NONISOTHERMAL RADIOFREQUENCY DRYING OF RED OAK

Rajeev G. Joseph

Graduate Research Assistant
Department of Forest Resources
Clemson University
Clemson, SC 29634-1003

and

Perry N. Peralta†

Assistant Professor
Department of Wood and Paper Science
North Carolina State University
Raleigh, NC 27695-8005

ABSTRACT

The combination of nonisothermal moisture movement and radiofrequency heating has a potential application in lumber drying as it affords rapid heating of wood and provides an additional driving force for the removal of water. This paper describes the experimental setup and presents the results of the nonisothermal radiofrequency (NIRF) drying of red oak (*Quercus* spp.). NIRF drying is implemented by bulk heating the lumber at a preset temperature using radiofrequency energy while continuously circulating air conditioned at a lower temperature over the wood surface. The temperature at mid-thickness of the lumber is maintained at the dry bulb temperature required by the appropriate kiln-drying schedule, while the air temperature is maintained so as to establish a temperature gradient of 3°C/cm from the mid-thickness to the surface of the material. Excessive checking was observed when green lumber was dried using the NIRF method. The drying defect is due mainly to the high drying rate and steep surface moisture content gradient during the early stages of drying. Nonisothermal radiofrequency drying was successfully implemented when a pre-drying step was incorporated at the start of the process. When red oak was pre-dried to 40% MC, the modified NIRF method required a total of 275 h to dry 25-mm-thick boards from 85% to 12% MC. For lumber pre-dried to 60% MC, the total drying time for the modified NIRF method was 160 h. These drying times are significantly shorter than the 530 h needed to dry red oak over the same moisture content range using the conventional kiln-drying method.

Keywords: Drying, Soret effect, radiofrequency, convection, red oak, nonisothermal, drying strain.

INTRODUCTION

The flow of heat and the flow of mass through wood have traditionally been treated essentially as independent processes. However, studies have confirmed that such is not the case, but that each affects the other. To illustrate, consider the nonisothermal moisture movement in wood shown in Fig. 1. A wood sample initially at a uniform temperature T_i and moisture content M_i is sealed on all six faces and heat-insulated at the four edges to prevent moisture and heat exchange with the surrounding environment. If the two opposite and uninsulated wide faces are then exposed to two different but constant temperatures, a temperature profile T_f will soon be established across the wood thickness. Because of the temperature gradient, the moisture profile will also start to change to an intermediate shape shown by M_x in Fig. 1. Despite the moisture gradient, water will continue to flow from right to left, in apparent contradiction to Fick's law of diffusion, until eventually at the steady state, a moisture profile shown by M_f is estab-
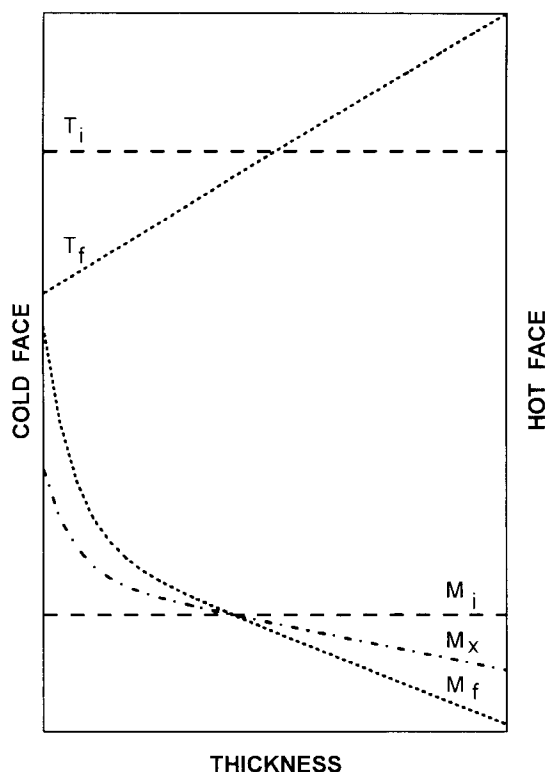
† Member of SWST

THICKNESS

Fig. 1. Hypothetical temperature (T) and moisture content (M) profiles in a sealed wood sample whose opposite faces were exposed to different but constant temperatures. The subscripts i, f, and x refer to the initial, final, and intermediate cases, respectively.

lished and will remain invariant with time. There will be no further net moisture flux in the wood since the flow of moisture from left to right due to the moisture gradient will be offset by the flow of moisture from right to left due to the temperature gradient. This coupling between mass and heat flow is known as the thermal-diffusion or Soret effect, which is defined as the transport of mass in the direction of decreasing temperature even opposite to, or in the absence of, a concentration gradient. A reciprocal phenomenon called the diffusion-thermo or Dufour effect occurs when heat is transported under the influence of a concentration gradient (Bird et al. 1960). These couplings between mass and heat flow have been observed to occur in many systems (Jost 1960), the Soret effect being easier to

measure and thus better documented than the Dufour effect. The experiments on nonisothermal moisture movement using sealed wood specimens as described above were first performed by Voigt et al. (1940) on European beech, and by Choong (1963) on western white fir. A similar study was later conducted on yellow poplar and hard maple laminates by Peralta and Skaar (1993).

