EMPIRICAL MODEL TO CORRELATE PRESS DRYING TIME OF LUMBER TO PROCESS AND MATERIAL VARIABLES

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ABSTRACT

Loblolly pine lumber was press dried with thickness and platen temperature as variables. Drying times ranged from about 20 to 85 minutes, depending on thickness and platen temperature. The dried lumber was free of collapse and surface and internal checking, although some surface darkening was noted at the highest platen temperature. A heat-transfer-based empirical model that relates press drying time of lumber to certain process and material variables was developed and tested. The potential use of the model is for a segregation system that will group boards of similar drying times so that they can be dried together, thus reducing variability in final moisture content and taking fullest possible advantage of the warp suppression benefits of press drying. The model relates drying time to several board characteristics that can be measured at production line speed so that an immediate grouping decision can be made on each board just before drying. The model predicts the expected consequences of changing the process and material variables and has potential as the base for a segregation system.

Keywords: Drying, press drying, southern pine, warp.

INTRODUCTION

In a study recently completed (Simpson et al. 1988), we found that warp, which often occurs in kiln drying fast-grown plantation southern pine 2 by 4s, can be suppressed by press drying instead of kiln drying. The percent of 2 by 4s downgraded because of warp could be kept to below 4% in press drying compared to 18% to 30% in lumber kiln dried in a laboratory dry kiln. Drying time from 120% to 15% moisture content is about 90 minutes at a platen temperature of 350 F.

Current research at the Forest Products Laboratory (FPL) is aimed at optimizing press drying, that is, minimizing warp, press time, and variability in final moisture content. One way to approach optimization is to develop a mathematical model that will relate press drying time to process and material variables. With such a model, it is possible to estimate the effect of the variables on drying and thus

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make decisions on how best to manipulate or control them during drying. The objective of our study was to develop one possible model and test it with experimental data.

The benefits of press drying can be optimized by dealing with the variability in lumber, which can be dealt with by modeling. Thickness of lumber entering a press is variable; the degree of variability depends on the precision of sawing or if the lumber was presurfaced with a planer before drying. Nonuniform thickness causes variability in the degree of restraint each board receives. Too little pressure on thin boards may not effectively restrain warp, and excessive pressure on thick boards also has adverse effects (Simpson et al. 1988). Variable thickness also causes drying time to final moisture content to vary because thin boards may not receive good heat transfer from the platens.

Initial moisture content and specific gravity are also variables that affect drying time. Final moisture content after press drying is thus also variable; neither overdrying nor underdrying are desirable. Overdrying is not desirable because of the correlation between final moisture content and warp—the lower the moisture content, the more warp expected. Underdrying is not desirable because boards may not meet grade moisture content specifications and because more warp may develop during the additional drying that will occur after removal from the restraint of a press.

A step in the direction of optimizing press drying will be a segregation system to reduce variability in response by grouping like boards within the same press cycle, thus preventing widely differing boards from being dried together in the same press cycle. Such a model will provide the basis for a segregation system, and the potential of the model developed in this paper will be evaluated.

LITERATURE REVIEW

Models to describe drying of wood have been developed by many investigators. The purpose of modeling is to mathematically describe drying in terms of the response of the wood to process and material variables, so that we can estimate the responses as well as gain insight into drying. When we can do this with some degree of confidence, then it is possible to run simulations to estimate the consequences of manipulating these variables. The result is a savings of time-consuming and expensive laboratory and pilot experiments.

Rosen (1983) has reviewed a number of models that describe wood drying and categorized them by type—diffusion models, heat and mass transfer models, and empirical models. Diffusion models are based on the mathematics of diffusion and require a knowledge of the diffusion coefficient and how it varies with temperature, moisture content, and species. They also require knowledge of boundary conditions that are not always well known. Heat and mass transfer models are usually based on the partial differential equations that describe transfer phenomena in capillary-porous materials. They can be quite complex in terms of the mathematics and numerical analysis involved, the knowledge required of material properties, and the conceptual theory of the mechanisms involved in water flow within the wood and from the surface. Empirical models are often a compromise from rigorous theoretical models that are too complex to deal with in a practical way. They can draw on theory for the basic framework of a model but then follow a more expeditious route in making simplifying assumptions and relying on experimental data to correlate variables. Rigorous theoretical models are more difficult to develop than empirical models but, in general, would be expected to have broader applicability. The narrower range of applicability of empirical models, however, may be offset by the relative ease and speed with which they often can be developed for a specific application. We hope investigators will continue to pursue both approaches.

