A NUMERICAL MODEL FOR HEAT TRANSFER AND MOISTURE EVAPORATION PROCESSES IN HOT-PRESS DRYING—AN INTEGRAL APPROACH

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ABSTRACT

A numerical model, which was based on the energy principle that the rate of water evaporation from the interface (or wet line) at a given time during hot-press drying was controlled by the rate of heat energy reaching the interface at that time, has been developed. The model treated the drying as a process in which the retreat of the interface and free water flow to the interface occur simultaneously. After all parameters were determined according to the available literature and experiments, the numerical model worked well in predicting the drying curves from process and material variables. The model, which has a sound theoretical base but is numerically simple, has a good potential to be expanded for general high temperature drying and to be adopted in a production line to presort the lumber for good drying practice.

Keywords: Drying, wood drying, press drying, drying model, numerical model, heat transfer, moisture evaporation, southern pine.

INTRODUCTION

Hot-press drying has received much study as a potential process for drying veneer and lumber of various species as well as paper products (Koch 1964; Hann 1964, 1966; Schmidt 1967; Hittmeier et al. 1968; Ziegler et al. 1971; Wang and Beall 1975; Mustakllio and Paaki 1977; Chen 1978, 1980; Brooklyser and Pierson 1980; Okoh 1984; Loehnertz 1988; Simpson 1982, 1984; Simpson and Tang 1990; Simpson et al. 1988; Tschernitz 1985; Quarles and Nagoda 1990). The main advantage of press drying is that it gives the highest rate of drying due to good heat transfer from platen to wood. Press drying was reported to produce greater uniformity of veneer thickness and much flatter and smoother veneer than jet drying (Loehnertz 1988).

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A recent study (Simpson et al. 1988) has shown that compared to kiln drying, press drying significantly reduces the warp of lumber cut from fast-grown plantation loblolly pine.

Development of an analytical tool to analyze the real system has been a primary goal for any field of research, and this is true for press drying. Although several empirical models have been developed for press drying (Ziegler et al. 1971; Chen 1980; Tschernitz 1985; Simpson and Tang 1990), there is no generalized theoretical model to quantitatively describe the drying process. To optimize the drying process, the effects of process and material variables on the final moisture content of wood have to be predictable. For example, the drying time to reach a certain final moisture content has to be predicted in order to segregate the lumber into different drying groups and so reduce the variation in final moisture content after the drying. Therefore, the objective of this study is to develop a generalized theoretical model for heat transfer and the moisture evaporation process during press drying. This model is expected to be capable of extension to a general high-temperature kiln drying process.

MATERIAL AND TESTS

Material and preparation

Green 2 by 4 boards 8 ft long were sawn from trees of loblolly pine (*Pinus taeda* L.) from a 25-year-old plantation near Boulton, North Carolina. After the boards were planed to a uniform thickness and width, three specimens of 1.750 × 3.750 × 32.0 inches and four 1-inch long moisture content (MC) sections were cut. The initial MC of the specimens was estimated from the MC sections, and their density was calculated from their dimensions, weight, and MC. The boards were end-coated with heavily pigmented aluminum paint to prevent drying from their ends. They were wrapped in plastic and kept in cold storage until press-dried.

To study the effect of wood density on the drying rate, the boards were sorted into ten different initial density groups according to the ranked values of their density. Each group consisted of nine boards, the maximum number that could be dried at a time in the 3- × 3-ft experimental press. For example, the nine boards with the lowest values of density comprised the first group, the nine boards with the next lowest values of density comprised the second group, and so on.

Apparatus and testing procedure

The press drying was done at the Forest Products Laboratory, Madison, Wisconsin, in a single opening, 3- by 3-ft oil-heated hot press with microcomputer control and a data recording system. Screens were used for cauls to facilitate vapor movement. For each press-drying run, three thermocouples were placed inside each of two boards to measure the temperature changes at the center, one-quarter thickness, and surface of the boards.

The test variables were three levels of platen temperature, 350 F, 415 F and 475 F, and ten wood density groups. There were nine replications so that 90 specimens were tested at each temperature. Preliminary tests using several pressures up to 75 psi were found statistically to have no significant effect on drying times, so all tests were carried out at a platen pressure of 25 psi.

Each board was weighed immediately before being placed in the press and after the drying. Each board was oven-dried after the drying to obtain its oven-dry weight so that its moisture content and density could be determined.

