WOOD AND FIBER SCIENCE

JOURNAL OF THE SOCIETY OF WOOD SCIENCE AND TECHNOLOGY

VOLUME 21 JULY 1989 NUMBER 3

DRYING DOUGLAS-FIR LUMBER: A COMPUTER SIMULATION[1]

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(Received February 1988)

ABSTRACT

Three experimental kiln runs were designed to investigate how well the drying rate of 2-inch-thick lumber from Douglas-fir heartwood can be simulated by Hart's computer model. Simulated data were compared with gravimetric records and with electrical measurements obtained using the moisture-monitoring system designed by Forrer. This thermomoisture meter proved useful in continuously measuring moisture gradients and temperatures in boards. The first step of the computer simulation showed how diffusion coefficients varied with moisture content; however, two adjustments of the computer inputs were needed to arrive at good agreement between simulated and observed drying rates.

It was concluded that Hart's computer simulation programs and Forrer's thermomoisture meter are excellent tools for future lumber drying research and improvement of kiln schedules.

Keywords: Drying, computer simulation, moisture measurement, Douglas-fir lumber.

INTRODUCTION

The goal of kiln-drying lumber is to reduce moisture content as rapidly as possible without inducing defects. Steep moisture gradients develop if lumber is dried too rapidly, causing unequal shrinkage and producing defective lumber. If moisture gradients in drying boards can be predicted, kiln schedules and drying conditions can be controlled so as to prevent such defects.

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Wood and Fiber Science, 21(3), 1989, pp. 207–218

Hart (1983) developed a computer simulation of lumber drying in which drying rates and average moisture contents of boards are used to predict moisture gradients, both within a board and between boards within a stack. After the simulation program is tuned to fit actual drying records, any chosen drying parameter can be varied and the effect of such changes on the drying rate assessed. The simulation thus provides a tool for modifying dry-kiln schedules. Hart verified his simulation on lumber of both fast- and slow-drying species. The research reported here was designed to investigate how well the drying rate of 50-mm (2-in.)-thick boards from Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] heartwood can be simulated by Hart's program. Simulated data were compared with gravimetric data and with electrical measurements obtained with the moisture-monitoring system designed by Forrer (1984).

BACKGROUND

Mathematical models of lumber drying

Researchers studying wood-moisture relations have long recognized the advantages of mathematical models of lumber drying for improving kiln schedules. Wide and increasing use of computers has facilitated practical applications of theoretical considerations. Claxton (1966) was one of the first to develop a simple, computer-based drying model. His model combines the effects of permeability (based on Fick's second diffusion equation) and water evaporation caused by the vapor-pressure differential between a wood surface and the surrounding air. Moschler and Martin (1968) published a simple diffusion model that is also based on Fick's second law, while Kawai et al. (1978) took a similar approach using chemical potential as the driving force. Hart (1977) combined Fick's diffusion equation and evaporation parameters in a model to predict moisture profiles in wood.

Bramhall (1979a, b) and Hart (1981, 1983) developed relatively complete models that cover most transfer processes encountered in drying lumber. The models differ in some respects. Hart assumed that all moisture movement in wood, even above the fiber saturation point, is driven by diffusion, while Bramhall considered the water vapor-pressure gradient as the driving force. The former verified his model using white oak, which is a refractory species. The latter employed alpine fir, a rather fast-drying wood.

Before developing a user's manual (Hart 1983) for a family of simulations of moisture sorption in wood, Hart had laid some groundwork on the drying of wood (1965), on the effective surface moisture content of wood during sorption (1977), and on the computer simulation of water movement through wood (1981). The simulation, as described in Hart's manual (1983), combines heat and vapor transfer between the air and the wood surface with a finite-difference solution for the wood-moisture profile across the thickness of the board, adjusting for changing air conditions across the stack. The rate of moisture diffusion between adjacent cells is assumed to be directly proportional to the difference in moisture content and to the diffusion coefficient (Siau 1984). The program requires good estimates of lumber-drying parameters, such as sticker thickness; the velocity of air, its dry-bulb and wet-bulb temperatures and the distance it travels across drying boards of specified thickness; and the specific gravity and initial moisture content of wood.