The steady-state form of the mathematical equation describing the coupling of mass and heat transfer contains two terms: one showing the contribution of a moisture content gradient and the other showing the contribution of a temperature gradient to the total moisture flux, i.e.,

$$J_w = -\left(k_{WM}\frac{dM}{dx} + k_{WT}\frac{dT}{dx}\right) \qquad (1)$$

where J_w is the total moisture flux, dM/dx the moisture content gradient, dT/dx the temperature gradient, and k_{WM} and k_{WT} are phenomenological coefficients. Equation (1) suggests that under nonisothermal conditions, the flow of water may be enhanced if a temperature gradient can be imposed in the same direction as the moisture content gradient. Research results (Peralta 1990; Peralta and Skaar 1993) have shown that for a piece of wood at 9% initial moisture content (MC), maintaining a temperature gradient of 1°C/cm in the wood will cause moisture to move as if a moisture gradient of 0.5%/cm is present in the material. At 14% initial MC, the unit temperature gradient is equivalent to maintaining a unit moisture content gradient; while at 20% initial MC the unit temperature gradient will cause moisture to move as if a 5%/cm gradient is present in the material. Traditional methods of heating wood could not be employed to maintain a temperature gradient in the same direction as the moisture content gradient. In fact, studies (Beard et al. 1985; Adesanya et al. 1986; and Avramidis et al. 1992) indicate that during conventional drying, a temperature gradient from the surface to the center (i.e., opposite to the moisture gradient) actually exists in wood.

An attractive alternative involves the use of high-frequency (both radiofrequency and microwave) heating.

Heating involves the production of thermal energy and its transfer to the body to be heated. In the case of conventional heating, heat is generated directly in the thermal form and then carried to the surface of the product by radiation, convection, and/or conduction. Thereafter, the thermal characteristics of the material control the rate of heating. In the case of high-frequency heating, energy is generated and transferred in the form of electromagnetic vibrations that are then converted into heat when they interact with the body. There are many mechanisms for the energy conversion process during dielectric heating, one of which involves dipole rotation (Skaar 1988). When a dielectric, like wood, is placed in an alternating electric field, the charged asymmetric molecules that make up the dielectric are oriented one way at a given instant and another way at the next instant. The asymmetric molecules attempt to align themselves with the rapidly changing electric field resulting in intermolecular friction that generates heat. The molecules affected most by the field are those that have permanent dipoles, water being the most important one from the drying standpoint. Thus, high-frequency heating is distinctly different from conventional means. Whereas conventional methods depend upon the slow flow of heat from the surface of the heated material to its interior as determined by the temperature gradient between the hot surface and the cold interior, high-frequency heating is, in effect, bulk heating in which the electromagnetic field interacts with the material as a whole and heat is generated within the material (Schiffmann 1987). High-frequency heating is a very rapid method and, in homogeneous materials, the heating is uniform throughout.

The amount of power that can be generated in a dielectric or nonconductor placed in an electromagnetic field is given quantitatively by the expression (Brown et al. 1947):

$$P = 2 \pi \epsilon_o F E^2 \epsilon' \tan \delta \qquad (2)$$

where P is the power generated in a unit volume of material, W/m^3; ϵ_o (=8.85 $\times$ 10^{-12} C^2 N^{-1} m^{-2}) is the permittivity of free space; F is frequency, Hz; E is electric field strength, V/m; ϵ' is dielectric constant of the material; and tan δ is loss tangent of the material. The product (ϵ' tan δ) often called the loss factor ϵ'' indicates the relative heating rate of different materials under high-frequency electromagnetic fields of a given frequency and intensity. For wood, this material property ϵ'' and its components (ϵ' and tan δ) have been extensively investigated and found to be strongly dependent on the frequency of the applied voltage and on the wood density, temperature, structural orientation, chemical composition, and most especially moisture content (Skaar 1988; Norimoto 1976; James 1975; Lin 1967). The loss factor increases with moisture content. Thus, with everything else being constant, the regions in the wood with high moisture content receive more power and develop greater heat. This means that in samples with a moisture gradient from the center to the surface, there is a pattern of heat liberation that increases the driving force, which brings moisture to the surface, i.e., wetter inner regions get somewhat warmer (Cross et al. 1982). Also, since heat is generated within the material during high-frequency heating, a temperature gradient within a piece of wood may be established by maintaining an ambient temperature lower than the temperature of the bulk wood. Thermal gradient from the center to the surface results as ambient air cools the surface, and dielectric heating maintains a higher temperature within the material.

