

SIMULTANEOUS HEAT AND MOISTURE DIFFUSION DURING MICROWAVE HEATING OF MOIST WOOD

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ABSTRACT. *The influence of simultaneous heat and moisture diffusion on moisture movement in porous materials, such as cotton, has been known since the late 1940s. Until now this theory has not been applied to the problem of microwave heating in moist materials.*

Derivation of the partial differential equation, which describes simultaneous heat and moisture diffusion under the influence of microwave heating, yields two independent values for the combined heat and moisture diffusion coefficient. The slower diffusion coefficient of this coupled system is always less than either of the isothermal diffusion constant for moisture or the constant vapor concentration coefficient for heat diffusion. The faster diffusion coefficient is always many times greater than either of the independent diffusion constants. Based on the earlier work with moisture movement in cotton, it was anticipated that the combined diffusion coefficient for heat and moisture during microwave heating should be approximately 7.8 times greater than the constant vapor concentration coefficient for heat diffusion for wood.

An analytical solution to the derived partial differential equation was used to model the temperature distribution inside wood heated by 2.45-GHz microwaves in a wave-guide applicator. Using the default constant vapor concentration coefficient for heat diffusion in moist wood did not model the temperatures inside the wood very well; however when this value was multiplied by a factor of 7.8 there was very good agreement between theoretical and measured temperatures.

Keywords. *Microwave, Microwave radiation, Modeling, Lumber, Wood.*

Industrial microwave heating has been used since the 1940s (Metaxas and Meredith, 1983). The initial experiments were conducted by Dr. Percy Spencer in 1946. Since then many heating, drying, thawing (Liu et al., 2003), and medical applications (Bond et al., 2003) have been developed. Many studies into microwave heating and drying of wood have been carried out (Zielonka and Dolowy, 1998; Afzal and Thomson, 2004). For the most part these studies concentrated on using microwave energy to dry wood from the green state (Afzal and Thomson, 2004).

Microwave heating depends on the ability of the microwave's electric field to polarize dipolar molecules (Metaxas and Meredith, 1983). Depending on the frequency, the dipole may move in time with the electric field, lag behind it, or remain apparently unaffected (Chaplin, 2004). When the dipole lags behind the field, interactions between the dipole and the field lead to energy dissipation within the material and heating. The extent of heating depends on the phase difference between the applied fields and the dipole moment of the molecules. The ease with which dipole movement occurs depends on the viscosity and the mobility of the electron clouds within the molecule (Chaplin, 2004). In the case of water, these, in turn, depend on the strength and extent of the hydrogen-bonded network (Chaplin, 2004). In free liquid water this movement occurs at GHz frequencies

whereas in more restricted 'bound' water it occurs at MHz frequencies and in ice at kHz frequencies (Tikhonov, 1997).

Debye (1929) deduced the well known equation for the complex dielectric constant (ϵ^*) as:

$$\epsilon^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} = \epsilon' + j\epsilon'' \quad (1)$$

where ϵ_∞ is the dielectric constant of the material at extremely high frequencies, ϵ_s is the dielectric constant of the material in a static field, $j = \sqrt{-1}$, ω is the angular frequency of consideration (Radians s^{-1}), τ is the relaxation time of the dipolar molecules in the material (s), ϵ' is the relative dielectric constant, and ϵ'' is the dielectric loss.

The relaxation time τ (a measure of the time required for polar molecules to rotate), and hence the frequency range in which dipole movement occurs, depends on the temperature and physical state of the dielectric material. In the free liquid state, the strength and extent of the hydrogen bonding determines the relaxation time of water molecules (Buchner et al., 1999). As the temperature increases, the strength of the hydrogen bonding decreases, causing the relaxation time to reduce (Chaplin, 2004).

The relaxation time for bound water is longer than the relaxation time of free water, because the water molecules are much more restricted (Tikhonov, 1997). This implies that the frequency at which dipole movement of the water molecules occurs in bound water is usually lower than for free water. Tikhonov (1997) and Boyarskii et al. (2002) suggest that relaxation time for bound water decreases as the number of mono-molecular layers in the bound water film increases.

The relaxation time for dipole moment of water molecules in ice is much longer than for either free or bound water, because the water molecules are tightly bound in the

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crystalline structure of ice. Therefore the frequency at which dipole movement of the ice molecules occurs is lower than for either bound or free liquid water (Tikhonov, 1997).

The relative dielectric constant (ϵ') expresses the material's ability to store electrical energy (Singh and Heldman, 1993) and thus represents the reactive nature of the material's dielectric properties. In particular, ϵ'' influences the wave impedance of the space occupied by the dielectric material, causing reflections at the inter-facial boundary between the air and the material. Changes in wave impedance also cause refraction of the wave due to the change in the propagation velocity of the microwave within the dielectric material compared with its velocity in air or vacuum (Montoro et al., 1999). The dielectric loss ϵ'' represents the resistive nature of the material's dielectric properties. Resistive losses within the medium reduce the amplitude of the microwave field and generate heat inside the material.

Water is not the only molecule in moist wood to interact with microwaves. Macromolecules such as cellulose, hemicellulose, and lignin, which make up the wood cell wall, are also subject to dipole polarization (Torgovnikov, 1993). This is associated with the displacement of polar groups such as OH and CH₂OH relative to the motionless parts of these macromolecules (Torgovnikov, 1993); however these interactions contribute very little to microwave heating and water remains the key substance that interacts with microwave fields during microwave heating of moist wood (Zielonka and Gierlik, 1999).