A detailed description of the many models that have been developed for wood drying is beyond the scope of this paper. The reader is referred to Rosen (1983) for a description of many of these models. Some papers of particular interest are by Ashworth (1980), Bramhall (1979), Comstock (1971), Hart (1981), Spolek and Plumb (1980), Stanish et al. (1986), and Tschernitz (1985).

DESCRIPTION OF THE MODEL

Our objective was to develop a model to correlate drying time to material and process variables. In addition, we wanted the model to predict drying time from characteristics that can be easily, quickly, and nondestructively determined from green boards, so that an immediate sorting decision can be made for each board just before drying. The model developed by Tschernitz (1985) for thick southern pine veneer provided the framework to develop such a model. It is a heat transfer model based on an expanding dry zone and retreating wet zone, separated by an interface where water is evaporating (Fig. 1). This model assumes that heat transfer is the mechanism controlling drying rate. The point of departure from Tschernitz's model is his Eq. (8):

$$\tau = \frac{M_0 \rho Q (L/2)^2 (1 - M_f/M_0)^2}{2k(T_s - T_c)} \tag{1}$$

where

- τ = time,
- M_0 = fractional wet zone moisture content (green),
- M_f = average fractional moisture content of wet and dry zones (approximated by final moisture content),
- ρ = wood density,
- Q = latent heat of vaporization of water,
- L = thickness,
- k = thermal conductivity of dry wood,
- T_s = surface temperature of the wood (approximated by platen temperature), and
- T_c = temperature at the center of the board (usually near 212 F in a permeable species).

Equation (1) does not predict the drying time of veneer very well because of the difficulty of estimating the terms ρ, Q, k, and T_c. Tschernitz modified it to a generalized form where these terms are adjustable coefficients that can be determined by fitting the equation to experimental data by nonlinear regression. The

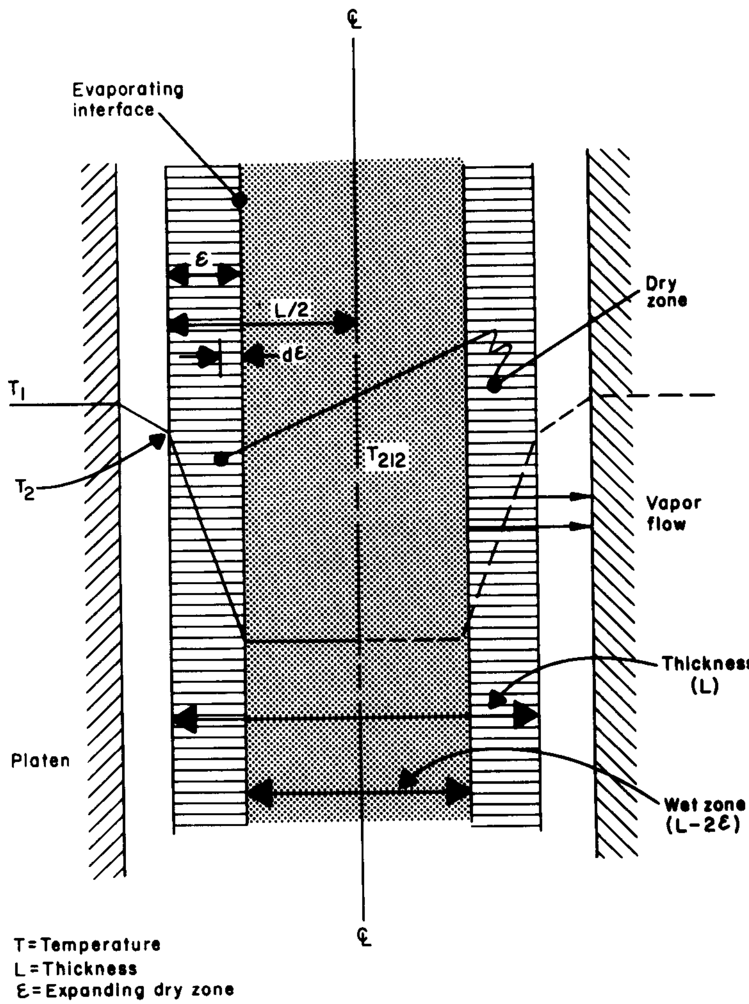

FIG. 1. Model for heat transfer and vapor flow in press drying. (ML88 5750)

result is an equation with empirically determined coefficients that correlates drying time to platen temperature and thickness.