DEVELOPMENT OF MODEL

Basic assumptions for model

The process and material variables affecting press drying are platen temperature, board thickness, wood density, initial moisture content, and species of wood. The removal of free

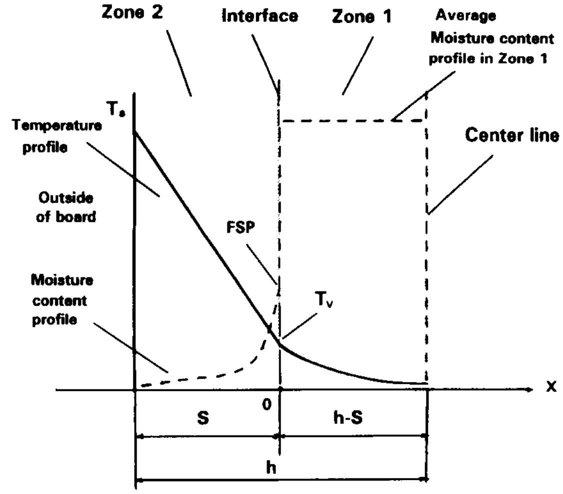

FIG. 1. Model for heat transfer and retreat of interface in the press-drying process.

water from wood during press drying has been shown to be controlled by heat transfer (Hann 1964, 1966), whereas the removal of bound water is influenced by mass transfer within the wood (Hittmeier et al. 1968). A model is a simplified real system, so some reasonable assumptions have to be made before the model can be developed. The following assumptions were made:

(1) Initial temperature and initial moisture content were uniformly distributed through the board before drying.
(2) Surfaces of the board reach the temperature of the press platens immediately after the press is closed.
(3) Moisture evaporates from wood only at an interface where the moisture content remains at fiber saturation point (FSP) and temperature remains at the boiling point.
(4) Heat transfer and moisture evaporation occur only perpendicular to the surface of a board. Therefore, press drying is treated as a one-dimensional heat transfer phenomenon with a retreating evaporating interface, as shown in Fig. 1.

Development of governing equation for the drying

Based on the above assumptions, the drying rate of a board at time t is controlled by the amount of heat energy reaching the interface (Fig. 1). Mathematically, it can be written as follows:

$$\left(K_2\frac{\partial T_2}{\partial X} - K_1\frac{\partial T_1}{\partial X}\right)\Bigg|_{X=0} = -\frac{\rho_L}{12}\cdot L\frac{\partial S}{\partial t} \tag{1}$$

where zone 1 (wet zone) is the area where moisture content is above FSP, and zone 2 (dry zone) is below FSP. K_1 = thermal conductivity of zone 1 (BTU·in./hr/ft²/°F); K_2 = thermal conductivity of zone 2 (BTU·in./hr/ft²/°F); T_1 = temperature in zone 1 (°F); T_2 = temperature in zone 2 (°F); T_S = surface (or platen) temperature (°F), Fig. 1; T_V = temperature at interface (212 F), Fig. 1; ρ_L = weight of liquid water per unit volume of wood evaporable at interface,

(lb/ft^3); L = latent heat of evaporation of water at interface, (BTU/lb); S = distance of the interface from the surface of board at time t (inch), Fig. 1; h = half-thickness of board (inch). Fig. 1; t = drying time (hour); X = coordinate axis along a thickness of board (inch), The FSP = 22.5% at the interface according to Stamm's measurement (Stamm and Nelson 1961) of the fiber saturation point of southern pine wood at 212 F. The minus sign on the right side of Eq. (1) is due to the origin being at the interface.

The physical meaning of the left side of Eq. (1) is the heat energy available to evaporate liquid water at the interface, i.e., the difference between the heat energy reaching the interface from the surface of the board and that entering the wet zone to heat up that zone. The right side of Eq. (1) is the heat energy needed to evaporate a certain amount of water ($\rho_L \cdot ds/dt$) at the interface.