Any realistic analysis of microwave heating in moist wood must account for simultaneous heat and moisture diffusion through the porous wood material. The coupling between heat and moisture transfer is well known but not very well understood (Chu and Lee, 1993). Henry (1948) first proposed the theory for diffusion of heat and moisture into a textile package. Crank (1979) presented a more thorough development of Henry's work. The theory of simultaneous heat and moisture diffusion through porous materials, based on Henry's original work, has been rewritten and used by many authors (Chu and Lee, 1993; Vos et al., 1994; Fan et al., 2000; Wang et al., 2002; Casada, 2002; Fan et al., 2004; Barba, 2005; Frydrych and Ralek, 2005).

Modeling of microwave heating processes is a very difficult undertaking. Considerable progress has been made toward coupling the thermal-electromagnetic processes in temperature-dependent dielectric media (Alpert and Jerby, 1999). Both numerical and analytical techniques have been successfully used to simulate the interaction between the radiated medium (and its environment) and the microwave power (Ayappa et al., 1991; Zielonka and Gierlik, 1999; Liu et al., 2003). Unfortunately, there is little evidence to suggest that the well-established principles of simultaneous heat and moisture diffusion have been incorporated into the growing theory of microwave heating. This article attempts to incorporate the principles of simultaneous heat and moisture diffusion, as originally described by Henry (1948), into a model for microwave heating in moist wood.

MODELING MICROWAVE HEATING

The differential forms of Maxwell's equations (Giancoli, 1989), in the frequency domain, for a medium with a conductivity parameter greater than zero, but no net charge, are:

$$\nabla \cdot \vec{E} = 0 \quad (2)$$

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} \quad (3)$$

$$\nabla \cdot \vec{H} = 0 \quad (4)$$

$$\nabla \times \vec{H} = \sigma\vec{E} + j\omega\epsilon\vec{E} \quad (5)$$

where \vec{E} is the electric field (V m⁻¹), \vec{H} is the magnetic field (Webers m⁻¹), ω is the angular frequency of the wave (Radians m⁻¹), μ is the magnetic permeability of the medium (Henry's m⁻¹), ϵ is the dielectric permittivity (Faradays m⁻¹), $j = \sqrt{-1}$, and σ is the electrical conductivity of the medium (Ω^{-1} m⁻¹).

Electrical conductivity is not the only factor contributing to dielectric losses in a material. Other factors include dipolar, electronic, atomic and Maxwell-Wagner losses (Metaxas and Meredith, 1983). In the most general case, the dielectric permittivity and the magnetic permeability are spatially dependent tensors (Giancoli, 1989).

Taking the curl of equation 3, substituting for $\nabla \times \vec{H}$ from equation 5, applying the vector identity: $\nabla \times \nabla \times \vec{E} = \nabla(\nabla \cdot \vec{E}) - \nabla^2 \vec{E}$, and substituting for $\nabla \cdot \vec{E}$ from equation 2 gives the well-known wave equation:

$$\nabla^2 \vec{E} = \omega^2 \mu \left(\epsilon - j \frac{\sigma}{\omega} \right) \vec{E} = \omega^2 \mu \epsilon_o (\epsilon' - j\epsilon'') \vec{E} \quad (6)$$

Sadiku (2001) suggests that a useful solution to equation 6 is:

$$\vec{E} = y \cdot E(x, y) \cdot e^{j(\omega t - \beta z)} \cdot e^{-\alpha z} \quad (7)$$

where z is the distance from the origin (m), t is the time (s), and the electromagnetic attenuation factor and phase factor are defined by equations 8 and 9, respectively:

$$\alpha = \frac{w}{\sqrt{\epsilon_o \mu_o}} \sqrt{\frac{\epsilon'}{2} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2} - 1 \right)} \quad (\text{m}^{-1}) \quad (8)$$

$$\beta = \frac{w}{\sqrt{\epsilon_o \mu_o}} \sqrt{\frac{\epsilon'}{2} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2} + 1 \right)} \quad (\text{m}^{-1}) \quad (9)$$

Equation 7 implies that the electrical field inside the material will decay exponentially with distance from the surface, as shown in figure 1.

Applying Poynting's theorem to equation 7 yields the average power density at a distance z below an irradiated surface:

$$q(z) = \pi f \epsilon_o \epsilon'' \left[E_m \vec{E}(x, y) \right]^2 \cdot e^{-2\alpha z} \quad (\text{W m}^{-2}) \quad (10)$$

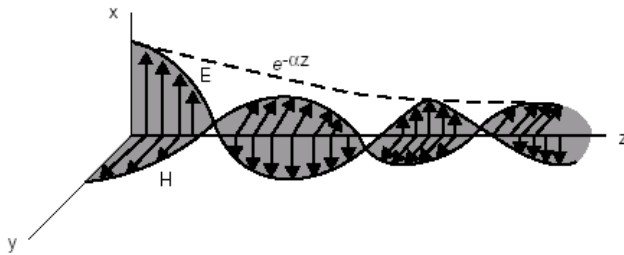


Figure 1. The magnetic and electric field components of a plane wave in a lossy medium (Source: Sadiku, 2001).

where f is the frequency (Hz) and τ_m is the transmission coefficient at the interfacial boundary between the heated material and its surroundings.

