Ultrasound-Assisted Vacuum Drying of Wood: Effects on Drying Time and Product Quality

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Ultrasonic energy was applied to assist the wood vacuum drying process. At a drying temperature of 60°C, the absolute pressure was either 0.05 MPa or 0.08 MPa; the ultrasonic power and frequency were 100 W and 28 kHz, respectively. The results showed that the effective water diffusivity of the specimens dried by the ultrasonic assisted vacuum drying at 0.05 MPa or 0.08 MPa were higher than that of the samples dried without ultrasound. The ultrasound-vacuum drying rate was much faster than that of drying without ultrasound, especially for wood with a moisture content above the fiber saturation point. Drying at the absolute pressure of 0.05 MPa was faster than that of 0.08 MPa. Ultrasound-assisted drying was especially more beneficial when removing free water. The ultrasound-vacuum drying method could be applied in the wood drying industry as a means of saving energy and minimizing product quality damage.

Key words: Drying time; Ultrasound; Effective water diffusivity; Wood vacuum drying

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INTRODUCTION

Wood drying is one of the most important steps in wood products manufacturing. The drying process consumes roughly 40 to 70% of the total energy in the entire wood products manufacturing process (Zhang and Liu 2006). Compared with the traditional drying methods, wood vacuum drying has many advantages. For example, it could significantly shorten the drying time (particularly when the moisture content is below the wood fiber saturation point), it could increase suitability for drying large dimensions of timber, it incurs less risk of discoloration, and it has good energy efficiency (Ressel 1999; Welling 1994). 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, especially when the drying temperature is high; 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 (Kanagawa and Yasujima 1993; Avramidis *et al.* 1994). Therefore, exploring new energy-efficient technologies for low temperature vacuum drying and improving product quality are important goals in the development of new drying technologies.

Ultrasound is an efficient non-thermal alternative for increasing the drying rate without significantly heating up the material (Cohen and Yang 1995). When ultrasonic power is applied in liquid media, ultrasound waves cause a rapid series of alternative compressions and expansions, in a way similar to a sponge when it is squeezed and released repeatedly. Also, ultrasound produces cavitation, which is beneficial for the removal of moisture that is strongly attached to the solid. Micro-deformation of porous solid materials, caused by ultrasonic waves, is likely responsible for the creation of microscopic channels that enhance diffusion and increase convective mass transfer (Fuente-Blanco *et al.* 2006; Gallego-Juárez *et al.* 1999; Soria and Villamiel 2010; Tarleton 1992).

In recent years, ultrasound has been implemented as an alternative method for drying, and the results have shown that ultrasound can greatly reduce the overall processing time (Aversa *et al.* 2011; Mothibe *et al.* 2011; Jangam 2011), increase the mass transfer rate (Cárcel *et al.* 2011; García-Pérez *et al.* 2009, 2011; Zhao and Chen 2011), and increase the effective water diffusivity (Bantle and Eikevik 2011; Fernandes and Rodrigues 2008). However, no reports so far have addressed the application of ultrasound-assisted vacuum drying of wood.

Chinese catalpa wood (Lignum *Catalpa ovata*) is planted in large areas in China, especially in the Yangtze River Basin, Hunan province, and Zhejiang province. However, it is not widely used currently because the drying schedule is still a major problem to obtain dried lumber of acceptable quality.

MATERIALS AND METHODS

Material

Chinese catalpa wood (Lignum *Catalpa ovata*) provided by Chengde Rongxing Furniture Co., Ltd, Hunan, China, was used as the specimen. Heartwood and sawn wood were used because the proportion of the heartwood is much higher than that of sapwood in this kind of wood. The dimension of the test specimens was 200 mm long by 100 mm wide by 20 mm thick, with the initial moisture content of 85 to 100% (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-Vacuum Drying System

The scheme of the experimental set-up of the ultrasound-vacuum drying system is shown in Fig. 1. The ultrasound-vacuum dryer was modified by applying a power ultra-sound to a wood vacuum drying device (Shanghai Laboratory Instrumental Works Co., LTD, Shanghai, China). The pressure controller, vacuum pump, and pressure meter of this instrument could control the pressure with an accuracy of ±0.002 MPa automatically. The electronic generator driving the ultrasonic transducer was composed of an impedance matching unit, a power amplifier, and a resonant frequency control system. This system was specifically developed to keep constant power at the resonant frequency of the transducer during the drying process. The ultrasonic generator has a maximum power capacity of about 1200 W. The ultrasonic transducer (with a weight of 0.9 kg and a diameter of 0.066 m) was connected to the ultrasonic generator with corresponding power and frequency; it was also put on the wood specimen by its own weight to avoid ultrasonic energy attenuation. The gas valve was used to adjust the vacuum condition in the drying chamber. The air velocity was controlled by the pulse width modulation (PWM) at a constant rate of 1 m/s and measured using a hot-wire anemometer. The temperature monitor was used to control the temperature according to the setting value. The heat generator consisted of two sets of heat generators and the highest temperature achievable was 200°C.