In order to obtain the two slope terms of temperature T_1 and T_2 in Eq. (1), the heat transfer processes in the wet zone and dry zone have to be considered separately. Assume that the initial temperatures in both the wet and dry zone are T_0. For the wet zone, the following differential equation and boundary conditions, as illustrated in Fig. 1, can be written

$$\frac{\partial T_1}{\partial t} = D_1 \frac{\partial^2 T_1}{\partial X^2} \tag{2}$$

$$T_1 = T_0 \text{ at } t = 0$$

$$T_1 = T_V \text{ at } X = 0$$

$$\frac{\partial T_1}{\partial X} = 0 \text{ at } X = h - S$$

where D_1 = thermal diffusion coefficient in the wet zone, assumed constant. The solution of Eq. (2) is (Barrer 1941)

$$T_1 = T_v - \frac{4(T_v - T_0)}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cos \frac{2n+1}{2(h-S)} \pi[X - (h-S)] \cdot \exp\left[- \frac{(2n+1)^2 \pi^2 D_1 t}{4(h-S)^2} \right] \tag{3}$$

Differentiating Eq. (3) for the boundary condition X = 0, we obtain the slope of the temperature curve T_1 at the interface as a function of t,

$$\left. \frac{\partial T_1}{\partial x} \right|_{X=0} = \frac{2(T_0 - T_V)}{h - S} \sum_{n=0}^{\infty} \exp\left[- \frac{(2n+1)^2 \pi^2 D_1 t}{4(h-S)^2} \right]. \tag{4}$$

The differential equations and boundary conditions for the dry zone (Fig. 1) can be written as

$$\frac{\partial T_2}{\partial t} = D_2 \frac{\partial^2 T_2}{\partial X_2} \tag{5}$$

$$T_2 = T_0 \text{ at } t = 0$$

$$T_2 = T_v \text{ at } X = 0$$

$$T_2 = T_s \text{ at } X = -S$$

where D_2 = thermal diffusion coefficient in the dry zone and assumed to be a constant. The solution for Eq. (5) is (Barrer 1941)

$$
\begin{aligned}
T_2 = {} & T_V + (T_S - T_V)\frac{X}{S} \\
& - \frac{2}{\pi}\sum_{n=0}^{\infty} \frac{T_s\cos(n+1)\pi - T_V}{n+1}\cdot\sin\frac{(n+1)\pi X}{S}\cdot\exp\left[-\frac{(n+1)^2\pi^2 D_2 t}{S^2}\right] \\
& - \frac{4T_0}{\pi}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin\frac{(2n+1)\pi X}{S}\cdot\exp\left[-\frac{(2n+1)^2\pi^2 D_2 t}{S^2}\right]
\end{aligned} \tag{6}
$$

The differential form as regards X at the interface X = 0 is

$$
\begin{aligned}
\left.\frac{\partial T_2}{\partial X}\right|_{X=0} = {} & \frac{T_V - T_S}{S} - \frac{2}{S}\sum_{n=0}^{\infty}[T_s\cos(n+1)\pi - T_V]\cdot\exp\left[-\frac{(n+1)^2\pi^2 D_2 t}{S^2}\right] \\
& - \frac{4T_0}{S}\sum_{n=0}^{\infty}\exp\left[-\frac{(2n+1)^2\pi^2 D_2 t}{S^2}\right].
\end{aligned} \tag{7}
$$

Equations (4) and (7) establish the relationships for the slopes of temperature curves T_1 and T_2 with time t at the interface, respectively. A numerical testing of the model discussed later shows that the first term in Eq. (7), which represents a steady-state heat transfer process, is quite an accurate approximation of the whole equation (unsteady-state heat transfer) for this particular case of press drying. Thus, after substituting Eq. (4) and (7) into Eq. (1), we obtain the simplified equation governing the rate of moisture evaporation at the interface in the drying process,

$$
K_2\frac{T_V - T_S}{S} - K_1\frac{2(T_0 - T_V)}{h - S}\sum_{n=0}^{\infty}\exp\left[-\frac{(2n+1)^2\pi^2 D_1 t}{4(h-S)^2}\right] = -\rho_L\cdot L\frac{\partial S}{\partial t}. \tag{8}
$$

Equation (8) mathematically relates the rate of the interface retreat during drying to platen temperature T_S, initial temperature of board T_0, half-thickness of board h, drying time t, thermal parameters K_1, K_2, D_1, and amount of evaporable water at the interface, ρ_L.

Determination of initial boundary drying conditions for the model

Before Eq. (8) can be solved numerically to obtain the change of the retreating evaporating interface S with time t, two discontinuous points at S = 0 and S = h in Eq. (8) have to be taken care of. Corresponding to the point S = 0 is an initial drying boundary condition at t = 0, and the final drying condition is set up at S = h in the model.