The simulation requires estimates of the surface transfer coefficient and of the internal diffusion coefficients for the applicable moisture contents. Hart's manual (1983) includes an equation for estimating the surface transfer coefficient for a known air velocity. Internal diffusion coefficients can vary widely with species and reliable values may not be readily available. However, they can be estimated from actual drying data by a fitting program. From these estimates, the final simulation calculates the simulation drying rates, which should agree with the actual rates. Repetition of this procedure may be required, especially if the actual drying rates are values averaged over relatively long periods. Diffusion coefficients from another source may be used in the final program without the fitting program, greatly simplifying the simulation.

This simulation approach became especially interesting when Forrer (1984) developed his electronic system for monitoring moisture gradients in wood, because researchers can now compare predicted and measured moisture distributions in drying boards.

Measurements of moisture gradients

Comparison of predicted and actual moisture gradients developing in drying lumber requires a monitoring system that can measure moisture contents at various depths in boards. The gravimetric method usually provides the most accurate values for moisture content (the ratio of the weight of water to the oven-dry weight). However, where knowledge of moisture gradients is required, oven-dry weights of different layers in boards can be determined accurately only by slicing, and thus destroying, the boards. Therefore, this method is not suitable for continuous measurements. Certain electrical properties of wood can be used, however, to measure moisture content at different depths without destroying the pieces being measured. The most suitable moisture meters for this purpose use the relationship between moisture content and electrical resistance. Such meters allow measurement in relatively small areas.

Since Stamm (1927) pointed out the usefulness of electrical resistance in measuring moisture contents, it has been studied by several researchers. For resistance-based meters, moisture content is derived from empirical formulas (Keylwerth and Noack 1956). James (1963) found a rough linear relationship between the logarithm of the electrical resistance and the inverse of the logarithm of the moisture content, in the moisture-content range from the fiber-saturation point to oven-dry. Skaar (1964) has pointed out the difficulties in directly measuring moisture content of wood by electrical resistance: temperature effects; polarization phenomena, which cause resistance to change with time; voltage gradients; and concentration of resistance near electrodes, caused by electrode geometry, poor contact, and deposits on electrodes.

Several workers (Skaar 1948; Davidson 1958; Brown et al. 1952) have investigated the effects of temperature on the electrical resistance of wood. Lin (1965) showed that the relationship between electrical resistivity and the inverse of the absolute temperature is curvilinear at high moisture content from -60 to $+165$ C. Clark and Williams (1933) suggested, and Davidson (1958) confirmed, that electrical conductance in wood is an ionic process. Two forms of ions are present: bound ions, whose number is dependent on the temperature; and free ions, the only ions able to conduct a charge. This theory could explain the dependence of electrical resistance of wood on temperature.

Electrode geometry (defined by pin size and spacing) also influences the immediate force fields of electrodes. Because resistance is concentrated very near the electrodes, the linear spacing of electrodes in resistivity measurements is less critical for small-diameter than for large-diameter pins (Skaar 1964).

Considering all these factors, Forrer (1984) developed an apparatus to monitor moisture gradients in lumber by resistivity measurements. The system uses a slowly alternating current and is controlled by a microprocessor. He used the formula originally devised by Siemens and Halle, as described by Keylwerth and Noack (1956):

$$\log(\log(r) - 4) = -0.0322U + 1.009 \quad (1)$$

where r = specific resistance (ohm-cm), and U = moisture content (%). This formula agrees well with experimental data (James 1963) on the relationship of electrical resistance to moisture content of Douglas-fir wood.

EXPERIMENTAL PROCEDURE

Douglas-fir heartwood was chosen for this study because the species is of high commercial importance and the moisture content of the fresh heartwood normally is between 35% and 45%, close to the maximum moisture content (30%) that can be measured accurately with a resistance meter.

There were two kiln runs in a laboratory kiln for determining moisture gradients within a board and one kiln run in an industrial kiln for determining moisture gradients between boards. Two kinds of electrodes were used: probes with four measurement points (Forrer 1984) and ball electrodes with one measurement point. The probes and ball electrodes were used for laboratory and industrial kiln runs, respectively.