Equation 10 has been stated and used by several authors (Singh and Heldman, 1993; Torgovnikov, 1993; Van Remmen et al., 1996). The derivation of equation 10 assumes an absorbing material that extends away from the electromagnetic source without change in electromagnetic properties. In reality, it only describes the case of an infinitely long material; however Ayappa et al. (1991) have shown that equation 10 is an adequate approximation for real microwave heating problems when the thickness of dielectric slabs is greater than the critical thickness (W_{cr}) given by:

$$W_{cr} = \left(\frac{270}{\alpha} - 0.08 \right) \times 10^{-2} \text{ (m)} \quad (11)$$

The Dielectric Properties of Wood

The anatomy of wood, which can be described in terms of early and later wood, longitudinal tracheids, ray cells, resin channels, and vessels (Jackson and Day, 1989; Torgovnikov, 1993), results in anisotropic dielectric behavior. The dielectric properties of wood must be described by a tensor rather than a single value (Torgovnikov, 1993). It is generally accepted that the dielectric properties of wood do not change significantly with the revolution of the electric field vector through 180° (Torgovnikov, 1993); therefore the dielectric behavior of wood can be adequately described by three values representing the complex dielectric permittivity in the radial, the tangential and the longitudinal directions (Torgovnikov, 1993).

If the difference in wood parameters in the radial and tangential direction is assumed to be negligible (Torgovnikov, 1993), then the dielectric behavior of wood can be described by the complex electrical permittivity parallel to the grain and perpendicular to the grain (Torgovnikov, 1993). For the same field frequency and wood density, the largest values of complex electrical permittivity is found when the electric field vector is oriented parallel to the wood grain (Torgovnikov, 1993).

SIMULTANEOUS HEAT AND MOISTURE DIFFUSION

The amount of water vapor moving into a small section of porous material is the sum of any net increase in moisture content in the air space and the net increase in moisture content of the material's fibers (Crank, 1979). Therefore:

$$a_v \tau_v D_a \cdot \nabla^2 M_v = a_v \frac{\partial M_v}{\partial t} + (1 - a_v) \rho_s \frac{\partial M_s}{\partial t} \quad (12)$$

where a_v is the air space fraction in the material, τ_v is a tortuosity factor, D_a is the vapor diffusion coefficient of water in air ($\text{m}^2 \text{s}^{-1}$), M_v is the moisture vapor concentration in the wood pores (kg m^{-3}), M_s is the moisture content of the wood fibers (kg kg^{-1}) and ρ_s is the density of the wood's solid material (kg m^{-3}).

Heat is evolved because of microwave heating and moisture absorption by a material; therefore the thermal diffusion equation, which includes a volumetric heat source, is:

$$C\rho \frac{\partial T}{\partial t} = k\nabla^2 T + L\rho \frac{\partial M_s}{\partial t} + \dot{q} \quad (13)$$

where C is the thermal capacity of the composite material ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), ρ is the composite material density (kg m^{-3}), k is the thermal conductivity of the composite material ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$), L is the latent heat of vaporization of water (J kg^{-1}), and \dot{q} is the volumetric heating in the material (W m^{-3}).

If it is assumed that some linear relationship exists between the moisture content of a material, the moisture vapor concentration in the air spaces in the material and the temperature (Henry, 1948; Crank, 1979), then:

$$\frac{\partial M_s}{\partial t} = \sigma \frac{\partial M_v}{\partial t} - \omega \frac{\partial T}{\partial t} \quad (14)$$

where σ and ω are constants of association between heat transfer and moisture vapor concentration.

Substituting from equation 14 into equations 12 and 13 and combining the two equations yields:

$$\begin{aligned} \nabla^2 (pM_v + nT) - \frac{\partial}{\partial t} \left\{ \left[\frac{1}{\tau_v D_a} \left(1 + \frac{(1 - a_v) \sigma \rho_s}{a_v} \right) - \frac{n\rho\sigma L}{pk} \right] pM_v + \left[\frac{C\rho}{k} \left(1 + \frac{\omega L}{C} \right) - \frac{p(1 - a_v) \omega \rho_s}{n\tau_v D_a a_v} \right] nT \right\} \\ + \frac{n\dot{q}}{k} = 0 \end{aligned} \quad (15)$$

This can be expressed in a simpler form if $\Omega = pM_v + nT$ and p and n , which are constants of association, are calculated to satisfy:

$$\begin{aligned} \frac{1}{\gamma} &= \left[\frac{1}{\tau_v D_a} \left(1 + \frac{(1 - a_v) \sigma \rho_s}{a_v} \right) - \frac{n\rho\sigma L}{pk} \right] \\ &= \left[\frac{C\rho}{k} \left(1 + \frac{\omega L}{C} \right) - \frac{p(1 - a_v) \omega \rho_s}{n\tau_v D_a a_v} \right] \end{aligned} \quad (16)$$

When equation 10 is used to describe the volumetric heating term, equation 15 yields:

$$\nabla^2 \Omega - \frac{1}{\gamma} \frac{\partial \Omega}{\partial t} + \frac{n\pi f \epsilon_0 \epsilon''}{k} \left[\vec{E}(x, y) \right]^2 \cdot e^{-2\alpha z} = 0 \quad (17)$$

