

HIGH-FREQUENCY HEATING OF WOOD WITH MOISTURE CONTENT GRADIENT

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ABSTRACT

The influence of moisture content (MC) gradient on the development of a temperature gradient in wood heated in a high-frequency (HF) electromagnetic field was investigated. Fifteen layers of 1.6-mm-thick beech veneer (*Fagus sylvatica* L.), with dimension 400 × 400 mm, were used to simulate a moisture content (MC) gradient. A uniform MC of 5, 10, 15, and 20%, and two MC gradient schemes ranging from 20% to 5%, were used in the experiment. The dielectric constant and loss tangent were measured before HF heating at 6.3 MHz. During HF heating of wood, the magnitude of the MC, the shape of the MC gradient, and the potential for thermal losses influence the development of the temperature gradient. An MC gradient in a laminated composite could be used to control the shape and severity of the temperature gradient during HF heating.

Keywords: High-frequency, radio-frequency, heating of wood, dielectric properties.

INTRODUCTION

Over the last few decades, high-frequency electromagnetic fields, with operating frequencies between 3 and 30 MHz, have been used in the wood-processing industry for the drying, bending, and gluing of wood. The speed and degree to which wood can be heated under high-frequency (HF) conditions depend on many factors, all of which have an influence on the dielectric properties of wood. These factors include the structure of the wood, its physical and chemical properties, its moisture content, its temperature, and the direction of

the fibers with respect to the direction of the electromagnetic field (Torgovnikov 1993). The losses of electrical energy in the wood as a dielectric material, and consequently in the heating process, vary, and also depend on the frequency and electric field strength. In the case of HF heating of wood, it is the loss factor, which is a property of the wood calculated as the product of the dielectric constant and the loss tangent, that is of critical importance.

The results of numerous investigations (Kröner and Pungs 1953; James 1977; Pound 1959) have shown that it is the moisture con-

tent of wood which has the greatest influence on the dielectric constant. This is easy to understand since water has a dielectric constant of 80, whereas wood with a moisture content of between 8 and 10% has a dielectric constant of about 4. Numerous investigations have been published regarding the influence of moisture content on dielectric properties of wood. However, all of these studies considered only a uniform moisture content, when in fact a moisture content gradient is normally encountered in practice. The objective of this paper is to demonstrate the influence of a moisture content gradient on the heating of wood in an HF electromagnetic field.

An example of how the dielectric value depends on the moisture content of wood was published by Skaar (1948), where the increase in the dielectric constant is exponential from the absolutely dry state up to the point of full saturation of the cell walls. Beyond this point the increase is linear. The extent to which moisture content affects the dielectric constant also depends on a number of other physical and chemical properties of the wood, particularly density (Skaar 1948; Torgovnikov 1993; Tsutsumi and Watanabe 1966).

The influence of a higher moisture content is twofold. A high moisture content means that there is more water in the wood absorbing energy in the electromagnetic field, and thus a higher dielectric constant. In addition, the polar molecular components of the cell wall obtain more space for molecular motions, which contribute to the dielectric behavior in an electromagnetic field (Lin 1967).

The variation of the loss tangent with moisture content is more complicated than in the case of the dielectric constant. In the region between zero and 8% moisture content, the loss tangent increases sharply. Between 8 and 20% the increase is more gradual (a slight decrease even occurs in the longitudinal direction), and in the case of wood with a moisture content greater than 20%, the loss tangent again increases sharply (Vermaas et al. 1974). Lin (1973) found that the loss tangent of green wood reaches a maximum at a moisture con-

tent of 30% and that changes above 40% moisture content are hardly noticeable. The interaction between moisture content and loss tangent depends on the frequency level, where at higher frequency the influence of moisture content on loss tangent is greater.