Equation (1) would be even more useful if, in addition to adjustable coefficients that can be determined empirically, there were also physical characteristics that affect drying time that could be measured on green boards just before press drying. As a result, the press time required for any particular board to reach the desired final moisture content could be estimated. Initial moisture content M_0, density ρ, and thickness L are physical characteristics that influence drying rate, but M_0 and ρ cannot be quickly and accurately determined before drying. Equation (1) can be modified to substitute characteristics that can be estimated at production line speeds. If we define M_0 and M_f in terms of the definition of moisture content,

$$M_0 = \frac{W_0 - W_d}{W_d}$$

and

$$M_f = \frac{W_f - W_d}{W_d}$$

where

W_0 is initial green weight,
W_f is final weight, and
W_d is oven-dry weight.

Then substituting into Eq. (1),

$$\tau = \frac{\rho Q(L/2)^2[W_0 - W_d(M_f + 1)]^2}{2kW_d(W_0 - W_d)(T_s - T_c)} \tag{2}$$

Density ρ still appears in Eq. (2) and is not quickly measurable. However, it can be expressed in terms of oven-dry weight W_d and green volume V_0:

$$\rho = \frac{W_d}{V_0}$$

Substituting into Eq. (2),

$$\tau = \frac{Q(L/2)^2[W_0 - W_d(M_f + 1)]^2}{2kV_0(W_0 - W_d)(T_s - T_c)} \tag{3}$$

Equation (3) considers both density and initial moisture content but expresses them in terms of initial green weight W_0 and initial green volume V_0, which can be scanned at production line speeds. Thickness L is also easily measured, and final moisture content M_f and platen temperature T_s are both known quantities. Note that Eq. (3) will tend to group thick boards together, which is advantageous from both the drying time and warp suppression standpoints. The exponent 2 on the thickness term $(L/2)$ is a theoretical value and in practice is often found to be between 1.5 and 2 (Kollmann and Côté 1968; Tschernitz 1985). Thus, Eq. (3) should be rewritten so that the exponent is adjustable, that is

$$\tau = \frac{Q(L/2)^n[W_0 - W_d(M_f + 1)]^2}{2kV_0(W_0 - W_d)(T_s - T_c)} \tag{4}$$

The remaining parameters that must be estimated are latent heat of vaporization Q, thermal conductivity k, wood temperature T_c, thickness coefficient n, and oven-dry weight W_d. There are several ways we can use Eq. (4), all of which involve fitting experimental data by nonlinear regression to determine adjustable coefficients that will allow the equation to calculate drying times. The five potential adjustable regression coefficients in Eq. (4) are thus Q, n, W_d, k, and T_c. There are several ways to proceed, depending on how many of the five are to be estimated by regression and how many by some means based on physical principles. All approaches involve experimentally determining the time τ required to reach final moisture content M_f as a function of L, W_0, V_0, and T_s, and then fitting the data by nonlinear regression. A few of the possible approaches are as follows:

1. Treat all five terms as regression coefficients. In doing this we can first combine $Q/2k$ into one coefficient. We could also combine the terms $T_s - T_c$ with $Q/2k$, but it is desirable to retain the individuality of T_s because of its physical importance in using the model.

2. Make physical estimates of Q and k. The relationship between Q and temperature is well known, and over the temperature range of interest in press drying, it can be approximated as 950 Btu/lb; k can be estimated from (Forest Products Laboratory 1987)

$$k = SG(1.39 + 0.028M) + 0.165 \quad (5)$$

where

M is moisture content (%), and
SG is specific gravity.

Equation (5) is based primarily on data taken at 75 F and is likely to be somewhat in error at the high temperature of press drying. Thermal conductivity increases approximately 10% for every 90 F increase in temperature. The problem in using Eq. (5) is in determining the correct value for M. Final moisture content M_f is the only moisture content available in the model and provides an approximation of M that may or may not suffice.

3. Correlate W_d with initial green weight W_0. There is no quick and easy way to measure oven-dry weight W_d. If W_d is treated as a regression coefficient, the value that comes from the regression analysis will be some average value for all boards used to establish it. In reality, each board has its own individual W_d. Thus, it would be desirable to estimate W_d more closely than regression analysis allows.

EXPERIMENTAL PROCEDURE

The experimental material was 35-year-old plantation loblolly pine from Arkansas. It was obtained as freshly sawn, nominal 2- by 4-inch lumber. The experimental plan was to press dry boards for certain time periods to different final moisture contents, and then fit that data to Eq. (4) to determine the nonlinear regression coefficients. Three nominal thicknesses were dried (1.0, 1.3, and 1.6 inch) and three platen temperatures (350, 415, and 475 F) were used. After surfacing to thickness, the green weight, exact thickness, width, and length were measured on each board. Press drying was done in a single opening, 3- by 3-foot press. All press runs contained nine boards. Each board was cut to a 32-inch length and end coated with two coats of a heavily pigmented aluminum paint to retard drying from the end of the boards.

