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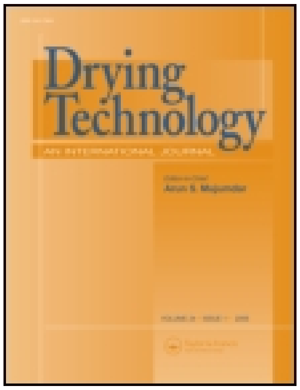

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Radio-Frequency Heating Kinetics of Softwood Logs

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The project assessed the radio-frequency (RF) heating characteristics of logs of two softwood species, namely, Engelmann spruce (*Picea* spp.) and subalpine fir (*Abies lasiocarpa*). Sixty logs, equally divided between the two species, were RF heated in two different circumstances—with or without bark—until the temperature sensor from a number of those scattered within each specimen with the lowest reading indicated 70°C. Both species heated in short periods of time (~60 min), regardless of bark presence or absence, with relatively small energy requirements and without noticeable negative consequences on quality. The sapwood heated up faster, thus reaching higher temperatures because of its high moisture content and better complex permittivity values. Between the two tested species, fir is more prone to RF heating due to its higher ability to convert an electric field into heat.

Keywords Dielectric heating; Radio frequency; Softwood logs

INTRODUCTION

The United States and several countries in eastern Asia, among which China, Korea, and Japan are the most important, are the main markets for softwood log exports from the western regions of Canada. The recent demand is for the Japanese market in a form of high-quality raw material needed for the construction industry[1] or to substitute for the Russian softwoods used in the manufacturing of various products exported by China.[2,3]

Transporting logs can move more than a simple sale product—it can also help spread pests living in wood and therefore any shipment is considered a phytosanitary risk. The method used to alleviate this conflict consists of pasteurization heat treatments by several methods: conventional heating, hot water bath/steam, and, in the future, microwave or radio-frequency (RF) dielectric heating. The two former methods are associated with long treatment times and poor economical feasibility mainly due to the low thermal conductivity during convective/conductive heat transfer in large size wood specimens. RF heating, which has the advantage of not depending on the dimensions of the wood, has not yet been properly investigated and brought to a standard.

Studies regarding logs exposed to RF fields are scarce and have been reported in recent years by Fang et al.[4,5] and Bucki and Perré[6] and in association with steam by Dwinell.[7,8] More general studies, however, were dedicated to RF heating in combination with vacuum, aiming to dry large wood commodities; see Koumoutsakos et al.[9] and Avramidis et al.[10]

This study assessed the RF heating of Engelmann spruce (*Picea* spp.) and subalpine fir (*Abies lasiocarpa*) logs along with the energy requirements, damage levels, and process economics.

MATERIALS AND METHODS

Experimental Heating Setup

The RF heater used for this study consists of a custom-made, small aluminum box (interior volume ~3 m^3) connected to a push–pull oscillator-type RF generator whose energy was directed to the electrodes through a twin conductor balanced transmission line. The maximum dc power coming from the oscillator was given by the product of 3.4 kV and 2 amps (7.2 kW), which were converted into radio-frequency power at 14–16 MHz. An oscilloscope and a capacitor divider probe with known calibration were used to measure RF voltage values inside the heating area.

The wood specimens exposed to RF fields are characterized by their complex permittivity;[11,12] the separation of their real and imaginary parts is denoted by

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

where ε' is the relative dielectric constant and ε'' is the dielectric loss factor (both are dimensionless).

Because these two dielectric properties are anisotropic for wood and they can vary greatly with species, density, moisture content, temperature, and frequency used[12–14] several measurements were performed prior to heating experiments. The complex permittivity was measured for sapwood, mature and juvenile, at different moisture contents (M) by placing a rectangular wood sample in the capacitive section of a parallel resonant circuit. The technique, described in more detail by İçer and Baysal[15] and

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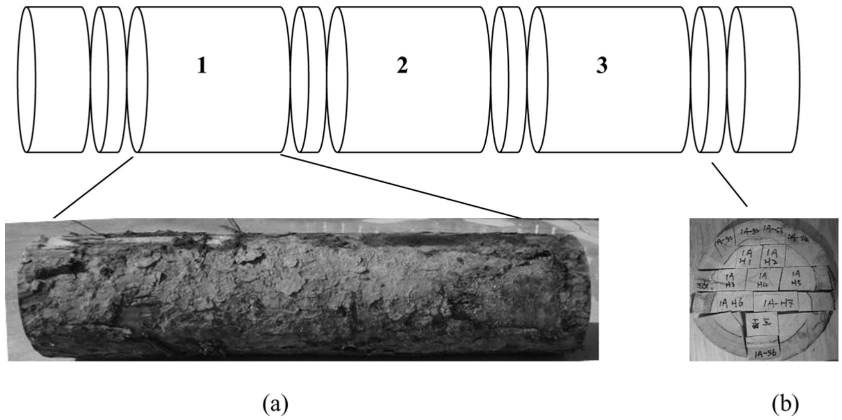

FIG. 1. (a) Log trimming and (b) cookies for moisture content measurements.

