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EFFECT OF ULTRASOUND PRETREATMENT ON WOOD PRIOR TO VACUUM DRYING*

Zhengbin He¹, Zijian Zhao¹, Fei Yang¹, Songlin Yi^{1,*}

ABSTRACT

The influence of ultrasonic pretreatment prior to vacuum drying of Chinese fir specimens was examined in this work. In the pretreatments, wood samples were immersed in a distilled water bath and were treated using two wave frequencies for four different elapsed times to investigate effects of ultrasonic frequency and treatment duration. Then the wood samples were vacuum-dried at 80°C and absolute pressure of 0,05 MPa. After the pretreatment, microscopic analysis was carried out on the wood samples to check micro-cracks, the loss of extractives from the cell walls and other micro-structural changes on the wood. Results show that the ultrasonic treatment prior to vacuum drying significantly shortened the wood drying time. The drying time decreased with increase in the wave frequency and the treatment time. Furthermore, ultrasound pretreatment tended to reduce the content of extractives in the wood cell walls and cause cell-wall micro-cracking.

Key words: Drying time, effective water diffusivity, ultrasound, wood vacuum drying.

INTRODUCTION

Wood drying is one of the most important steps in wood processing which consumes roughly 40 to 70% of the total energy in the entire wood processing and takes long time to complete (Zhang and Liu 2006). Wood vacuum drying offers the potential of fast drying and better drying quality in comparison to conventional drying operations (Ressel 1994). Some commercial vacuum drying operations can achieved drying rates which are 3-17 times faster than those of conventional drying (Harris and Taras 1984). However, vacuum drying methods are not suitable for timber with high initial moisture contents (Welling 1994), and surface checking and internal checking can be significant problems with wood vacuum drying when the drying temperature is high (Li *et al.* 2009); This is because of insufficient moisture movement from the center of the wood samples to the surface during the vacuum drying process which can cause steep moisture gradients from the core to wood surface layers; such gradients can lead to checking (Avramidis *et al.* 1994). In order to reduce the drying defects and to reduce the drying time, various methods of pretreatment of wood before drying have been reported to modify the material tissue structure (Madamba and Lopez 2002, Stojanovic and Silva 2006, Yong *et al.* 2006).

Ultrasound technology is based on mechanical waves at a frequency above the threshold of human hearing (>20 kHz) (Chandrapala *et al.* 2013). The ultrasonic pretreatment involves the immersion of the material in water or in a hypertonic aqueous solution or in other solutions to which ultrasound is applied (Fernandes *et al.* 2008). Ultrasonic waves can cause rapid series of alternative compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly. In addition, ultrasound produces cavitation, a phenomenon produced by sonication, in the liquid which can explosively collapse and generate localized pressure (Wan 1992), and may be helpful to remove strongly attached moisture from solid material immersed in the liquid. The mechanical and physical effects of ultrasound

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can be used to enhance many processes where diffusion takes place (Floros and Liang 1994). The sponge effect caused by ultrasound application may be responsible for the creation of microscopic channels in porous materials, such as fruits, that reduces the diffusion boundary layer and increases the convective mass transfer in the fruit (Tarleton 1992, Tarleton and Wakeman 1998, De La Fuente-Blanco *et al.* 2006).

In recent years, ultrasound has been implemented as an alternative pretreatment method for drying, and the results have shown that this pretreatment can greatly reduce the overall processing time (Duan *et al.* 2008, Aversa *et al.* 2011, Jangam 2011, Mothibe *et al.* 2011) which can attribute to the following factors: i). increase in the mass transfer rate (Garcia-Perez *et al.* 2009, Xu *et al.* 2009, Carcel *et al.* 2011, Garcia-Perez *et al.* 2011), ii). increase in the effective water diffusivity (Bantle and Eikevik 2011, He *et al.* 2012), iii). increase in wood specific permeability coefficient (Tanaka *et al.* 2010), iv). loss of cellular adhesion, v). formation of large cell interspaces, vi). rupture of the cell walls, and vii). formation of large channels (He *et al.* 2012).