At this point, we did not know the time required to dry to the target moisture content of 15%, thus, we were unable to chose experimental drying times with any degree of confidence. Our only previous experience in press drying loblolly pine was at 350 F and about 1.8 inch in thickness. To establish the experimental drying times, we conducted nine exploratory press runs (three temperatures times three thicknesses). We estimated those nine exploratory run times using the general observation from our previous experience that loblolly pine 2 by 4s, 1.8 inch thick, 120% green moisture content, and specific gravity of about 0.45, will dry to 15% moisture content at 350 F platen temperature in about 90 minutes. This provided information to approximate the regression coefficients of Eq. (4) and

TABLE 1. *Experimental press drying times.*

Board thickness (inch)	Press drying time (minutes) at three platen temperatures					
	350 F		415 F		475 F	
	t_1	t_2	t_1	t_2	t_1	t_2
1.0	30	40	20	25	18	24
1.3	55	65	35	45	30	38
1.6	80	90	55	65	40	50

calculate these nine exploratory press times. They ranged from a low of 17 minutes for 1.0-inch thickness at 475 F platen temperature to 82 minutes for 1.6-inch thickness at 350 F. After press drying the boards in the exploratory runs, they were weighed and measured again and then oven-dried at 220 F for 48 hours, so that green moisture content and moisture content after press drying could be determined.

The actual final moisture contents observed in the exploratory runs provided a basis to establish the press times in the main part of the study. By observing how close they were to the target moisture content of 15%, judgments could be made of the best experimental drying times. To fit Eq. (4) to actual drying data, it is desirable to have experimental data that cover a reasonably wide range of drying times and final moisture contents. Thus, for each of the nine combinations of thickness and platen temperature, we chose two experimental drying times. The combination of two times plus the natural variation of the wood ensures a range of final moisture contents. The experimental drying times are listed in Table 1. Weights and measurements were recorded before and after press drying, and then the oven-dry weight of each board was determined. On one board in each press run, thermocouples were placed at the surface and at depths of half and quarter thicknesses.

RESULTS

Drying

Drying times ranged from less than 20 minutes for 1.0-inch-thick boards at 475 F to about 85 minutes for 1.6-inch-thick boards at 350 F. Boards were

TABLE 2. *Summary of wood temperatures at end of press drying.*

Platen temperature (F)	Board size (inch)	Wood temperature (F)		
		Half thickness	Quarter thickness	Surface
350	1.0	206	211	—
	1.3	205	211	335
	1.6	209	217	341
415	1.0	211	386	395
	1.3	206	303	393
	1.6	209	302	410
475	1.0	212	221	467
	1.3	210	217	470
	1.6	209	217	473

TABLE 3. *Regression coefficients and residual mean squares for Eq. (4).*

Coefficients from regression	$Q/2k$ (hour·feet·F) / (pounds)	n	W_d (pounds)	T_c (F)	Residual sum of squares (minute²)
All	1,256	2.205	−0.8157	194.3	37.2
$Q/2k$, n, T_c	1,102	1.651	—	145.97	79.5
n, T_c	—	2.18	—	96.2	130.1

essentially free of collapse and surface and internal checking. Only occasional short, narrow, and shallow surface checks were noted. Surface darkening was noted at 475 F.

A summary of the internal and surface temperatures at the end of each drying cycle is given in Table 2. At all platen temperatures, the temperature at the half thickness remained near the boiling temperature. At the quarter thickness, the temperature was somewhat higher than at the center, although there was no apparent explanation of the considerably higher temperatures at 415 F platen temperature. Surface temperatures approached the platen temperatures.

Evaluation of the model

Attempts were made to evaluate Eq. (4) by all three of the methods outlined in the section on the description of the model. The basic approach was to fit the experimental data to Eq. (4) by nonlinear regression to relate drying time to final moisture content through the material and process variables thickness, green weight, green volume, platen temperature, and the regression coefficients $Q/2k$, n, W_d, and T_c. In the first analysis, all four coefficients, $Q/2k$, n, W_d, and T_c, were treated as regression coefficients. In the second analysis, oven-dry weight W_d was related (in a separate experiment) to green weight W_0 over the moisture content range of approximately 80% to 150% by

$$W_d = 303.9 + 0.3436 W_0 \quad \text{grams}$$

TABLE 4. *Predicted and experimental drying times.*

Board thickness (inch)	Press drying time (minutes) at three platen temperatures					
	350 F		415 F		475 F	
	Exp[a]	Model	Exp	Model	Exp	Model
1.0	33.0	34.7	22.0	25.3	17.0	18.9
	30.0	26.2	20.0	15.3	18.0	17.0
	40.0	34.5	25.0	18.9	24.0	22.7
Average	34.3	31.8	22.3	19.8	19.7	19.5
1.3	55.0	55.3	38.0	41.1	29.0	29.9
	55.0	49.4	35.0	35.3	30.0	31.6
	65.0	59.6	45.0	45.4	38.0	34.8
Average	58.3	54.8	39.3	40.6	32.3	32.1
1.6	82.0	73.7	55.0	52.1	43.0	42.1
	80.0	81.4	55.0	52.7	40.0	39.6
	90.0	88.7	65.0	63.8	50.0	49.0
Average	84.0	81.3	58.3	56.2	44.3	43.6

[a] Experimental.