In most published investigations of the effect of moisture content on the dielectric properties of wood, the measurements were carried out under laboratory conditions, on relatively small specimens (e.g. $2 \times 2 \times 2$ cm), and the moisture content was uniform throughout the specimen. Wood is electrically and dielectrically a nonhomogeneous material. As the dimensions of a piece of wood are increased, heterogeneous features (i.e. growth increments, heartwood and sapwood, and slope of grain) begin to have a significant influence on properties. Larger pieces are also more likely to exhibit an MC gradient. No published results exist on the influence of an MC gradient on HF heating.

MATERIALS AND METHODS

To produce a moisture content gradient in wood, sheets of veneer were used, which had been conditioned to different moisture contents (MC). The veneer was combined together in layers to form a test specimen. This meant that an MC gradient was achieved over the cross section of the specimen. In this way either veneer sheets with the same MC were used to make the specimen, so that there was no MC gradient, or veneer sheets with different moisture contents were used, which resulted in a specimen with specified MC gradient.

The measurements of dielectric constant and loss tangent were carried out on test specimens made of 15 layers of rotary-peeled beech veneer (*Fagus sylvatica* L.), made under industrial conditions, of thickness 1.6 mm and dimensions 400×400 mm. The veneer sheets were divided into four groups. Each group was conditioned in a climate chamber to a selected MC as follows: the first group to 5%, the second group to 10%, the third group to 15%,

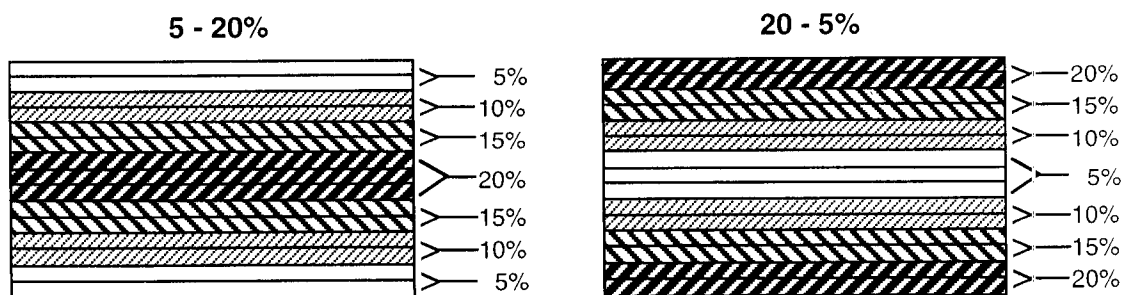


FIG. 1. Constructions of the moisture content gradient specimens indicating the moisture content of each of the 15 veneer layers.

and the fourth group to 20% MC. The actual MC was verified by the gravimetric method. The layered specimens were then constructed from the veneer groups to yield six MC treatments. Four of the treatments consisted of a uniform MC of 5, 10, 15, and 20%. Two additional treatments were constructed: one with progressively higher MC from the center to the outside, and one with progressively lower MC from the center to the outside (Fig. 1). The dielectric constant and loss tangent were then measured for each of the MC treatments, including five replications. The measurements were made using a press-capacitor with aluminium electrodes of size 400×400 mm and thickness 2 mm, to which an impedance analyser was connected (Fig. 2).

During the measurements, the sample was placed in the HF press, where a pressure of 16 bar was then applied. The HF generator, which usually operates together with the HF press, was switched off and galvanically separated from the electrodes of the capacitor during the measurements of the dielectric constant and loss factor.

Measurements of dielectric properties were carried out using a Hewlett-Packard Model 4191A RF Impedance Analyser at a frequency of 6.3 MHz. The loss tangent was measured directly, whereas the dielectric constant was calculated according to Eq. 1 (Torgovnikov 1993):

$$\epsilon = (C \cdot d)/(\epsilon_0 \cdot S), \quad (1)$$

where C is the measured capacitance of the capacitor with the inserted veneer sample, d is the distance between the electrodes, ϵ_0 is the

electric constant, which is equal to 8.85×10^{-12} F/m, and S is the surface area of the electrode (m^2).