Nonisothermal radiofrequency (NIRF) heating has a potential application to lumber drying. The presence of two driving forces for moisture movement suggests that shorter drying times can be realized. A study to evaluate such hypothesis was conducted. This paper describes the experimental setup and presents the results of that study.

MATERIALS AND METHODS

The experimental setup (Fig. 2) will be described only briefly here since a more detailed
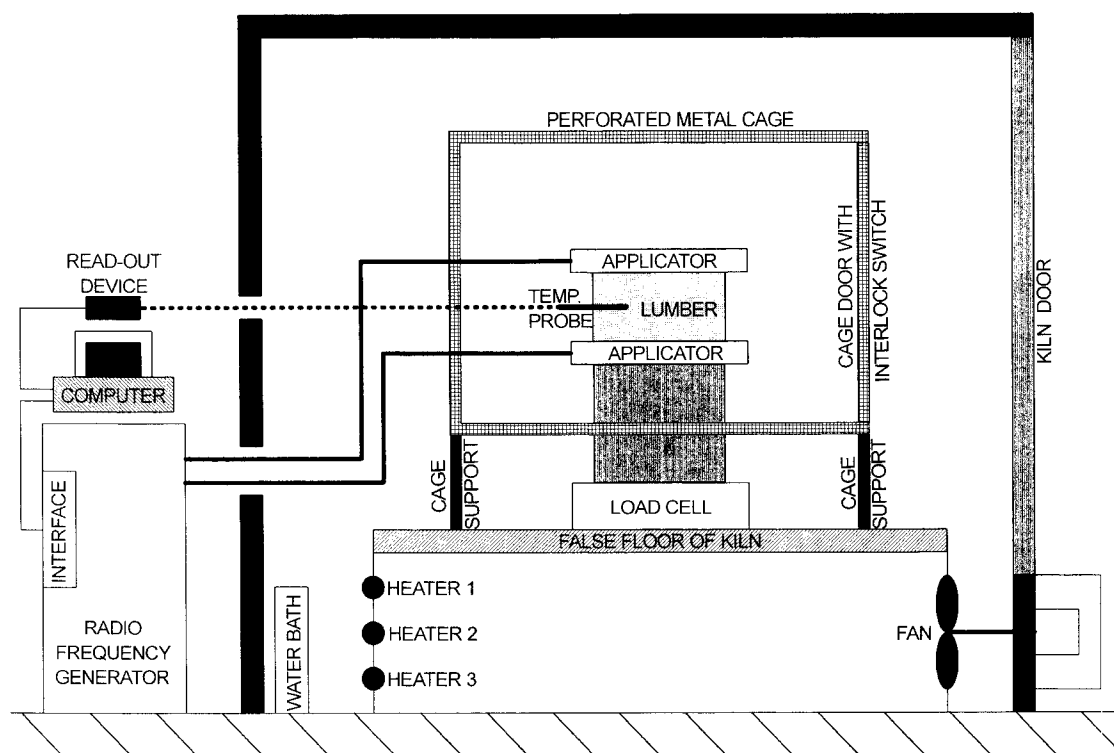
FIG. 2.   Schematic diagram showing the experimental setup for the nonisothermal radiofrequency drying of lumber.

description was given in an earlier paper (Peralta and Joseph 1996). A red oak (*Quercus* spp.) board 15 cm wide × 91 cm long is sandwiched between 0.6-cm-thick perforated aluminum applicator plates each measuring 25 cm wide × 100 cm long. Moisture evaporated from the lumber surface passes through the plates' perforations and eventually is carried away by the circulating air. To monitor the weight of the sample during the drying process, the wood and applicator plates are supported by Delrin columns that are attached to two 14-kg capacity load cells. This load cell system allows weight measurements to be taken to the nearest 8 g. Thus, since the lowest oven-dry weight was 1800 g, moisture content measurement error was no greater than 0.5% MC. The voltage output of the load cells is sent to the computer to allow continuous recording of sample weight and moisture content. The lumber and applicator plates are enclosed in a perforated aluminum cage to pre-

vent the escape of high-frequency waves. The whole setup is then placed inside a kiln to control the temperature and relative humidity of the air surrounding the sample. The kiln is a laboratory-size, electrically heated unit that is humidified with steam from a hot-water bath. The kiln has a forced-air venting system and is equipped with four reversible fans capable of developing air velocities of 3 m/s.