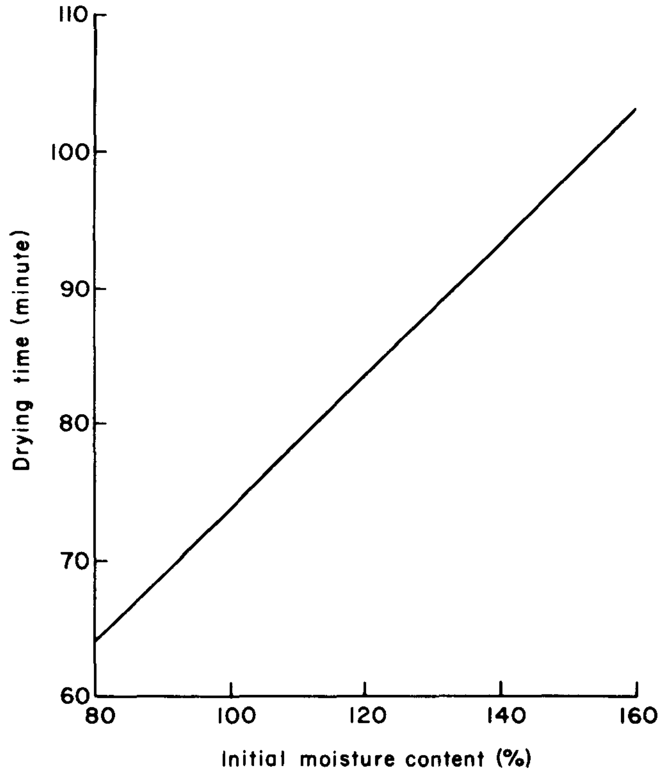

FIG. 2. Effect of green moisture content on the estimated time required to press dry loblolly pine 2 by 4s to 15% moisture content at 415 F platen temperature. (ML88 5751)

leaving $Q/2k$, n, and T_c as the regression coefficients. In the third analysis, latent heat of vaporization Q and thermal conductivity k were estimated as described in the section on the description of the model, leaving only n and T_c as the regression coefficients. The regression coefficients and the residual mean squares of each of the three analyses are shown in Table 3. The residual mean square is minimum when all four coefficients are treated as regression coefficients. However, the oven-dry weight coefficient W_d is negative, and it causes Eq. (4) to predict a decrease in drying time as final moisture content decreases, which makes no physical sense. When oven-dry weight W_d is estimated from green weight W_0 instead of being treated as a regression coefficient, the residual mean square is higher, but, as will be shown later, Eq. (4) predicts reasonable responses to changes in variables. When Q and k are estimated from physical principles, the residual mean square is higher still, but Eq. (4) also predicts reasonable responses to variable changes.

When the results were examined, it was apparent that the data from the exploratory runs were as valid as that of the main runs. Thus, the regression coefficients in Table 3 were determined from combining data from both the exploratory and main press runs.

Table 4 shows the comparison of the drying times calculated using Eq. (4) with

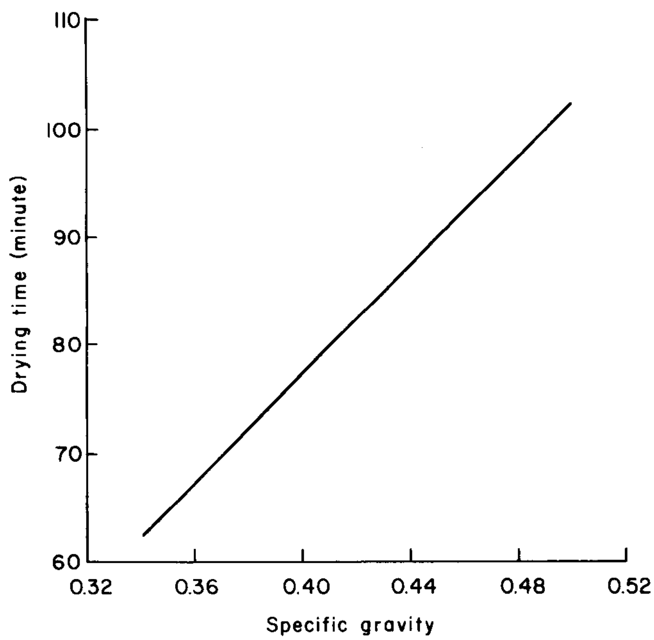

FIG. 3. Effect of specific gravity on the estimated time required to press dry loblolly pine 2 by 4s to 15% moisture content at 415 F platen temperature. (ML88 5752)