Equation 17 is now a diffusion equation in terms of Ω while equation 16 is a quadratic polynomial in terms of γ . After some rearrangement, equation 16 yields:

$$\gamma = \left\{ 2 \frac{k\tau_v D_a}{C\rho \left(1 + \frac{L}{C}\omega\right) \left[1 + \frac{(1-a_v)\rho_s\sigma}{a_v}\right]} \right\} \pm \left\{ \frac{k}{C\rho \left(1 + \frac{L}{C}\omega\right)} + \frac{\tau_v D_a}{\left[1 + \frac{(1-a_v)\rho_s\sigma}{a_v}\right]} \right\} \pm \left[\frac{k}{C\rho \left(1 + \frac{L}{C}\omega\right)} - \frac{\tau_v D_a}{\left[1 + \frac{(1-a_v)\rho_s\sigma}{a_v}\right]} \right]^2 \left. \right\}^2 \quad (18)$$

$$+ 4 \frac{k\sigma\rho_s\omega L\tau_v D_a}{aC^3\rho \left(1 + \frac{L}{C}\omega\right)^3 \left[1 + \frac{(1-a_v)\rho_s\sigma}{a_v}\right]^2} \left. \right\}$$

Equation 18 implies that the combined heat and moisture diffusion coefficient (γ) has two independent values. This is consistent with Henry's (1948) equation for simultaneous heat and moisture diffusion in textiles.

Henry (1948) shows that a change in external temperature or humidity (or both), "results in a coupled diffusion of moisture and heat which is mathematically analogous in many respects to a pair of coupled vibrations." The combined process is equivalent to the independent diffusion of two quantities, each of which is a linear function of moisture vapor concentration and temperature (Henry, 1948; Crank, 1979). Henry (1948) states that "the diffusion constants appropriate to these two quantities are always such that one is greater and the other less than either of the diffusion constants which would be observed for the moisture or heat, were these not coupled by the interaction."

The slower diffusion coefficient of the coupled system is less than either the isothermal diffusion constant for moisture or the constant vapor concentration coefficient for heat diffusion, whichever is less, but never by more than one half (Henry, 1948). The faster diffusion coefficient is always many times greater than either of these independent diffusion constants (Henry, 1948).

Henry (1948) states that similar reasoning should be applied in the case where either moisture or heat are released or absorbed inside the material in a way that is independent of the diffusion process. Microwave heating is quite independent of any diffusion processes.

Considerable evidence exists in literature for rapid heating and drying during microwave processing (Rozsa, 1995; Zielonka and Dolowy, 1998; Torgovnikov and Vinden,

2003); therefore it is reasonable to assume that the faster diffusion wave should dominate microwave heating in moist materials. A slow heat and moisture diffusion wave should also exist; however observing this slow wave during microwave heating may be difficult and no evidence of its influence has been seen in literature so far.

In summary, the problem at hand is to determine a solution to equation 17, while realizing that this solution represents two waves of heat and moisture propagating at two different rates through the material. The following boundary conditions must be applied:

$$h\Omega|_{surface} = -k \frac{\partial\Omega}{\partial z}|_{surface} \quad (19)$$

Taking the Laplace transformation of equation 17 yields:

$$\nabla^2\Omega(s) - \frac{s}{\gamma}\Omega(s) + \frac{n\pi f\epsilon_o\epsilon''}{sk} [\vec{\tau E}(x, y)]^2 \cdot e^{-2\alpha z} = 0 \quad (20)$$

Solutions to equation 20 are found by combining the solution to the complementary function $\nabla^2\Omega_o(s) - \frac{s}{\gamma}\Omega_o(s) = 0$ with particular solutions to the full differential equation (Bowman, 1965).

Rectangular coordinate systems apply when rectangular wood is heated in rectangular microwave cavities or wave-guides; so, applying rectangular coordinates to the complementary function and enforcing the limit theorem $\left(\lim_{t \rightarrow 0} f(t) = \lim_{s \rightarrow \infty} F(s)\right)$ to ensure that the solution is bounded at time $t = 0$, yields the one dimension solution to the complementary function:

$$\Omega_o(s) = Ae^{-\sqrt{\frac{s}{\gamma}}z} \quad (21)$$

A particular solution to equation 20 is:

$$\Omega_p(s) = \frac{n\pi f\epsilon_o\epsilon''}{s\left(\frac{s}{\gamma} - 4\alpha^2\right)k} [\vec{\tau E}(x, y)]^2 \cdot e^{-2\alpha z} \quad (22)$$

So the general solution for rectangular coordinates is:

$$\Omega(s) = Ae^{-\sqrt{\frac{s}{\gamma}}z} + \frac{n\pi f\epsilon_o\epsilon''}{s\left(\frac{s}{\gamma} - 4\alpha^2\right)k} [\vec{\tau E}(x, y)]^2 \cdot e^{-2\alpha z} \quad (23)$$

From tables found in Crank (1979) and Mansfield (1972), the inverse Laplace transformation of equation 23 is:

$$\Omega = \frac{Az}{2\sqrt{\pi\gamma t^3}} e^{-\frac{z^2}{4\gamma t}} + \frac{n\pi f\epsilon_o\epsilon''}{4\alpha^2 k} [\vec{\tau E}(x, y)]^2 \cdot e^{-2\alpha z} \left(e^{4\gamma\alpha^2 t} - 1 \right) \quad (24)$$

Applying the boundary condition to evaluate A yields:

$$\Omega = \frac{n\pi f \epsilon_o \epsilon''}{4k\alpha^2} \left[\vec{E}(x, y) \right]^2 \left(e^{4\gamma\alpha^2 t} - 1 \right) \times \left\{ e^{-2\alpha z} + \left(\frac{h}{k} + 2\alpha \right) z e^{\frac{-z^2}{4\gamma t}} \right\} \quad (25)$$

Equation 25 is very similar to a solution for microwave heating in soil presented by Hermann (2000). Since, according to Henry's original interpretation, Ω represents both the temperature and moisture vapor distribution, equation 25 can be used to explore the influence of simultaneous heat and moisture movement during microwave heating.