During temperature measurement, the generator was connected to the press and activated. A constant 650V/cm electromagnetic strength field, frequency of 6.3 MHz, and 16 bar pressure were applied to each specimen. The HF press (Slovenijales - KLI Logitec, model VFG 23/4) generates a resonant frequency in air of 6.9 MHz. The temperature was measured at four points inside the specimen and at one point outside of the capacitor (Fig. 2). Measurements of the temperature were carried out using iron-constantan (Type J) thermocouples. While the temperature data were being read, the HF generator was switched off for 15 seconds. Five replications were carried out for each veneer group. Heat generated in the specimen is transferred to the press platens by conduction. Hence the press platens increase in temperature during HF pressing. To account for the influence of platen heating on the temperature of the specimen, the HF press was preheated, using a dummy specimen in the HF field, to approximately 50°C before testing. The results of the measurements are given in Table 1 and in Figs. 3 to 8.

RESULTS AND DISCUSSION

The mean values for dielectric constant and loss tangent for the samples with 5, 10, 15, and 20% uniform MC correspond with the re-

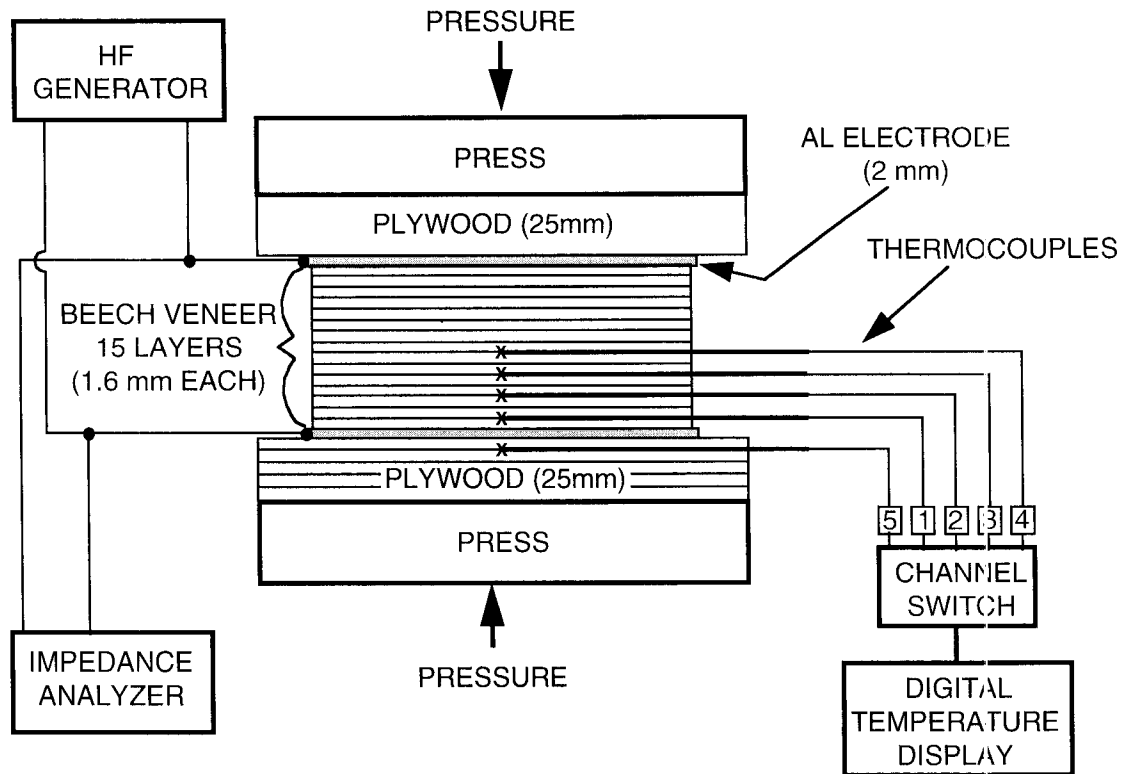


FIG. 2. Schematic diagram of the high frequency press and the 5 temperature measurement locations.