For laboratory kiln runs, freshly cut boards [2,450 mm (8 ft) long, nominal 152 mm (6 in.) wide and 51 mm (2 in.) thick] were obtained. Actual thickness, which ranged from 38 mm (1.50 in.) to 48 mm (1.88 in.), averaged 45 mm (1.75 in.). After the boards had been stored for one week at 2 C (35 F), a section was cut from the center of each board to produce matching samples 1,140 mm (45 in.) long. These were end-coated immediately with rubber-based paint to prevent moisture loss from the ends. The initial moisture content of each board was estimated by oven-drying a 25-mm (1-in.)-thick section from the center portion.

Before each of the two laboratory kiln runs, twelve pairs of matched boards were stacked in a small 1.9 m^3 (67 ft^3) experimental kiln. The stack consisted of six layers, with four boards side by side in a layer. The rest of the kiln was filled with freshly cut boards from Douglas-fir sapwood, which provided a humid atmosphere, especially at the first stage of drying. Members of each matched pair were placed in adjacent locations in the kiln to expose them to similar drying conditions. One sample board from each matched pair was used for gravimetric measurement and the other for a drying stress test.

The board at the left edge of the second layer from the top of the stack was chosen to monitor internal temperature and moisture content. In accordance with the design by Forrer (1984), each probe (electrode) was constructed of a ceramic tube and four stainless steel rings that were sensors for both temperature and electrical resistance. Four pairs of copper-Constantan thermocouple wires ran through the ceramic tube; one pair was soldered to each of the four rings. Two probes were driven into predrilled holes [4.8 mm (0.2 in.) in diameter and 25.5

mm (1 in.) deep] in the board until the center of the top ring was 6 mm (0.25 in.) below the surface. The holes were 60 mm (2.4 in.) apart, which provided a resistance-to-resistivity ratio of 1.0. [According to Skaar (1964), Eq. (1) requires values for specific resistance, rather than resistivity, which is measured by Forrer's thermomoisture meter. However, when the ratio of spacing between electrodes to their diameters is 12.5, the value for resistivity can be used directly as specific resistance.] The probes were connected to Forrer's thermomoisture meter (Forrer 1984), which was connected to a microcomputer.

The seven-step drying schedule was that used by the industrial kiln where the third kiln run of this study was carried out. The dry-bulb temperature increased from 65.6 C (150 F) to 82.2 C (180 F) by 2.8 C (5 F) increments every 12 h; wet-bulb temperature was constant at 60.0 C (140 F). Air flow was unidirectional with a velocity of 2 m/s (400 ft/min). Total drying time was 84 h.

One sample board from each matched pair was weighed before the experiment and every 12 h during drying. A 25-mm (1-in.)-wide cross-section was sawed 102 mm (4 in.) from the end of the matching stress-sample boards to determine stress patterns by the prong stress test (Rasmussen 1961). The reaction of the outer prongs was examined immediately after cutting and after 30 min at ambient conditions. Freshly exposed board ends were coated to eliminate drying effects. Final kiln settings were maintained for about 3 days after completion of the drying schedule to equalize moisture content within the boards as much as possible. The plot of drying rate versus average moisture content during this period was extrapolated to zero drying rate, as recommended by Hart's manual (1983), to estimate the final experimental equilibrium moisture content. The fitting program adjusts for the difference between this estimated experimental equilibrium moisture content and that obtained from the simulation isotherm equation. Finally, all moisture-content sample boards were weighed, and three well-spaced sections 25 mm (1 in.) thick were taken from each board and oven-dried. The drying rate of each sample board in each drying step was calculated from these data.

The effect of temperature on readings of the moisture meter was determined from two sample boards of Douglas-fir heartwood [127 mm (5 in.) long, 100 mm (4 in.) wide, and 38 mm (1.5 in.) thick]. The two samples had been conditioned to equilibrium moisture contents of 8.3% and 11.5%, respectively. Two stainless steel ball electrodes [3 mm (0.1 in.) diameter] were embedded in each board, and the board was subjected to several elevated temperature conditions at the same equilibrium moisture content as its initial moisture content. The resulting temperature correction curve followed the equation:

$$\text{Moisture content correction (\%)} = [(°\text{C} - 19.68)/30.86]^2 \qquad (2)$$

with $r^2 = 0.97$.