Henry (1948) presents a nomogram, shown in figure 2, relating the fast diffusion coefficient to the default diffusion coefficient for the material at 20°C and 65% Relative Humidity (RH). The relationships represented in the nomogram were derived from experimental data and therefore should account for variability of the parameters due to changes in temperature, moisture content, and humidity. The default values represent the standard range of conditions used during textile testing (Henry, 1948). In spite of this, the ratio of the fast diffusion coefficient and the default thermal diffusion coefficient for other materials at different initial conditions should still be discernable from figure 2.

If microwave experiments result in a significant increase in humidity ($\approx 90\%$ RH) and temperature ($\approx 90^\circ\text{C}$), figure 2 suggests that the default thermal diffusivity should be increased by a factor of approximately 7.8.

PRELIMINARY TEST OF THE CONCEPT

A preliminary test of this concept was made by comparing theoretical temperatures calculated using equation 25 with experimental data published by Zielonka and Dolowy (1998). They used a 350-W microwave oven with internal dimensions of 360 × 360 × 247 mm to heat samples of spruce cut into 170- × 60- × 300-mm blocks.

Zielonka and Dolowy (1998) do not indicate the strength of the microwave fields in their experiment; therefore a Finite Difference Time Domain (FDTD) computer program, based on the well-known algorithm proposed by Yee (1966), was

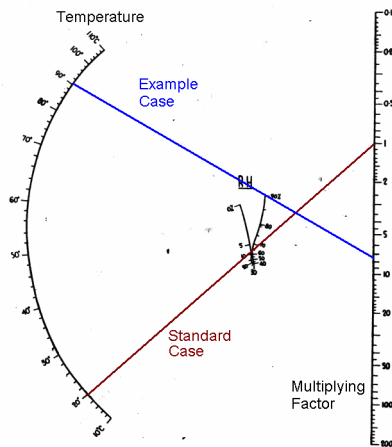


Figure 2. Nomogram of variation in γ with temperature and relative humidity (Source: modified from Henry 1948).

written to calculate the electric field distribution that would be expected inside the oven cavity during their experiment.

Because wood is an anisotropic material, the complex dielectric constant (ϵ^*) for the wood was assumed to be 7.0 + j 1.26 when the electric field was parallel to the wood grain and 3.59 + j 0.58 when the electric field was perpendicular to the grain (Torgovnikov, 1993).

Constant vapor concentration thermal diffusivity (γ') of a material is determined from the density, heat capacity, and the thermal conductivity of the material (Steinhagen, 1977). The relationship between these values is defined by:

$$\gamma' = \frac{k}{\rho C} \quad (26)$$

From charts found in Steinhagen (1977), the thermal capacity of wood at 80% moisture content and 20°C is 2.97 kJ kg⁻¹ K⁻¹ and the thermal conductivity of wood under the same conditions is 0.37 W m⁻¹ K⁻¹. Spruce has an average density of 470 kg m⁻³ (Jackson and Day, 1989); therefore the constant vapor concentration thermal diffusivity for wood was estimated to be 2.65 × 10⁻⁷ m² s⁻¹. Applying a multiplying factor of 7.8 implies that the fast wave diffusion coefficient will be 2.07 × 10⁻⁶ m² s⁻¹. From tables in Crank (1979) the amplitude factor (n) in equation 25 was estimated to be 0.13.

Determining the Strength of the Applied Microwave Fields

A microwave oven has a short section of wave-guide feeding microwave energy into a resonant chamber. In general, a wave-guide consists of a hollow metallic tube of uniform cross section. Common wave-guide shapes are rectangular, circular, or ridged (USNASC, 1999).

It is possible to propagate several modes of electromagnetic waves within a wave-guide. The physical dimensions of a wave-guide determine the cutoff frequency for each mode. If the frequency of the impressed signal is above the cutoff frequency for a given mode, the electromagnetic energy can be transmitted through the guide with minimal attenuation. Electromagnetic energy with a frequency below cutoff will be attenuated to a negligible value in a relatively short distance. The distribution of the electric and magnetic fields inside the wave-guide is not uniform.

The field distribution patterns are used to describe the operation mode of the wave-guide system. The usual designation for fields that have only transverse electrical field components is TE_{mn}, where the m and n values indicate the number of half waves present in the horizontal and vertical aspects of the wave-guide, respectively. Figure 3 shows a graphical depiction of the electric field variation in a wave-guide for the TE₁₀, TE₂₀, and TE₃₀ modes.

The TE₁₀ mode has the lowest cutoff frequency in rectangular wave-guides; therefore most wave-guide feeds for microwave processing are designed to operate in TE₁₀ mode. The maximum electric field strength in a wave-guide propagating in TE₁₀ mode can be calculated using (Metaxas and Meredith, 1983):

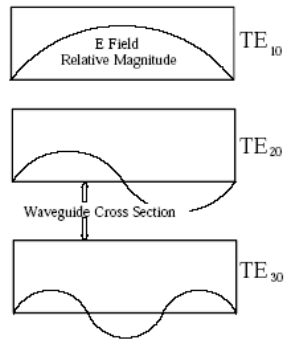


Figure 3. TE modes (Source: USNASC, 1999).

$$E_{\max} = 2 \sqrt{\frac{120\pi P}{ab \sqrt{1 - \left(\frac{\lambda_0}{2} \sqrt{\left(\frac{m}{a} \right)^2 + \left(\frac{n}{b} \right)^2} \right)^2}} \quad (27)$$

where P is the applied microwave power (W), a and b are the width and height of the wave-guide respectively, λ_0 is the wavelength of the microwave as measured in free space (m), and m and n are the mode designators as discussed earlier.

