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A single cell model for pretreatment of wood by microwave explosion

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Abstract

A theoretical model was developed to better understand the process of microwave explosion treatment of wood cells. The cell expansion and critical conditions concerning pressure and temperature of ray parenchyma cells in *Eucalyptus urophylla* were simulated during microwave pretreatment. The results indicate that longitudinal and circumferential stresses were generated in the cell walls owing to the internal steam pressure during extensive microwave treatment. The circumferential stress is twice as high as the longitudinal stress. The pressure difference reaches its maximum value of 0.84 MPa when the extension ratio is 1.20 for the longitudinal direction and 1.62 for the circumferential direction. The maximum pressure difference at the theoretical yielding point is the critical pressure difference that can eventually rupture the ray cell. The critical pressure difference decreases with increasing cell radius and decreasing shear modulus in the cell wall. This simulated result provides useful information to modify wood at the level of ray parenchyma cells.

Keywords: microwave explosion; pretreatment; single cell model; wood.

Introduction

Microwave pretreatment is a technique in the forest product industry to improve process efficiency and product performance. Intensive microwave energy usually generates high internal steam pressure that could rupture weaker elements of wood structure (such as ray cells). As a result, wood permeability is increased and the moisture movement during drying is considerably facilitated. This type of modification is a new technology that has been evaluated in recent years for different purposes.

Since the first report of Torgovnikov et al. (1999) about this topic, many related research works have been published. Torgovnikov and Vinden (2000, 2001) reported that the thin-walled ray cells were ruptured first and that micro-voids in the radial-longitudinal planes of wood were created. Although the modulus of elasticity (MOE) decreased by 12–17%, several other properties were improved. For example, the volume of the pretreated eucalyptus lumber was increased by 13.4%, the preservative absorption was elevated by factors of 10–14, and the drying rate was 5–10 times higher. In 2006, the first 300-kW microwave device equipped with three microwave sources with a frequency of 0.922 GHz was developed and installed at the Melbourne University in Australia (Torgovnikov and Vinden 2004, 2005, 2006). Harris et al. (2008) found that microwave pretreatment before the conventional kiln drying process could significantly reduce both the number and size of the surface checks when drying eucalyptus wood (*Eucalyptus muelleriana, Eucalyptus obliqua*) which are usually designated as ‘‘messmate stringybark’’. Zhou et al. (2009) pretreated eucalyptus samples with high energy microwaves to achieve stress relaxation. The authors observed that drying efficiency and drying quality of eucalyptus lumbers were improved when compared with conventional hot-air drying in traditional kilns. Liu et al. (2005) reported that the permeability of larch wood was improved without noticeable reduction of strength and stiffness if the conditions of microwave treatment were optimized. Microwave treatment was also applied to new wood-based composites: fixation of copper-ethanolamine treated wood was accelerated and the formaldehyde emission of plywood was reduced (Hooda and Banerjee 2000; Cao and Kamdem 2004; Saito et al. 2004; Simon et al. 2007).

Regardless of the promising results indicated above, microwave pretreatment is not yet widely accepted in the wood product industry. This is partly owing to insufficient knowledge of the complex interaction between material and process parameters and partly because of commercial reasons, i.e., lack of readiness to invest in equipment.

Understanding the mechanism and critical condition of ray cells rupture is particularly important for process control during microwave pretreatment. Mathematical modeling is a useful way to describe the variation of stress and deformation in ray cell walls and to determine the critical conditions for microwave pretreatment. This study is focused on the ray parenchyma cells of *Eucalyptus urophylla*.

Methods, results and discussion

Model formulation

The traditional approach to determine elasticity of plant cells is by means of the bulk modulus (ε), which is commonly

used to describe stress-strain relations of solid and homogeneous bodies undergoing small deformations. A plant cell taken as a whole is neither solid nor homogeneous, and its deformation under load is not small. The application of the bulk elastic modulus to pressure-volume relations of plant cells is inconsistent with its definitions and it was demonstrated to be physically meaningless (Wu et al. 1985). The research conducted by Wu et al. (1985) and Wei and Wang (2005) suggested an alternative approach, which is based on principles of polymer elasticity to describe the stress-strain relation of a cell wall. One of the polymer elasticity principles is the assumption that the shear modulus is constant for a polymer and that the mechanical analysis of a cell wall is based upon the shear modulus of its wall material. Wood is a natural polymeric material, and the volume changes of its ray cells under pressure are relatively large during microwave explosion. Therefore, the polymer elasticity approach was used in this study to describe the stress-strain relation for the ray cells of *E. urophylla* wood. The following rational assumptions are made for simplifying theoretical calculations of the model.

