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On the loss factor of wood during radio frequency heating

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Abstract The radial direction loss factor of full-size western hemlock sapwood and heartwood, as well as western red cedar heartwood timbers was measured using the direct calorimetric method with a laboratory-scale radio frequency/vacuum dryer at the frequency of 13.56 MHz, moisture content range between 10 and 80%, temperature range between 25 and 55 °C, and root mean square (rms) electrode voltages of 0.8 and 1.1 kV, respectively.

The results indicated that the moisture content, temperature, electric field strength and wood type significantly affected the loss factor. Empirical regression equations were derived based on the experimental data that made possible the calculation of the loss factor and power density within wood during RF heating.

Introduction

Dielectric heating of wood, due to its unique features of quick and uniform internally produced thermal energy, has played an important role in drying, gluing, impregnation, and pressing (Biryukov, 1961). One of the recent significant applications of dielectric heating in lumber manufacturing is the so-called radio frequency/vacuum (RF/V) drying. Previous studies revealed that RF/V drying is a promising method for the hard-to-dry species and for thick timbers that are almost impossible to dry with conventional methods (Zwick et al., 1995; Avramidis et al., 1996; Avramidis and Zwick, 1996; Avramidis and Zwick, 1997).

In order to develop and optimize RF/V drying schedules, a better understanding of the dielectric properties of wood as a function of wood characteristics and properties is required. Another benefit of investigating wood dielectric properties is that such knowledge could help to further understand its micro- and macro-structure and the mechanisms of interaction between water and wood (James and Hamill, 1965; Norimoto, 1976; Cao et al., 1986). Therefore, the study of wood dielectric properties has both theoretical and practical significance.

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Wood under an RF electric field reveals its dielectric properties, which are characterized by three parameters, namely, dielectric constant (ε'), loss tangent ($\tan\delta$) and loss factor (ε''). In order to determine the power dissipated in a dielectric material that is under the influence of a high frequency electric field, knowledge of its ε'' is needed. This is defined as the product of ε' and $\tan\delta$, (Pound, 1973). It is noticed that these three important dielectric parameters, namely, ε', $\tan\delta$ and ε'' are dimensionless since the former two are ratios of capacitances and currents, respectively. The power loss in unit volume of a dielectric material such as wood under the influence of an external high frequency electric field is known as power density (PD, W/m^3), and can be calculated as (Torgovnikov, 1993):

$$PD = \left(5.56 \times 10^{-11}\right) E^2 f \varepsilon''$$

where, E (=V/d) is the field strength, V/m; d is the thickness of the material between the electrodes, m; and f is the frequency, Hz.

If heat loss due to the moisture evaporation is not taken into account, and if it is assumed that there are no chemical reactions inside the wood, the equation to calculate the time rate of temperature change ($\partial T/\partial t$) inside the wood, resulting from the conversion of high frequency energy from the electric field to heat, can be expressed as (Nelson and Kraszewski, 1990):

$$\frac{\partial T}{\partial t} = \frac{PD}{\rho c_p}$$

where, ρ is the wood density Kg/m^3; and c_p is the specific heat, J/kg °C.

A considerable amount of past research work has shown that density, moisture content, temperature, frequency, and grain direction have a major effect on the dielectric properties of wood (Skaar, 1948; Lin, 1967; Nanassy, 1970; James, 1975; Torgovnikov, 1993).

Over the frequency range of 1 to 300 MHz, the measurement techniques of the dielectric properties of wood used by researchers can be classified into two categories: the Q-meter and the direct calorimetric method, the former being the most common one for measuring ε' and $\tan\delta$ of small wood specimens (Skaar, 1948; Vermaas, 1973; James, 1975; Cao et al., 1986). According to Biryukov (1961) and Torgovnikov (1993), the accuracy of this method is questionable due to the small sample size and volume, and due to the so-called "edge effect" which causes changes in the actual capacitance of the capacitor containing the wood sample.

The direct calorimetric method was used in the past by Biryukov (1961). With this method, the ε'' and PD can be obtained directly from calorimetric data based on Eqs. (1) and (2), the former being most important in practical wood drying applications for the calculation of the energy dissipated in wood.

When the moisture content is above the fibre saturation point, it is difficult to obtain accurate measurements of ε', thus, dielectric data measured at high moisture contents are not very reliable (Skaar, 1948). This is caused by the fact that the Q-meter's power is not high enough to measure the dielectric properties of wood at very high moisture contents (Avramidis and Dubois, 1993). However, it seems that this problem becomes obsolete in the direct calorimetric method when a high power generator is used.

The objective of this study was to investigate the loss factor of western hemlock and western red cedar, two of the most important local softwoods, as a function of moisture content, temperature and rms electrode voltage, by using the direct calorimetric method.