In the third kiln run, the moisture content distribution across a 2.4-m (8-ft)-wide stack of lumber was measured in an industrial 190-m^3 (80 M-bd-ft)-capacity single-track kiln. Air velocity was 1 m/s (200 ft/min); direction of air flow changed every 12 h. Six matched kiln samples [0.9 m (3 ft) long, 153 mm (6 in.) wide and 22.2 mm (7/8 in.) thick] were cut from a freshly sawn 6.7-m (22-ft)-long board and immediately end-coated. Four of them, which were used to monitor the moisture gradient across the stack electrically, were placed every other board from the air-entering side of the first 12-h period in the layer 1.22 m (4 ft) above the ground. Ball electrodes [3 mm (0.1 in.) diameter] were inserted to a depth one-

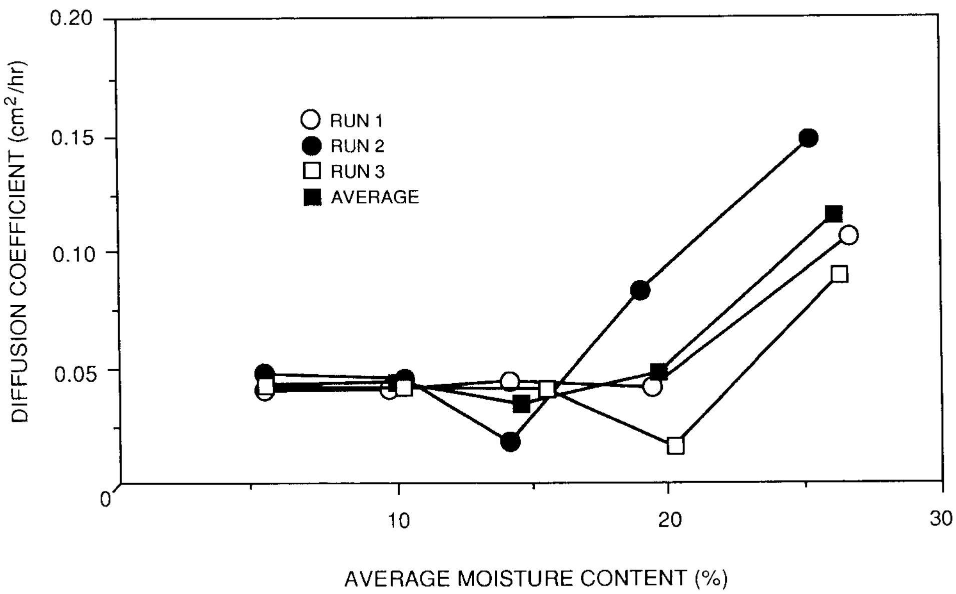

FIG. 1. Diffusion coefficients obtained by using Hart's computer simulation (T$d and RAE parameters in the computer program were 180 F and 0.65, respectively).

fourth of the board thickness; at this depth the moisture content probably represents the average of the entire board. The other two samples, which were weighed repeatedly throughout the run to determine moisture-content changes, were placed in pockets on each side of the stack, two layers above the monitoring samples.

RESULTS AND DISCUSSION

Stress patterns tests revealed the point at which drying stresses reversed. In Run 1, eight out of twelve boards showed stress reversal between 36 and 48 h; another three, between 48 and 60 h; and the last board, after 60 h. Stress reversal occurred in the first board at 18.2% moisture content, and in most other boards, between 17% to 15%; the lowest moisture content for stress reversal was 14.7%. Therefore, it would seem reasonable to accelerate drying conditions after 60 h, when the average moisture content has reached 14.5%.

As the first step of simulation, actual drying rates were used in Hart's (1983) fitting program to determine how diffusion coefficient varied with moisture content. The diffusion coefficients obtained by the fitting program represent the values physically determined by using the interval diffusion equation [Eq. (6) in McNamara and Hart (1971)], which holds true unless the drying rates are limited by the surface transfer rates. The diffusion coefficient decreased as moisture content decreased from 30% to 5.14%, the experimental equilibrium moisture content at the end of the run (Fig. 1). Each curve was obtained by fitting the average drying rates of an entire layer, including monitored sample boards. For the sake of accuracy, the plots of the individual kiln runs, rather than the average plot, were used in subsequent simulations.