Nonisothermal radiofrequency drying is implemented by bulk heating the lumber at a preset temperature using radiofrequency energy while continuously circulating air maintained at a lower temperature over the wood surface. The latter is controlled through the kiln's heating, humidification, and air circulation system described earlier, while the former is done through the control unit of the radiofrequency (RF) generator. The RF unit has a continuous power output of 3.5 kilowatts at a frequency of 13.6 megahertz. Temperature feedback to the RF unit is provided by a fiber-optic tem-

TABLE 1. *Temperature settings at various stages during the nonisothermal radiofrequency drying of 25-mm- and 50-mm-thick southern red oak lumber.*

Moisture Content (%)	25-mm-thick lumber			50-mm-thick lumber		
	Mid-thickness temperature (°C)	Kiln dry bulb temperature (°C)	Kiln wet bulb temperature (°C)	Mid-thickness temperature (°C)	Kiln dry bulb temperature (°C)	Kiln wet bulb temperature (°C)
>50	43.3	41.9	41.1	43.3	42.5	41.7
50 to 40	43.3	41.4	40.6	43.3	42.0	41.1
40 to 35	43.3	39.7	38.9	43.3	40.8	40.0
35 to 30	43.3	39.6	35.6	43.3	38.6	37.8
30 to 25	48.9	45.1	32.2	48.9	41.4	35.0
25 to 20	54.4	50.7	32.2	54.4	46.9	32.2
20 to 15	60.0	56.2	32.2	60.0	52.5	32.2
15 to final	82.2	78.5	54.4	71.1	63.6	43.3

perature probe inserted at the lumber's mid-thickness through a 1.5-mm hole drilled at mid-length of the sample. The temperature measurement system has an accuracy of ±0.1°C at the calibration point and ±0.5°C within ±50°C of calibration point. The fiber-optic temperature probe is also connected to a read-out device that sends analog signals (resolution of 0.024°C) to the desktop computer for continuous data acquisition. When heating of the lumber is demanded, the RF unit's low-temperature setpoint relay is activated, thereby closing its normally open switch. A signal is then sent to the variable capacitor drive motor to increase the capacitance value, thereby allowing for a more intense heating of the material. Once the desired temperature is attained, the low-temperature setpoint relay is deenergized, thus, stopping the drive motor. The high-temperature setpoint relay is subsequently activated to let the variable capacitor drive motor decrease the capacitance value and cause the load to be out of tune. This process of tuning and detuning of the load through the variable capacitor enables the system to maintain the mid-thickness temperature of the lumber at the desired level. The temperature-regulation capability of the system was excellent, with the mid-thickness temperature being maintained to within 0.2°C of the setpoint.

The samples' mid-thickness temperature and the kiln's wet bulb temperature were set according to the dry bulb and wet bulb tem-

perature values specified in the U.S. Forest Products Laboratory's (FPL) dry kiln schedules for the conventional drying of lumber (Boone et al. 1993). Since only southern red oak was investigated in this study, schedule T4-D2 was used for the drying of 25-mm-thick samples, and T3-D1 was used for the 50-mm-thick samples (Table 1). Except during the early stages of drying, the kiln's dry bulb temperature was set so as to establish a temperature gradient of 3°C/cm in the board thickness direction. This gradient corresponds to the "mild drying condition" recommended by Biryukov (1961). Thus, the dry bulb temperature was maintained at 3.75°C and 7.5°C less than the mid-thickness temperature for the 25-mm-thick samples and the 50-mm-thick samples, respectively. This scheme does not apply during the early stages of drying since it would have caused the dry bulb temperature to be set below the wet bulb temperature and result in kiln control problems and excessive condensation. Instead, the dry bulb temperature was set so as to maintain a relative humidity of 95% inside the kiln.

RESULTS AND DISCUSSION

The NIRF drying of red oak boards from the green condition was not successful. All drying runs were terminated after 48 h because of severe surface and end checking. This was first explained in terms of the lower effective relative humidity on the lumber surface

compared to that of the kiln air because of the higher temperature of the former (Peralta et al. 1997). Such temperature difference between the wood surface and the kiln air was observed in experiments performed by the authors in the past (Peralta and Joseph 1996). From psychrometric principles, air initially at a temperature of 41.9°C and relative humidity of 95%, when heated to a temperature of 42.6°C at a constant humidity ratio, will have a reduced relative humidity of 91%. These are more or less the conditions that exist during the NIRF drying of lumber. Because of the temperature gradient being maintained in the lumber, kiln air at a given dry bulb and wet bulb temperatures gets heated upon contact with the lumber surface. Thus, the effective relative humidity on the lumber surface during NIRF drying is lower and the drying conditions more severe than what is indicated by the dry bulb and wet bulb temperatures. Still, this does not completely explain the occurrence of checking in the lumber. The temperature values indicated in Table 1 were selected explicitly to prevent the development of conditions that are harsher than what is asked for in the FPL drying schedule. For instance, when the moisture content of lumber is greater than 50%, the FPL schedule for 25-mm-thick boards recommends a dry bulb temperature of 43.3°C and a wet bulb temperature of 41.1°C to yield a relative humidity and equilibrium moisture content of 87% and 17.6%, respectively. On the other hand, the kiln air during the initial stages of NIRF drying was maintained at a dry bulb temperature of 41.9°C and a wet bulb temperature of 41.1°C, which correspond to a relative humidity and equilibrium moisture content of 95% and 22.6%, respectively. Even if this air is heated to the mid-thickness temperature of 43.3°C, the relative humidity and equilibrium moisture content go down only to 88% and 18.2%, respectively. Since the mid-thickness is supposed to have the highest temperature at any point in the material, then the condition at any other location, including the wood surface, should be milder than what is called for in the FPL schedule.