Experimental procedure

Twenty green timbers of western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], half of which were all-heartwood and the other half all-sapwood, and ten all-heartwood green timbers of western red cedar [*Thuja plicata* Donn] were used in this study. The western hemlock timbers were 110 mm by 200 mm by 3 m long, and the western red cedar were 100 mm by 200 mm by 3 m long. All timbers were chosen so that their thickness coincided with the radial direction, and they were free of surface checking, stain, and other visual defects.

A 13.56 MHz and 10 kW maximum power output laboratory size RF/V dryer with horizontal electrode plates, described in Avramidis et al. (1994), was used in this study. This eliminated the requirement of a complicated device such as the ones used in the past by other researchers, thus making the results of this method more suitable for a real-life situation and therefore, commercial scale applications. It was not just the size of the RF/V unit that made the difference, but also the large size of the specimens used in this study.

The rms voltage between the two electrode plates was monitored by an RF voltage meter. Since the precise value of the voltage is essential in the direct calorimetric method, calibration of the meter was carried out with solid plexiglas blocks of the same cross-sectional dimensions as the specimens, and of known dielectric properties that were placed at various locations along the length of the electrodes.

At the beginning of the study, and from each green timber, two 20 mm thick initial moisture content (M_i) sections were cut at a distance of 470 mm from each end, thus resulting in a dielectric specimen 2 metres long (Fig. 1a). The two M_i sections were immediately weighed with a digital balance to 0.01 g and dried in a oven at 103 ± 2 °C until constant weight. The calculated M_i values for western

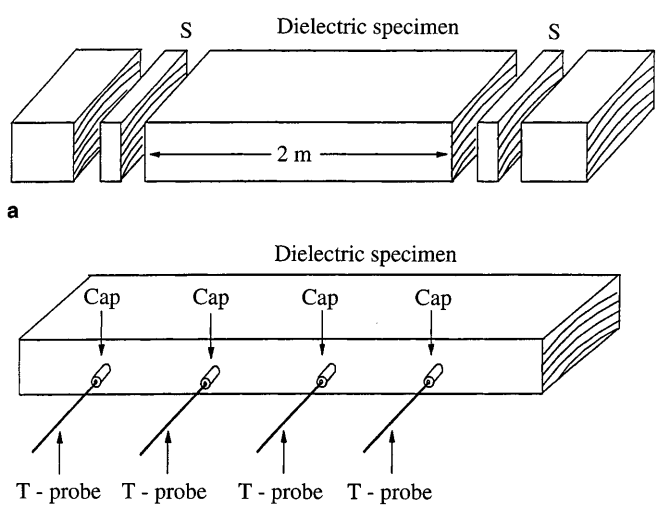

Fig. 1a, b. Location of sections (S) for determination of the initial moisture content of each dielectric specimen. Location for fibre-optic temperature probes in each dielectric specimen hemlock sapwood and heartwood, and western red cedar heartwood were about 85% and 55%, and 50%, respectively. After cutting the M_i sections, the dielectric specimen was weighed in order to calculate its total oven dry weight (W_o) based on the value of average M_i (Fig. 1a). Each dielectric specimen was weighed before and after each run, so that its average moisture content (M_a) and weight density (ρ) could be obtained. In this study, assuming negligible shrinkage during experimentation, the green volumes of western hemlock and western red cedar dielectric specimens were 0.044 m^3 and 0.040 m^3, respectively.

Four holes, each 5 mm in diameter and 100 mm in depth, were drilled at equidistant points from the middle of the side face to the geometric centre of each dielectric specimen (Fig. 1b). During each run, a fibre-optic thermocouple (2 mm diameter) was inserted into each hole in order to monitor the point temperature rise within each dielectric specimen. To make the thermocouples stable inside the holes, a plastic cap, which had a small hole fitting the thermocouple's diameter, was screwed into each hole.

The specific heat of wood required for the determination of ε'' was calculated by the following equation (Simpson, 1991):

$$c_p = 4187 \times \frac{0.2393 + (0.0003T_a) + m_a}{1 + m_a}$$

where, c_p is the specific heat of wood, J/kg °C; T_a is the average temperature range, °C; and m_a is the fractional moisture content, M_a/100, where M_a is the percent moisture content.

In each run, one green dielectric specimen was heated under a constant electrode voltage from approximately 20 to 60 °C. The dryer's computer was set to record the four temperature points once every six seconds through a data acquisition system. The temperatures of each run were classified into four ranges, namely, 20–30, 30–40, 40–50 and 50–60 °C. The average values (T_a) of each temperature range were considered as the four temperature levels in this study, namely, 25, 35, 45 and 55 °C.