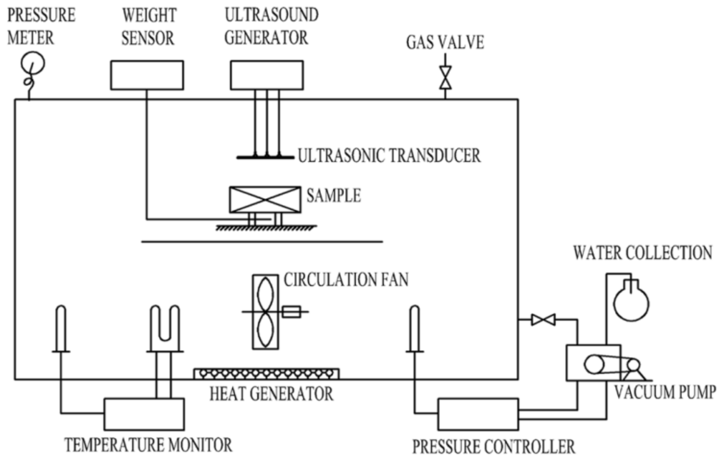

Fig. 1. Schematic of the experimental set-up of the ultrasound-vacuum dryer

Methods

In this experimental test, the drying time and water effective diffusion coefficient of the sample vacuum-dried with and without ultrasound treatment were examined. The effects of absolute pressure (0.05 MPa and 0.08 MPa) on wood drying characteristics at a temperature of 60°C and at the constant ultrasound power (100 W) and frequency (20 kHz) conditions were investigated. The drying characteristics of samples beyond and below the fiber saturation point were studied in particular to evaluate the effects of ultrasound on free water drying. The drying procedures were as follows:

1) The ultrasound transducer with the power of 100 W and the frequency of 20 kHz was installed and connected to the ultrasonic generator. Then, the frequency of the ultrasonic generator was set to match the impedance of the ultrasonic transducer.

2) Six samples were put into the ultrasound-vacuum drying system. Three of them were attached with ultrasonic transducers to obtain ultrasonic waves; the other three samples were used as control samples. The drying process was carried out at 60°C with the absolute pressures of 0.05 MPa and 0.08 MPa, respectively. The sample mass was measured at an interval of 2 h. The sample was dried until its final moisture content was below 10%. The state of drying of the test specimens was checked afterwards.

3) All the specimens were subsequently dried to oven dry at 103±2°C.

RESULTS AND DISCUSSION

Drying Dynamics under Different Conditions

In order to estimate the effect of the ultrasound on the wood vacuum drying rates, the drying dynamic curves were plotted by the moisture content versus time (shown in Figs. 2 and 3).

As shown in Fig. 2, the drying times of the specimens treated by ultrasound (ultrasound 1, 2, and 3) were shorter than those of specimens dried without ultrasound (control 1, 2, and 3). On average, it took only 41 h for the ultrasound-vacuum system to dry the wood with the initial moisture content of 99% to 11% at 60°C with the absolute pressure of 0.05 MPa. When the samples were dried by using the same ultrasound-vacuum drying system and using the same drying schedule but without the ultrasound, it would take 52 h to dry them from the moisture content of 99% to 11%. In addition, there was little difference within the ultrasound group (ultrasound 1, ultrasound 2, and ultrasound 3) and within the control group (control 1, control 2, and control 3), and both groups had good repeatability.