Because Zielonka and Dolowy (1998) did not specify the electric field strength at any point during their experiments, equation 27 was used to determine that the maximum electric field strength in the wave-guide feeding into the oven cavity was 14,250 V m⁻¹. From this value, the FDTD simulation was used to calculate the electric field strength in the wood sample. The output of this simulation is shown in figure 4. The strength of the electric field at the wood surface was approximately 2100 V m⁻¹. This was used in equation 25 to calculate the theoretical temperature curves shown in figure 5.

Figure 5a compares Zielonka and Dolowy's published temperature measurements with theoretical temperatures, calculated using the constant vapor concentration thermal diffusivity of $2.65 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ and amplitude factor (n) equal to unity, while figure 5b uses a value of thermal diffusivity of $2.07 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ (7.8 times larger) and an amplitude factor (n) of 0.13. This preliminary examination showed considerable promise, so an experiment was developed to properly investigate the role of simultaneous heat and moisture movement during microwave heating of moist wood.

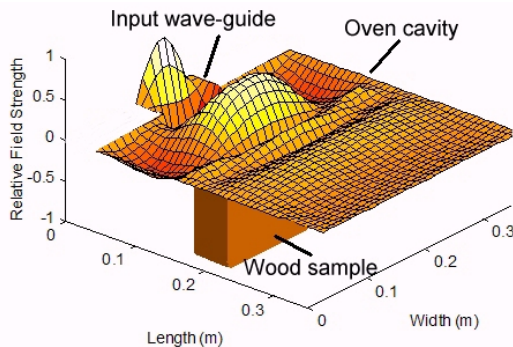


Figure 4. Electric field strength, calculated using an FDTD simulation of the oven experiment described by Zielonka and Dolowy (1998).

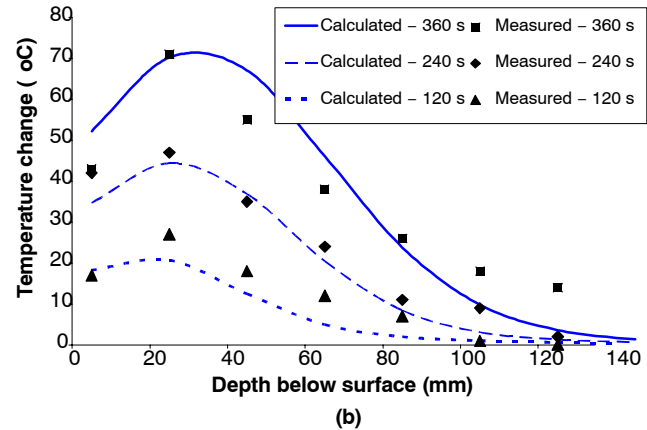
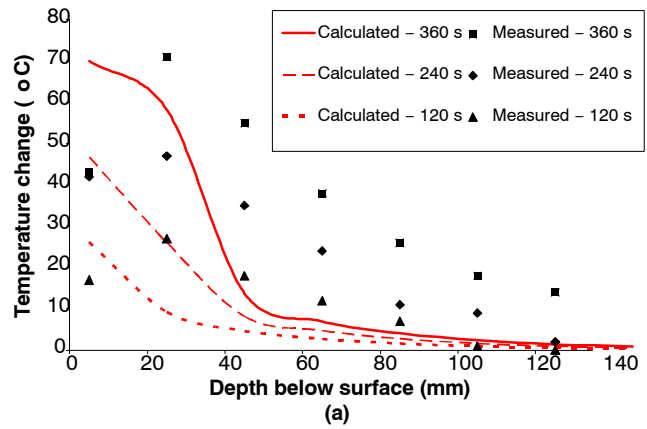


Figure 5. Comparison of measured temperature, published by Zielonka and Dolowy (1998) with theoretical temperature, estimated using equation 6 - (a) using the constant vapor concentration thermal diffusivity of wood and (b) using a thermal diffusivity that is 7.8 times larger.

METHOD

Ten samples of *Eucalyptus regnans* cut to $85 \times 55 \times 300$ mm long were placed longitudinally in a wave-guide applicator (fig. 6). A matched water load was placed at the end of the wave-guide to absorb any remaining microwave energy.

The wave-guide, which consisted of a $248 \times 124 \times 1200$ -mm heating chamber, was fed from an 86×43 -mm wave-guide excited by the magnetron of a 750-W domestic microwave oven operating at 2.45 GHz. An expansion section of 300-mm length was used to join the 86×43 -mm wave-guide to the larger chamber. This arrangement is similar to that described by Zhao et al. (1998). An FDTD program was used to calculate the microwave field distribution inside the wave-guide system.

Samples were placed in the same location on the center-line of the wave-guide and remained stationary throughout irradiation. Temperatures were measured in pre-drilled 2-mm diameter holes at 25-mm intervals along the center line of the wood, using NoEMI-TS series fiber optic thermal probes. The first of these test holes was 5 mm from the front surface. The probes were sealed into the holes using silicon sealant.