After heating, the specimen was wrapped with a plastic sheet and was stored in a cold room to cool down until it was below 20 °C. Another run was then repeated using the same sample following the same procedure mentioned above, but at another voltage level. Two electrode voltage levels, 0.8 and 1.1 kV, were chosen in this study. After these two series of heating runs, the specimen was dried to a lower moisture content in the same RF/V dryer under an electrode voltage of 0.5 kV and ambient pressure of 3.3 kPa. By this process, a series of $\partial T/\partial t$ curves at different moisture content levels were obtained. By solving Eqs. (1) and (2), the ε'' and PD of the specimens were calculated at various moisture content, temperature and rms electrode voltage levels.

Results and discussion

The mean ε'' values of western hemlock heartwood (WHH), western hemlock sapwood (WHS) and western red cedar heartwood (RCH) at various moisture contents, temperatures and rms electrode voltages are listed in Table 1. The accuracy of the final results (ε'' values) depended on the error accumulation from each individual measurement. In this study, the error of the calculated ε'' could be attributed to the following sources: the $\partial T/\partial t$, rms electrode voltage, wood density and its calculated specific heat. In order to estimate the accuracy of the ε'' values, the maximum relative errors of the $\partial T/\partial t$, rms electrode voltage, wood density

Table 1. Calculated loss factor values for western hemlock sapwood (WHS) and heartwood (WHH), and western red cedar heartwood (RCH) at various temperatures, moisture contents and voltages

T (°C)	M (%)	V = 0.8 kV			V = 1.1 kV		
		WHS	WHH	RCH	WHS	WHH	RCH
25	10	0.94	1.31	1.51	0.86	1.11	0.88
	20	1.89	2.86	3.17	1.43	1.93	1.74
	30	2.63	3.90	4.42	2.13	2.56	2.44
	40	3.12	4.80	5.44	2.69	3.25	3.05
	50	3.54	5.88	6.37	3.20	3.84	3.70
	60	3.86			3.67		
	70	4.24			4.13		
	80	4.58			4.52		
35	10	1.11	1.43	1.59	1.05	1.18	0.94
	20	1.92	2.88	3.17	1.73	2.10	1.88
	30	2.85	4.06	4.53	2.29	2.66	2.60
	40	3.49	5.01	5.70	3.00	3.34	3.33
	50	4.00	6.18	6.80	3.40	4.01	4.03
	60	4.48			4.07		
	70	4.88			4.46		
	80	5.39			4.86		
45	10	1.16	1.50	1.63	1.10	1.21	1.16
	20	2.02	3.00	3.37	1.76	2.06	2.27
	30	2.77	4.11	4.63	2.49	2.79	3.18
	40	3.59	5.18	5.96	3.28	3.45	4.04
	50	4.14	6.25	7.25	3.71	4.18	4.74
	60	4.61			4.06		
	70	5.10			4.77		
	80	5.75			5.31		
55	10	1.39	1.63	1.85	1.26	1.35	1.31
	20	2.62	3.19	3.62	1.99	2.14	2.35
	30	3.38	4.50	4.97	2.79	2.93	3.38
	40	4.05	5.67	6.26	3.52	3.67	4.28
	50	4.70	6.81	7.70	4.07	4.38	5.25
	60	5.29			4.42		
	70	5.90			5.06		
	80	6.48			5.46		

and calculated specific heat were used. The uncertainty or error and relative error of $\partial T/\partial t$ were then calculated. The results indicated that the error values were low since all of them were less than 1.0. All the total mean relative errors were in the range of 14.71 to 17.19% with a mean value of 16.14%, and their majority below 16% with the only exception of those at 10% moisture content.

In order to evaluate the effects of the independent variables on ε'', the experimental data were analysed using the fully factorial ANOVA procedure. The results showed that the moisture content, temperature, rms electrode voltage and species had a highly significant effect ($a = 0.01$) on the ε'' values.

The effect of the moisture content on ε'' is graphically shown in Fig. 2. In this figure, the mean ε'' values for the ten dielectric specimens for each species at two rms electrode voltages are plotted against the moisture content. A quadratic regression equation, $\varepsilon'' = aM^2 + bM + c$, was fitted to the experimental data for