Apparently, factors other than the reduction in effective relative humidity are causing the lumber to develop excessive surface checks. Analysis of the drying situation points to the kinetics of NIRF drying as the cause of the drying defects. As mentioned earlier, with nonisothermal drying, an additional driving force is causing water to move within the material. It is possible that with the higher drying rate, the moisture content gradient in the lumber is also higher. This means that with NIRF drying, the rate of stress development and the magnitude of stresses are also higher. Figure 3 shows half of the moisture content profile in 50-mm-thick boards before and after drying for 48 h using conventional and NIRF drying methods. The data were obtained by slicing a one-inch section (along the grain) of the lumber into ten wafers in the thickness direction and then determining the moisture content of each wafer by the oven-drying method. The initial moisture content profile was rather uniform since the surface layers were removed by planing the lumber from a thickness of 63 mm to a thickness of 50 mm before drying. A marked difference in the moisture content profile was observed between the boards dried using the conventional method and those dried using the NIRF method. While the average final moisture content of the latter was 69.0%, the former had an average final moisture content of 77.1%, indicating that the lumber subjected to NIRF drying had a higher drying rate. Also, the moisture content gradient near the surface for the lumber dried using the NIRF method was steeper and, by extrapolation, the wood surface was already below the fiber saturation point. These data indicate that tremendous stresses have developed early during NIRF drying of red oak. An average tensile strain of 0.0046 cm/cm was measured in the surface layer, and an average compressive strain of 0.0008 cm/cm was measured in the core of the lumber subjected to NIRF drying (Fig. 4). This average tensile strain value is larger than the maximum tensile strain of 0.0030 measured by McMillen (1963) on red oak lumber dried by the conventional method.
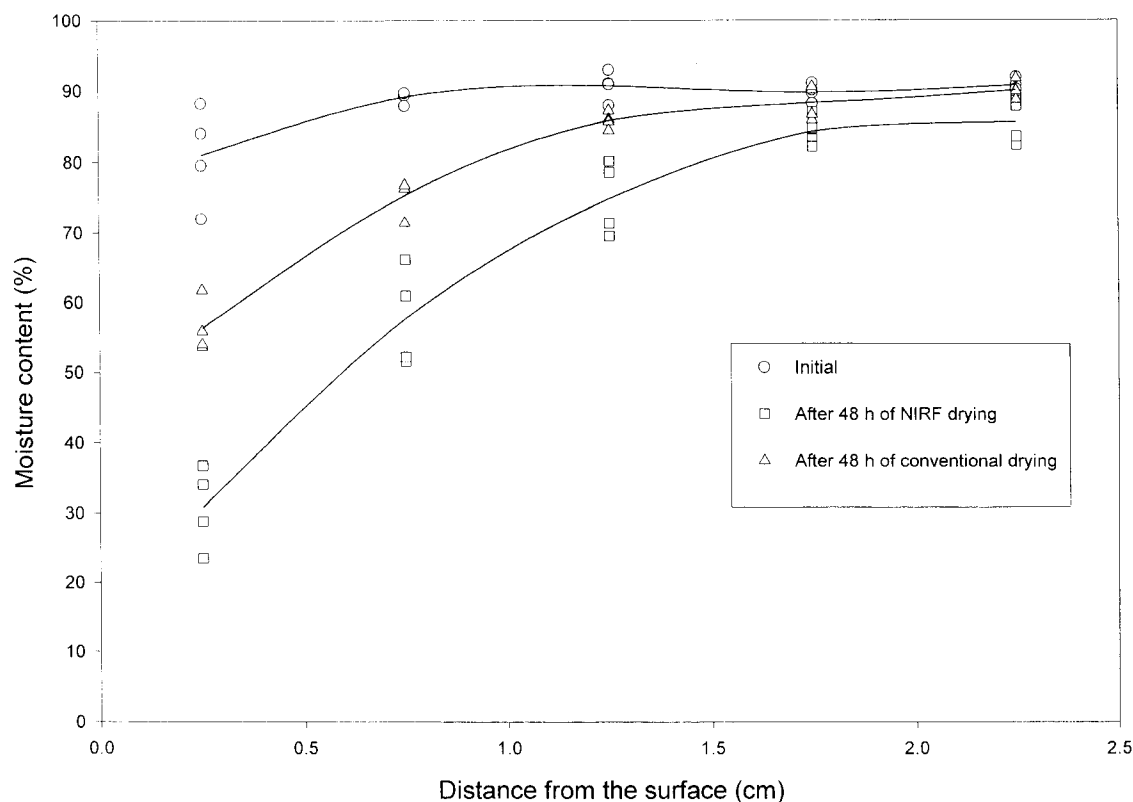
FIG. 3.   Half-thickness moisture content profiles in 50-mm-thick red oak lumber before and after drying for 48 h using conventional and nonisothermal radiofrequency (NIRF) drying methods.