It is acknowledged that these holes will interact to some extent with the microwave field distributions inside the

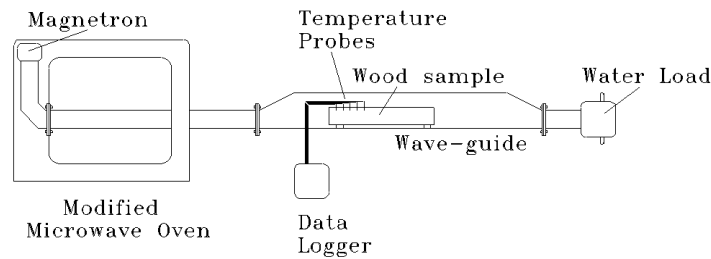


Figure 6. Schematic diagram of experimental apparatus borrowed from Professor Grigori Torgovnikov of the University of Melbourne's Creswick campus.

wood; however their diameter is so small in comparison to the wavelength of the microwaves inside the wood ($\lambda \approx 65$ mm) that their influence should be reasonably small. It is also acknowledged that some localized cooling may occur due to surface evaporation inside the holes, but this can not be avoided and the silicon sealant was used to reduce this to some extent.

Samples were initially at 19°C and were irradiated until the peak temperature measured by any of the probes was approximately 80°C. Mean air-dry wood density was calculated using gravimetric analysis of 10 sections taken from the experimental samples.

Theoretical temperature profiles were calculated using equation 25 and compared to measured data. The comparison between measured and theoretical temperatures was made using default values for constant vapor pressure thermal diffusivity determined from data found in literature (Steinhagen, 1977; Studman, 1990) and again when this value was multiplied by a factor of 7.8.

Other multiplying factors were also considered during the analysis. These were determined by calculating the value of thermal diffusivity that provided the best statistical agreement between theoretical and measured results and calculating the ratio between these values and the default value determined from literature sources (Steinhagen, 1977; Studman, 1990).

RESULTS

The mean air-dry wood density was 481 kg m⁻³ and the mean initial moisture content was 52%. From charts found in Steinhagen (1977), the thermal capacity of wood at 50% moisture content and 20°C is 2.68 kJ kg⁻¹ K⁻¹ and the thermal conductivity under the same conditions is 0.29 W m⁻¹ K⁻¹,

therefore the default thermal diffusivity was estimated to be 2.25×10^{-7} m² s⁻¹. The default amplitude factor (n) in equation 25 was assumed to be 1.0.

Applying a multiplying factor of 7.8 implies that the fast wave diffusion coefficient was 1.75×10^{-6} m² s⁻¹ and the amplitude factor (n) was 0.13. The mean final moisture content for the samples was 31%.

From the FDTD computer simulation, shown in figure 7, the maximum electric field strength in the large chamber was estimated to be 6200 V m⁻¹, of which 3500 V m⁻¹ was transmitted into the wood sample.

Figure 8 compares theoretical and mean measured temperatures in the wood samples. The Pearson's correlation coefficients comparing calculated and measured data in figure 5a were 0.60, 0.36, and 0.06 for heating times of 40, 100, and 300 s, respectively, while in figure 5b they were 0.80, 0.91, and 0.96, respectively.

Figure 9 compares theoretical and mean measured temperatures in the wood samples when other multiplying factors were used for heating times of 40 and 100 s. In these cases the constant vapor pressure thermal diffusivity of the wood was multiplied by 13.1 and 11.5 times for the 40- and 100-s heating times, respectively. The Pearson's product moment correlation coefficients were 0.96 for all comparisons at 40, 100, and 300 s.

DISCUSSION

In the simulation shown in figure 7a, the empty wave-guide appears to propagate microwaves in the TE₁₀ mode. Although this is possible, at 248 mm wide, the larger chamber in the wave-guide is wide enough for TE₂₀ mode propagation when operating at 2.45 GHz. It was quite likely that the real

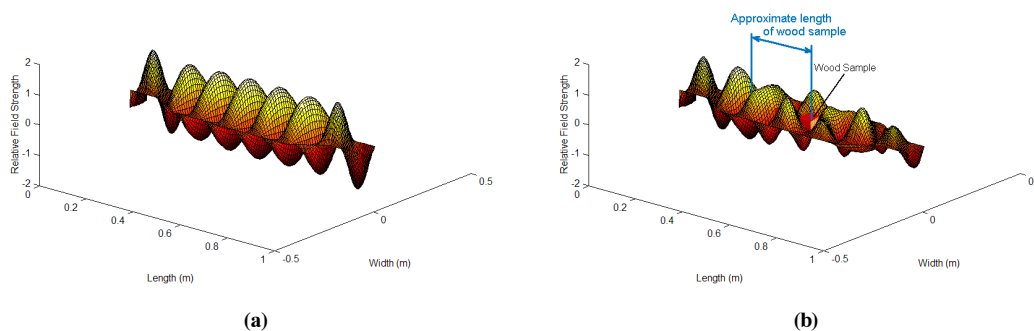


Figure 7. Results of the FDTD simulation for the wave-guide applicator shown in figure 3 - (a) without wood and (b) with a wood sample.