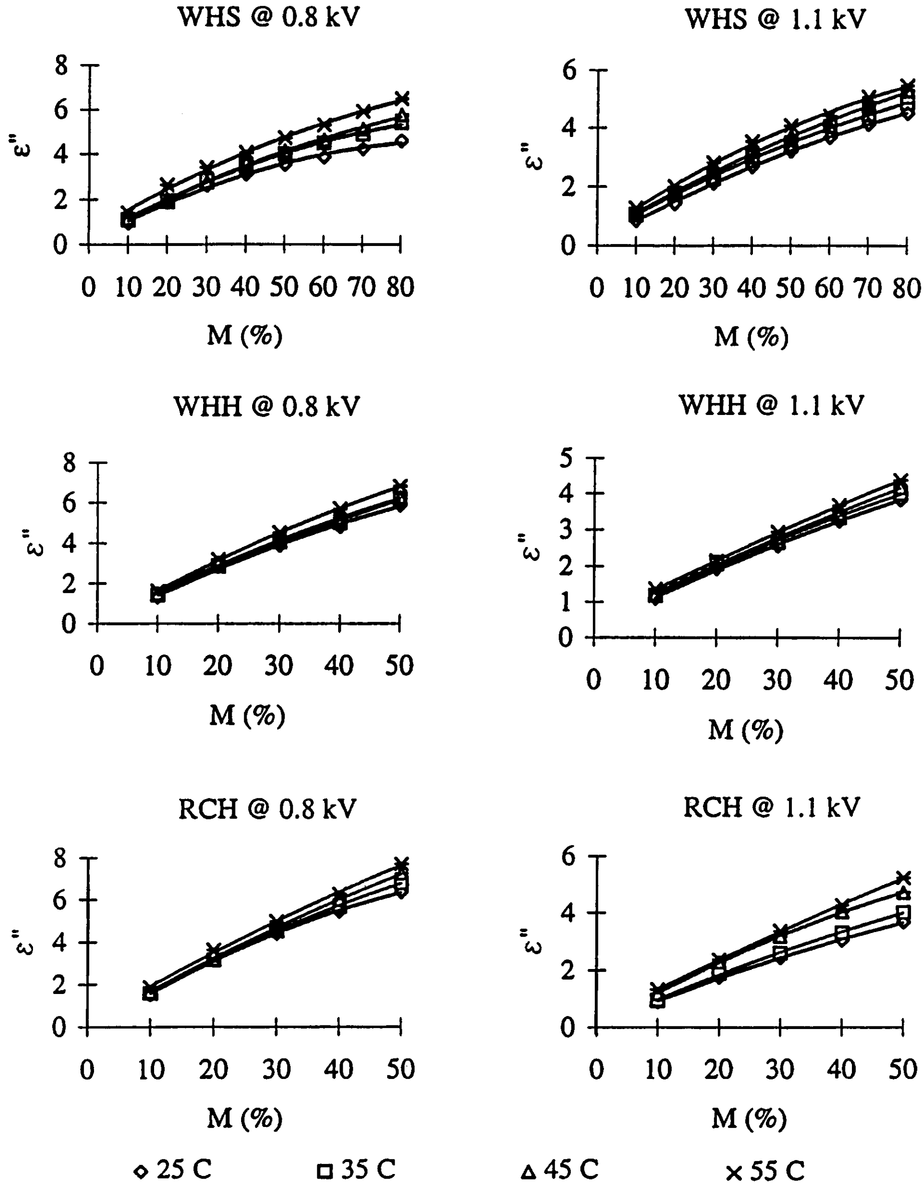

Fig. 2. Plot of loss factor against moisture content for western hemlock sapwood and heartwood, and western red cedar heartwood at 0.8 kV and 1.1 kV

each species at different rms electrode voltages using nonlinear least square fitting. The quadratic regression lines are also shown in Fig. 2. It is apparent that the equation fitted the ε'' data quite well. The above results are in good agreement with the work conducted by Peyskens et al. (1984). They carried out dielectric measurements at 3 GHz for three softwoods, i.e., European pine, spruce and hemlock within a moisture content range of 6 to 35%. By fitting different types of equations to the experimental values, they concluded that the quadratic regression equation offered the best fit. They considered two facts when trying to explain this phenomenon; firstly, with increasing moisture content the amount of water within the wood matrix increases, which itself is characterized by high dielectric values, secondly, the polar components of cellulose acquired more freedom of rotation at higher moisture contents and in this way also contributed to a more pronounced dielectric behaviour. Therefore, when moisture was below the fibre saturation point, the combination of these two factors resulted in a rapid increase of ε''. However, at higher moisture contents, their importance diminished because their freedom of rotation reached a maximum when moisture content was at the fibre saturation point resulting therefore in a lower slope curve. It is not surprising that ε'' increased with increasing moisture content, since both ε' and tan δ have a positive relationship with moisture content (Skaar, 1948; Hearmon and Burcham, 1954; Vermaas et al., 1974; James, 1975).