While the maximum tensile strain recorded by McMillen occurred 120 h after the start of drying, that for lumber dried using the NIRF method most likely occurred less than 48 h into the drying process since the severe surface checks were already present when the drying runs were terminated.

NIRF drying experiments were also performed on 25-mm-thick red oak lumber. Excessive checking was again present, and the results of the moisture profile and drying strain analyses were similar to those of the 50-mm-thick materials. At this point in the investigation, several alternatives were considered to solve the drying quality problem. Increasing further the relative humidity in the kiln was discounted since the kiln was already pushed to maintain the highest RH value attainable without developing excessive conden-

sation problems. NIRF drying using a milder condition was the first option to be considered. The wood mid-thickness was maintained at 38.9°C, while the kiln air was maintained at a dry bulb temperature of 38.0°C and a wet bulb temperature of 37.2°C. Again, severe surface checks developed, so the drying runs were terminated 48 h into the drying process.

The next approach taken was the pre-drying of the lumber using conventional kiln schedule from an initial moisture content of approximately 85% down to a moisture content of 40%, followed by NIRF drying to the final moisture content of 12%. The quality of the lumber during and at the end of the drying process was very good; no defects were found on the surface and in the interior of the lumber. The average NIRF drying time from 40% MC to 12% MC for 25-mm-thick lumber was 41
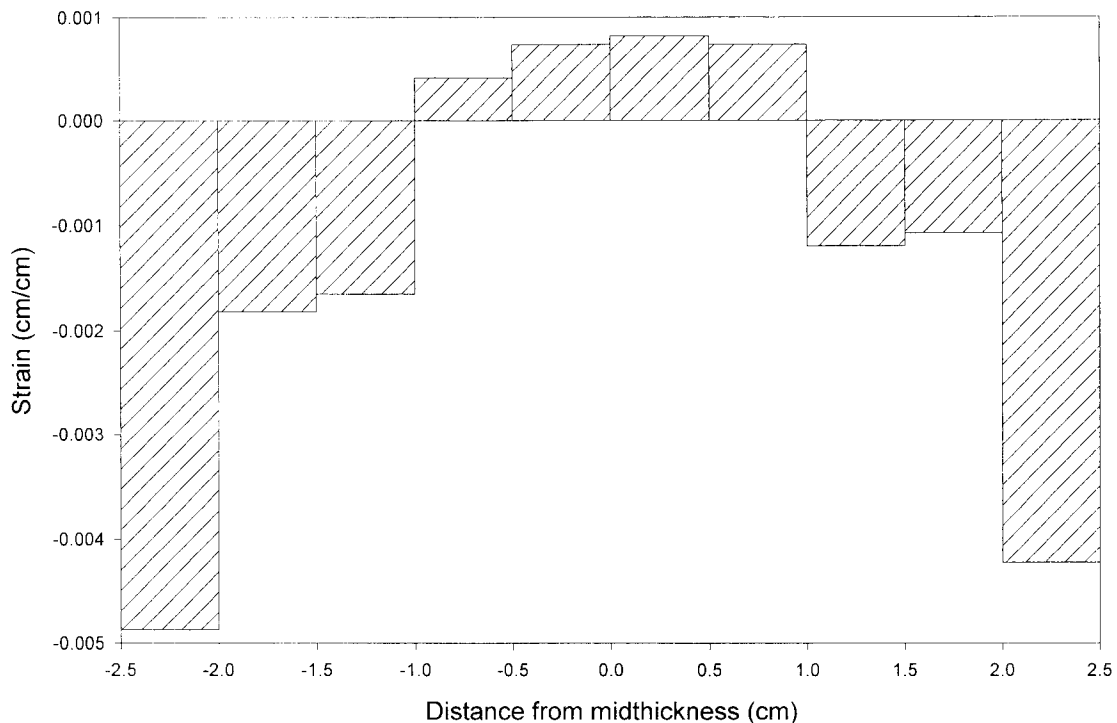
Fig. 4.   Drying strain at different layers along the thickness of 50-mm-thick red oak lumber after 48 h of nonisothermal radiofrequency drying.

h. This is roughly ⅛th of the time (295 h) required to dry lumber of the same thickness over the same moisture content range using the conventional drying method. If the 234 h of pre-drying is taken into account, the total drying time from the green condition to 12% MC for the modified NIRF method is 275 h, roughly half the 530 h needed to dry the lumber using only the conventional kiln-drying method.