the experimental press times for each combination of platen temperature and nominal thickness (including the exploratory runs). The comparisons in Table 4 are based on the analysis with three regression coefficients, $Q/2k$, n, and T_c, and W_d estimated from W_0. The results show that, on the average, the model can estimate drying time reasonably closely.

NUMERICAL EXAMPLES OF THE MODEL

We can test the ability of Eq. (4) to predict the effect of the variables on drying time by systematically varying them and observing the effect on estimating drying time. For this example, the base values of the variables are 1.75 inch thick, 120% green moisture content, 15% final moisture content, a specific gravity of 0.425, and a platen temperature of 415 F.

Green moisture content

If we maintain a constant specific gravity (0.425) and vary green moisture content, we expect the model to predict an increase in drying time as green moisture content increases, because there is more water to be evaporated. Figure 2 shows that the model predicts this and that we might expect drying time to vary from about 64 to 103 minutes over a typical spread of initial moisture contents—80% to 160% (Simpson et al. 1988).

Specific gravity

If we maintain a constant green moisture content (120%) and vary specific gravity, we expect the model to predict an increase in drying time as specific

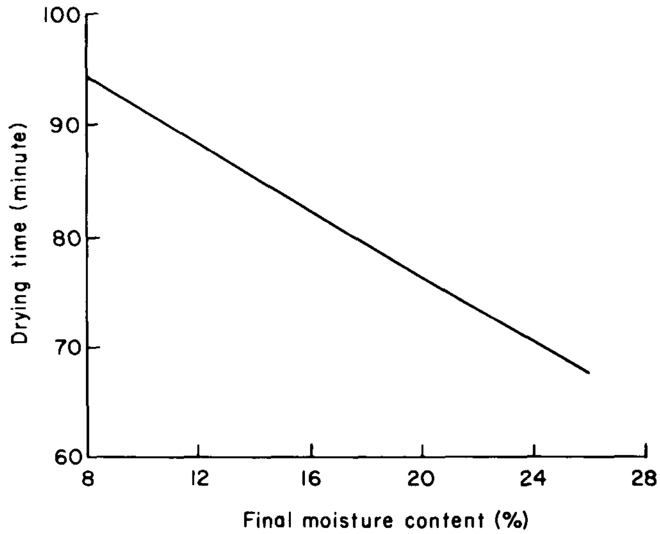

FIG. 4. Effect of final moisture content on the estimated time required to press dry loblolly pine 2 by 4s from 120% initial moisture content at 415 F platen temperature. (ML88 5753)

gravity increases, because there is more water present for a given moisture content. Figure 3 shows that the model predicts this, with a drying time to 15% moisture content of about 63 minutes for a specific gravity of 0.34 and about 102 minutes for a specific gravity of 0.50. (In this example, W_0 and W_d are adjusted for the varying specific gravity.)

Final moisture content

We expect the model to predict an increase in drying time as final moisture content decreases. Figure 4 shows this to be the case—a predicted 67 minutes to dry to 26% moisture content and 94 minutes to dry to 8% moisture content.

Platen temperature

We expect drying time to decrease as platen temperature increases. Figure 5 shows that the model predicts this, with drying times to 15% moisture content ranging from 215 minutes at 250 F to 63 minutes at 500 F.

Thickness

We expect drying time to increase as thickness increases, and Fig. 6 shows that this is predicted by the model. Drying time to 15% moisture content is predicted to be about 25 minutes for 1.0-inch-thick lumber and about 163 minutes for 2.5-inch-thick lumber. (In this example, V_0, W_0, and W_d are adjusted for varying thickness.)