Shown in Fig. 3 are plots of the mean ε'' of the ten dielectric specimens for the three wood types versus temperature at different moisture contents and rms electrode voltages. A linear regression equation, $\varepsilon'' = a + bT$, was fitted to the mean experimental data where a and b are the intercept and slope of the regression line, respectively, and T is the temperature °C. The linear regression lines, also included in Fig. 3, indicated how well the linear regression model has fitted the mean experimental data. Furthermore, all slopes were positive and in most cases their slopes increased as the moisture content increased. In summary, the influence of the temperature on ε'' was positively linear, and more pronounced at higher moisture contents. In addition, this trend was held irrespective of the different species and rms electrode voltages.

Lin (1967) also reported that the effect of temperature and frequency on wood dielectric properties were more pronounced at high moisture contents. He theorised that, when temperature was increased, ε' and the relaxation spectrum shifted towards a higher frequency. This shift was caused by changes in the mobility of polar molecules with temperature. In addition, Nanassy (1970) also confirmed this study's findings. In his study, from the relaxation spectra of oven-dry yellow birch over the frequency range from 20 Hz to 2 GHz and temperature range from 20 to 100 °C, it was found that at 10–100 MHz, ε'' was increased as the temperature increased. Since he did not carry out a detailed data analysis, the exact relationship of the temperature and ε'' could not be identified.

The mean values of ε'' of the ten dielectric specimens for each wood type at various moisture contents and temperature of 45 °C are plotted against the rms electrode voltage in Fig. 4. In order to evaluate the effect of the electric field strength on ε'', the slopes of the straight line formed by two mean experimental data points at 0.8 and 1.1 kV rms electrode voltages were calculated. The results revealed that all slope values were negative, thus indicating higher ε'' values at 0.8 than at 1.1 kV, i.e., the higher rms electrode voltage (electric field strength) resulted in a lower ε'' value. Furthermore, another trend seemed to reveal itself, namely, the higher the moisture content, the more pronounced its effect on ε'' because the absolute values of the slopes were larger at higher moisture contents, particularly for WHH and RCH. The electric field strength effects at 25, 35 and 55 °C temperature also exhibited the same trend.

Since the influence of the electric field strength on wood dielectric properties had not yet been studied sufficiently, past research work regarding the effect of electric field strength on the water dielectric properties would be a good model to explain our results. Briggs (1928), after a literature review, cited results where ε' of liquid water in the region of an interface was assumed to be equal to that of water in bulk. The ε' of water in the presence of an electric field could be lowered from a