For the particular problem of press drying, Eq. (2) governs the heat transfer process when t = 0 and S = 0 or t and S are very small. This is because the amount of heat energy required to create a very small dry zone (Zone 2) could be neglected at the very beginning of the drying process, i.e., when $t = t_1$ is very small, and corresponding $S = S_1$ is also very small. Thus Eq. (3) can be used to approximate the initial condition for Eq. (8) by setting S = 0 and $T_V = T_S$. For instance, by setting up initial condition of $X = S_1 = 0.01$ h, its corresponding t_1 can be easily determined by solving Eq. (8) for different drying temperatures.

As drying goes on, the interface moves toward the center of the board and S becomes large. When the heat transfer rate in the wet zone becomes very small compared to the heat transfer rate in the dry zone, i.e., $K_2\left.\frac{\partial T_2}{\partial X}\right|_{x=0} \gg K_1\left.\frac{\partial T_1}{\partial X}\right|_{x=0}$, the term $K_1\left.\frac{\partial T_1}{\partial X}\right|_{x=0}$ in Eq. (8) can be omitted. Thus, Eq. (8) without the term $K_1\left.\frac{\partial T_1}{\partial X}\right|_{x=0}$ automatically takes care of the other discontinuous point at the final drying condition S = h. The evaluation of initial and final drying conditions, discussed above, was automatically performed by the numerical analysis program.

With the two discontinuous points in Eq. (8) taken care of, Eq. (8) can be written in the following form for numerical evaluation and programming,

$$S_{i+1} = S_i + \left\{K_2\frac{T_S - T_V}{S_i} - K_1\frac{2(T_V - T_0)}{h - S_i}\sum_{n=0}^{\infty}\exp\left[-\frac{(2n + 1)^2\pi^2 D_1}{4(h - S_i)^2}(t_1 + i\cdot\Delta t)\right]\right\}\cdot\frac{\Delta t}{\rho_L\cdot L},$$
$$i = 1, 2, 3, \ldots, n. \qquad (9)$$

where S_1 and t_1 are the initial conditions, and Δt is the time increment.

Equation (9) can be used to obtain the position S of the retreating interface as a function of drying time t. Then the average moisture content of the board can be obtained as a function of S after the value of all thermal parameters and amount of evaporable liquid water ρ_L at the interface in Eq. (9) are determined.

Determination of the thermal parameters in the model

The thermal parameters were determined from research results in the literature.

(1) Coefficient of Thermal Capacity: C_W (BTU/lb/°F).

According to McMillin's study (1969), the specific heat of loblolly pine wood changes as follows with wood temperature and moisture content,

$$C_W = (C_d + M/100)/(1 + M/100) \qquad (10)$$

where $C_d = 0.253912 + 0.0005276\ T$; T = temperature of wood (°F), calculated from Eq. (3) and (6) for average T_1 and T_2, separately; M = moisture content of wood (%), M_1 or M_2.

An average M_2 in the dry zone was calculated by the following regression equation according to Hart's EMC simulation (Hart 1988) for water vapor equilibrium in wood,

$$M_2 = 50.26 - 0.2779\ \bar{T}_2 + 0.0003996\ \bar{T}_2^2 \qquad (11)$$

where $\bar{T}_2$ is the average temperature of the dry zone.

An average M_1 in the wet zone will be defined separately in a later section.

(2) Thermal Conductivity Coefficient K (BTU·in./ft²/hr/°F).

From the Wood Handbook (FPL 1987), we have

$$K_1 = S_g(1.39 + 0.038M_1) + 0.165 \qquad (30\% < M_1) \qquad (12)$$

$$K_2 = S_m(1.39 + 0.028M_2) + 0.165 \qquad (0 < M_2 < 30\%) \qquad (13)$$

where S_g = specific gravity of wood based on green volume; S_m is specific gravity of wood based on the volume at given moisture content, M%. S_m was estimated from the volumetric shrinkage value from the Wood Handbook (FPL 1987) and M_2 calculated by Eq. (11).

(3) Thermal Diffusion Coefficient D (in.²/hr) (Kollmann and Côté 1968).

$$D = 12K/\rho_W C_W = 12K/[S_m(1 + M/100)\cdot 62.4\cdot C_W] \qquad (14)$$

where ρ_W = density of wood and water (lb/ft³).