Catalá-Civera et al.[16] consisted of measuring with an open-ended coaxial probe the resulting shift in resonant frequency and shunt impedance with a Hewlett-Packard vector impedance meter (model 4193A, Mississauga, Ontario, Canada).

Twenty freshly felled spruce and fir logs (3.8 m long) were trimmed to 1-m-long specimens. During the trimming, four 20-mm-thick round wood sections (cookies) were cut (Fig. 1). The cookies were cut into smaller blocks in order to obtain the average M of sapwood and heartwood (Fig. 1b) by the oven-drying method (ASTM D 4442); lengthwise the moisture content distribution was assumed to be the same. The heating tests were conducted either on barked or debarked specimens in a 2:1 ratio. The first two parts of the long logs were tested per se and the third part was debarked. The temperature was continuously monitored using fiber optic sensors connected to three universal signal conditioning boxes (FISO UMI 4-channel, Technologies Inc., Quebec, Canada).

It was initially thought that the log ends could be areas prone to heating at a lower rate due to water evaporation. After several preliminary experiments, designed to compare log-end heating rates with other locations, it was concluded that there were no significant variations along the cross section of log ends with the only exception between sapwood vs. heartwood (Fig. 2). These tests allowed us to limit the number of sensors to 11, namely, two at one end of the log (one in sapwood and the other one in heartwood, 5–10 mm deep) and the other 9 at three different depth levels in three planes 100, 500, and 900 mm from the log butt—sapwood (S; 5–10 mm), heartwood (H; 70–80 mm), and juvenile wood (JW; geometric center). Each experiment stopped when the temperature indicated by all probes was at least equal to 70°C.

The RF heating strategy followed throughout the entire study was to adjust the intensity of the direct current from the oscillator (I, in amps) as a function of wood volume (V_L, in m^3) in order to obtain the same power density in each experiment ($P_D = 70\,\mathrm{kW/m^3}$). Previous experience developed throughout several lumber heating experiments[17] showed that this particular power density could heat up the wood in a short amount of time without any heating damage. The following formula was used for dc intensity calculations:

$$I = \frac{P_D \cdot V_L}{V_{DC} \cdot k} \tag{2}$$

where V_{DC} is the direct current voltage from the oscilloscope, $V_{DC} = 3400\,\mathrm{V}$, and k is an empirical efficiency coefficient whose exact value for our particular system was considered to be 0.65.[18]

The effect of temperature/power density over log quality was examined after each heating scenario by sectioning the logs in the areas where the sensors were placed. Potential adverse heating effects such as burning and/or checking were visually analyzed.

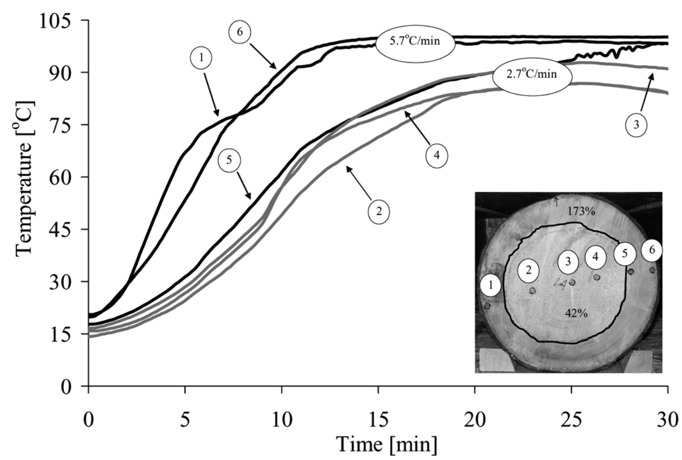

FIG. 2. Heating rates of sapwood (1 and 6) and heartwood (2 to 5) at one end of the log during the preliminary experiments.

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RF Power Calculations

The variation of the electric field inside a log was computed using Poisson Superfish, a set of programs designed to calculate electromagnetic fields in a two-dimensional cavity that resonates at discrete frequencies.[19] The kiln geometry model in Superfish was created by accounting for the symmetry of the wood load (Fig. 3). The frequency of the fundamental mode was adjusted at 14–16 MHz by changing the permeability of a ferrite tuner and all calculations were done assuming a thickness of 10 mm, imposed by program design, which was extrapolated to the whole length.