The gravimetrically determined, the electrically monitored, and the computer-simulated drying curves of Runs 1 and 2 are compared in Figs. 2 and 3. The

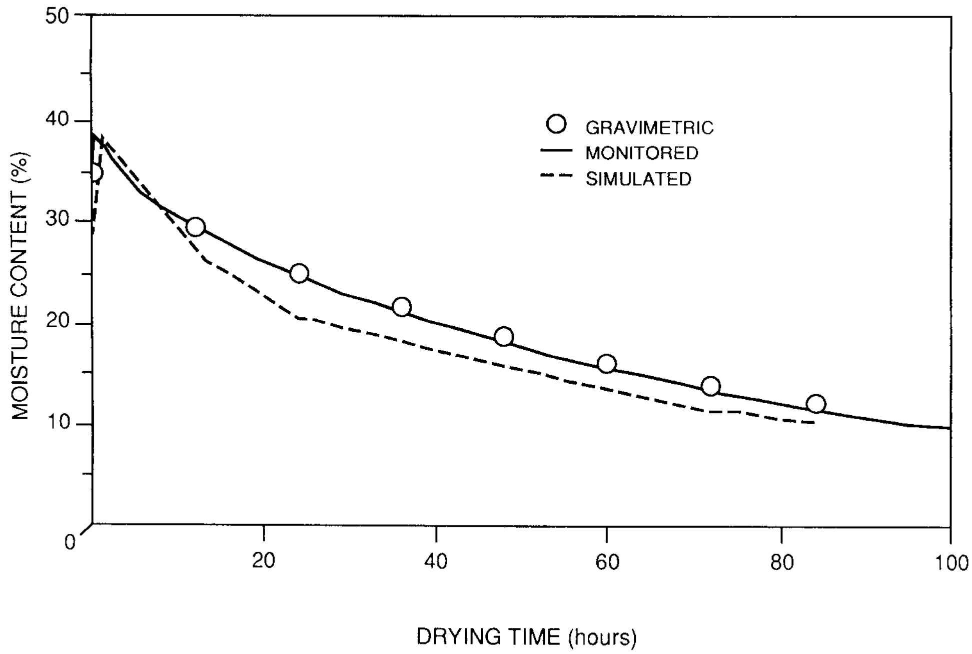

FIG. 2. Drying curves of the sample board in kiln Run 1, obtained by gravimetric and electric measurements and by computer simulation.

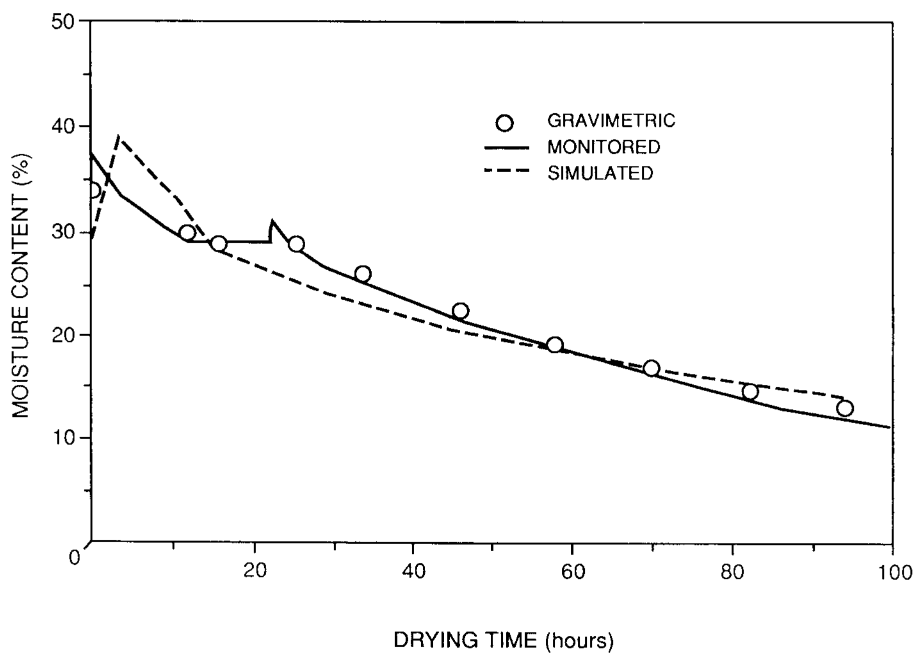

FIG. 3. Drying curves of the sample board in kiln Run 2, obtained by gravimetric and electric measurements and by computer simulation.