sults published in the cited literature (Torgovnikov 1993; Lin 1967). Table 1 shows mean values from 5 replications. The dielectric constant and loss tangent for each treatment, consisting of a uniform MC, were significantly different at the 0.05 confidence level, as determined by an analysis of variance. In the case of the samples with the MC gradients, no statistically significant difference of dielectric constant and loss tangent values were observed. A slight difference in the dielectric properties of the MC gradient specimens was expected due to the difference in average MC

between the two treatments. In the case of the specimens with the higher MC in the outside layers, the average MC was slightly higher (13%) than the average MC of the samples with the lower MC in the outside layers (12%). The small difference in the MC should have caused a small difference in the dielectric properties between the MC gradient specimens; however, the observed difference between the means was not statistically significant.

The temperature development and total power consumption measurements are shown

TABLE 1. Dielectric properties of beech specimens at various moisture contents, room temperature, and frequency of 6.3 MHz.

Specimen	5% Uniform	10% Uniform	15% Uniform	20% Uniform	5-10-15-20% Gradient	20-15-10-5% Gradient
Mean MC (%)	5	10	15	20	12	13
Dielectric constant	4.08	4.95	6.31	7.38	5.40	5.58
Loss tangent	0.0764	0.0782	0.0965	0.1286	0.0889	0.0876

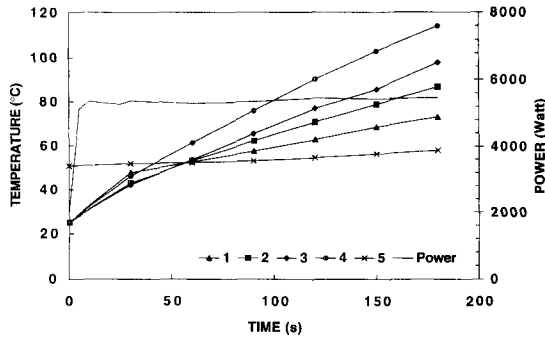


FIG. 3. Mean temperature of 5 replications, at 5 locations (see Fig. 2) during HF heating, and total power consumption of the HF generator. Specimen MC is uniform at 5%, and electric field strength is constant at 650V/cm.

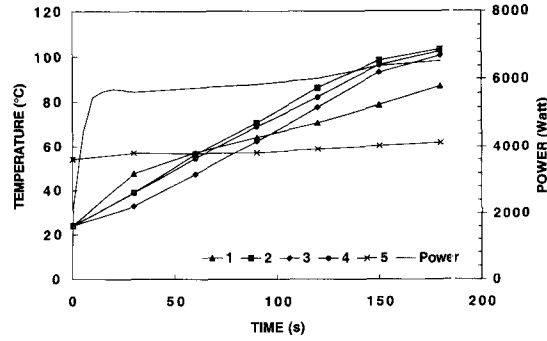


FIG. 5. Mean temperature of 5 replications, at 5 locations (see Fig. 2) during HF heating, and total power consumption of the HF generator. Specimen MC is uniform at 15%, and electric field strength is constant at 650V/cm.

in Figs. 3 to 8. The oscillating-circuit, self-adjusting generator used in the experiment resulted in a power output to the capacitor dependent on the dielectric properties of each specimen. Specimens with a greater loss factor (greater MC) absorbed more power from the HF field, and thus more power was consumed. The frequency output from the generator varied from 5.3 MHz with the 5% MC specimens to 6.0 MHz with the 20% MC specimens. The electromagnetic field strength was controlled and held constant at 650V/cm for all specimens. The total power consumption of the HF generator (shown in Figs. 3 through 8) included all energy losses in the equipment as well

as the power absorbed by the specimen. The "stand by" generator power is represented at time equal to zero in Figs. 3 to 8, which varied according to the demand for automatic cooling of the generator during the experiment. The power consumption increased with an increase of MC, ranging from a peak power load of 5,500 watts at a 5% MC to 7,800 watts at a 20% MC.