The computational area was discretized into triangular finite volume elements and the electric field values were defined at the nodes of the finite element mesh—a finer mesh was preferred for the log areas. The finite differential equations were solved by using one of the Poisson/Superfish solvers, and the result was the distribution of the electromagnetic field based on the dielectric properties of the material. The electromagnetic field was interpolated within the finite element using a linear shape function and a scale factor was used to match the experimental peak-to-peak oscilloscope read voltage value.

The electric field value for each area of interest (sapwood and heartwood) was used to measure the power deposited in the material:[12]

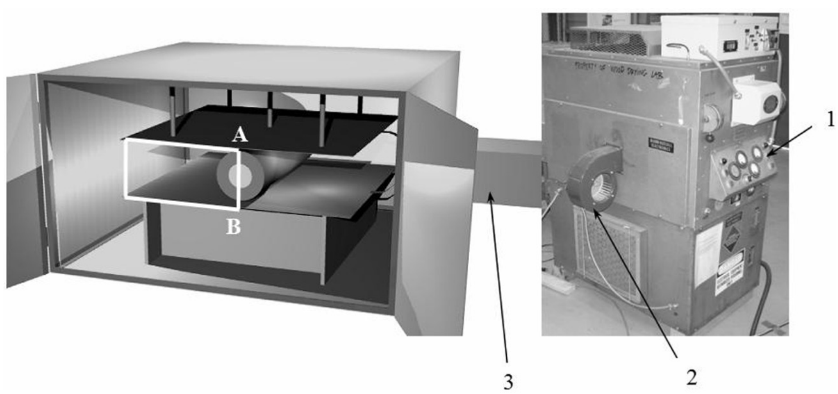
$$P_L = \pi f \varepsilon_o \varepsilon'' \int_{V_L} |E|^2 dV_L \tag{3}$$

where P_L is the power loss (W); f is the frequency (MHz); ε_0 is the permittivity of free space, $\varepsilon_o = 8.85 \cdot 10^{-12}$ (F/m); E is the electric field in sapwood or heartwood (V/m); and V_L is the volume of one of the two components (m^3). Power density (P_D, in kW/m^3), another common way to express energy loss in dielectric processes, was computed by dividing power loss by the volume. The general energy balance equation developed by Koumoutsakos et al.[9] was used to describe the heating process:

$$\rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + P_D \tag{4}$$

where ρ is wood density (kg/m^3), C_p is wood specific heat (J/kg°C), K is the thermal conductivity of wood (J/ms°C), and x is the coordinate originating from the wood center (m).

Equation (4) was replaced by one-dimensional finite difference equations, and wood temperature in every point was calculated using an iterative procedure whose detailed



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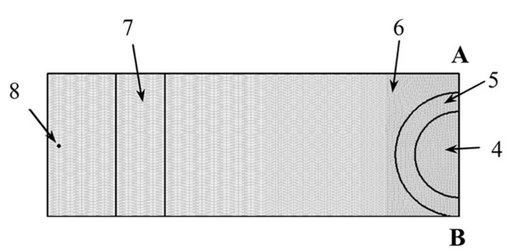

(b)

FIG. 3. (a) The oscillator and the RF heating box and (b) the Poisson Superfish geometric modeling of the oven taking advantage of the symmetry: 1, power dial indicators; 2, air cooling system; 3, transmission line box; 4, heartwood; 5, sapwood; 6, finer mesh used in the interest area; 7, ferrite tuner; 8, H-field drive point.

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steps and conditions are explained in Watanabe et al.[20] The density, specific heat, and thermal conductivity were calculated based on green specific gravity (G) values of the two species ($G = 0.38$ for spruce and $G = 0.33$ for fir[21]) and moisture content measurements.

RESULTS AND DISCUSSION

Electric Field Characteristics

An enhanced value of the electric field was obtained, for all simulations, at the upper and lower parts of the log (Fig. 4) because of the abrupt change in complex permittivity values in areas where the electric field lines are perpendicular. Considering that the product between permittivity and the electric field value inside a medium is supposed to remain constant, these facts are explained by the relationship:

$$K_{air} \cdot E_{air} = K_{wood} \cdot E_{wood} \quad (5)$$

where K_{air} is the relative permittivity of air, $K_{air} = 1$; E_{air} is the electric field in air (V/m); K_{wood} is the relative permittivity of wood $K_{wood} = \varepsilon_{wood}/\varepsilon_0$; ε_{wood} is the absolute permittivity of wood (F/m); and E_{wood} is the electric field in wood (V/m).