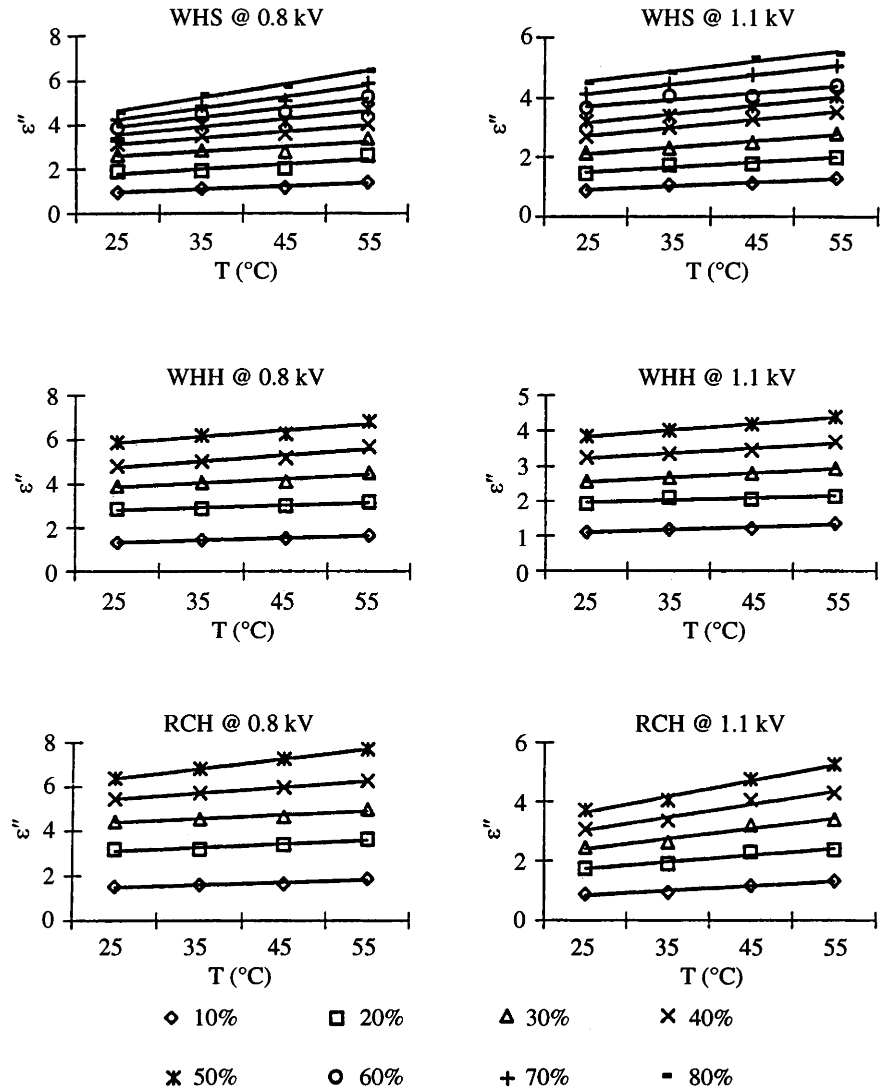

Fig. 3. Plot of loss factor against temperature for western hemlock sapwood and heartwood, and western red cedar heartwood at 0.8 kV and 1.1 kV

value of 80 to a value of 1 by placing water in an electric field strength of the order of 5×10^5 V/cm. However, when Nanassy (1972) carried out dielectric measurements on moist wood at 25 °C in electric fields from 4 to 500 V/cm and over a frequency range from 100 Hz to 100 kHz, he found that at any frequency, a change in the applied electric field strength left the calculated value of ε' unchanged. For the vacuum dried specimen there was no change of tan δ, but for the moist specimen ($M < 30\%$), an increase in the electric field strength caused an increase in tan δ only at frequencies lower than 10^4 Hz. It should be noticed that the frequency used by Nanassy (1972) is much lower than the one used in this study. Nevertheless, in the light of this investigation, a definite effect of the

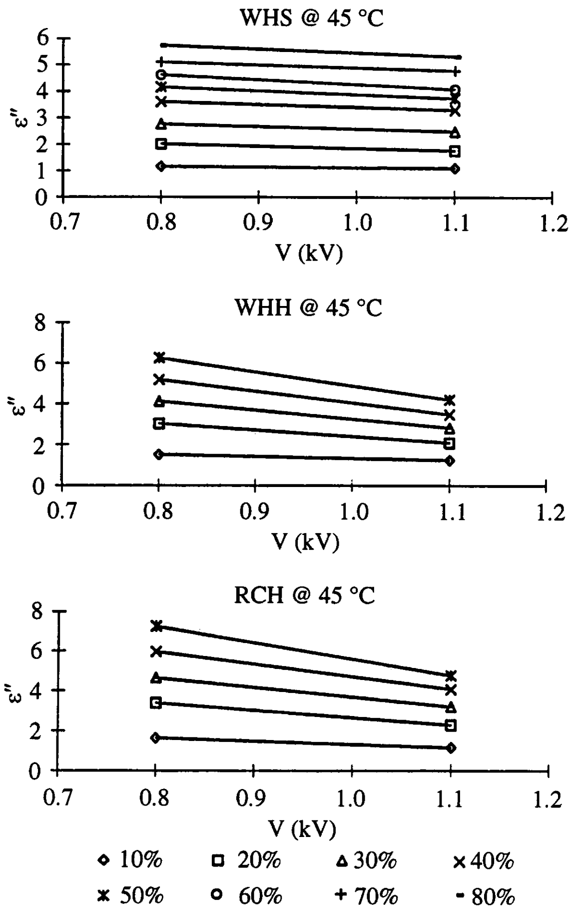

Fig. 4. Plot of loss factor against voltage for western hemlock sapwood and heartwood, and western red cedar heartwood at 45 °C

electric field strength on ε″ was identified and an inversely proportional relation was derived.

Figure 5 shows typical plots of the mean ε″ of the ten dielectric specimens for the three wood types at different temperatures and 0.8 kV rms electrode voltage. Also, the regression lines obtained by fitting the quadratic equation to ε″ and moisture content data are plotted in this Figure. It can be seen that most ε″ values were highest for RCH and lowest for WHS, if all other conditions are kept the same. By close inspection of Fig. 5, it can be seen that the differences between ε″ values among the three wood types were larger at higher moisture contents than those at lower moisture contents. In order to explain this, two factors should be taken into account – extractives content of the species and the actual weight of moisture that is present in wood. Considering the extractives content, RCH possesses a higher extractives content level than WHS and WHH (Hosie, 1976). Vermaas (1973) and Vermaas et al. (1974) stated that although tan δ in the grain direction was not influenced by the amount of the extractives, it increased linearly with increasing extractive content in the radial direction, and slightly decreased in the tangential direction. As it was pointed out, the mechanism of the difference in tan δ due to the extractive content was difficult to explain, however, it must be correlated with their distribution in wood, their chemical composition and an