The development of a temperature gradient (see Fig. 9) in the layered specimens was influenced by both the veneer MC and the heat loss into the press platens. In the case of specimens having a uniform MC (Figs. 3-6), an influence of heat conduction from and to the

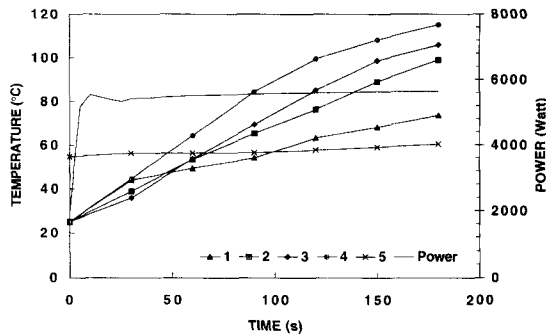


FIG. 4. Mean temperature of 5 replications, at 5 locations (see Fig. 2) during HF heating, and total power consumption of the HF generator. Specimen MC is uniform at 10%, and electric field strength is constant at 650V/cm.

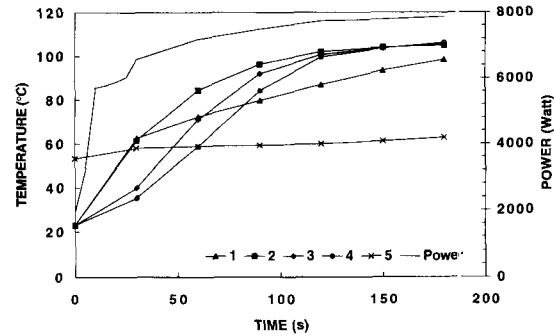


FIG. 6. Mean temperature of 5 replications, at 5 locations (see Fig. 2) during HF heating, and total power consumption of the HF generator. Specimen MC is uniform at 20%, and electric field strength is constant at 650V/cm.

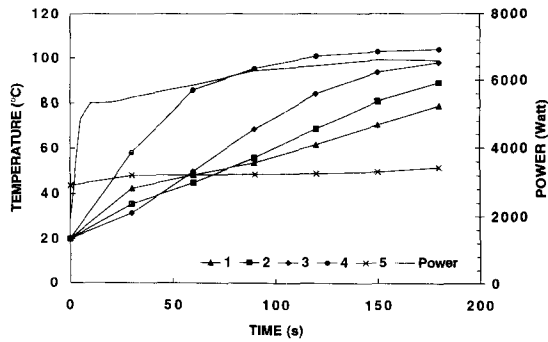


FIG. 7. Mean temperature of 5 replications, at 5 locations (see Fig. 2) during HF heating, and total power consumption of the HF generator. The specimen MC gradient is shown in Fig. 1, with the highest MC in the center. The electric field strength is constant at 650V/cm.

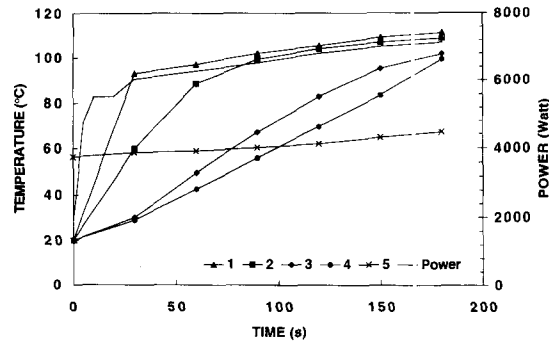


FIG. 8. Mean temperature of 5 replications, at 5 locations (see Fig. 2) during HF heating, and total power consumption of the HF generator. The specimen MC gradient is shown in Fig. 1, with the lowest MC in the center. The electric field strength is constant at 650V/cm.