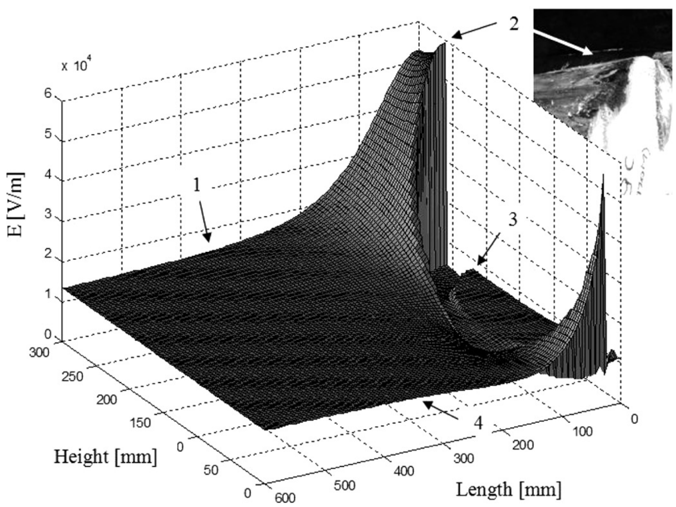
This enhancement phenomenon was particularly amplified by the fact that the interacting media were air and sapwood; the latter had high M values and consequently high absolute permittivities. During two particular experiments the electric field value in air became so high that arcing appeared inside the oven, resulting in small wood burns (Fig. 4a). Several features explain the causes of these incidents:

- Both logs were parts of the same fir tree having a large diameter, resulting in little or no space between the upper electrode and the top part.
- The relatively small amount of sapwood, usually half the size of the spruce, had a very high M (over 160%).
- The M difference between sapwood and heartwood, which was over threefold, resulted in higher E field values in sapwood.

As stated above, the expectations were that wood volume-based dc adjustments would generate an RF voltage (V_{RF} measured with the oscilloscope, in volts) of proportional value. At the end of the 60 runs the correlations between the two values for both wood species were individually analyzed using SAS/STAT® software (SAS Institute, Cary, NC); a binary variable Z, which was null for fir and unity for spruce, was used to test the wood species effect over the analytical fit:

$$V_{RF} = I \cdot (-1.65) + 0.41 \cdot Z + 7.89, \; R^2 = 0.29 \quad (6)$$

Equation (6) points toward two major suppositions. First, the RF voltage was poorly and negatively correlated with the intensity of the direct current from the oscilloscope and, second, the wood species influenced the value of the RF voltage—the Z coefficient was not dropped by the stepwise procedure of SAS because of its statistical significance ($p < 0.05$). The low R^2 is explained by the alterations in the electric field mainly caused by the change in geometry and dielectric properties of the tested



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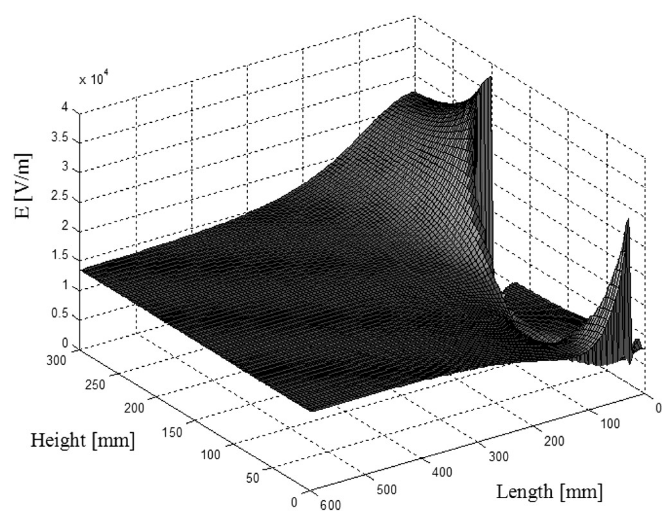

(b)

FIG. 4. Example of electric field distribution along the height and length of the RF oven obtained for either a (a) large or (b) small log: 1, top electrode; 2, the upper part of the log (highest E field value and the place where the two burns occurred); 3, borderline between sapwood and heartwood; 4, bottom electrode. The graphs were generated using MATLAB language (R2007b, MATLAB version 7.5.0. 342, MathWorks, Inc., Natick, MA).