(4) Latent Heat of Evaporation of Water at Boiling Point: L.

According to Skaar's equation (1972), L = 971.2 (BTU/lb water) at 212 F.

(5) Weight of Liquid Water Evaporating at the Interface Per Unit Volume of Wood: ρ_L (lb/ft^3).

$\rho_L = W_W/V$ and density of dry wood $\rho_{wood} = W_{OD}/V$; where W_W = weight of water evaporated; W_{OD} = weight of oven-dry wood; V = unit volume wood. Thus

$$\rho_L = \frac{W_{OD}}{V} \cdot \frac{\Delta M}{100} = \frac{\rho_{wood} \cdot \Delta M}{100} = \frac{S_g}{100} \cdot \Delta M \tag{15}$$

where $\Delta M = M_1 - FSP = M_1 - 22.5$, the differential moisture content between the interface and the wet zone. ρ_L can be obtained only after the moisture content in the wet zone (M_1) is determined. Determination of M_1 is quite critical for the model to predict correctly the drying curve because the rate of interface retreat is significantly affected by the amount of water flowing from the wet zone to the interface.

Estimation of moisture content in the wet zone: M_1

The whole drying process was modelled as one in which the retreat of the interface and free water flow to the interface occur simultaneously. To determine the amount of free water in the interface, the free water flow in the wet zone was modelled as a capillary flow process.

The movement of wood moisture, when free water exists, is found to be controlled by capillary flow (Spolek and Plumb 1980). The capillary flow is driven by the difference in tension between points in the liquid system. The tension exerted by a meniscus is determined by its radius and must be a function of MC, since free water concentrates in the tapered ends of tracheids due to the tendency for the radius of the meniscus to become a minimum value. Consequently, the difference of tension between two points must be a function of the difference of MC between the points (Bramhall 1979). To simplify the estimation of M_1, the following linear relation was used,

$$F_W = (12/100) \cdot D_C \cdot dW/dx \tag{16}$$

where F_W = free water flux from the wet zone to the interface due to capillary forces (lb/ft^2/hr); D_C = free water conductivity coefficient (lb/ft/hr); $dW = M_1 - FSP$, free water content, or the differential moisture content between the wet zone and the interface; $dx = h - S$, the distance between the center line of the board and the interface (Fig. 1).

The total free water conductivity D_C should be proportional to the number of flow paths available. Since a decrease in the quantity of free water in the tracheids results in a proportional decrease in the number of pits immersed, and therefore in the number of flow paths, the conductivity is assumed to be proportional to the free water content in the wet zone. Consequently the conductivity can be written to be proportional to the position of the interface,

$$D_C = C \cdot (1 - S/h)/h \tag{17}$$

where C = constant or coefficient determined by experiments. For example, when S = 0, the moisture content of the board is in the initial MC state, and D_C has its maximum value; when the interface reaches the center line of a board, no free water exists in the board and $D_C = 0$. The denominator h in Eq. (17) is used to account for the thickness effect on the total conductivity D_C because the model testing described later indicated that the conductivity was inversely proportional to the half-thickness h. The physical meaning that D_C decreases with h indicates that resistance to movement of the free water increases with distance through where the water has to flow, and consequently the total conductivity becomes smaller.

Based on Eq. (16) and (17), therefore, the average moisture content M_1 in the wet zone can be calculated by the following numerical equation,

$$\overline{M_{1_{i+1}}} = \overline{M_{1_i}} - \frac{12}{100}\frac{C}{S_g}\left(1 - \frac{S_i}{h}\right)\frac{1}{h}\frac{\overline{M_{1_i}} - FSP}{h - S_i}\Delta t. \quad (18)$$

If we assume that water evaporates at the interface and leaves the board at the surface of a board, the water vapor has to be heated up to the platen temperature. Furthermore, one must take into account the energy needed to heat the wood and water at an increment of the interface $(S_{i+1} - S_i)$ up to the mean temperature between the interface and platen temperature in the time increment Δt. Therefore, the total heat energy required to create the $dS = S_{i+1} - S_i$ (Fig. 1) in the Δt is

$$\left\{[L + C_V(T_S - T_V)]\rho_L + \left(C_d + \frac{FSP}{100}\right)\frac{T_S - T_V}{2}62.4S_g\right\}\frac{S_{i+1} - S_i}{\Delta t} \quad (19)$$

where $C_V = 0.45$, specific heat for water vapor (BTU/lb/°F).