In this work, ultrasound was used as a pretreatment method prior to vacuum drying. Pretreatment time and ultrasonic frequency levels were varied to determine their effects on vacuum drying time and the effective water diffusivity.

MATERIALS AND METHODS

Material

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) collected from Guangxi Province, China, was used as test specimens. The dimension of the test specimens was 100 mm long (Longitudinal) by 100 mm wide by 20 mm thick, with the initial moisture content of $70\pm 2\%$ (according to GB/T 1931-2009) (Zhao *et al.* 2009). To simulate the real production process, all the end cross-sections of specimens were blocked by covering them with wax.

Ultrasound Pretreatment

In each pretreatment experimental run, a set of six specimens was immersed in distilled water in an ultrasonic bath with internal dimensions: $300\times 250\times 200$ mm (Cheng-Cheng Ultrasonics, Beijing, China, model VGT-2200A). After the distilled water was added into the ultrasound bath, the water bath with wood specimens in it was heated to and maintained at 40°C then ultrasound was applied to the bath. In the experiments, two ultrasound frequency of 28 kHz and 40 kHz were used with the same intensity of 300 W or equivalent to 4000 W/m^2 . The ultrasound application timeshare were 0,5 h; 1 h; 1,5 h and 2 h; respectively. The controlled temperature of 40°C was chosen because higher temperatures do not enhance the effects of ultrasound (Simal *et al.* 1998). Control specimens to be dried together with the ultrasound pretreated wood were not subjected to ultrasonic. For each condition, the experiments were carried out in triplicate.

Vacuum Drying Procedure

After pretreatment, the treated specimens and the control specimens were vacuum-dried (Yi *et al.* 2010) at 80°C and an absolute pressure of 0,05 MPa (the saturated vapor pressure at the temperature of 80°C). The mass of each specimen was recorded automatically by the weight scales (Hangzhou Bigle Tech., Hangzhou, China) at 2 h intervals. When the moisture contents reached 6%, the specimens were oven-dried at $103\pm 2^{\circ}\text{C}$ (Zhao *et al.* 2009), and drying rates for all the samples were obtained according to the weight during the drying procedure and the oven-dried.

Electron Microscope Scanning

After drying, a section was selected randomly from each pretreatment condition and cut into 5-mm cubes for image analysis using a scanning electron microscope (SEM, Hitachi S-3400N II, Tokyo, Japan).

Effective Water Diffusivity

The effective water diffusivity represents the ability of water to move within the wood during drying. The following equation was used to describe the falling-rate period of the drying process (Phoungchandang *et al.* 2008),

$$MR = (M - M_e) / (M_0 - M_e) = A \exp(-kt) \quad (1)$$

Where MR is non-dimensional moisture content (%), M is moisture content at time t , M_e is equilibrium moisture content, M_0 is initial moisture content at time $t=0$, k is the drying rate constant (s^{-1}), and t is the drying time (s).

Values of MR were plotted against time on semi-logarithmic graphpaper to obtain a $\ln MR-t$ diagram. The slope of the line k was a constant of the drying rate defined by equation (2)

$$dMR/dt = -k(M - M_e) \quad (2)$$

According to the linear relationship obtained from the $\ln MR-t$ diagram, it was possible to apply Fick's second law of diffusion and obtain the effective diffusion of each specimen. The effective water diffusivity, D_e ($m^2 \cdot s^{-1}$) could be calculated using k , the drying rate constant (s^{-1}), L , the thickness (m), π , constant with the value of 3,14 according to equation (3) (Marinos-Kouris and Maroulis 1995).

$$D_e = kL^2 / \pi^2 \quad (3)$$

RESULTS AND DISCUSSION

Drying Time under Different Conditions

In order to evaluate the effects of ultrasound pretreatment time and frequency levels on the vacuum drying time after pretreatment, the drying time at different conditions were presented in Figure 1.