- The ray parenchyma cell of *E. urophylla* has a simple cylindrical shape, and the cell wall is a homogeneous polymer substance. During microwave pretreatment, the cell wall volume remains constant and at a uniform thickness.
- The curvature radius of the cell wall under stress is much longer than its thickness, therefore the stresses along the direction of cell wall thickness can be ignored.
- The moisture content (MC) of the wood remains above the fiber saturation point (FSP) during the microwave treatment, and the movement of both moisture and air within the cell are neglected because of the short treatment time.

Based on the above assumptions, an ideal ray cell model and its force conditions during microwave pretreatment are illustrated in Figure 1. During pretreatment, moisture inside the cell cavity quickly turns to steam creating a high vapor pressure, causing the cell to expand and deform. The extension ratio is the relation of the stretched cell to its original dimension. In the case of the cylindrical cell, the cell extension ratios for the three directions can be defined as:

$$\lambda_1 = l/l_0 \quad \lambda_2 = r/r_0 \quad \lambda_3 = h/h_0 \tag{1}$$

where λ_1, λ_2, λ_3 are cell extension ratios in longitudinal, circumferential, and radial directions (thickness of cell wall), respectively; l, r, and h are the length, cell cavity radii and wall thickness of a strained cell. The subscript 0 denotes the original or unstrained state.

Based on the polymer elasticity principle, the following stress-strain relation for a polymer-like substance was used for the mechanical analysis of wood ray cells (Wu et al. 1985):

$$\sigma_i = G\lambda_i^2 + \sigma_0 \tag{2}$$

where δ_i and λ_i are the directional stresses and the extension ratios, respectively. G is the shear modulus, and δ_0 is an

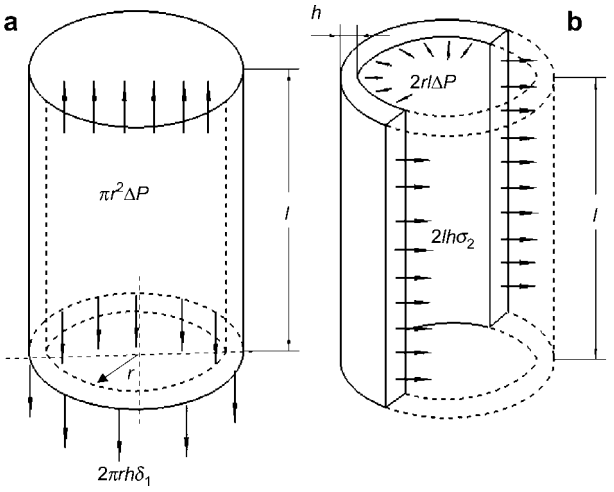

Figure 1 An idealized cylindrical parenchymatic cell illustrating the force balance along the longitudinal and circumferential direction of the cell wall.

arbitrary constant stress such as hydrostatic pressure. Because the stress along wall thickness was ignored, i.e., $\delta_3 = 0$, the arbitrary stress constant δ_0 can be evaluated from Eq. (2):

$$\sigma_0 = -G\lambda_3^2 \tag{3}$$

Based on the previous assumption that the cell wall volume remains constant during the microwave pretreatment and neglecting the end walls volume of the cylinder, the following relation can be established:

$$\lambda_1\lambda_2\lambda_3 = 1 \tag{4}$$

Substituting Eqs. (3) and (4) into Eq. (2), the following two relations can be obtained:

$$\sigma_1 = G\lambda_1^2 + \sigma_0 = G\lambda_1^2 - G\lambda_3^2 = G(\lambda_1^2 - \lambda_3^2) = G(\lambda_1^2 - \lambda_1^{-2}\lambda_2^{-2}) \tag{5}$$

$$\sigma_2 = G\lambda_2^2 + \sigma_0 = G\lambda_2^2 - G\lambda_3^2 = G(\lambda_2^2 - \lambda_3^2) = G(\lambda_2^2 - \lambda_1^{-2}\lambda_2^{-2}) \tag{6}$$