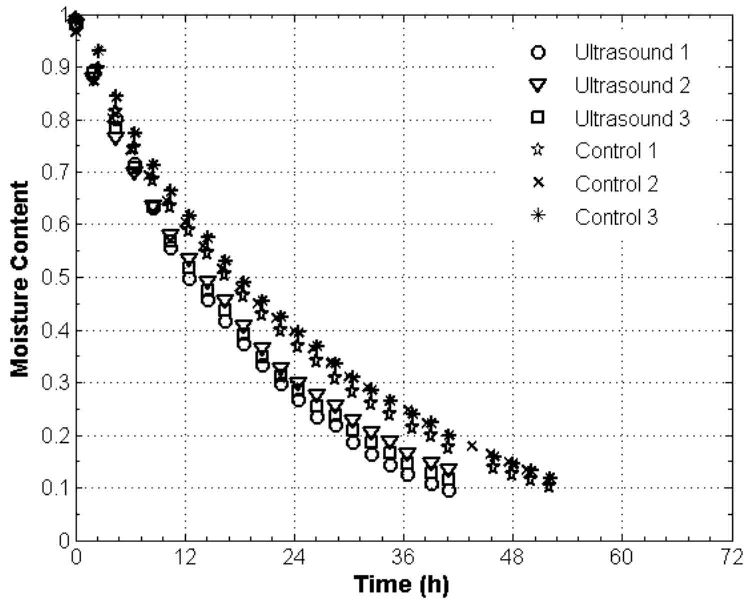

Fig. 2. Comparable drying kinetics of Chinese walnut specimens vacuum dried with and without ultrasonic assistance at 0.05 MPa pressure and 60°C

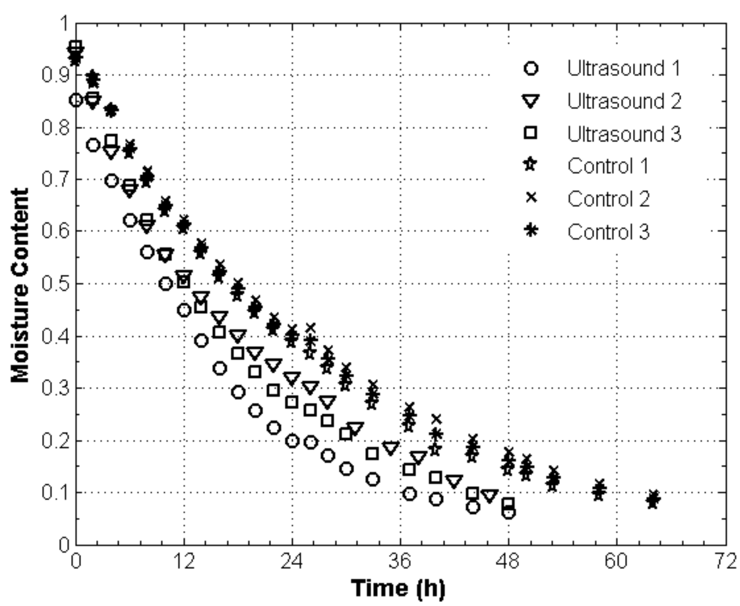

Fig. 3. Comparable drying kinetics of Chinese walnut specimens vacuum dried with and without ultrasonic assistance at 0.08 MPa pressure and 60°C

As shown in Fig. 3, when the samples were dried at 60°C with the absolute pressure of 0.08 MPa, on average, 48 h was needed to dry the wood from the initial moisture content of 95% to 11% by using the ultrasound-vacuum drying method, while 64 h was required to dry wood to the same condition without ultrasound. Generally, both the ultrasound group and the control group had good repetitions. Compared with the ultrasound 2 and ultrasound 3 series, the ultrasound 1 group had a bigger difference, for the reason that the initial moisture of specimens in this group was lower than that of the other group.

It took less time for the specimens vacuum-dried with the aid of ultrasound than that without ultrasound. Significant differences between the ultrasound-treated and the untreated samples ($p<0.05$) (Mathworks, Matlab 7.0, America) were observed. The effects were attributed to the ability of the ultrasound waves to squeeze and release the water repeatedly, and also to the generation of cavitation. It could be helpful to remove both free water and strongly attached moisture (such as bound water in wood). Furthermore, the drying rates of specimens at the absolute pressure of 0.05 MPa were faster than those at the absolute pressure of 0.08 MPa. The reason could be that when the absolute pressure in the drying chamber was low; the water boiling point would decrease correspondingly (Siau 1984). Lower pressure in the drying chamber implies generation of a higher pressure gradient between the internal wood and the ambient pressure. As a result, water would be easier to move out of the wood. In addition, no drying defects occurred in any of the samples during the whole drying process. This was mainly attributable to the fact that the experiment was done at a relative low temperature (60^{o}C), and the moisture gradient of the inner wood was not steep enough to generate drying defects. Thus, this combined drying method could dry wood at a relative low temperature with a high drying rate.

