Effects of Ultrasound on Mass Transfer within the Boundary Layer during Wood Vacuum Drying

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Ultrasound was applied to enhance mass transfer within the boundary layer during wood vacuum drying. Fast growing poplar (*Populus tomentosa*) was used as the specimen in this work. The water migration rates and the mass transfer coefficients were studied at temperatures of 35 and 50 °C, absolute pressures of 0.03, 0.06, and 0.1 MPa, and ultrasound power-frequency groups of 60 W-28 kHz, 100 W-28 kHz, and 100 W-20 kHz, respectively. The results indicated that ultrasound could markedly increase the water migration rates within the boundary layer. The water migration rates increased with increasing ultrasound power and frequency. The mass transfer coefficients within the boundary layer for specimens treated with ultrasound were much higher than those of the control group, and the mass transfer coefficients increased with decreasing absolute pressure. Ultrasound could be applied in the wood drying industry as a means of saving time and energy.

Keywords: Ultrasound; Boundary layer; Vacuum drying; Water migration rates; Mass transfer coefficients

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INTRODUCTION

All kinds of wood, which is the main raw material used in the furniture, building, and woodworking industries, must be dried after harvesting (Zhang *et al.* 2005). Thus, 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 the entire wood product manufacturing process (Zhang and Liu 2006; He *et al.* 2012). Vacuum drying has been widely used in many fields, including wood drying, sludge drying, and food drying. Compared with traditional wood drying methods, wood vacuum drying processes offer the potential of high-speed drying and higher drying quality in comparison with conventional drying operations (Ressel 1994; He *et al.* 2010). Additionally, the drying rate of commercial vacuum systems is approximately 3 to 17 times higher than that of conventional drying (Harris and Taras 1984). During the drying process, two types of resistances control the water transport: internal resistance to water movement inside the wood, and external resistance between the solid surface and air. Internal resistance is a characteristic of the material. External resistance depends on the thickness of the diffusion boundary layer. Thus, reducing the thickness of this diffusion layer could lead to a higher drying rate (Cárcel *et al.* 2007).

High-power ultrasound may have an influence on external or internal resistance to mass transfer (Gallego-Juarez *et al.* 1999). The effects of pressure variations at solid-fluid interfaces could increase the transport rate of moisture. The oscillating velocities and the microstreaming on the solid-gas interfaces improve the water transfer rate from the solid surface to the air medium (Breitbach *et al.* 2002; Mason and Lorimer 2002; Hamdaoui *et al.* 2005; Lim and Okada 2005; Juang *et al.* 2006). Meanwhile, water transfer on a wood surface may also be improved due to alternating expansion and compression cycles produced by power ultrasound in the materials (a phenomenon known as the "sponge effect"). In addition, the rapid formation and collapse of gas bubbles in a liquid at a rate corresponding to the frequency of ultrasonic waves generates high instantaneous pressures that can cause physical damage to make water move out of the material (Gallego-Juárez *et al.* 2007). Ultrasonic vibration also could convert the liquid to droplets and enhance the mass transfer (Rajan and Pandit 2001; Avvaru *et al.* 2006). Also, ultrasound produces cavitation, which generates high-frequency vibration and decreases the thickness of the boundary layer (Zhi *et al.* 2007). Furthermore, ultrasound produces disturbance heat radiation and thus increases the water concentration gradient and water diffusion coefficients (Yao 2010). During the drying process, water at the wood surface should move through the boundary layer by diffusion and then evaporate to the drying media. Therefore, the water transfer could be enhanced by decreasing the thickness of the boundary layer. Although much research has been done on ultrasound-enhanced mass transfer (Ozuna *et al.* 2011; Beck *et al.* 2014; Gamboa-Santos *et al.* 2014) and water movement in wood (Olek *et al.* 2005), no reports thus far have addressed the application of ultrasound to enhance water transfer within the boundary layer at the wood surface during the vacuum drying process.

EXPERIMENTAL

Materials

Fast-growing poplar (*Populus tomentosa*), provided by Landbond Furniture Co., Ltd, ShanDong, China, was used as the specimen. The dimension of the test specimens was 320 mm long by 100 mm wide by 20 mm thick with an initial moisture content of 100 (±5)% (according to GB/T 1931-2009) (Zhao *et al.* 2009). To simulate the real production process, all the faces of the specimens, except one face with dimensions of 320 mm long by 100 mm wide, were blocked by covering them with wax.