TABLE 1
Power density variation with wood volume

RF voltage (V)	Wood species	Volume (m^3)	Power loss (W)	Power density (kW/m^3)	Power/volume drop[a] (%)
4,145	Spruce	0.053	2,139	40.29	0/0
		0.042	1,224	29.47	26.86/20.75
		0.031	7.50	23.87	40.75/41.5
	Fir	0.053	2,685	50.58	0/0
		0.042	1,468	35.34	30.13/20.75
		0.031	877	27.92	44.8/41.5

[a]Power and volume drop values were calculated as the difference between 100% and percentage ratios between individual and maximum values of each species class.

specimens. The negative correlation points toward higher average voltages around smaller heating cavities—smaller electrical intensities were used for the small logs to match the same targeted power density. The obvious explanation is that the amount of dielectric attractive volume is smaller in logs having a small diameter and the electric field is deflected to air—even though the electric field value has a higher maximum value for large logs (Fig. 4a), the average voltage for the whole cavity is higher in small logs (Fig. 4b). Numerous computer simulations proved that the effect is consistent with experimental results—a twofold drop in volume value resulted in an almost threefold drop in power loss at the same RF voltage (Table 1). The power drop was almost equal to the volume drop (±10%) and the explanation was also backed by temperature monitoring results.

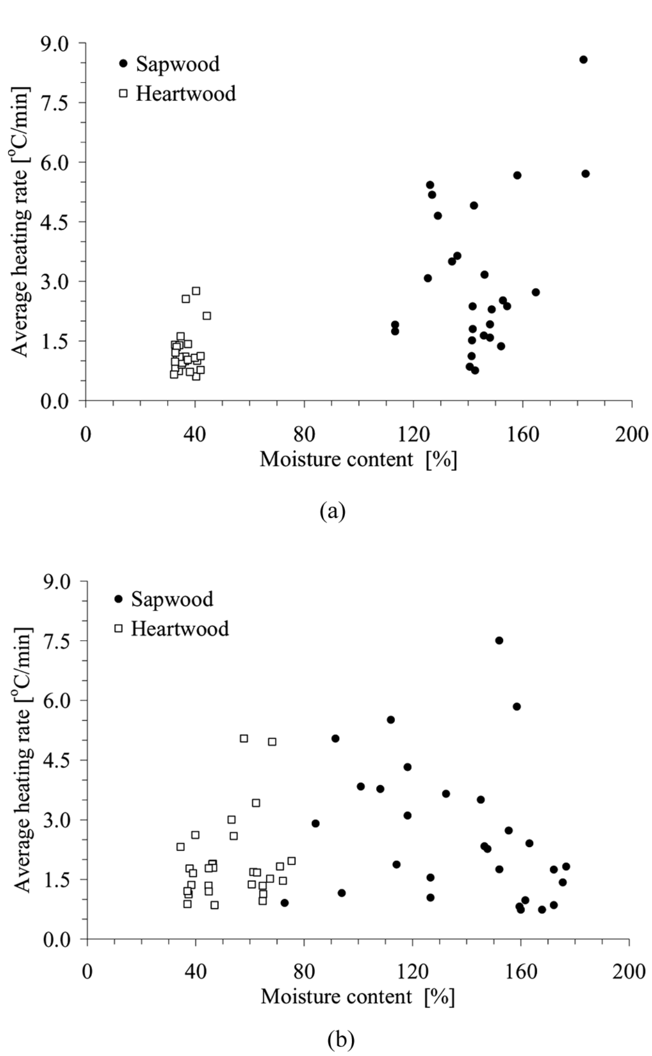

FIG. 5. Average heating rates in sapwood and heartwood for (a) spruce and (b) fir.