Wood Drying Properties above and below the Fiber Saturation Point (FSP)

Wood vacuum drying is beneficial in removing bound water within wood, while it is not suitable for drying wood with free water, especially, wood with a high initial moisture content (Ressel 1999; Welling 1994). Therefore, it was necessary to consider the drying rates beyond and below the fiber saturation point during the wood ultrasound-vacuum drying and to understand the effect of ultrasound on the drying characteristics of free water.

Fiber saturation point (FSP)

The water in wood mainly exists in two basic forms: free water and bound water (Salin 2008). The wood properties are not affected by the existence of free water in wood cavities above the FSP (free water has been totally removed from cell cavities, but the wood cell walls are still saturated with bound water). When the wood moisture content is below the FSP, wood properties do change when the bound water is increased or decreased.

The FSP decreases linearly with increasing temperature. It is reduced by 0.1% when the temperature is increased by 1°C, and the FSP is 30% when the temperature is 20°C (Stamm and Loughborough 1935). Thus, the FSP equation could be written as follows,

$$M_{fsp}=0.3-0.001(T-20) \tag{1}$$

where M_{fsp} is the fiber saturation point (%) and T is the temperature (°C).

According to Equation (1), the fiber saturation point is 26% when the temperature is 60°C.

Effective water diffusivity

The effective water diffusivity represents the ability of water to leave from the wood during the drying procedure. The following equation was used to describe the falling-rate period (wood moisture content above the fiber saturation point) of the drying process,

$$MR=(M-M_e)/(M_0-M_e)=A\exp(-kt) \qquad (2)$$

where MR is non-dimensional moisture content (%); M is moisture content at time t (g_w/g_{dw}); M_e is equilibrium moisture content (g_w/g_{dw}); M_0 is initial moisture content at time t=0 (g_w/g_{dw}); k is the drying rate constant (s^{-1}); and t is the drying time (minute).

Values of MR were plotted in the semi-logarithmic graph against time to obtain a lnMR-t diagram. A linear relationship could be obtained. The slope of the line k was a constant of the drying rate defined by Equation (3),

$$dMR/dt=-k(M-M_e) \qquad (3)$$

According to the linear relationship obtained from the lnMR-t diagram, it was possible to apply Fick's second law of diffusion and experimental effective diffusion to each test sample. The effective water diffusivity could be calculated using the constant of drying rate, K, with the thickness (L) of the specimen according to Equation (4) (Marinos-Kouris and Maroulis 1995).

$$D_e=KL^2/\pi^2 \qquad (4)$$

In Eq. 4, D_e is the water effective diffusion coefficient ($m^2 \cdot s^{-1}$) and L is the thickness of the specimen (m).

Effective water diffusivities in wood samples were calculated using the moisture content values recorded during the drying process. Table 1 presents effective water diffusivities values calculated for the vacuum-dried wood samples above and below the fiber saturation point under different experimental conditions.

Table 1. The Wood Water Effective Diffusion Coefficient (D_e) beyond and below the Fiber Saturation Point under Different Conditions

	D_e×10^8 ($m^2 \cdot s^{-1}$)			
Pressure (MPa)	0.05		0.08	
Drying types	Ultrasound	Control	Ultrasound	Control
Moisture content beyond FSP	2.91	2.25	2.89	2.05
Moisture content below FSP	1.12	1.00	1.06	0.86
Ratio of D_e beyond FSP to that below FSP	2.60	2.25	2.73	2.38

Table 1 shows that the samples treated with ultrasound had higher water effective diffusion coefficients than the untreated ones beyond and below the FSP. Furthermore, the effective water diffusivity of the ultrasound treated and untreated specimens dried at 0.05 MPa was higher than when samples were dried at 0.08 MPa. However, compared with the control group, the effective water diffusivity ratio of the ultrasound group was higher. The results demonstrated that the application of ultrasound was beneficial to the wood vacuum drying, especially for wood moisture content beyond the fiber saturation point. Therefore, an ultrasound-assisted wood vacuum drying method could improve the drying rates both for the bound water and free water during the whole drying process.

CONCLUSIONS

1. The drying rates of the specimens treated by ultrasound were faster than those of the specimens dried without the ultrasound during vacuum drying process.
2. Samples treated with ultrasound had higher effective water diffusivity than the untreated ones beyond and below the FSP, and the ultrasound was beneficial to the wood vacuum drying, especially for wood with a moisture content beyond the fiber saturation point.
3. The wood drying rates at 0.05 MPa were faster than at 0.08 MPa.
4. The ultrasound-vacuum drying method could be applied in the drying industry as a means for saving energy and minimizing product quality damage.

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