Equipment

A schematic of the experimental set-up of the ultrasound vacuum drying system is presented in Fig. 1. This ultrasound-assisted vacuum dryer is based on a wood vacuum drying device (Shanghai Laboratory Instrumental Works Co., Ltd., Shanghai, China), which has been modified to allow the application of power ultrasound. It consists of nine parts: (1) Pressure controller, vacuum pump, and pressure meter, which can control the pressure with an accuracy of 0.002 MPa automatically, while the absolute pressure ranges from 0.096 MPa to 0.1 MPa (ambient pressure); (2) the specimens were weighed automatically by the weight sensor during the drying process; (3) the electronic generator driving the ultrasonic transducer is composed of an impedance matching unit, a power amplifier, and a resonant frequency control system, and this system is specifically developed to keep the power applied constantly at the resonant frequency of the transducer during the process; (4) the ultrasonic generator has a maximum power capacity of approximately 1200 W with frequencies of 20, 28, and 40 kHz; (5) the ultrasonic transducer is connected to the ultrasonic generator with corresponding power and frequency levels, and it also directly contacts the wood to avoid ultrasonic energy attenuation; (6) the gas valve brings the drying chamber to ambient pressure whenever the chamber needs opening; (7) the air velocity is controlled by pulse width modulation (PWM) and is measured with a hot-wire anemometer to perform the test at a constant velocity of 2 m/s; (8) the temperature monitor controls the temperature according to pre-set values; and (9) the heat generator consists of two sets of heat generators.

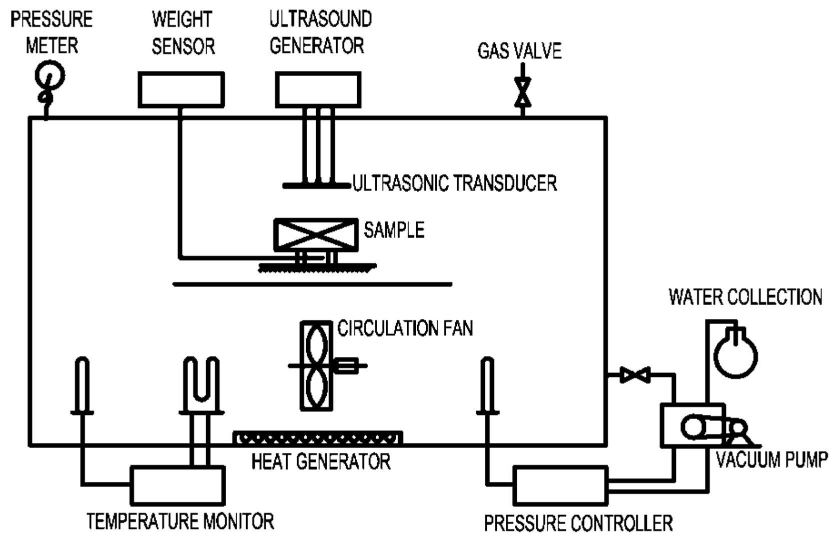

Fig. 1. Schematic of the experimental set-up of the hot air ultrasound vacuum dryer

Methods and Procedures

The effects of ultrasound on water transfer within the boundary layer during wood vacuum drying were studied in this work. The experiments were performed at temperatures of 35 and 50 °C, at absolute pressures of 0.03, 0.06, and 0.1 MPa, and using ultrasound power-frequency groups of 60 W-28 kHz, 100 W-28 kHz, and 100 W-20 kHz. The experimental steps were as follows:

(1) The weight module was installed in the vacuum dryer, and the temperature of the inner vacuum dryer was set to 35 °C.

(2) When the temperature of the inner wood dryer increased to 35 °C, wood specimens were placed on the weight module.

(3) An ultrasound transducer with a power of 60 W and frequency of 28 kHz was installed above the treated specimens, and the control group was not subjected to ultrasound.

(4) The vacuum dryer's door was closed, the absolute pressure was set at 0.03 MPa, and the vacuum pump was started.

(5) The weight module system began to work when the absolute pressure in the inner vacuum dryer achieved 0.03 MPa; ultrasound was then started, and all the data were collected automatically. The vacuum dryer was stopped and its door was opened when the experiment finished.

(6) Following steps (1) to (5), similar processes were performed at 50 °C, at 0.06 and 0.1 MPa, and with ultrasound power-frequency groups of 100 W-28 kHz and 100 W-20 kHz.

(7) For each condition, the experiments were carried out in triplicate, and average values are reported.

RESULTS AND DISCUSSION

Water Migration Rates within the Boundary Layer

To finish the wood drying process, water in the wood must pass through the boundary layer. Therefore, wood drying rates could be considered as water migration rates within the boundary layer. The wood drying rates are shown in Figs. 2 to 4. The results showed that, compared with the control group, ultrasound can markedly increase the water migration rates within the boundary layer. Figure 2 shows that at the ultrasound power of 60 W and frequency of 28 kHz, compared with those of the control group, water migration rates were increased by 12.6%, 24.0%, and 7.7% at 35 °C and increased by 37.8%, 19.8%, and 15.3% at 50 °C when the absolute pressures were 0.03, 0.06, and 0.1 MPa, respectively. Figure 3 shows that at the ultrasound power of 100 W and the frequency of 20 kHz, compared with those of the control group, the water migration rates were increased by 36.7%, 57.4%, and 9.4% at 35 °C and increased by 60.0%, 21.0%, and 35.0% at 50 °C when the absolute pressures were 0.03, 0.06, and 0.1 MPa, respectively.