Comparison of Eq. (8) with Eq. (19) shows that the right hand side of Eq. (9) should be replaced by Eq. (19). Thus, the final form of Eq. (9), which governs the rate of interface retreating during the drying, can be written as

$$S_{i+1} = S_i + \frac{\left\{K_2\frac{T_S - T_V}{S_i} - K_1\frac{2(T_V - T_0)}{h - S_i}\sum_{n=0}^{\infty}\exp\left[-\frac{(2n+1)^2\pi^2D_1}{4(h - S_i)^2}(t_1 + i\cdot\Delta t)\right]\right\} 12\cdot\Delta t}{[L + C_V(T_S - T_V)]\frac{62.4\cdot S_g}{100}(\overline{M_{1_i}} - FSP) + \left(C_d + \frac{FSP}{100}\right)\frac{T_S - T_V}{2}62.4\cdot S_g}$$

$$i = 1, 2, 3, \ldots, n. \quad (20)$$

The average moisture content of the board during drying can be calculated by

$$\overline{M_{i+1}} = \frac{1}{h}[\overline{M_2}\cdot S_i + \overline{M_{1_i}}(h - S_i)]. \quad (21)$$

After the amount of heat energy reaching the interface and the amount of water flowing to the interface have been determined, the drying curve can be predicted by solving Eq. (20), (18) and (21) along with the equations for calculating the thermal parameters K_1, K_2 and D_1. The above equations in the model were solved numerically by a program written in PASCAL.

COMPARISON OF PREDICTED RESULTS WITH EXPERIMENTS

First, the sensitivity of the model to the input variables was tested. The predicted drying times were found to be very sensitive to platen temperature, board thickness, initial and final moisture content, and wood density, but not very sensitive to the time increments Δt (when $\Delta t < 0.02$ hr) and initial temperature of the board, T_0.

In initial trials to fit the model to the data, it was quickly apparent that to get an acceptable fit, either the free water C value or the heat transfer K_2 values had to increase with increasing press temperature. There seems to be no rationale for expecting the C value to increase, but there is some suggestion from the literature (Kollmann and Côté 1968; Steinhagen 1977) for the possibility that the K_2 values might increase. Thus the following procedure was used.

Using K_2 as calculated from Eq. (13), C values that fitted the model to the data were determined separately for the nine C press loads at 350 F (North Carolina data). The average

TABLE 1. *The estimated C and K_c value for different locations of wood material and platen temperature.*

Wood sources	C	K_c 350 F	415 F	475 F
North Carolina	1.0892	−0.0123	0.2577	0.3134
Arkansas	1.8625	0.0538	0.3211	0.5646

of these nine C values was then used in the model, and the nine K_2 values to give a good fit were calculated and their average was compared with the average Eq. (13) value. The difference between these two K values was termed K_C. Using the same C, this procedure was repeated for the two higher press temperatures to determine the correction constant, K_C, for reach temperature. This entire procedure was then separately applied to previously reported data from Arkansas. The results are shown in Table 1.

TABLE 2. *Comparison of predicted and experimental press drying times of southern pine lumber from North Carolina.**

Drying temp. (F)	Specific gravity	Initial MC (%)	Final MC (%)	Exp. drying time (min)	Predicted drying time (min)	Difference** (%)
350	0.570	90.5	15.7	150	146.8	−2.1
350	0.536	98.7	16.9	170	149.3	−12.2
350	0.522	105.1	18.5	160	149.5	−6.6
350	0.521	103.6	15.0	163	161.9	−0.7
350	0.511	113.7	18.2	150	159.8	+6.5
350	0.507	105.7	23.5	136	129.9	−4.5
350	0.504	114.4	17.9	150	160.7	+7.1
350	0.462	122.7	15.2	174	172.6	−0.8
350	0.422	134.5	22.7	132	147.9	+12.0
			Average	153.9	153.2	−0.1
415	0.55	90.7	14.9	114	102.1	−10.4
415	0.548	98.4	15.0	114	111.8	−1.9
415	0.531	99.8	14.5	114	111.9	−1.8
415	0.526	103.0	16.2	124	110.1	−11.2
415	0.512	113.1	15.1	135	121.9	−9.7
415	0.511	104.4	15.8	102	110.8	+8.6
415	0.504	109.9	21.7	102	100.5	−1.5
415	0.468	125.5	24.8	91	103.2	+13.4
415	0.447	130.8	15.0	132	128.1	+3.0
415	0.438	130.1	23.5	91	105.4	+15.8
			Average	111.9	110.6	−0.2
475	0.553	95.3	14.8	94	90.4	−3.8
475	0.525	99.4	14.9	94	91.7	−2.4
475	0.517	107.4	15.0	102	98.3	−3.6
475	0.516	94.6	14.5	94	87.0	−7.4
475	0.511	107.3	15.3	102	96.9	−5.0
475	0.495	115.1	15.4	102	102.2	+0.2
475	0.492	115.7	20.9	84	90.2	+7.4
475	0.453	130.0	14.4	108	110.3	+2.1
475	0.449	128.6	24.3	74	88.8	+20.0
475	0.431	123.7	16.2	108	98.5	−8.8
			Average	96.2	95.4	−0.1