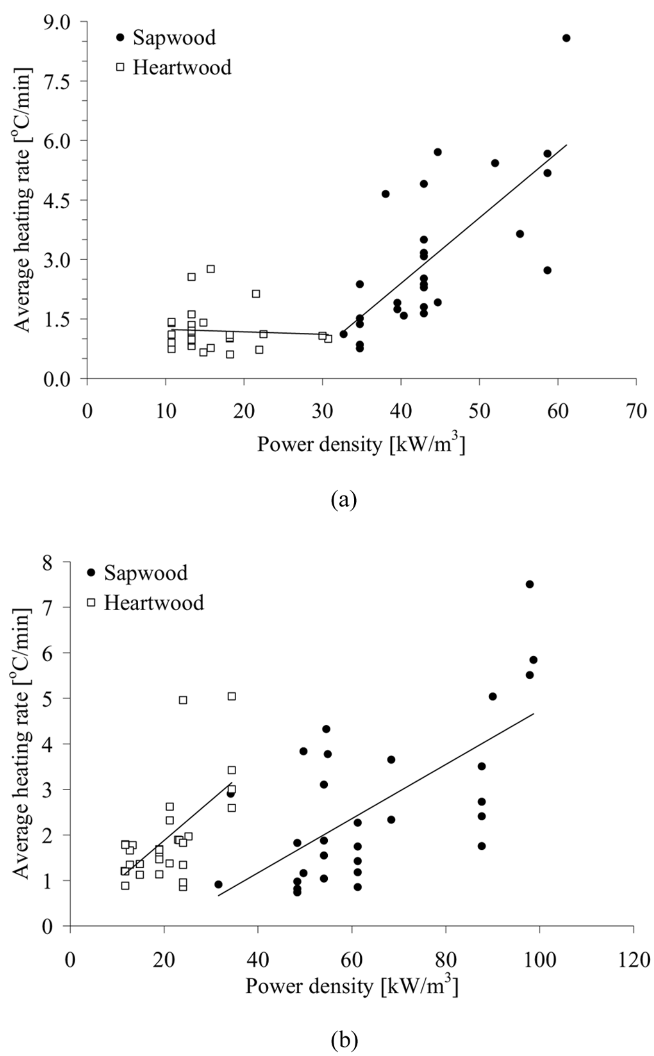

FIG. 6. Average heating rate as a function of power density for (a) spruce and (b) fir.

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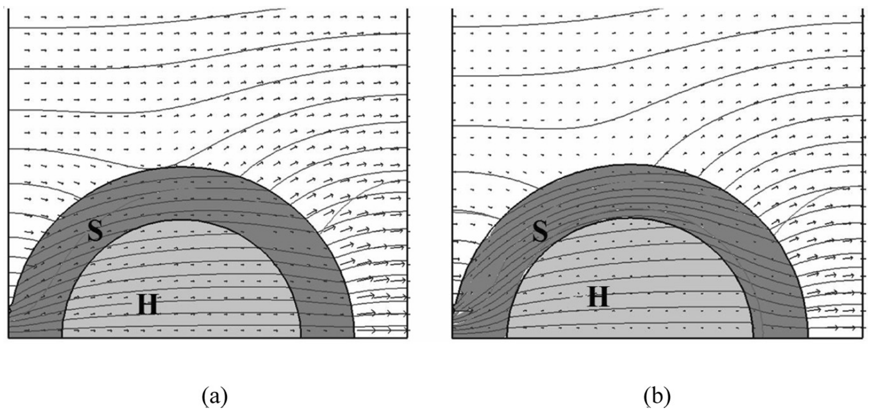

FIG. 7. Electric field lines for two moisture content distributions: (a) sapwood 80%, heartwood 44% and (b) sapwood 183%, 44% heartwood. S and H stand for sapwood and heartwood, respectively.

That wood species influenced the RF voltage value was not a surprise either. Both dielectric characteristics of spruce—ε' and ε''—are smaller than those of fir, which has a higher oven-dry density (ρ_0), and therefore a smaller amount of power was deposited inside the wood and more power reflected to the generator (~10%). Wood species with a higher ρ_0 are more prone to the RF technology because of the higher ability to convert an electric field into heat.[12] Small dielectric characteristics, that is, $\varepsilon' = 1.8$ and $\varepsilon'' = 0.5$, may also generate overheating followed by the automatic shutdown of the generator—one case during a spruce experiment.

Among other findings, particularly interesting is the constant drop in RF voltage value during every heating run while supplied by the same constant amount of direct current. The explanation for this drop (~25% less at the end of the heating process) is that both dielectric coefficients—dielectric constant and loss factor—increased with temperature.[22,23] More energy was deposited into wood as the temperature rose and consequently the field voltage decreased.

TABLE 2
Results of the regression analysis for the heating rate of sapwood

Wood species	Treatment	Heartwood	Sapwood	Eq.
Spruce	Bark No bark	$HR = 1.145$	$HR = 0.166 \cdot P_D - 4.33^a$, $R^2 = 0.51$	(7)
Fir	Bark	$HR = 1.82$	$HR = 0.058 \cdot P_D - 0.7$, $R^2 = 0.59$	(8)
	No bark		$HR = 0.035 \cdot P_D - 0.7$, $R^2 = 0.59$	(9)

[a] HR is the heating rate (°C/min) and P_D is the power density (kW/m^3).