With the success of the foregoing experiments, the next step taken was to determine whether the pre-drying period could be shortened and thus maximize the benefit to be gained from NIRF drying. Since the maximum tensile strain in the conventional drying of 50-mm-thick red oak occurred 120 h into the drying process (McMillen 1963), that for thinner boards would most likely occur earlier. Rice (1988), in drying 3.8-cm-thick red oak boards in a conditioning chamber maintained at 43.3°C temperature and 85% RH, observed

that a maximum tensile strain of 0.003 cm/cm developed at the surface layer of the lumber on the 72nd h of drying. Hence for our study, the 25-mm-thick boards were pre-dried by the conventional method for 72 h from 85% to 60% MC. The moisture content profile at the end of the pre-drying period (Fig. 5) is typical of lumber that is dried using conventional kiln-drying. After the pre-drying stage, the lumber was dried further to 12% MC using NIRF drying. As in the earlier NIRF drying experiments that incorporated a pre-drying step, the quality of the lumber was very good. Although the moisture content profile at the end of the NIRF drying process was relatively flat (Fig. 5), an average difference of 3.5% MC existed between the mid-thickness and the surface layer of the lumber. The drying curves in Fig. 5 show that it took 88 h for the lumber to dry from 60% to 12% MC using the NIRF method, which is roughly ⅕th of the 458 h it took to dry lumber over the same moisture
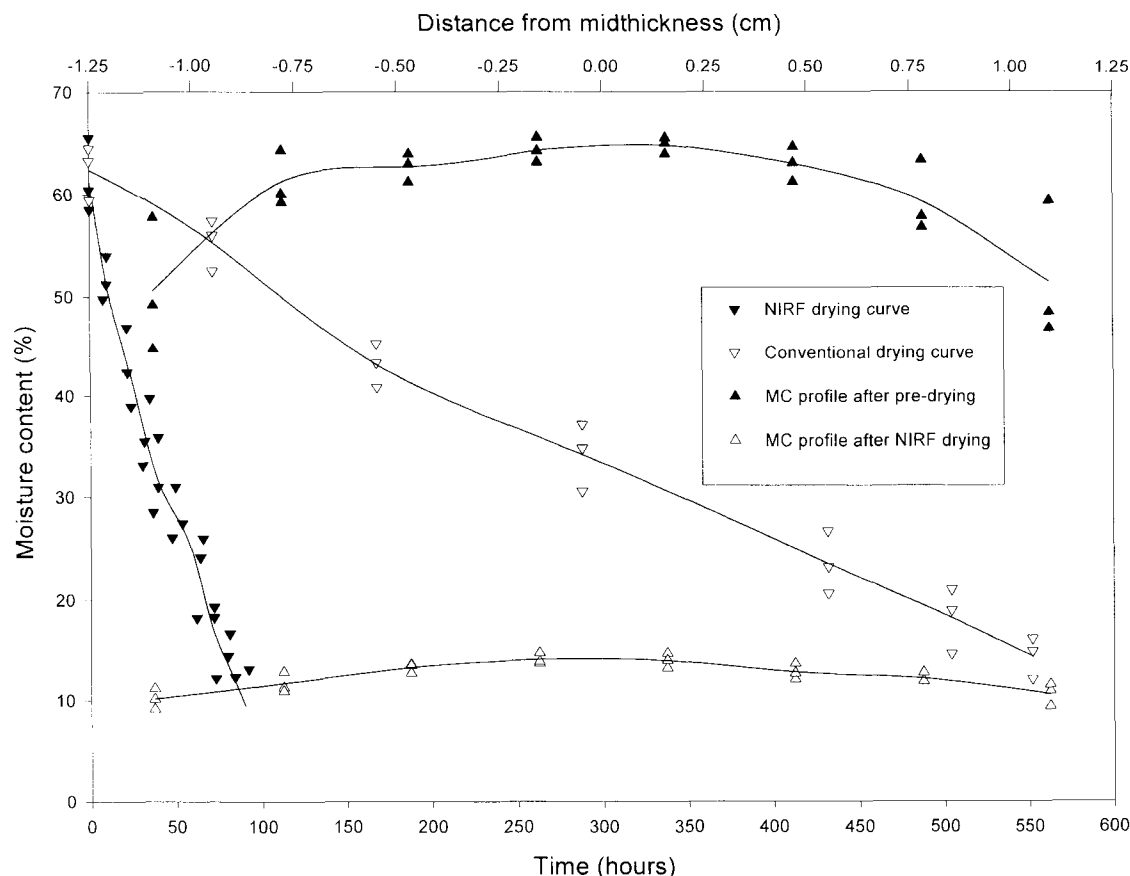
FIG. 5.   Drying curves (downward pointing triangles) for 25-mm-thick red oak lumber dried from 60% to 12% moisture content using conventional and nonisothermal-radiofrequency (NIRF) drying methods. Also shown are the moisture content profiles (upward pointing triangles) in the thickness direction after pre-drying and after NIRF drying.

content range by the conventional method. If pre-drying is taken into account, the total drying time from the green condition to 12% MC for the modified NIRF method is 160 h, roughly a third of the 530 h needed to dry the lumber using only the conventional kiln-drying method. By shortening the predrying period and applying the NIRF drying method at 60% instead of 40% MC, the total drying time was reduced by 40% from 275 to 160 h.