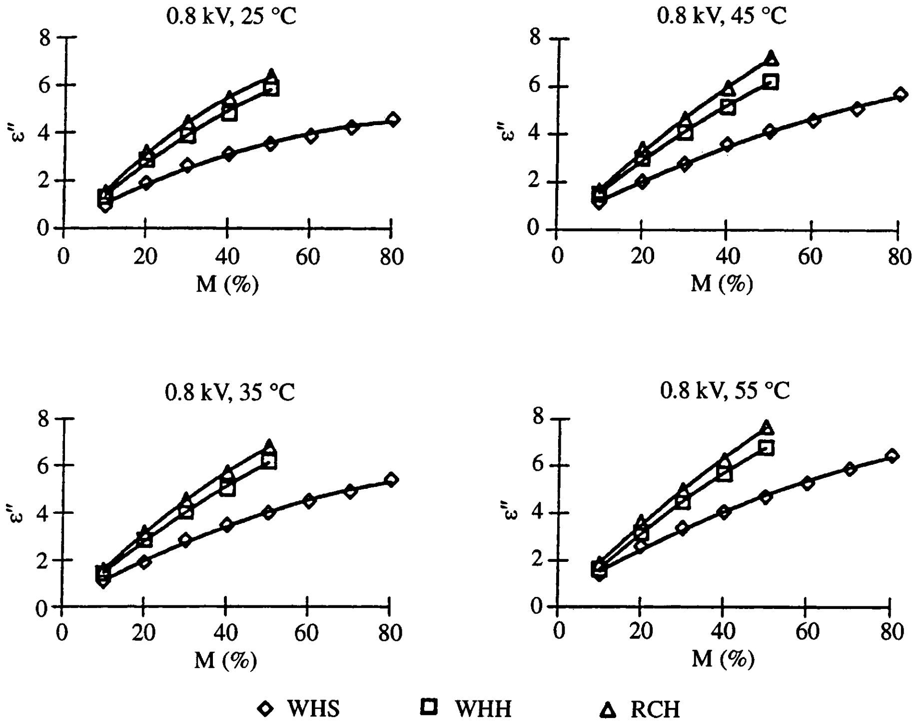

Fig. 5. Plot of loss factor against moisture content for western hemlock sapwood and heartwood, and western red cedar heartwood at 0.8 kV and various temperatures

orientational positioning or association of cellulose and extractive molecules. Based on this study's results, it would be premature to reach for a satisfying conclusion on the significance of the extractives influence on ε'' since none of the heating experiment were carried out with extracted specimens.

The actual weight of moisture present in the wood can be expressed as the ratio of the moisture weight per unit oven-dry volume of the wood. Therefore, for a certain percent of moisture, a higher absolute moisture quantity is present in an equal volume of a heavier wood species. That means that ε'' has perhaps been influenced more by the moisture weight than by wood species (Peyskens et al., 1984). Also, it can be concluded that increasing the same moisture content in two wood species will result in a larger increase of the actual moisture weight in the heavier compared with that in a lighter wood species. In this study, the basic densities of WHS, WHH and RCH were calculated based on the measured green volume and calculated oven-dry weight of the specimens. Their mean values were 439.71, 444.47, and 339.29 kg/m^3, respectively. Obviously, the basic density of WHH was higher than that of WHS. This could explain why ε'' values of the former were higher than those of the latter, and why this trend was more pronounced at higher moisture contents. However, considering the actual moisture weight, no explanation on why ε'' values of RCH were higher than those of both WHS and WHH could be found, since the RCH had the lowest basic density value. The higher extractive content of RCH could have contributed to this discrepancy.

From the shape of the curves shown in Figs. 2 to 5, six regression equations in the general form of Eq. (4) containing the terms of second power of moisture

Table 2. Regression equations for the three wood types tested

Species	Voltage (kV)	
WHS	0.8	$\varepsilon'' = -4.188M^2 + 7.249M + 0.006T + 0.064MT$
	1.1	$\varepsilon'' = -0.212 - 2.432M^2 + 6.798M + 0.013T + 0.026MT$
WHH	0.8	$\varepsilon'' = -8.442M^2 + 16.628M + 0.017T$
	1.1	$\varepsilon'' = 0.241 - 2.814M^2 + 7.721M + 0.003T + 0.026MT$
RCH	0.8	$\varepsilon'' = -9.932M^2 + 18.972M + 0.017T$
	1.1	$\varepsilon'' = -4.545M^2 + 7.07M + 0.005T + 0.097MT$

content (M^2), moisture content (M), temperature (T) and the first order interaction of moisture content and temperature (MT) for each species at two rms electrode voltages were obtained following a stepwise regression procedure. Only the independent variables which were significant at the 5% level in the analysis of variance were chosen. Furthermore, in favour of the calculation process, the percent of moisture content data were converted to the fractional ones. The equation was of the form

$$\varepsilon'' = a + bM^2 + cM + dT + eMT$$

where, a, b, c, d and e are the coefficients. The six derived regression equations are listed in Table 2. For all practical purposes, the empirical equations made possible the calculation of ε'' and in turn, the power density deposited within wood during RF heating without the requirement of direct measurements. It should be emphasized here that the above empirical equations are applicable only within the test conditions applied to this study.