press platens was present, where the direction of the heat transfer was dependent on the temperature of the electrodes relative to the temperature of the specimen. At the beginning of the press cycle, the press platens have a greater temperature (measurement location 5) than the specimen, which results in heat flow by conduction from the platens into the specimen. Hence, measurement location 1 experiences a faster rate of temperature increase than positions 2 and 3. As the temperature of the outer veneers approaches the temperature of the platens, the rate of heat conduction slows, and the temperature rise due to the electromagnetic field predominates. When the temperature of the specimen exceeds the platen temperature, heat loss by conduction occurs into the platens. As time continues, and the interior temperature of the specimen rises, the rate of heat loss to the platens increases. The pattern of the temperature gradient development, as seen in Fig. 9, is initially a mild gradient with a greater temperature in the outside layers. The gradient then reverses with a lower temperature occurring in the outside layers.

The MC has an influence on both the rate of heat loss and the rate of energy absorption by the wood. Thermal conductivity of wood increases with an increase in MC. This can be observed by comparing the initial rate of temperature increase at location 1 in Figs. 3 and

6. When the MC was only 5% (Fig. 3), the rate of initial temperature rise was slower and more uniform than the specimens with an MC of 20% (Fig. 6). Later in the press cycle, the temperature of the layers in the 20% MC specimens converged due to the relatively high thermal conductivity, while the low thermal conductivity 5% MC specimens were still diverging in temperature. The 20% MC specimens also experienced a much greater rate of power absorption, and an overall greater rate of temperature rise. However, without the influence of the heat loss, the temperature rise would have been uniform throughout the specimen. If the electrodes are initially greater in temperature than the wood, conduction heat transfer into the wood will promote a less severe temperature gradient during HF heating.

In the specimens that contained an MC gradient (Figs. 7 and 8), the temperature gradient development was quite different from the specimens with a uniform MC. By placing the 20% MC veneer in the outside layer and the 5% MC veneer in the center (Fig. 8), a very steep temperature gradient develops early in the press cycle, and does not reverse after 180 seconds of heating. In this case the temperature rise is greatest in the outside layer, which has the highest MC and is closest to the warm platen. When the 5% MC veneer is placed in the outside layer and the 20% veneer is placed