TABLE 1. *Comparison of monitored and simulated moisture contents with gravimetric measurements for Run 1.*

Time (h)	Measurements (% moisture content)			Difference between	
	Gravimetric (1)	Monitored (2)	Simulated (3)	(1) and (2)	(1) and (3)
12	29.5	27.0	29.5	2.5	0.0
24	25.2	20.7	24.9	4.5	0.3
36	21.7	18.2	21.2	3.5	0.5
48	19.0	16.0	18.3	3.0	0.7
60	16.2	13.8	15.8	2.4	0.4
72	14.3	11.7	13.7	2.6	0.6
84	12.4	10.6	11.7	1.8	0.7
			Mean ± standard error	2.90 ± 0.83	0.46 ± 0.25

average of the moisture contents at three or four different depths was determined by a least square fit to a parabolic equation. Moisture gradient in a board was assumed to be parabolic, with the apex at the center of the board. The moisture contents of the surface and center of the board were also obtained from the parabolic equation. The average moisture content was then calculated as follows:

$$M_{avg} = M_s + 2/3(M_c - M_s) \tag{3}$$

where M_{avg} is the average moisture content and M_c and M_s are center and surface moisture contents, respectively.

Drying curves for the monitored boards were simulated from the average drying rates of all four boards in the layer including the monitored board. The fitting procedure was repeated until the resulting diffusion coefficients gave simulation outputs in satisfactory agreement with the actual drying curves and drying rates. Then, using these diffusion coefficients, the computer simulation for moisture gradients across a stack was run to calculate separately the drying behavior of each of the four boards in each run, rather than the average behavior of all four boards. Their quantitative comparisons are listed in Tables 1 and 2.

The simulated and the gravimetric drying curves for Run 1 were in very good agreement, but the curve of monitored moisture contents deviated slightly from them (Fig. 2). This deviation might have been caused by limited accuracy in correcting high moisture-content values for temperature effects. At moisture con-

TABLE 2. *Comparison of monitored and simulated moisture contents with gravimetric measurements for Run 2.*

Time (h)	Measurements (% moisture content)			Difference between	
	Gravimetric (1)	Monitored (2)	Simulated (3)	(1) and (2)	(1) and (3)
12	30.0	31.8	29.0	−1.8	1.0
34	26.2	23.0	25.1	3.2	1.1
46	22.6	20.4	21.8	2.2	0.8
58	19.3	18.6	18.9	0.7	0.4
70	16.8	16.6	16.1	0.2	0.7
82	14.7	15.3	13.7	−0.6	1.0
94	13.0	14.0	11.9	−1.0	1.1
			Mean ± standard error	0.41 ± 1.78	0.87 ± 0.26

