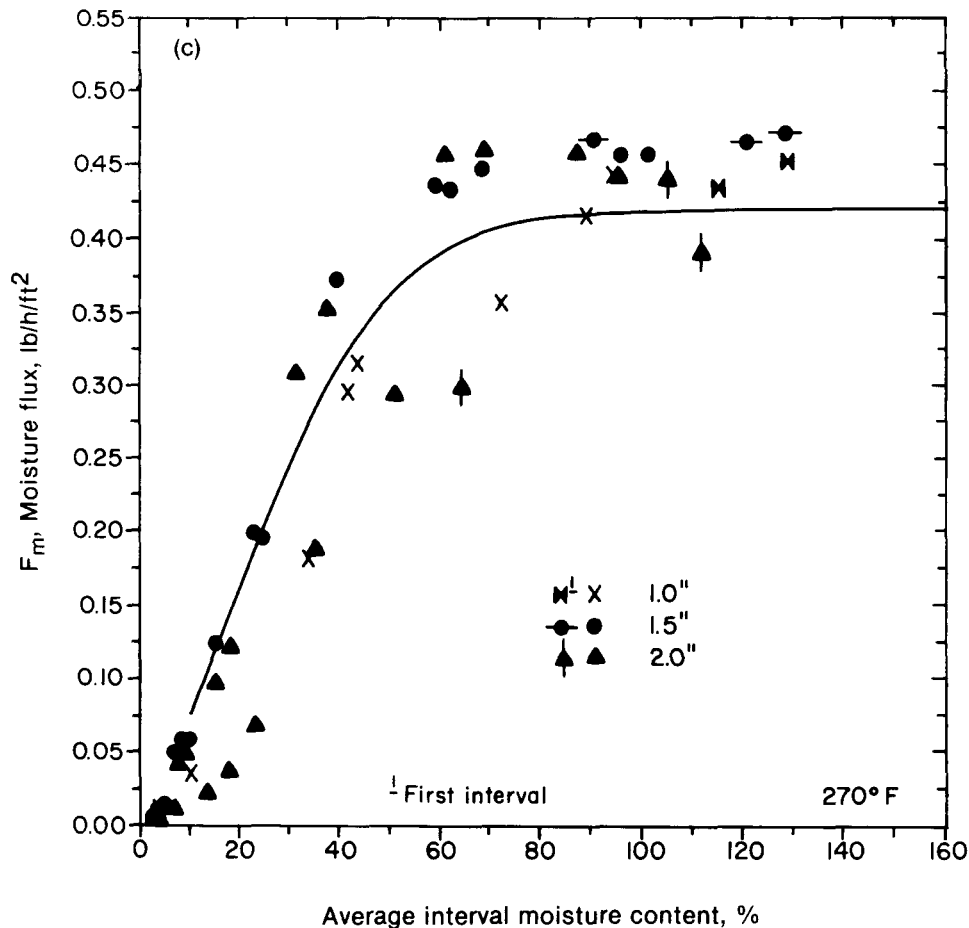


FIG. 5. Continued. Each symbol represents a single board. Also shown are the first interval fluxes. These were not used in the analysis. (ML89 5749; ML89 5750; ML89 5751)

$$\begin{aligned}
 n &= 0.75 + 0.093(T_d - T_w) & (T_d - T_w < 46 \text{ F}) \\
 n &= 5 & (T_d - T_w > 46 \text{ F})
 \end{aligned}
 \tag{8}$$

Since Eq. (2) is relatively insensitive to n for values greater than 5, n can be considered a constant, $n = 5$, for all values of $T_d - T_w > 46 \text{ F}$. The effect of n on the position of the curve generated by Eq. (2) is shown by the segmented line in Fig. 2. At this time, no physical significance can be attributed to this coefficient, n .

A very high value of n indicates that the data follow the two asymptotes (Fig. 2), curving sharply at their intersection point. Lower values of n decrease the sharpness in the knee of the curve. Presenting n as a linear function of wet-bulb depression up to 46 F in Eq. (8) is necessary, at least in part, due to the predicted S_T being too high at conditions with low wet-bulb depressions. This may occur because, at low wet-bulb depressions, the EMC is high and the assumption of a constant H_D may be violated.

