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# WATER DISTRIBUTION DURING ULTRASOUND-ASSISTED VACUUM DRYING OF WOOD

Zhengbin He, Yu Zhang, Shu Qiu, Zijian Zhao, Songlin Yi
Beijing Forestry University
Beijing Key Laboratory of Wood Science and Engineering
Beijing, P.R. China

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## ABSTRACT

Wood ultrasound drying is an innovation method, it can reduce overall drying time, increase the mass transfer rate, and increase the effective water diffusivity. In this paper, poplar was taken as experimental material. The drying process was carried out under the conditions that the drying medium temperature is 60°C, the absolute pressure is 0.02 MPa, the ultrasound power is 100 W and the ultrasound frequency is 20 kHz. The moisture content distribution and water diffusion coefficient were studied, and the model among wood moisture content variation, drying time and water diffusion coefficient was established. Results indicated that the moisture gradient increases along with the increase of drying time during the drying process, free water and bound water are dried simultaneously when wood moisture content is above the fiber saturation point; Wood moisture decreased linearly when moisture is above the fiber saturation point, while the descending rate decreases when the moisture content is below the fiber saturation point. The water diffusion coefficient decreases along with the increase of drying time and increases exponentially along with the increase of moisture content. The moisture diffusion coefficient is $2.89\times10^{-4}$ at the beginning stage, it is $3.02\times10^{-6}$ when the moisture content is at the fiber saturation point, and it is $2.27\times10^{-7}$ $cm^2.s^{-1}$ when the moisture content is 10 %; The equation between the water diffusion coefficient and the moisture content was established and it could be used to predict the water diffusion coefficient during ultrasound-assisted vacuum drying.

KEYWORDS: Ultrasound; water distribution; water diffusion coefficient; vacuum drying.

## INTRODUCTION

Most of the different types of woods used as raw material in furniture and woodworking industries are dried artificially after felling (Zhang et al. 2005). To this effect, wood drying is one of the most important steps in wood product manufacturing. The drying process consumes roughly 40 to 70 % of the total energy in a typical process of wood product manufacturing (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 has 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, which could lead to checking (Kanagawa et al. 1993; Avramidis et al. 1994). Therefore, exploring energy efficient new technologies for low temperature vacuum drying and improving product quality is an important goal in development of new drying technologies.

Ultrasound technology utilizes mechanical waves at frequencies above the threshold of human hearing (>20 kHz) (Kadam et al. 2015). It is an efficient non-thermal alternative to increasing the drying rate without significantly heating up the material (Cohen and Yang 1995). When ultrasound power is applied in liquid media, Ultrasonic waves cause a rapid series of alternating compressions and expansions, in a similar way to a sponge when it is squeezed and released repeatedly (Azoubel et al. 2010). Ultrasound also produces cavitation, a phenomenon produced by sonication, which can explosively collapse and generate localized pressure, this may be beneficial in removing strongly attached chemically bound water from solid material (Wan et al. 1992). 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 pretreatment method for drying different materials. Results have shown that ultrasound pretreatment can greatly reduce overall processing time (Aversa et al. 2011; Mothibe et al. 2011; He et al. 2012), increase the mass transfer rate (Cárcel et al. 2011; García-Pérez et al. 2011; Zhao and Chen 2011), and increase the effective water diffusivity (Bantle and Eikevik 2011). Until now, many previous researchers have been done on water distribution during wood drying process (Cserta et al. 2011; Peplinski et al. 2008; Han et al. 2014), no studies that have addressed the mass transfer during the ultrasound-assisted vacuum drying process. In this work, poplar (*Populus* spp.), a fast-growing wood species very common in China, was taken as material, and wood drying time, water diffusion coefficients and water transfer characteristics were studied during the ultrasound-assisted vacuum drying process.

## MATERIAL AND METHODS

### Sample preparation and moisture content determination

Poplar (*Populus cathayana*) sapwood obtained from Landbond Furniture Co., Ltd (Guangdong, China) was used as test specimens. The test specimens were each 450 long by 100 wide by 40 mm thick, with initial moisture content of 130±5 % (according to GB/T 1931-2009) (Zhao et al. 2009). To simulate the real production process, all the faces of specimens, except one face with the dimension of 450 long by 100 mm wide, were blocked by covering them with epoxy resin.

## Ultrasound-vacuum drying system

The scheme of the experimental set-up of the ultrasound-assisted vacuum drying system is shown in Fig. 1. The ultrasound-vacuum dryer is modified by applying a power ultrasound 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 is composed of an impedance matching unit, a power amplifier, and a resonant frequency control system. This system is 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) is connected to the ultrasonic generator with corresponding power and frequency; it is also put on the wood specimen by its own weight to avoid ultrasonic energy attenuation. The gas valve is used to adjust the vacuum condition in the drying chamber. The air velocity is controlled by the pulse width modulation (PWM) and measured using a hot-wire anemometer. The temperature monitor is used to control the temperature according to the setting value, the heat generator consists of two sets of heat generators, and the highest temperature achievable is 200°C.