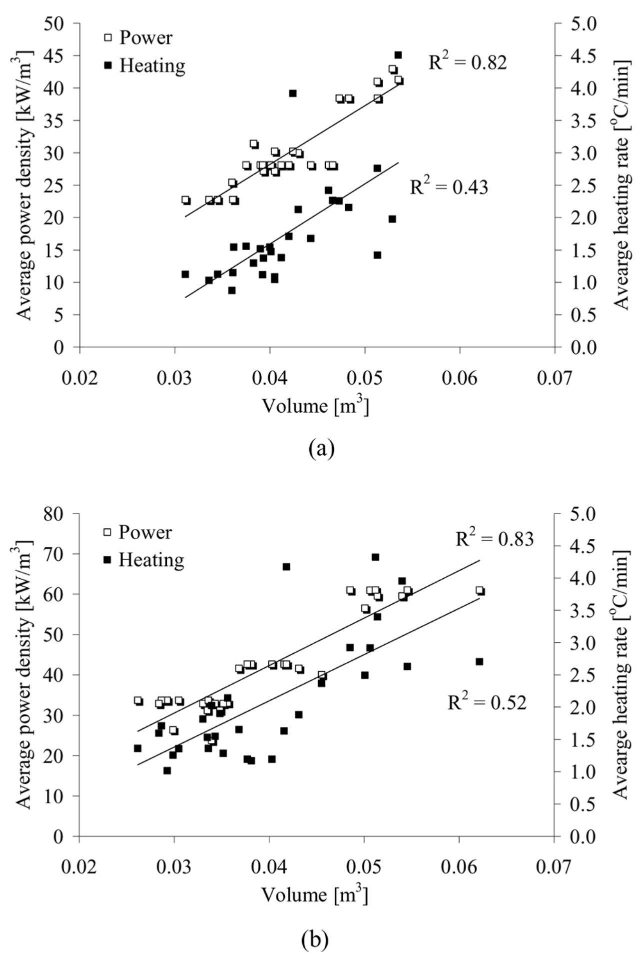

FIG. 8. Correlation between volume, power density, and heating rate for (a) spruce and (b) fir.

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Heating Analysis

The covariance analysis, performed in SAS/STAT software, showed no difference between the two inner structural positions (juvenile wood and heartwood) in terms of heating rate; thus, the term *heartwood* continued to be used to describe the unified inner part of the logs. Plots of the average heating rates ($\overline{HR}$), calculated as the average of all values recorded for a log either in sapwood or heartwood, are illustrated in Fig. 5, average heating rate versus moisture content, and Fig. 6, average heating rate versus power density.

Both wood species received more power density and consequently heated faster in the sapwood areas. This phenomenon, called a *shield effect* by Bucki and Perré,[6] resulted in dielectric energy coupling directly to the areas most in need, namely, the wettest parts of the log. Computer simulation revealed that, given two different Ms for sapwood and the same M for heartwood, it would result in a higher deflection of the electric field, and consequently a higher voltage value, in the sapwood area having a higher M (Fig. 7). Processed lumber, which lose water close to surface during green storage and retain more water in the core, would start to heat up faster in the middle section.[17] Further analysis of the heating rate as a function of M and P_D resulted in three equations for sapwood, under conditions of independence, normality, and equal variance, and two least square mean values for heartwood (Table 2).

As one may notice, the M is not present in the sapwood equations, Eqs. (7) to (9), because the stepwise statistical procedure from SAS eliminated this independent variable due to poor F-values (above the 0.05 significance level). However, because P_D calculations included M, the two values are highly interconnected. The heartwood heating process was best characterized by two least square values instead of equations mainly because of the low variability in M, and consequently, P_D. Both sapwood and heartwood areas heated faster in fir logs, and the presence or absence of bark was a significant factor only for fir. The relatively small R^2 values (0.51, . . . , 0.59) are probably a consequence