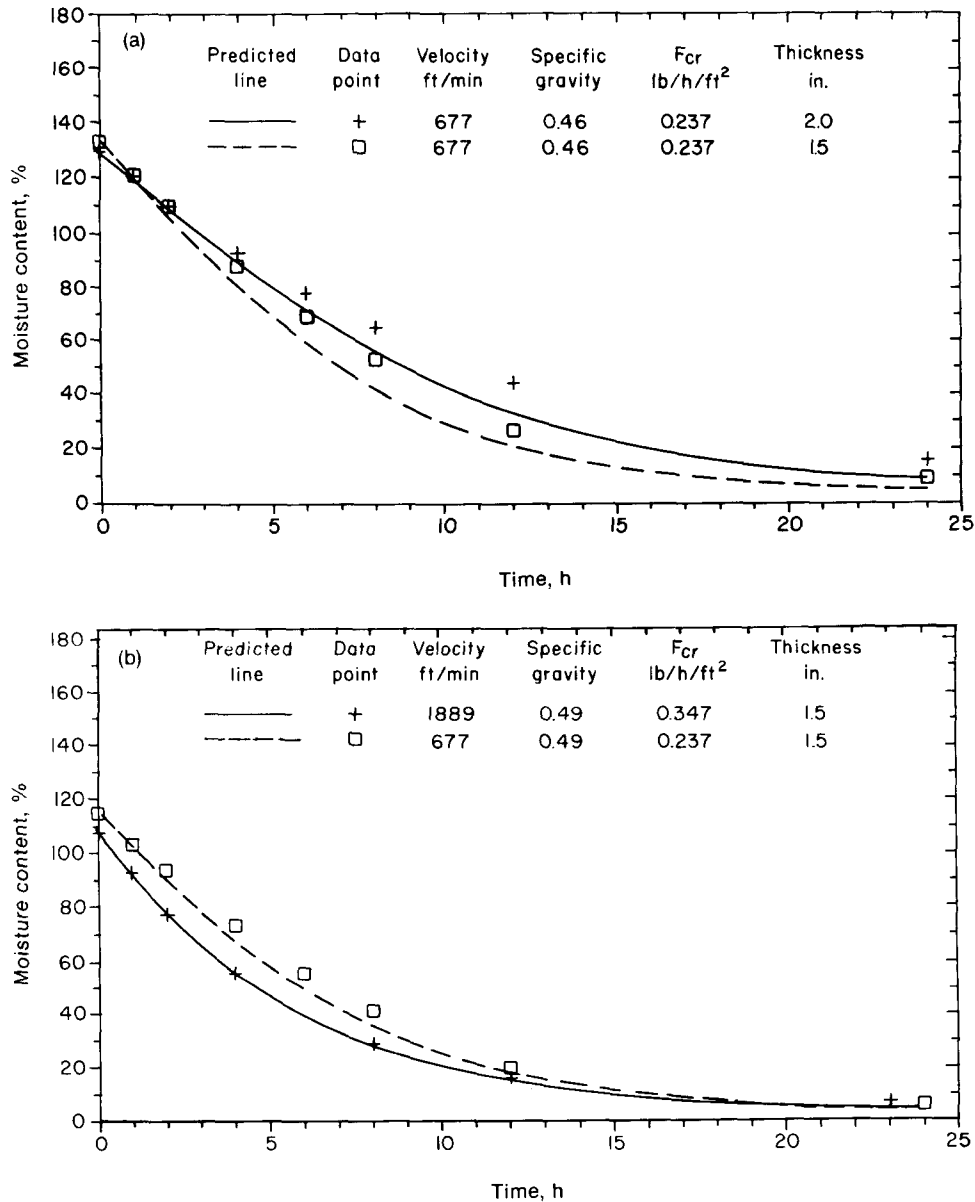


FIG. 6a, b, c. Moisture content versus time; data and predicted curves for dry- and wet-bulb temperatures of 210 F and 160 F, respectively. Each symbol represents data from a single board. Each line is predicted from Eq. (9). (ML89 5746; ML89 5747; ML89 5748)

DISCUSSION OF CORRELATION

The experimental range used in these experiments represents that which is found in commercial, high-temperature southern pine dryers. Within this range, the correlation will reliably predict the flux. Figure 5 shows the experimental data at a wet-bulb temperature of 180 F and three dry-bulb temperatures, (a) 210 F,