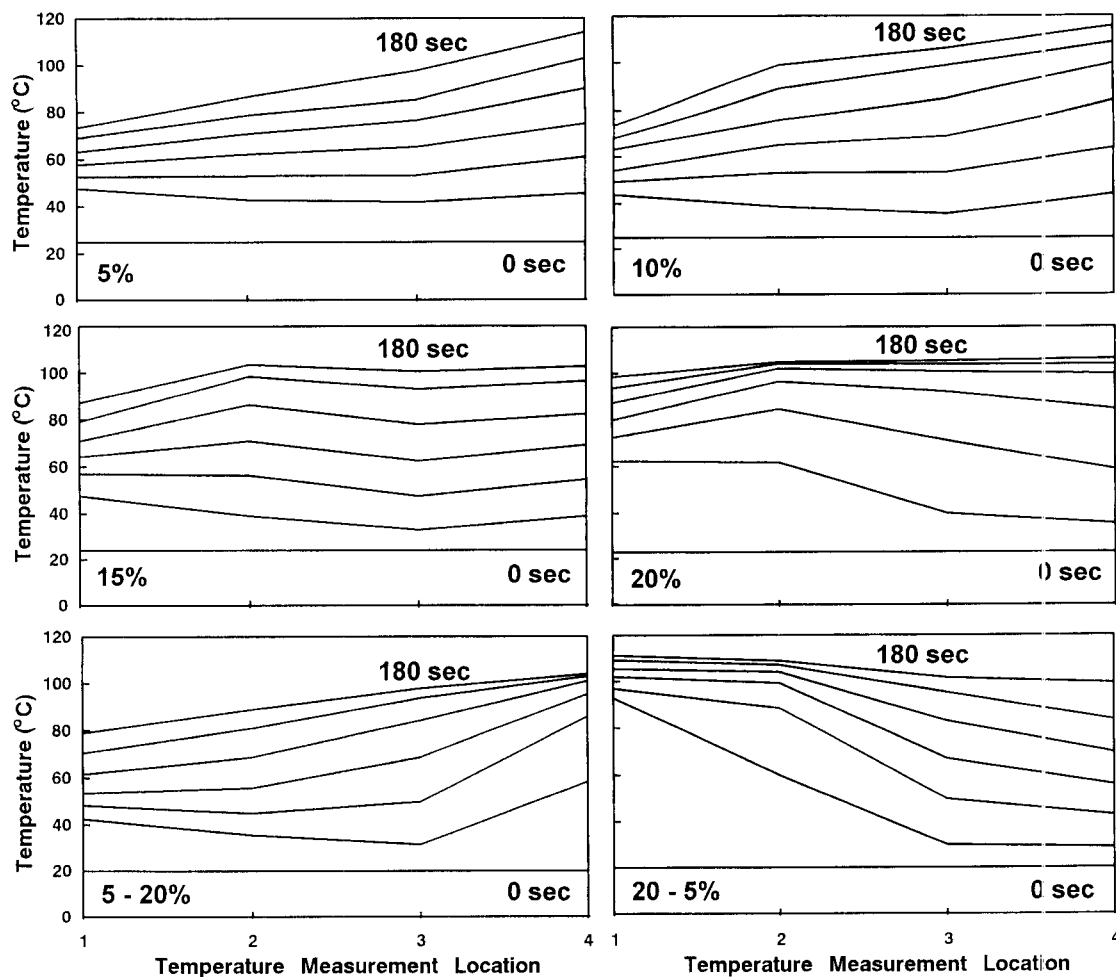


FIG. 9. Measured temperature gradient, averaged for 5 replications, for each moisture content treatment. Gradient lines are shown for times 0 to 180 seconds, at intervals of 30 seconds. See Fig. 2 for the measurement location.

in the center (Fig. 7), a less severe temperature gradient develops, with the greatest temperature rise in the center veneer. If one compares the temperature gradient development of the specimens with an MC gradient to the specimens with the uniform 15% MC (see Fig. 9), the uniform 15% MC produces a significantly less severe temperature gradient. Figure 9 clearly illustrates that, even when the average MC is nearly the same (as was the case for the uniform 15% specimens and both of the MC gradient specimens), the temperature gradient will have a distinctly different shape if an MC gradient is present. Although the tem-

perature rise is influenced by MC throughout the thickness of the wood during HF heating, it is the outer layer that experiences the greatest variability in temperature. The temperature at location 1 varied by as much as 30°C after 180 seconds. In all cases studied here, both conduction heat transfer and the MC gradient influenced the shape and severity of the temperature gradient.

CONCLUSIONS

The moisture content of wood, as expected, has a great influence on HF heating. The mag-

nitude of the MC and the presence of an MC gradient will influence the shape and severity of the temperature gradient. The potential for thermal losses by conduction influences the development of the temperature gradient. HF heating of wood with a uniform MC will result in a temperature gradient due to thermal loss by conduction. Uniformly increasing the MC reduces the severity of the temperature gradient. Less power is consumed to achieve approximately the same ending temperature with a lower MC, although the initial rate of temperature rise is slower. In regard to lumber drying, an MC gradient will cause an uneven distribution of power absorption. The resulting temperature gradient may be dampened if significant thermal loss by conduction occurs. In the case of HF heating of a laminated composite, judicious selection of the MC for each layer can be used to achieve a wide variety of temperature gradients to optimize adhesive cure or protect temperature-sensitive materials.

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