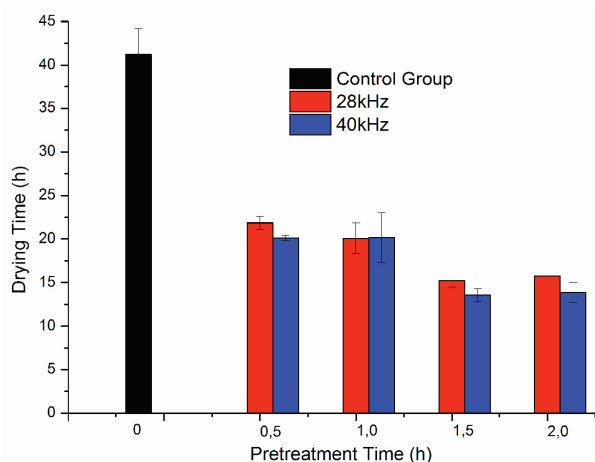


Figure1. Drying time of wood samples pretreated under different pretreatment conditions.

Figure 1 shows that the drying time of the specimens pretreated by ultrasound was much shorter than that of the control specimens. It is also observed that the drying time was decreased with increase in the pretreatment time and in the ultrasound frequency. On average, the drying time for specimens pretreated with 28 kHz ultrasound was 22; 20; 16 and 15 h; respectively, for pretreatment time of 0,5; 1; 1,5 and 2 h. With ultrasound frequency of 40 kHz, the corresponding drying time was 20,4; 16,8; 14,4 and 12,6 h. In contrast, the drying time for control specimens was 42,5 h for the specimens to reach the similar final moisture content. Therefore, differences in the drying time were significant between the ultrasound treated wood and the untreated samples ($p<0.05$) (Mathworks, matlab 7.0, America).

The decreased drying time, for specimens with ultrasound pretreatment, during the vacuum drying process could be due to the microscopic channels formed in the intercellular tissue and cell walls of the material, and the decrease of the extractives in porous wood with the ultrasound pretreatment. Similar phenomena have been observed in the previous publication (Duan *et al.* 2008, Fernandes *et al.* 2008a, Brncic *et al.* 2010, He *et al.* 2013).

Effective Water Diffusivity

Effective water diffusivities in wood samples were calculated using equation (3) based on the moisture content changes recorded during the drying period and the results are given in Table 1.

From Table 1, it can be seen that the effective water diffusivity increased with increasing pretreatment time. The effective water diffusivities of specimens pretreated at 0,5; 1,0; 1,5 and 2 h; at the frequency of 28 kHz were $2,17 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$; $2,41 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$; $3,03 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ and $3,28 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$; respectively. At the frequency of 40 kHz, the corresponding effective water diffusivity values were $2,55 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$; $2,70 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$; $3,56 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ and $3,83 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ respectively. Therefore, the effective water diffusivity of the pretreated wood also increased with ultrasound frequency, to a less extent than the effect of pretreatment time. In comparison, the effective water diffusivity for the control specimens was $1,29 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$; which is 2 to 3 timeshare lower than those of pretreated specimens.

However, when the pretreatment time was longer than 1,5 h; further increase in the effective water diffusivity was insignificant and the drying time was not expected to be decreased significantly. This is confirmed by the results presented in Figure 1. Therefore, there is no benefits to pretreat the wood for more than 1,5 h.

Table 1. Effective Water Diffusivity of Wood (D_e) at different pretreatment conditions.

Effective water diffusivity $D_e \times 10^8 / \text{m}^2 \cdot \text{s}^{-1}$			
Pretreatment Time (h)	Pretreatment Frequency (kHz)		
	28	40	Control
0,5	2,17	2,55	-
1,0	2,41	2,70	-
1,5	3,03	3,56	-
2,0	3,28	3,83	-
0	-	-	1,29

The increased effective water diffusivity during the wood vacuum drying process might be due to the phenomenon of cavitation during ultrasound pretreatment, the creation of microscopic channels in the intercellular tissue and the decreasing of the extracts content in porous wood. Our results were consistent with the previous reports by other researchers (Duan *et al.* 2008, Fernandes *et al.* 2008b, Brncic *et al.* 2010, He *et al.* 2012, He *et al.* 2013).