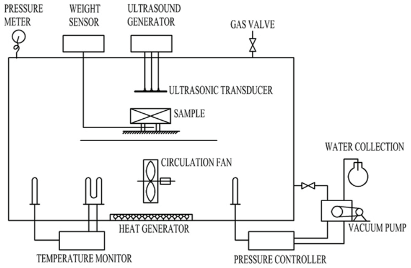

*Fig. 1: Schematic of the experimental set-up of the ultrasound-assisted vacuum dryer.*

## Methods

In this experimental test, the drying rates, wood moisture contents and water effective diffusion coefficient were examined at the drying conditions that the drying temperature was 60°C, the absolute pressure was 0.02 MPa, the ultrasound power was 100 W and the frequency was 20 kHz. The air velocity was 2 m.s$^{-1}$, which was always used in wood drying process (Zhang et al. 2005). 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) Samples were put into the ultrasound-assisted vacuum drying system and were attached with ultrasonic transducers to obtain ultrasonic waves. The drying process was carried out at 60°C with the absolute pressure of 0.02 MPa.

3) Two samples were selected randomly and taken out of the ultrasound-assisted vacuum drying system at an interval of 2 hours; and cylindrical samples with the diameter of 3 centimeters was cut from each selected wood sample; and the cylindrical sample were sectioned serially, the thickness of the section was 2 millimeters. Then, the section mass were measured and all the sections were oven dried at 103±2°C, and the moisture content of each section was obtained, which represents the wood layered moisture content at this moment.

4) Step (3) was done until the final moisture content of the wood samples was below 10 %.

5) Experiments were carried out in triplicate and the average values were reported.

## Water diffusion coefficient model

Both free water and boundary water are dried simultaneously during wood drying process (Siau 1984), thus, a comprehensive water diffusion coefficient was used during the whole drying process in this paper. Water only evaporation from the sample surface with the dimension of 450 long by 100 mm wide and only migration along the thickness direction during the ultrasound-assisted vacuum drying process, the sample dimension was the length of a, the width of b and the thickness of 2L, the initial moisture content is $C_0$ and the water concentration at wood surface is $C_1$, as showed in Fig. 2.

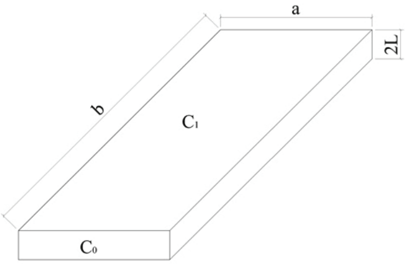

*Fig. 2: The schematic diagram of specimen..*

Making assumptions that:

1) The initial moisture content of sample is uniform and the moisture content is $C_0$.
2) The water evaporative rate at the plane of symmetry is the same, and no water migration at wood central layer.
3) Wood moisture content is C during the drying process.

Therefore, the water migration governing equation could be written as Eq. 1:

$$\begin{cases} \dfrac{\partial C}{\partial \tau} = \dfrac{\partial}{\partial x}\left(D\dfrac{\partial C}{\partial x}\right) \\ C(x,0) = C_0 \\ C(L,\tau) = C_1 \\ \dfrac{\partial C}{\partial x}\Big|_{x=0} = 0 \\ \overline{C} = \dfrac{1}{L}\displaystyle\int_0^x C(x,\tau)dx \end{cases} \tag{1}$$

Combined with method of separation of variables, method of Laplace transformation and method given by crank (Crank 1975), Eq. 2 could be gotten:

$$Y = \frac{C - C_0}{C_1 - C_0} = 1 - \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n+1}\cos\left(\frac{(2n+1)\pi x}{2L}\right)e^{-D(2n+1)^2\pi^2\tau/4L^2} \tag{2}$$

Wood moisture could be written as Eq. 3:

$$
\begin{aligned}
V_A &= abN_{Ax} = ab\left(-C_0 D\frac{\partial M(x,\tau)}{\partial x}\right) = ab\left(-C_0 D\frac{\partial Y(x,\tau)}{\partial x}\right)\\
&= ab(-C_0 D)\frac{\partial\left[1-\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{2n+1}\cos\left(\frac{(2n+1)\pi x}{2L}\right)e^{-D(2n+1)^2\pi^2\tau/4L^2}\right]}{\partial x}\\
&= ab(-C_0 D)\frac{2}{L}\sum_{n=1}^{\infty}(-1)^n\sin\left(\frac{(2n+1)\pi x}{2L}\right)e^{-D(2n+1)^2\pi^2\tau/4L^2}
\end{aligned}
\tag{3}
$$