* The dimension of lumber was 1.750 × 3.750 × 32.0 inches, and each experimental data point is the average value of 9 boards.
** Difference was based on experimental drying time.

TABLE 3. *Comparison of predicted and experimental press drying times of different thickness of southern pine lumber from Arkansas.**

Drying temp. (F)	Thickness of board (inch)	Specific gravity	Initial MC (%)	Final MC (%)	Exp. drying time (min)	Predicted drying time (min)	Difference** (%)
350	0.982	0.453	124.6	19.5	33	36.0	+9.1
350	1.008	0.431	121.2	28.4	30	28.8	−4.0
350	1.006	0.416	119.9	14.9	40	39.0	−2.5
				Average	34.3	34.6	+0.8
350	1.318	0.426	122.0	22.1	55	57.5	+4.5
350	1.343	0.418	120.4	19.0	65	62.9	−3.2
350	1.344	0.414	127.6	29.2	55	51.4	−6.5
				Average	58.3	57.3	−1.7
350	1.586	0.426	106.8	22.1	82	74.5	−9.1
350	1.607	0.416	124.3	17.9	90	94.4	+4.9
350	1.609	0.410	125.5	22.5	80	84.3	+5.4
				Average	84.0	84.4	+0.5
415	0.982	0.454	116.1	19.0	22	25.9	+17.7
415	1.010	0.417	116.9	33.5	20	18.5	−7.5
415	1.007	0.413	111.8	24.5	25	21.6	−13.6
				Average	22.3	22.0	−1.5
415	1.341	0.442	101.6	27.4	35	33.7	−3.7
415	1.34	0.437	105.9	16.6	45	46.2	+2.7
415	1.318	0.434	111.8	21.0	38	41.5	+9.2
				Average	39.3	40.5	+2.7
415	1.608	0.430	104.6	16.3	65	65.6	+0.9
415	1.608	0.424	104.5	25.1	55	51.7	−6.0
415	1.584	0.420	107.0	24.4	55	51.9	−5.6
				Average	58.3	56.4	−3.3
475	0.982	0.454	126.0	25.4	17	19.6	+15.3
475	1.006	0.438	115.2	25.5	18	18.2	+1.1
475	1.005	0.379	116.4	15.2	24	21.0	−12.5
				Average	19.7	19.6	−0.3
475	1.342	0.442	108.9	24.5	30	31.5	+5.0
475	1.318	0.426	112.2	25.6	29	29.7	+2.4
475	1.343	0.415	101.8	14.6	38	36.5	−3.9
				Average	32.3	32.6	+1.2
475	1.608	0.424	114.1	32.5	40	38.2	−4.5
475	1.583	0.416	106.6	24.4	43	40.9	−4.9
475	1.607	0.414	120.4	22.0	50	50.5	+1.0
				Average	44.3	43.2	−2.6

* and **: same as the notes in Table 1, except for board thickness.

Statistical analysis (Tang 1992) showed that the effect of press temperature on the K_C values was significant at the 99% level but that the difference between the two higher temperatures for the North Carolina values was not significant. Thus the data indicate that both the permeability and the heat conduction are higher for the Arkansas wood than the North Carolina wood.