When the internal steam pressure during microwave pretreatment is applied uniformly to the inner surface of the wall (Figure 1), both resultant forces along the longitudinal direction of the cylindrical cell and circumferential direction in the circumferential ring are equal to zero before the cell is ruptured:

$$\pi r^2\Delta P - 2\pi rh\sigma_1 = 0 \tag{7}$$

$$2rl\Delta P - 2lh\sigma_2 = 0 \tag{8}$$

where ΔP is the pressure difference between inside and outside cell; δ_1 and δ_2 are longitudinal and circumferential stresses in the cell wall, respectively.

Substituting Eqs. (1) and (4) into Eqs. (7) and (8), δ_1 and δ_2 can be expressed:

$$\sigma_1 = \frac{r\Delta P}{2h} = \frac{\Delta P \lambda_1 \lambda_2^2}{2} \frac{r_0}{h_0} \tag{9}$$

$$\sigma_2 = \frac{r\Delta P}{h} = \Delta P \lambda_1 \lambda_2^2 \frac{r_0}{h_0} \tag{10}$$

Equations (9) and (10) show the stress along the circumferential direction is twice that in the longitudinal axis.

Based on the Eqs. (5), (6), (9), and (10), the following equation can be derived:

$$\lambda_2^2 = 2\lambda_1^2 - \lambda_1^{-2}\lambda_2^{-2} \tag{11}$$

Solving for λ_2 in Eq. (11), the relation between λ_2 and λ_1 is obtained:

$$\lambda_2 = \sqrt{\lambda_1^2 + \sqrt{\lambda_1^4 - \frac{1}{\lambda_1^2}}} \tag{12}$$

Combining Eqs. (6), (10), and (12) a nonlinear relation can be obtained among pressure difference (ΔP), cell extension ratios and cell wall stress. A model for the minimum critical pressure to rupture ray cell can be then created with the given parameters G, r_0, and h_0.

Practically, it was impossible to measure accurately the steam pressure inside the wood or the pressure difference between the outside and inside of the wood. In this study, another mathematical model is developed to describe the relation between pressure and temperature. As assumed earlier, the microwave treatment time is very short and the movement of moisture and air inside cell cavities could be neglected. The wood cell could be considered as an enclosed space, and the total pressure inside the cell cavity is the sum of the dry air pressure and steam pressure based on Dalton's law. The dry air pressure can be described with the equation for an ideal gas. The steam pressure reaches its saturated pressure because the MC of wood before microwave pretreatment is usually very high and the steam generated during the treatment inside cell cavities remain in a saturated state (Liu et al. 2006; Cai and Kazuo 2007). The saturated steam pressure at its corresponding temperature in the cell cavities is given (Siau 1984):

$$P_{sv} = 1.163 \times 10^{11} \exp[-43212/R(T + 273.15)] \tag{13}$$

where, P_{sv} is the saturated vapor pressure, Pa; R is the universal gas constant, 8.31 J mol^{-1}; T is the temperature of wood, °C.

Before the microwave pretreatment, the initial temperature of wood is T_i °C, and the total pressure in cell cavity equals atmospheric pressure, so the following relation is obtained:

$$P_i = P_{iv} + P_{id} = P_{iv} + (P_a - P_{iv}) = P_a \tag{14}$$

where P_i is the initial total pressure in wood cell cavities before the treatment; P_{iv} and P_{id} are the partial pressures of vapor and dry air, respectively, in the cell cavities in initial state; and P_a is the atmospheric pressure.