SUMMARY AND CONCLUSIONS

Nonisothermal radiofrequency drying of red oak from the green condition results in excessive surface checking. Although the reduced effective relative humidity on the surface of

the wood is a contributing factor, the high drying rate and steep surface moisture content gradient are mainly responsible for the development of the drying defect. Nonisothermal radiofrequency drying can be successfully implemented if a pre-drying step is incorporated in the process. For 25-mm-thick lumber, the drying time can be reduced to a third of that for conventional kiln drying without sacrificing lumber quality.

for providing the financial assistance for this project.

REFERENCES

ADESANYA, B. A., J. N. BEARD, AND A. K. NANDA. 1986. Moisture distribution during high temperature drying of yellow poplar. *In* A. S. Mujumdar, ed. Drying '86. Vol. 1. Hemisphere Publishing Corp., New York, NY.

AVRAMIDIS, S., P. ENGLEZOS, AND T. PAPATHANASIOU. 1992. Dynamic nonisothermal transport in hygroscopic porous media: Moisture diffusion in wood. AIChE J. 38(8): 1279–1287.

BEARD, J. N., H. N. ROSEN, AND B. A. ADESANYA. 1985. Temperature distribution in lumber during impingement drying. Wood Sci. Technol. 19:277–286.

BIRD, R. B., W. E. STEWART, AND E. N. LIGHTFOOT. 1960. Transport phenomena. John Wiley & Sons, New York, NY. 780 pp.

BIRYUKOV, V. A. 1961. Dielectric heating and drying of wood. (Translated from Russian). Israel Program for Scientific Translations, Jerusalem. 117 pp.

BOONE, R. S., C. J. KOZLIC, P. J. BOIS, AND E. M. WENGERT. 1993. Dry kiln schedules for commercial woods: Temperate and tropical. Forest Products Society, Madison, WI. 158 pp.

BROWN, G. H., C. N. HOYLER, AND R. A. BIERWIRTH. 1947. Theory and application of radio-frequency heating. D. Van Nostrand Co., New York, NY. 370 pp.

CHOONG, E. T. 1963. Movement of moisture through a softwood in the hygroscopic range. Forest Prod. J. 13(11):489–498.

CROSS, A. D., P. L. JONES, AND J. LAWTON. 1982. Simultaneous energy and mass transfer in radiofrequency fields. I. Validation of the theoretical model. Trans. Inst. Chem. Eng. 60(2):67–74.

JAMES, W. L. 1975. Dielectric properties of wood and hardboard: Variation with temperature, frequency, moisture content, and grain orientation. USDA Forest Serv. Res. Paper FPL-245. 32 pp.

JOST, W. 1960. Diffusion of solids, liquids, and gases. Academic Press, New York, NY. 558 pp.

LIN, R. T. 1967. Review of the dielectric properties of wood and cellulose. Forest Prod. J. 17(7):61–66.

MCMILLEN, J. M. 1963. Stresses in wood during drying. USDA Forest Serv. Rep. No. 1652. Forest Prod. Lab., Madison, WI. 52 pp.

NORIMOTO, M. 1976. Dielectric properties of wood. Wood Research 59/60:106–152.

PERALTA, P. N. 1990. Nonisothermal moisture transport in wood. Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

———, AND C. SKAAR. 1993. Experiments on steady-state nonisothermal moisture movement in wood. Wood Fiber Sci. 25(2):124–135.

———, AND R. G. JOSEPH. 1996. Nonisothermal-radiofrequency drying of wood: Experimental setup and preliminary results. Proc. 5th International IUFRO Wood Drying Conference, Quebec City, Canada.

———, R. G. JOSEPH, AND A. W. C. LEE. 1997. Nonisothermal radiofrequency drying of red oak. Abstracts of Technical Sessions and Technical Forum Presentations, 51st Annual Meeting of the Forest Products Society, Vancouver, B.C.

RICE, R. W. 1988. Mass transfer, creep, and stress development during the drying of red oak. Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA. 152 pp.

SCHIFFMANN, R. F. 1987. Microwave and dielectric heating. Pages 327–356 *in* A. S. Mujumdar, ed. Handbook of Industrial Drying, Marcel Dekker, New York, NY.

SKAAR, C. 1988. Wood-water relations. Springer-Verlag, Berlin, Germany. 283 pp.

VOIGT, H., O. KRISCHER, AND H. SCHAUSS. 1940. Die Feuchtigkeitsbewegung bei der Verdunstungstrocknung von Holz. Holz Roh-Werkst. 3:305–321.