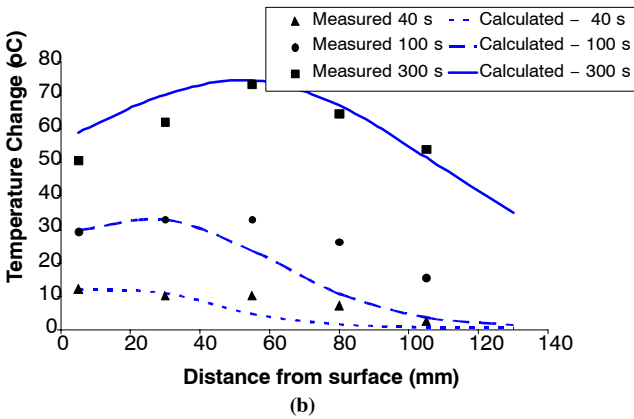
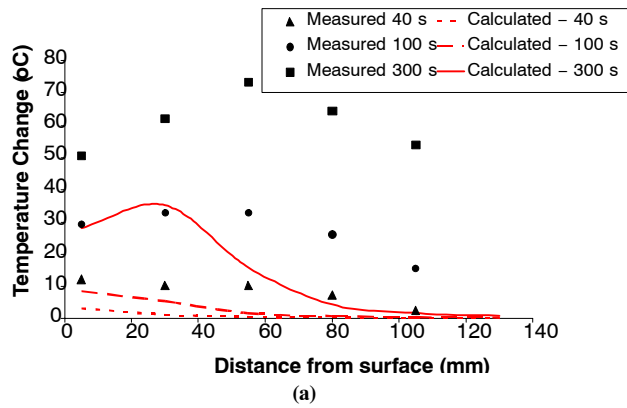


Figure 8. Comparison of mean measured temperature with theoretical temperature, estimated using equation 6 - (a) using the constant vapor pressure thermal diffusivity of wood and (b) using a thermal diffusivity that is 7.8 times larger.

wave-guide was propagating in multiple modes, with the TE₁₀ mode being the dominant mode.

When the wood sample was introduced into the simulation, the wave form was substantially altered. There was considerable attenuation of the microwave's electrical field inside the wet wood sample. Because the wood sample did not extend to the full width or height of the wave-guide, the field outside the wood sample remained quite strong and

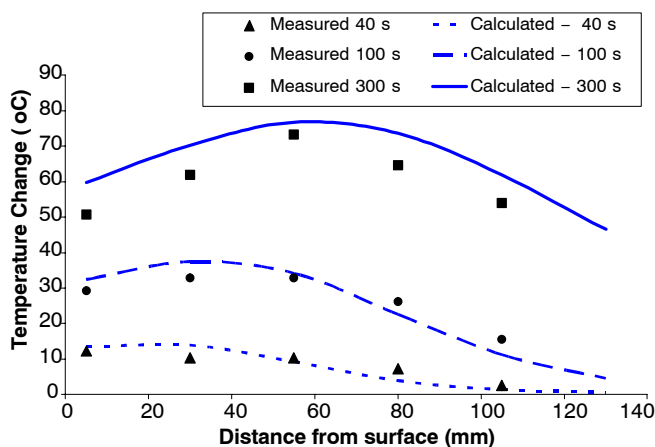


Figure 9. Comparison of mean measured temperature with theoretical temperature, estimated using equation 6 when the constant vapor pressure thermal diffusivity of wood was multiplied by 13.1 for 40-s data, 11.5 for 100-s data, and 7.8 for 300-s data.

propagated faster than the fields inside the wood sample. This would be expected because of the differing dielectric properties of air and wood. The resulting wave form, predicted by the simulation, exhibited a double peak appearance outside the wood sample; however the wave along the center line of the wood sample conformed to the exponentially decaying wave used during the derivation of equation 25; therefore equation 25 should be adequate to predict the temperature distribution along the center line of the wood sample.

Figures 5a and 8a show that using the default thermal diffusivity for wood does not model the temperatures inside the wood very well; however when the default thermal diffusivity is multiplied by a factor of 7.8 there is much better agreement between theoretical and measured temperatures. This is shown in Figures 5b and 8b and is consistent with Henry's (1948) discussion that, under the influence of simultaneous heat and moisture diffusion, the thermal diffusion constant associated with the faster wave of the coupled system is many times greater than the default values.

Figure 9 demonstrates that even better agreement between theoretical and measured data can be found when the multiplying factors are changed, depending on heating time. It is worthy of note that both the multiplying factors and moisture content of the samples decrease with heating time. In his discussion of simultaneous heat and moisture diffusion, Henry (1948) also stated that thermal diffusion would approach the constant vapor concentration thermal diffusivity of the material as the combined heat and moisture diffusion processes became decoupled. The decline in the multiplying factor, implied by the data shown in figure 9, may be linked to the loss of moisture and subsequent decoupling of the combined heat and moisture transfer mechanisms. This requires further investigation.

It appears that the faster of the two diffusion waves is the dominant factor during microwave heating and there does not appear to be any evidence of the slower wave in these results. Hot water vapor may be an important heat transport mechanism during microwave heating of moist wood.

This article presents early results from an ongoing investigation into this phenomenon. Clearly microwave heating is used to process a wide variety of moist dielectric materials and more investigation is needed to thoroughly investigate the validity of this concept.

CONCLUSION

Redistribution of the heat in moist wood during microwave heating appears to be described by the "fast wave" diffusion model predicted by the coupling of heat and moisture transport. The simple wood heating experiment and other comparisons, presented here, provides some supporting evidence for this phenomenon; however more investigation of the concept is warranted.

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