The effect of thickness variation around a target thickness on drying time is also of interest from the segregation standpoint. In our previous study (Simpson et al. 1988), the 2 by 4s had a total range from thinnest to thickest of about ¼ inch. Figure 7 shows the effect of this variation. The thinnest boards (1.63 inch) require about 73 minutes to reach 15% moisture content, while the thickest ones

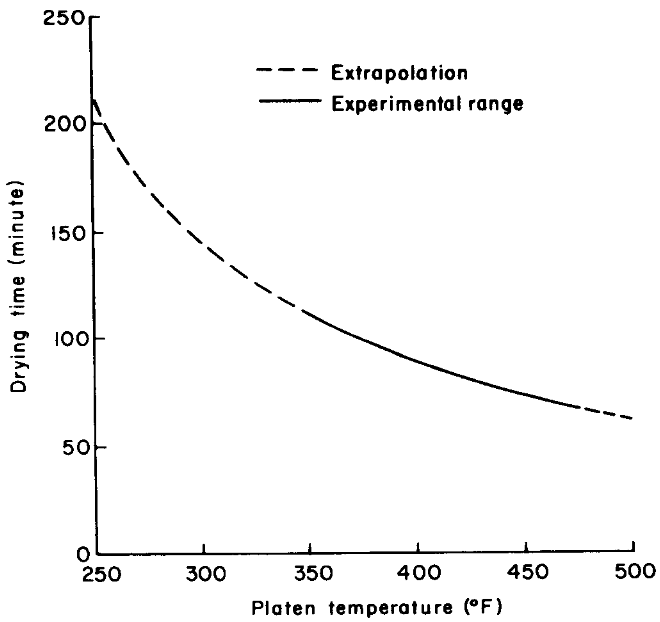

FIG. 5. Effect of platen temperature on the estimated time required to press dry loblolly pine 2 by 4s from 120% to 15% moisture content. (ML88 5754)

(1.87 inch) require about 95 minutes. Stated in different terms, if the thinnest boards were dried for 95 minutes, they would be oven-dried. If the thickest boards were only dried for 73 minutes, they would reach only 29% moisture content. By choosing the average time of 84 minutes, we would expect the thinnest boards to

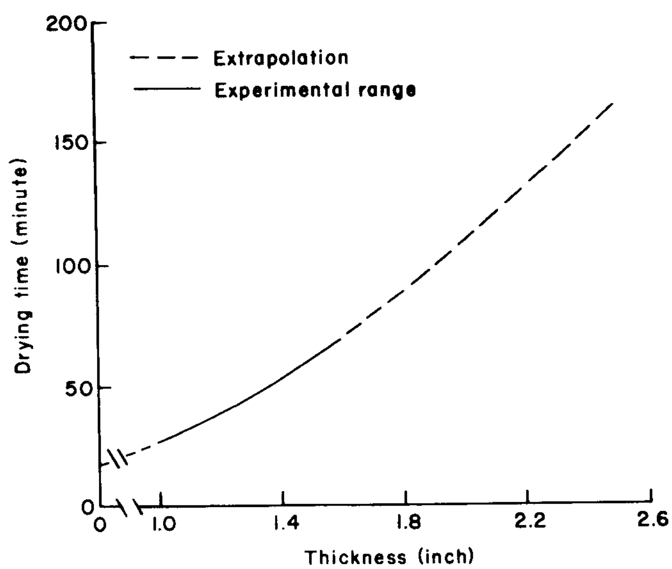

FIG. 6. Effect of thickness on the estimated time required to press dry loblolly pine 2 by 4s from 120% to 15% moisture content at 415 F platen temperature. (ML88 5755)

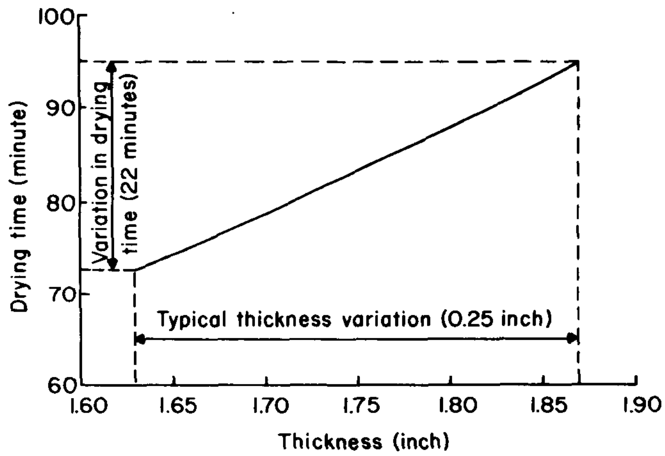

FIG. 7. Effect of thickness variation around a target thickness on the estimated time required to press dry loblolly pine 2 by 4s from 120% to 15% moisture content at 415 F platen temperature. (ML88 5756)

dry to about 7% moisture content and the thickest ones to about 22% moisture content.