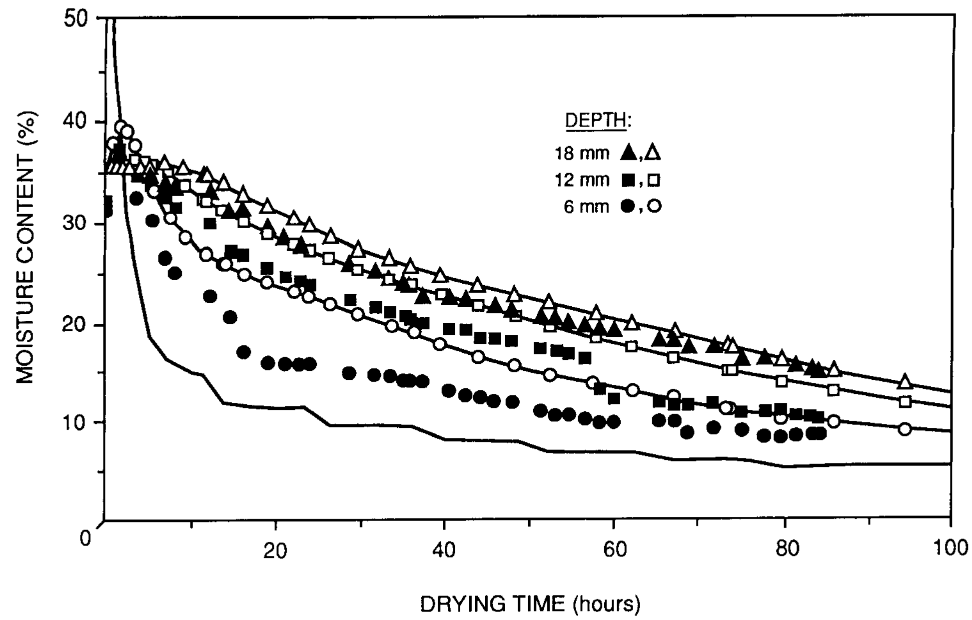

FIG. 4. Moisture distribution in the 44.4-mm (1.74-in.)-thick sample board in kiln Run 1: closed and open symbols indicate electrically monitored and calculated moisture contents, respectively, at depths of 18 mm (0.71 in.), 12 mm (0.47 in.), and 6 mm (0.24 in.) from the surface; the solid line of the lowest curve shows the calculated surface values.

tents below 20%, monitored and actual moisture contents differed by less than 3% and decreased with decreasing moisture content. The thermomoisture meter, like all resistance meters, is unreliable above 30% moisture content.

In Run 2, the drying curve of the monitored board also deviated from the gravimetric and simulated values. The computer simulation assumes that initial moisture content of boards in a stack is uniform. The initial moisture content of the electrically monitored board for Run 2 was only 0.7% higher than the average of the layer, the input value for the simulation, so this did not cause the lack of agreement. However, the actual drying rates of the monitored sample board were manifestly lower than those of the other boards and thus were not representative of the stack. The different drying rates may have been caused by a 10-h interruption of the run at 15.5 h. During this period the sample boards were kept in large plastic bags at room temperature to prevent moisture loss; however, decreased moisture gradients in the boards could not be eliminated. For this reason, the simulation for Run 2 was refitted to the real drying rates of the monitored board (Fig. 3).

Monitored and simulated moisture distributions in the monitoring board of Run 1 are depicted in Fig. 4. The drying curves were monitored and simulated at depths of 18 mm, 12 mm, and 6 mm (0.71, 0.47, and 0.24 in., respectively). [The drying curve at 24 mm (0.94 in.) is not plotted in Fig. 4 because the depth of 24 mm exceeded the half thickness of the monitoring board, 22.2 mm (0.87 in.).] The simulated drying curve at the board surface was also plotted as a reference. After an initial warm-up period, the monitored moisture contents at a