The partial pressures of steam and dry air in wood at initial state can be calculated with Eqs. (13) and (14). Based on the equation for the state of an ideal gas and volume expansion of cell cavities during microwave pretreatment, the pressure of dry air in cell cavities at an arbitrary temperature (T°C) during microwave pretreatment, can be determined by:

$$P_d = \frac{P_{id} \times (273.15 + T)}{273.15 + T_i} \times \frac{1}{\lambda_2^2 \times \lambda_1} \tag{15}$$

According to Eqs. (13), (15), and Dalton's law of partial pressure during the pretreatment, the total pressure in wood cell cavities at an arbitrary temperature can be expressed:

$$P = P_{sv} + P_d = 1.163 \times 10^{11} \exp[-43212/R(T + 273.15)] + \frac{P_{id} \times (273.15 + T)}{273.15 + T_i} \times \frac{1}{\lambda_2^2 \times \lambda_1} \tag{16}$$

where P, P_{sv}, and P_d are the total pressure and the partial pressures of vapor and dry air, respectively, in cell cavities at an arbitrary temperature (T°C).

Model simulation

According to the newly developed model, the critical pressure and its corresponding temperature that are required to damage ray cells can be calculated by the cell radius, cell wall thickness, and shear modulus of cell wall. In this study, 30 wood rays of *E. urophylla* samples were randomly selected and measured. An average thickness of 1.19 μm and a maximum radius of 9.25 μm of ray cells was obtained. The ray cell shear modulus of 8.71×10^6 Pa was adopted from the studies of Pitt and Davis (1984), and Wei and Wang (2005).

Based on the model simulation, the relation between pressure difference and the cell wall extension ratios is illustrated in Figure 2. When the pressure inside cell cavities increases, the extension ratio along the longitudinal and circumferential direction in the cell wall also increases. At a given pressure difference, the extension ratio along the circumferential direction is much larger than that along the longitudinal direction. The pressure difference reaches its maximum value of 0.84 MPa, when the extension ratio is 1.20 for the longitudinal direction and 1.62 for the circumferential direction. The pressure then slightly decreases with further increasing inflation (expansion). This plateau with slightly decreasing tendencies can be interpreted as the plastic flow state of the cell wall (''yielding''). Therefore, the pressure difference at the theoretical yielding point of 0.84 MPa is the critical pressure difference that can rupture the ray cell. The ray parenchyma cell can burst when the actual pressure difference is at or beyond the critical pressure difference. Practically, the critical pressure can be monitored through its corresponding critical temperature. From Eq. (16), the critical temperature is approximately 168°C, when the initial temperature of wood cell is 20°C and the values of extension ratios are $\lambda_1 = 1.20$ and $\lambda_2 = 1.62$.

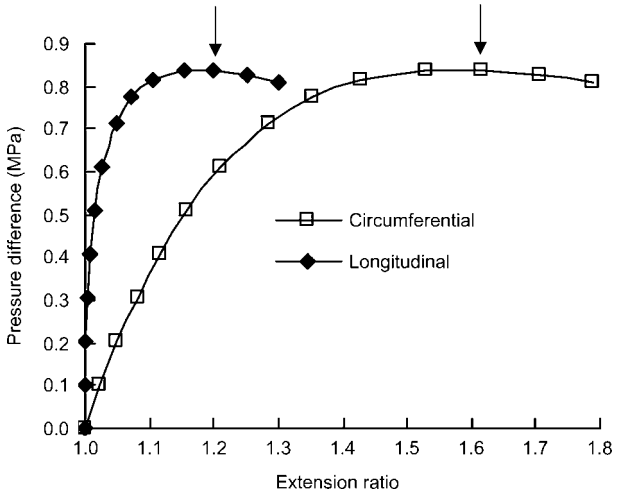

Figure 2 Relation between extension ratio and pressure difference (arrow indicating the yielding point at which maximum pressure difference is reached).

Wood is a heterogeneous material with high variation in its properties. The strength and radius of ray parenchyma cells are variable from one species to another, from one region of origin to another for the same species, and these properties can even deviate in different locations of the same timber. The effect of dimension and shear modulus of ray parenchyma cells on the critical pressure difference can be simulated also, based on the above model. Figure 3a,b shows that the critical pressure difference reaching to the yielding point decreases with increased cell radius and decreasing shear modulus in the cell wall. This result explains why a cylindrical cell with higher modulus and shorter radius could resist higher internal pressure and why a cell with a longer radius and lower strength is easier to rupture during microwave explosion pretreatment. The model results concur with experimental observations by Wei and Wang (2005).