For sample with the thickness of L, equation (3) could be written as Eq. 4:

$$
V_A = ab(-C_0 D)\frac{2}{L}\sum_{n=1}^{\infty}(-1)^n\sin\left(\frac{(2n+1)\pi L}{2L}\right)e^{-D(2n+1)^2\pi^2\tau/4L^2} \tag{4}
$$

Therefore:

$$
V_A = ab(-C_0 D)\frac{2}{L}\sum_{n=1}^{\infty}e^{-D(2n+1)^2\pi^2\tau/4L^2} \tag{5}
$$

Wood initial moisture content could be written as Eq. 6:

$$
m_{A0} = C_0 abL \tag{6}
$$

The decrement of wood moisture content in time τ could be written as Eq. 7:

$$
m_A(\tau) = \int_0^{\tau} V_A d\tau = \frac{8abLC_0}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}e^{-D(2n+1)^2\pi^2\tau/4L^2} \tag{7}
$$

Therefore, the ratio of moisture decrement and the whole moisture content could be written as Eq. 8:

$$
\frac{m_A(\tau)}{m_{A0}} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}e^{-D(2n+1)^2\pi^2\tau/4L^2} \tag{8}
$$

Therefore:

$$
\frac{m_A(\tau)}{m_{A0}} = \frac{8}{\pi^2}\frac{1}{(2n+1)^2}\sum_{n=1}^{\infty}\exp\left[-D(2n+1)^2\pi^2\tau/4L^2\right] \tag{9}
$$

## RESULTS AND DISCUSSION

### Wood moisture content variation along with the drying time

Wood moisture content distribution at different drying time and at different position in wood was shown in Fig. 3. It shows that wood moisture content is uniform at the beginning stage, and the average initial moisture content is about 130 %. The moisture gradient increases along with the increase of time, 6 h later, the moisture at wood surface layer is 62.7 %, while that at wood central layer does not change; 13 h later, moisture content at wood surface is below the fiber saturation point (with the value of 30 %), it is about 12.0 %, and 98 h later, moisture content for the whole wood is below the fiber saturation point. Therefore, as conventional drying process, wood is dried from surface layer to central layer during the ultrasound-assisted vacuum drying process, and both free water and bound water are dried simultaneously even though wood moisture content is above the fiber saturation point. For each wood layer, free water is dried at first, and then the bound water. It also indicates that wood moisture content from wood surface to wood layer, which at the distance of 2 centimeters from wood surface, is constant after 50 h, this result is for the reason that wood moisture content is lower than the fiber saturation point at these areas, while that at other wood layer is above the fiber saturation point.

What's more, for each wood layer, wood moisture content decrease along with the increase of drying time, and the drying rates is constant when the wood moisture content at wood surface layer is above the fiber saturation point, the drying rates decrease when wood moisture content is below the fiber saturation point. Drying rates for the layer, which is near to wood surface, are faster than that is far away from wood surface. The time for moisture content gets to the fiber saturation point are 98, 81, 53, 38, 25, 18 and 10 h, respectively, for the wood layers, which are 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 centimeter, away from wood surface. Moreover, moisture content at wood surface gets to 10 % at a short time, this phenomenon is mainly because that the drying rates at wood surface is about 100 to 1000 times faster than that inner wood (Zhu 1992), moisture inner wood could not get to wood surface immediately when moisture at wood surface is dried.

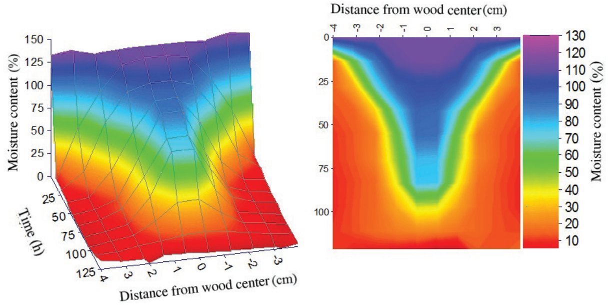

*Fig. 3: The moisture content distribution diagram at different time and position inner wood during ultrasound-assisted vacuum drying.*

## Water diffusion coefficient at different moisture content and drying time

Water diffusion coefficient is one of the most important parameters to measure wood drying rates and water migration rates. According to Eq. 9 and the drying parameters in this paper, the model among moisture content variation, drying time and water diffusion coefficient is shown in Eq. 10. Combined with wood moisture content at different drying time, the water diffusion coefficient at different drying time and moisture contents were got and shown in Fig. 4.