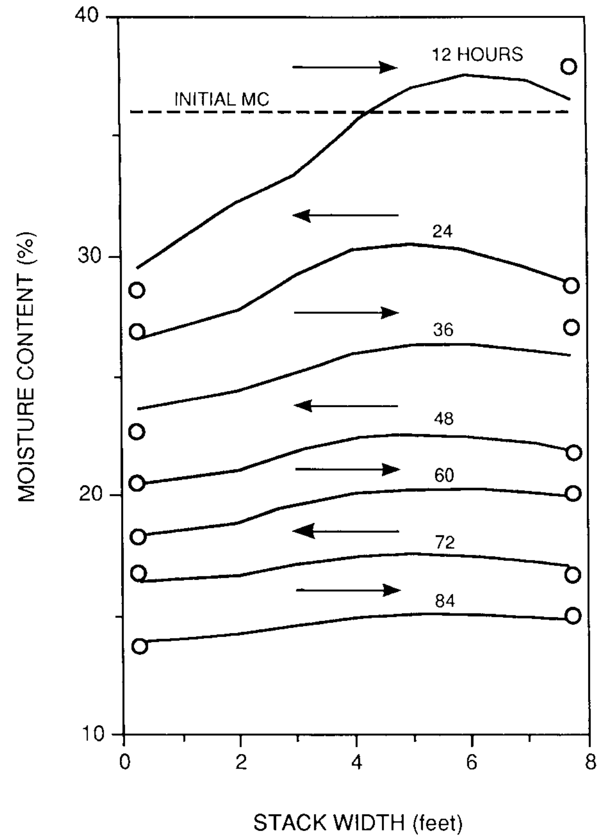

FIG. 5. Simulated moisture distribution between boards in the stack in kiln Run 3. Circles show the gravimetric moisture contents of outside sample boards; arrows indicate air direction.

given depth were generally lower than the corresponding simulated values; this was especially true at the 6-mm (0.24-in.) depth. This may be explained by the shrinkage of the monitored sample board by about 8% of its original thicknesses; the electrodes originally implanted at 6 mm were only 4.3 mm (0.17 in.) below the surfaces after drying was completed. Hart's computer simulation does not consider dimension changes during drying. Thus it was difficult to compare quantitatively the simulated moisture content with that monitored at a certain depth and time; however, moisture distributions in the sample boards of Runs 1 and 2 were very similar, except that the moisture gradients in the second monitoring board were somewhat lower than expected because of the 10-h interruption of drying.

The simulation program had to be run two or three times for each kiln run to provide satisfactory values. A major reason why the first runs of the computer simulation did not provide the same moisture content values as observed in the kiln runs was the low accuracy of the initial drying rate inputs. The program requires drying rate values to be determined at every step in the kiln schedule, after sample boards have equilibrated to new drying conditions. However, the drying rates used as computer inputs were only averages for 12-h periods of the individual steps, thus including times when drying rates changed abruptly after a change in kiln conditions.

In the industrial kiln run, the average moisture content of the two sample boards on the edges of the stack was taken to be representative of the entire course, even though edge boards dry somewhat faster. After two trials, the fitting procedure resulted in good agreement between simulated and actual data (Fig. 5), except that the simulated drying rates for 12-h periods were always slightly lower than the actual rates at the air-inlet side and higher at the air-exit side. Because Douglas-fir is a relatively fast-drying species, its drying rate could be controlled by the rate of evaporation from the surface, and the observed difference may result from underestimation of the surface transfer coefficient calculated from Hart's manual (1983). However, a simulation run with a doubled surface transfer coefficient but the same internal diffusion coefficients gave the same result as before. Therefore, one must conclude that drying rates of Douglas-fir with less than 30% moisture content are controlled not by surface transfer but by internal transfer rates. Hart (personal communication) suggested that the difference between actual and simulated drying rates may also result from a boundary layer effect, which is not considered in the simulation program. The simulation assumption that air stream in a stack is evenly mixed with moisture evaporated from boards probably is not true. Moisture gradients in the air stream must be highest at the boundary layers near the surfaces of boards and lowest at its center.

CONCLUSIONS

The thermomoisture meter developed by Forrer (1984) is very useful in continuously measuring moisture gradients and temperatures in wood. Meters manufactured in the future should have preprogrammed temperature corrections for moisture content, provided correction factors can be obtained for individual species and moisture contents. The newly developed probes for the thermomoisture meter also are useful for experimentation; however, their manufacture is slow and therefore costly. A simpler design is needed for commercial use.

Kiln drying of 50-mm (2-in.)-thick Douglas-fir heartwood lumber with the commercial kiln schedule used here leads to stress reversal between 15% and 17% moisture content, after which the danger of surface checking is greatly diminished and more rapid drying possible. This information is useful for modifying kiln schedules.

Very good agreement between simulated and observed moisture contents can be achieved after two adjustments of the simulation inputs, with differences not exceeding 0.5% moisture content. Drying rates can be simulated to agree within $\pm 0.05\%$ moisture content per hour. Thus Hart's computer simulation programs and Forrer's thermomoisture meter appear to be excellent tools for future studies of drying behavior of lumber and therefore for improvement of kiln-drying schedules.

ACKNOWLEGMENT

We thank Dr. C. A. Hart for the use of his computer program and for his advice.

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