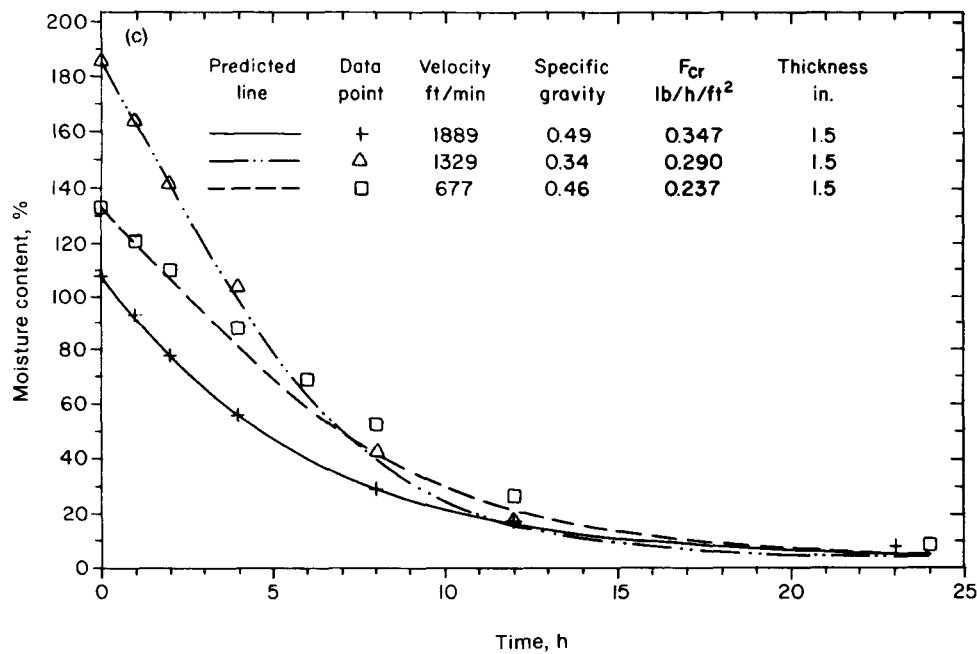


FIG. 6. Continued.

(b) 240 F, and (c) 270 F, respectively. The three solid lines were generated using Eq. (2). The three parameters in Eq. (2), F_{cr} , S_T , and n , were calculated from Eqs. (3), (7), and (8), respectively. The constant rate drying period is shown to end at about 80 to 100% moisture content. As the moisture content approaches the EMC, the slope of the curve increases with increasing dry-bulb temperature.

The usefulness of the flux correlation in Eq. (2) is in the calculation of board moisture content versus time for any drying condition. Eq. (2) is independent of board thickness ℓ and dry wood density ρ_d . These must be combined with the flux to obtain the rate of moisture change. Thus, the moisture content of a board at any time may be calculated by subtracting from the initial moisture content the rate of moisture content change times the elapsed time. This is expressed as an integral equation

$$M_c = M_i - \frac{200}{\ell \rho_d} \int_0^t F_m dt \quad (9)$$

Using this expression, the current moisture content, M_c , at any time in the drying process can easily be evaluated by numerical integration. The moisture content as a function of time is predicted and plotted with experimental data in Fig. 6. These examples are for individual boards at a dry-bulb temperature of 210 F and a wet-bulb temperature of 160 F.

The effect of board thickness on the relationship between moisture content and time can be seen by comparing the two lines in Fig. 6(a). These data were selected because the two boards had similar specific gravities and initial moisture contents. The 2-in. board changes moisture content at a slower rate than does the 1.5-in. board because of its larger mass per unit of surface area. Equation (2) predicts

identical flux versus moisture content relationships for each board. The application of Eq. (9) accounts for thickness and correctly predicts the experimental data.

The effect of air velocity can be seen by comparing the two lines in Fig. 6(b). The data were selected because the two boards had similar specific gravities and initial moisture contents. The 1,889-ft/min curve is slightly steeper.

The effect of specific gravity is similar to thickness. Ignore for the moment the differences in velocity between the lines in Fig. 6(c) and compare the line that starts at 186% moisture content to either of the other solid lines. The board represented by this line is low in specific gravity and changes moisture content at a very high rate. In this case, the velocity and therefore the predicted flux are between those of the other two boards. However, a pound of water leaving this board is a larger fraction of the dry-board weight, resulting in a larger rate of moisture content change than in either of the other two boards.

CONCLUSIONS

Applying the physics of drying to the development of a correlation based on data from full-sized southern pine boards resulted in a robust predictive equation for commercial, high-temperature drying conditions. The equation and experimental data agree well in the temperature range from 180 F to 270 F.

The assumption that heat transfer at the surface of the piece is controlling the drying flux at high moisture contents is valid. At low moisture contents, the drying flux is related to the dry-bulb temperature and difference between the moisture content and the equilibrium moisture content. Using flux instead of rate of moisture content change to model moisture removal from the board greatly simplifies the correlation procedure.

The main usefulness of this correlation will be to predict the moisture content of each board in a full-kiln dryer simulation. Such a simulation will allow the effect of new control schemes, drying schedules, and operating techniques to be modeled and optimized.

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