$$\frac{m_A(\tau)}{m_{A0}} = \frac{0.811392}{(2n+1)^2}\sum_{n=0}^{\infty} e^{-0.154D(2n+1)^2\tau} \tag{10}$$

Fig. 4 shows that it took 53 h to dry wood from moisture content of 126 % to the fiber saturation point, while 57 h was need to dry wood from the fiber saturation point to the moisture content of 10 %, the wood drying rate, whose moisture content is above the fiber saturation point, is 5.16 time faster than that, whose moisture content is below the fiber saturation point, so, ultrasound is beneficial to free water drying (He 2012). What's more, Fig. 4 also indicates that water diffusion coefficient decreases along with the increase of drying time, the water diffusion coefficient is $2.89\times10^{-4}$ at the beginning stage; it is $3.02\times10^{-6}$ when wood moisture content is at fiber saturation point and it is $2.27\times10^{-7}$ $cm^2 \cdot s^{-1}$ at the moisture content of 10 %. Many exiting researches have the similar results (Siau 1984).

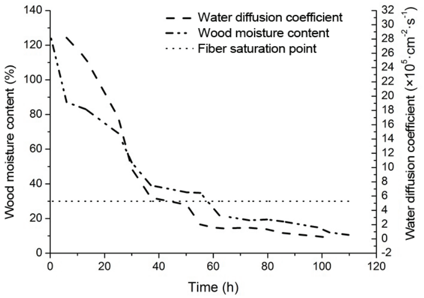

*Fig. 4: Water diffusion coefficient at different moisture content and drying time.*

## Relationship between water diffusion coefficient and wood moisture content

Wood moisture content has great effects on water diffusion coefficient (Siau 1984). To study the influence of wood moisture content on the average water diffusion coefficient, the relationship between wood moisture content and the water diffusion coefficient was established and shown in Eq. 11:

$$\overline{D} = -6.361 + 5.1841e^{0.0218M} \tag{11}$$

where: $\overline{D}_i$ - the average value of water diffusion coefficient, $10^{-5}$cm$^2$·s$^{-1}$,
M - the moisture content (%).

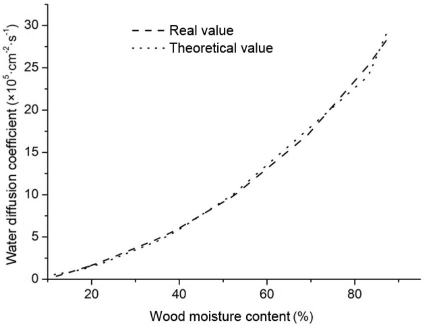

*Fig. 5: The theoretical and actual value of water diffusion coefficient during ultrasound-assisted vacuum drying process.*

To measure the difference between the theoretical values, which were calculated by Eq. 11, and the real values of water diffusion coefficients. Fig. 5 shows the real value and the theoretical value of wood water diffusion coefficients at different moisture content. It indicates that the water diffusion coefficient increases exponentially along with the increase of moisture content, few differences between the real value and the theoretical value, and Eq. 11 could be used to simulate the water diffusion coefficient at different moisture content during the ultrasound-assisted vacuum drying process.

## CONCLUSIONS

1. The model among wood moisture content variation, drying time and water diffusion coefficient was established, and the water diffusion coefficient could be calculated by this model.
2. The moisture gradient increases along with the increase of drying time during the drying process, 13 h later, moisture content at wood surface is below the fiber saturation point while that at wood central layer is much higher than the fiber saturation point. Wood is dried from surface layer to wood central layer during the ultrasound-assisted vacuum drying process, and both free water and bound water are dried when wood moisture content above the fiber saturation point.
3. The drying rates is constant when wood surface layer is above fiber saturation point, and the drying rates decrease when wood moisture content is below the fiber saturation point.
4. Water diffusion coefficient decreases along with the increase of drying time, the water diffusion coefficient is $2.89\times10^{-4}$ at the beginning stage, it is $3.02\times10^{-6}$ when wood moisture content is at fiber saturation point and it is $2.27\times10^{-7}$ $cm^2\cdot s^{-1}$ at the moisture content of 10 %.
5. Water diffusion coefficient increases exponentially along with the increase of moisture content, and the equation between the water diffusion coefficient and the moisture content could be used to predict the water diffusion coefficient during ultrasound-assisted vacuum drying.

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ZHENGBIN HE*, YU ZHANG, SHU QIU, ZIJIAN ZHAO, AND SONGLIN YI
BEIJING FORESTRY UNIVERSITY
BEIJING KEY LABORATORY OF WOOD SCIENCE AND ENGINEERING
BEIJING, 100083
P.R. CHINA
PHONE: +8613810184326
Corresponding author: hzbbjfu@126.com