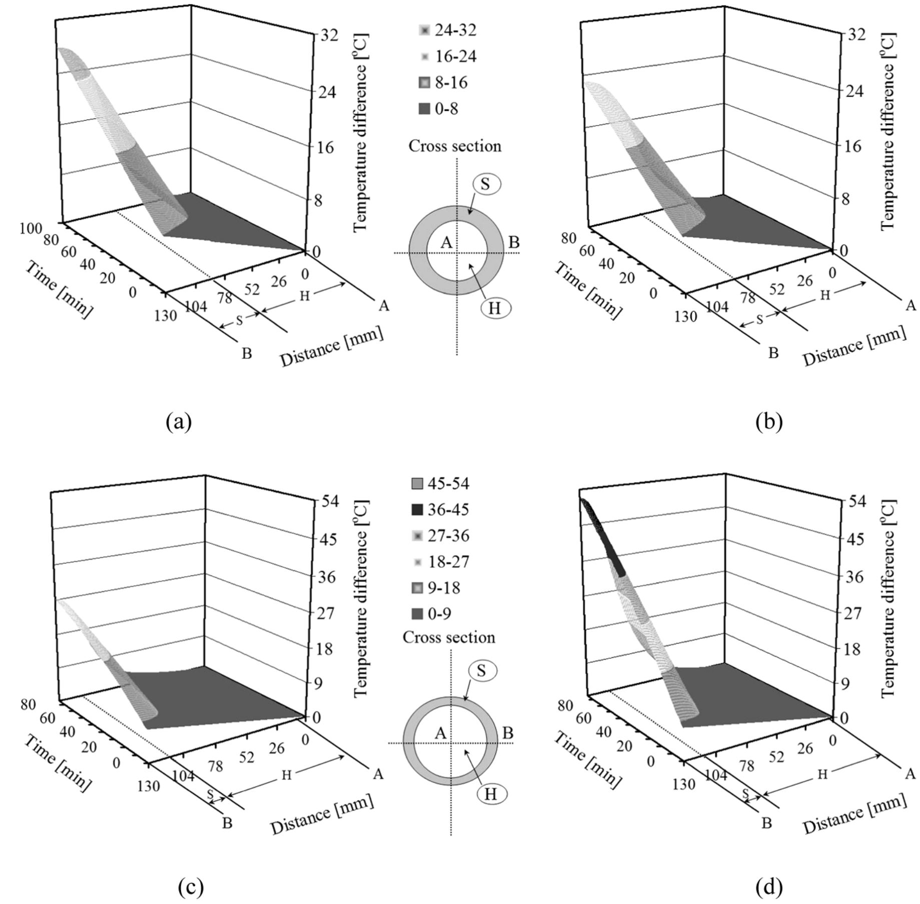

FIG. 9. Temperature difference between the center of the log and the other temperatures simulated along the cross section (from A to B) for spruce (upper graphs) and fir at different average moisture contents: a, 116%; b, 77%; c, 74%; and d, 58%. The simulation was stopped when the temperature in point A reached 70°C.

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of M distribution in wood; a probabilistic approach of the P_D distribution, similar to percolation,[24] might result in better regression coefficients.

The correlation between $\overline{HR}$ and volume for both species is shown in Fig. 8. As previously explained, the decrease in volume resulted in less power deposited inside the wood at the same field voltage value; the P_D was determined using computer simulations and $\overline{HR}$ was measured experimentally.

Two simple and straightforward heat transfer scenarios were simulated for each wood species (Fig. 9). The time and cross-section dimensions (center of the log to bark) from all charts were plotted versus the temperature difference between the center of the log (the coldest spot) and the other areas; the simulation was run until the core reached a temperature of 70°C. For comparison purposes, the radius of the cross section was kept constant (130 mm); the variables were sapwood/heartwood proportion between the two species—spruce had 48% and fir had 30.5% sapwood—and M distribution.

Spruce examples covered two extreme cases that might well describe the whole experimental spectrum: the same M of heartwood (32%), which had little variability during the initial measurements, and two extreme sapwood Ms, the first at 183% (Fig. 9a) and the second at 113% (Fig. 9b). A higher M in sapwood resulted in a higher RF time, ~90 min, 20% higher than in the lower moisture case, and in a slightly higher temperature difference between the center of the log and the sapwood area. Because heartwood M variability was higher in the fir group, the first example was chosen to show a small difference between the two components: sapwood at 73% and heartwood at 69.5% (Fig. 9c). It was an ideal combination for short RF times and a minimum temperature difference within the cross section. A high M difference between sapwood (115%) and heartwood (33%), depicted in Fig. 9d, resulted in a high amount of power loss deposited in the sapwood area, which led to an undesired temperature gradient of almost 45°C.

Overall, the simulations produced heating times slightly higher than the experimental ones. Most of the logs heated within the first 60 min, though the simulation stopped in one case at more than 80 min. The results are compared favorably with theoretical calculations of submerging the same type of logs in a fluid at 115°C, which will take almost 8 h or even much longer by conventional air flow kiln heating. This fast heating did not appear to have any negative consequences—cross-cuts in the areas where the sensors were fixed did not reveal any signs of internal checking or thermal degradation. The only negative effects that could be noticed were superficial end-checking and melted resin stains in the sapwood area. Each heated log lost on average 1 to 1.5 kg of water from the sapwood area, thus evening out the M gradient.

CONCLUSIONS

Dielectric RF heating can effectively heat spruce or fir logs in short periods of time with relatively low energy requirements and without internal checking and thermal wood degradation effects. It took less than 60 min to raise the internal temperature in the heartwood area to 70°C using a power density from 20 up to 30 kW/m^3. In case of heat treatments targeting only the pests living in sapwood, one might achieve even shorter times, reducing the time to 20–30 min; in this case more power is deposited in the sapwood area.

Every RF experiment is unique and a design able to match the load and the power reflected to the generator has to have the ability to constantly adapt to several issues. The exact power density may be determined only using computer simulations and a good knowledge of the dielectric properties.

The experimental evidence showed that sapwood areas heated up at higher temperatures because of their better complex permittivity values. Both sapwood and heartwood areas heated faster in fir logs because of their higher ability to convert an electric field into heat; the presence or absence of bark was a significant factor only for fir. The decrease in volume resulted in less power deposited inside the wood at the same field voltage value because less dielectric attractive material was present. In addition to volume, the distribution of moisture content was the second factor with a significant influence on the overall heating process.

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