Table 2 shows that the differences between the drying times predicted by the model and measured for the different density groups ranged from −12.2% to +20.0%, with average stan-

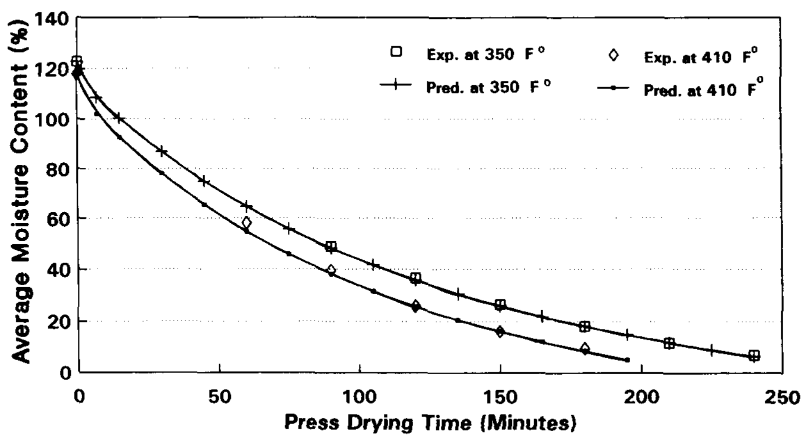

FIG. 2. Comparison of predicted (Pred.) and experimental (Exp.) curves for the drying temperatures 350 F and 410 F. (each point is an average value of 12 boards)

dard deviation (STD) of 8.1%. The model is a simplified representative of the real system and the physical properties of lumber are extremely variable, so such a range of variation is to be expected. Unpredictable variation of wood properties, assumptions made in the model, and possible experimental error all contribute to the discrepancies between the predicted and measured drying times. These discrepancies are expected to be randomly distributed with mean near zero, as was the case for this study.

Table 3 gives the comparison of the predicted and measured drying times for three different thicknesses of board. The boards were sawn from plantation loblolly pine trees from Arkansas (Simpson and Tang 1990). In spite of the difference ranging from −13.6% to +17.7% (average STD = 7.4%), the predicted drying times agree with experimental data reasonably well for most groups.

Figure 2 shows the comparisons of predicted press-drying curves with the experimental curves for platen temperatures 350 F and 410 F, respectively. The drying curves were obtained by quickly removing and weighing the lumber at intervals during press drying. The predicted curves agree with experimental data quite well. The good agreement between predicted and experimental data for the different temperatures and thicknesses of board indicates that the model and its parameters are soundly based.

APPLICATION OF THE MODEL

The model developed for press drying could be modified to simulate a general high-temperature drying process of lumber of a very permeable wood. To achieve this, boundary conditions have to be included in the models. In high-temperature drying, the temperature at the surface of a board is no longer equal to the drying temperature, and should be a function of dry-bulb temperature, relative humidity, and air velocity in the kiln. After a thermal transfer coefficient between the air and board surface is determined, a similar model to that used for press drying should be applicable to the high-temperature drying.

One of the advantages of modelling is to enable technologists to predict drying performance without a large number of trial-and-error kiln runs. James (1988) commented that many kiln-drying problems arise because of wide variation in the drying burden (MC and permeability of individual pieces). Presorting the lumber into more homogeneous loads according to their required drying time would ease these problems. Development of a reliable and applicable model, which can be adapted to a microcomputer operating the production line, could be a critical step to achieve this goal.

The main advantage of the model developed in this study is that the model, which has a sound theoretical base, is mathematically and numerically much simpler than both the moisture diffusion and transfer models solved by a finite difference (or finite element) method (Rosen 1983). The whole drying process can be modelled in seconds on an IBM-386 PC. Therefore, the models have a good potential to be used in a production line to sort the green lumber into different uniform drying loads according to the predicted drying time for each board.

SUMMARY

During hot-press drying, the rate of water evaporation from the interface (or wet line) at given time t was found to be controlled by the rate of heat energy reaching the interface at that time. Based on the heat energy principle, a model was developed to establish the mathematical relation between water evaporation rate, and process and material variables. The model treated the drying process as one in which the retreat of the interface and free water flow to the interface occur simultaneously. After all parameters were determined according to the available literature and experiments, the numerical model well predicted the drying curves from process and material variables. The model, which has a sound theoretical base but is numerically simple, has a good potential to be expanded for general high-temperature drying and to be adopted in a production line to presort the lumber for good drying practice.

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