From the simulation, it is also deduced that the critical temperature to rupture a ray cell increased by 40% (from 166°C to 232°C) when the radius of the cell with the same shear modulus (8.71 MPa) decreased from 10 to 2 mm. However, when the shear modulus of cell wall material increased by 10 times (from 2 to 20 MPa) with the same cell radius (10 μm), the critical temperature increased by 59% (from 124°C to 197°C).

The shear modulus of the ray parenchyma cells is also dependent on their temperature and MC. It is nearly impossible to monitor accurately the shear modulus of ray parenchyma cell walls during the microwave treatment. Therefore, the effect of the MC change and temperature, and microwave field on the shear modulus has not been taken into consideration in this study. In addition, the cell wall is assumed to be isotropic during the simulation. In reality, these assumptions are simplistic, but it provides the necessary groundwork for further research.

The simulated results could potentially provide better understanding of the microwave treatment process and guidance to improve the treatment quality. It is suggested that the high power microwave equipment is well suited to open the cells effectively for further application. Otherwise, the critical pretreated pressure and temperature can not be achieved in a very short time and treatment could be varied.

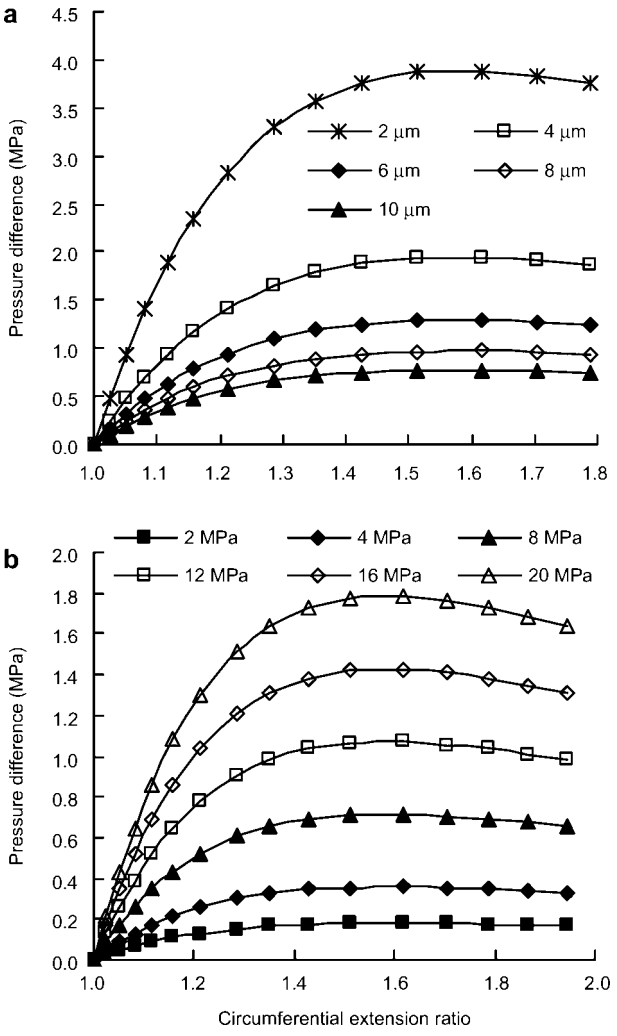

Figure 3 Relation between circumferential extension ratio and pressure difference. (a) Influence of cell radius (shear modulus $G = 8.71$ MPa). (b) Influence of shear modulus ($r = 10$ μm).

Conclusion

Circumferential and longitudinal stresses are generated in the cell walls owing to the internal steam pressure during extensive microwave treatment. The circumferential stress is twice as high as the longitudinal stress. The cell expansion increased with increasing steam pressure inside the cell. The simulated results indicated that the pressure difference reaches its maximum value of 0.84 MPa, when the extension ratio is 1.20 for the longitudinal direction and 1.62 for the circumferential direction. The maximum pressure difference at the theoretical yielding point is the critical pressure difference that can eventually rupture the ray cell. The critical pressure difference decreases with increasing cell radius and decreasing shear modulus in the cell wall. This simulated result

could provide useful information to modify wood at the level of ray parenchyma cells. Further studies are needed to investigate microwave modification of ray tissue and solid wood to validate the mathematical model.

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