EXAMPLE OF SEGREGATION

The ability of the model to segregate so that final moisture content variation is minimized can be shown in an example. The three variables that affect the time required to reach final moisture content are thickness, specific gravity, and initial moisture content. By choosing realistic ranges of these variables, the benefits of segregation can be illustrated. A high, medium, and low value was selected for each variable, as follows (the nature of the distribution that these variables might have is not considered in this example):

	Thickness (inch)	Initial moisture content (%)	Specific gravity
High	1.87	140	0.50
Medium	1.75	110	0.425
Low	1.63	80	0.35

The 27 combinations of these three variables at three levels result in calculated drying times [Eq. (4)] to 15% moisture content ranging from about 42 minutes (all three at low level) to 128 minutes (all three at high level). Without segregation, one might choose the average of 79 minutes as the drying time for all of the 27 conditions. Therefore, if all 27 were dried for 79 minutes instead of the exact time required to reach 15% moisture content, we would expect to see a large variability in final moisture content. By solving Eq. (4) for final moisture content as a function of press time (i.e., 79 minutes) and calculating final moisture content for all 27 conditions, a standard deviation (which includes two-thirds of the observations) can be calculated.

The first level of sorting could be into two groups—those whose estimated

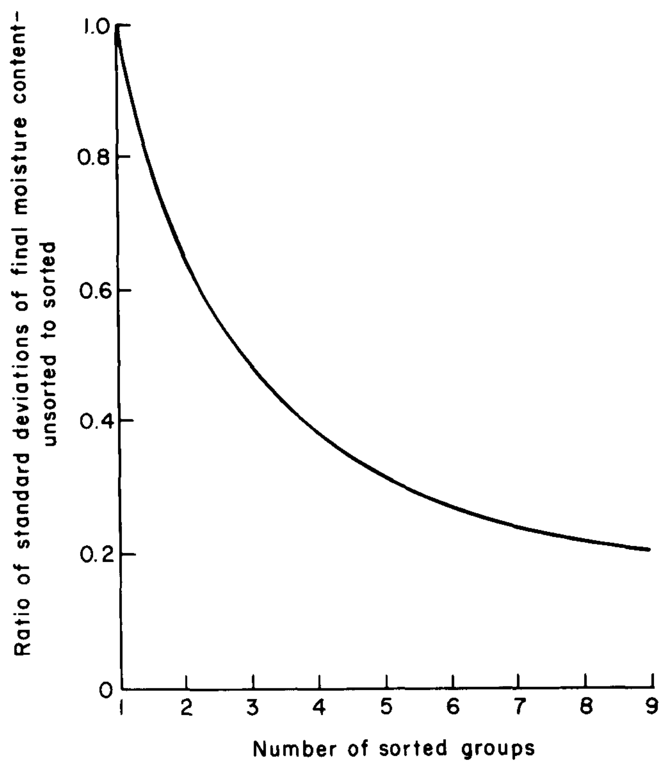

FIG. 8. Estimated decrease in the standard deviation of final moisture content in press drying as a function of the number of segregations by estimated drying time. (ML88 5757)

drying time to 15% moisture content is from 42 to 75 minutes and those from 75 to 128 minutes. The first group is dried for the average drying time in that group, 61 minutes, and the second group for the average drying time in that group, 95 minutes. With this sort, the standard deviation drops to 65% of the value with no sorts. The next level of sorting would be into three groups, those whose estimated drying times are below 70 minutes, those between 70 and 85 minutes, and those above 85 minutes. The drying times for these three groups are 57, 77, and 103 minutes, and the standard deviation now drops to 49% of the value with no sorting. As additional sorts are added, the standard deviation continues to drop, as shown in Fig. 8, and reaches 20% of the no-sort value after 10 sorts. The range of moisture content in this example is from 0% to 42% with no sorting to 9% to 21% after 10 sorts. Both the standard deviation and the range will approach zero as the number of sorts approaches the number of conditions (boards). The number of sorts would be determined considering both the reduction in variability desired as well as the practical limit on a manageable number of groups.

CONCLUSIONS

Loblolly pine lumber, ranging from 1.0 to 1.6 inch thick, can be press dried at platen temperatures ranging from 350 to 475 F without developing collapse, surface or internal checking. Drying times to 15% moisture content range from less than 20 minutes for 1.0-inch-thick boards at 475 F to about 85 minutes for 1.6-inch-thick boards at 350 F. The heat transfer model described and tested in this paper has the ability to correlate drying time to material and process variables in press drying. Using experimental data and regression analysis, drying time correlates well to initial green weight (or initial moisture content), final moisture content, thickness, green volume, oven-dry weight, and platen temperature. The model is able to predict drying times closely and the expected response of drying time to changes in the variables. A potential use for the model is as the basis of a segregation system where boards are presorted by similar estimated drying times. Boards would then be dried by groups so that variation in final moisture content would be minimized.

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