In the light of this investigation, the following conclusions can be summarized:

(1) The direct calorimetric method was practical and feasible for the measurement of ε'' of full-size dielectric wood specimens.
(2) The moisture content of wood had a significant effect on ε'' which increased proportionally to the second power of moisture content.
(3) The temperature significantly affected ε'', and their relationship was directly proportional and linear.
(4) The electric field strength had a significant effect on ε'' exhibiting an inversely proportional relationship.
(5) Different species and wood types had different ε'' values.

References

Avramidis S, Dubois J (1993) The study of dielectric properties of spruce, hemlock, western red cedar and Douglas-fir at varying MC, temperature, grain orientation and radio frequency. Report No. 93 (SA-3) (unpublished). Science Council of British Columbia, Vancouver, B.C., Canada

Avramidis S, Liu F, Neilson BJ (1994) Radio-frequency/vacuum drying of softwoods: drying of thick western red cedar with constant electrode voltage. Forest Prod. J. 44(1): 41–47

Avramidis SR, Zwick J, Neilson JB (1996) Commercial-scale RF/V drying of softwood lumber. Part 1. Basic kiln design considerations. Forest Prod. J. 46(5): 44–51

Avramidis S, Zwick RL (1996) Commercial-scale RF/V drying of softwood lumber. Part 2. Drying characteristics and lumber quality. Forest Prod. J. 46(6): 27–36

Avramidis S, Zwick RL (1997) Commercial-scale RF/V drying of softwood lumber. Part 3. Energy consumption and economics. Forest Prod. J. 47(1): 48–56

Biryukov VA (1961) Dielectric heating and drying of wood. GLBI Goslesbumizdat, Moskva-Leningrad

Briggs, DR (1928) The determination of the potential on cellulose – a method. Journal of Physical Chemistry 32: 641–675

Cao LJ, Liu ZQ, Liu YX, Dai CY (1986) Study on the dielectric constant of wood. Journal of Northeast Forestry University. 14(3): 57–66 (in Chinese)

Hearmon RFS, Burcham JN (1954) The dielectric properties of wood. Department of Science and Industry research, London. Forestry Products Research Special Report No. 8

Hosie RC (1976) Native trees of Canada. Canadian Forestry Service

James WL (1975) Dielectric properties of wood and hardboard: variation with temperature, frequency, moisture content and grain orientation. USDA, Forest Service Research Paper, FPL 245

James WL, Hamill DW (1965) Dielectric properties of Douglas-fir measured at microwave frequencies. Forest Prod. J. 15(2): 51–56

Lin RT (1967) Review of the dielectric properties of wood and cellulose. Forest Prod. J. 17(7): 61–66

Nanassy AJ (1970) Overlapping of the dielectric relaxation spectra in oven-dry yellow birch at temperatures from 20 to 100 °C. Wood Sci. Technol. 4(2): 104–121

Nanassy AJ (1972) Dielectric measurement of moist wood in a sealed system. Wood Sci. Technol. 6(1): 67–77

Nelson SO, Kraszewski AW (1990) Dielectric properties of materials and measurement techniques. Drying Technol. 8(5): 1123–1142

Norimoto M (1976) Dielectric properties of wood. Wood Research. No. 59/60: 106–152

Peterson RW (1951) Dielectric heating as applied to the woodworking industries. Department of Northern Affairs and Natural Resources. Forestry Branch. Bulletin No. 110

Peyskens E, de Pourcq M, Stevens M, Schalck J (1984) Dielectric properties of softwood species at microwave frequencies. Wood Sci. Technol. 18(4): 267–280

Skaar C (1948) The dielectrical properties of wood at several radio frequencies. New York State College of Forestry Technical Publication No. 69

Simpson WT (1991) Dry kiln operator's manual. USDA, FPL No. 188, Madison, Wisconsin

Torgovnikov GI (1993) Dielectric properties of wood and wood-based material. Springer-Verlag, Berlin Heidelberg, New York

Vermaas HF (1973) Regression equations for determining the dielectric properties of wood. Holzforschung. 27(4): 132–136

Vermaas HF, Pound J, Borgin KB (1974) The loss tangent of wood and its importance in dielectric heating. South African Forestry J. 89: 5–8

Zwick RL (1995) The COFI radio frequency/vacuum kiln project. The Council of Forest Industries, Vancouver, B.C., Canada