Electron Microscopic Analysis

The SEM micrographs of the samples before and after ultrasound pretreatment were presented in Figure 2 which shows that the ultrasound pretreatment had significant influence on the sample tissue structure and the content of extractives. It is well known that the extractives were formed by parenchyma cells at the heart-wood-sapwood boundary and were then exuded through pits into adjacent cells (Hillis 1996). The extractives also make cells occluded and thus reduce wood permeability (Wiedenhoeft and Miller 2005). From Figure 2, it is observed that for the specimens without ultrasound pretreatment (Figure 2-a1 and Figure 2-a2), the pits aperture were occluded and lots of extractives were attached to wood tissue surfaces and in the parenchyma cells. However, for the wood samples pretreated with ultrasound for 1 h, there were some collapses and microchannels on wood cells and the extractive content in parenchyma cells decreased (Figure 2-b1 and Figure 2-b2). The collapses might be caused by the cavitation of ultrasound during the pretreatment procedure. Furthermore, pits border were removed and most of the extractives on inner parenchyma cells disappeared and some cracks on cell wall appeared when the pretreatment time was 2 h (Figure 2-c1 and Figure 2-c2). This finding can be used to explain the reported observation that a longer ultrasound pretreatment time resulted in greater destruction of structure of material (Nowacka *et al.* 2012). Thus, the number of microchannels increased with the prolonged pretreatment time, and the longer the pretreatment time, the less content of extracts inner wood tissues.

Therefore, ultrasonic waves could promote cavitation and induce the formation of microchannels within the tissue of wood samples, and remove the extractives on the inner wood tissues, which could be found in many existing researches (Fernandes and Rodrigues 2007, Fernandes *et al.* 2008a, Fernandes *et al.* 2008c, Delgado *et al.* 2009, Fernandes *et al.* 2009, Cruz *et al.* 2011, Fernandes *et al.* 2011, Uribe *et al.* 2011). These microchannels and the decreasing extract might be considered to be mainly responsible for the shortened and reduced drying time.

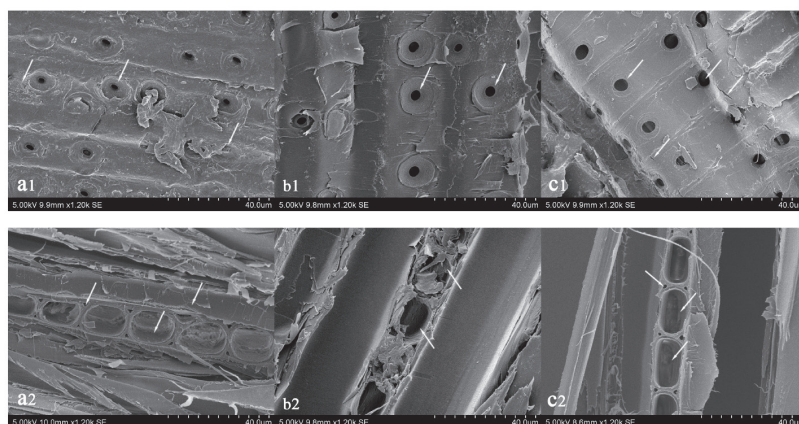


Figure 2. Photomicrograph of wood samples (1200×): (a1, a2) without pretreatment; (b1, b2) pretreatment carried out for 1h at 28 kHz; (c1, c2) pretreatment carried out for 2 h at 28 kHz.

CONCLUSION

The drying time of the specimens pretreated by ultrasound were much shorter than those of the specimens without ultrasound pretreatment during vacuum drying process. The drying time for the pretreated wood tends to decrease with the pretreatment time and the ultrasound frequency in the examined range.

The effective water diffusivity of pretreated wood is 2 to 3 times higher than the untreated wood and increases with increasing pretreatment time and, to a less extent, with ultrasonic frequency. However, the increase in the effective water diffusivity of pretreated wood is insignificant when the pretreatment time is longer than 1,5 h.

The effect of ultrasound pretreatment can be explained by the changes in wood microstructure and removal of extractives. Ultrasound pretreatment could remove the pits border, reduce the amount of extractives on the inner wood pores and create some microcracks on wood cell wall.

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