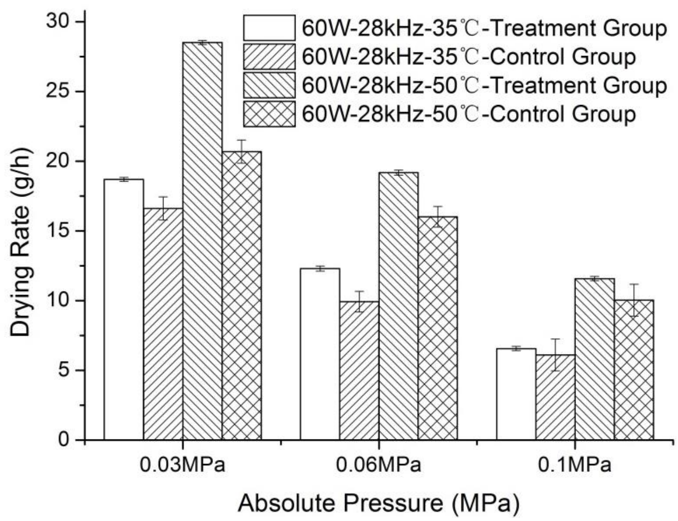

Fig. 2. Water migration rates within the boundary layer at the ultrasound power of 60 W and frequency of 28 kHz at various temperatures

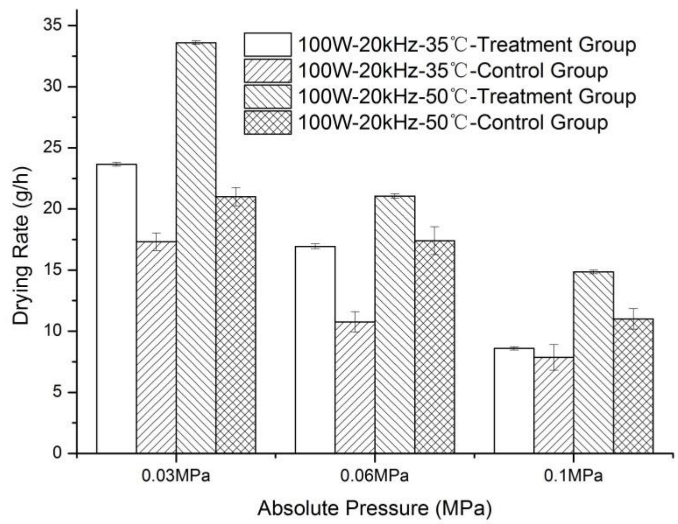

Fig. 3. Water migration rates within the boundary layer at the ultrasound power of 100 W and frequency of 20 kHz at various temperatures

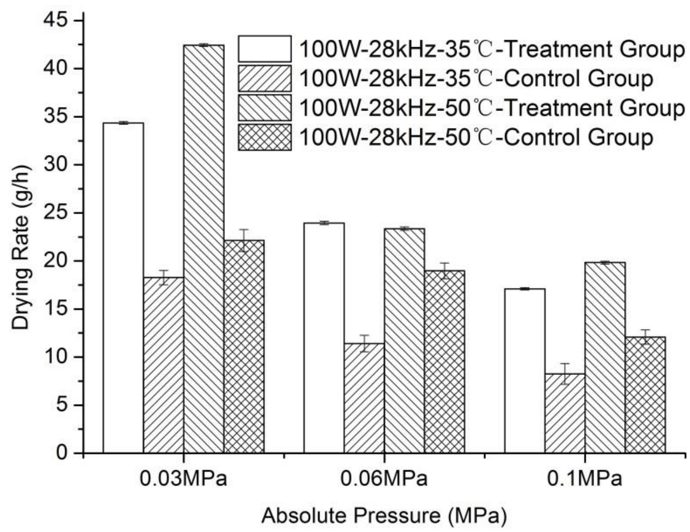

Fig. 4. Water migration rates within the boundary layer at the ultrasound power of 100 W and frequency of 28 kHz at various temperatures

Figure 4 shows that at the ultrasound power of 100 W and the frequency of 28 kHz, compared with those of the control group, the water migration rates were increased by 88.0%, 110.1%, and 107.3% at 35 °C and increased by 91.7%, 23.2%, and 64.1% at 50 °C when the absolute pressures were 0.03, 0.06, and 0.1 MPa, respectively. These results may have been found because ultrasound cavitation disturbed the boundary layer and generated bubbles in the boundary layer, thus decreasing the thickness of the boundary layer and enhancing the water migration.

In addition, energy generated by ultrasound within the boundary layer also enhances water migration (Breitbach *et al.* 2002; Chung *et al.* 2010). Moreover, Figs. 2 to 4 demonstrate that at the same ultrasound frequency condition, the water migration rates increased with increasing ultrasound power applied. The minimum and the maximum water migration rates were 6.57 g/h and 28.51 g/h, respectively, at the ultrasound power of 60 W, while the minimum and the maximum water migration rates were 17.10 g/h and 42.44 g/h, respectively, at the ultrasound power of 100 W. This may be due to the fact that high ultrasound intensity, attributed to high ultrasound power, could enhance the mechanical effect and ultrasound cavitation in the boundary layer at the wood surface, and as a result, the thickness of boundary layer decreases making water easy to evaporate from the wood surface (Kobayashi *et al.* 1999).

In addition, the results also indicated that the water migration rates increased with an increase in ultrasound frequency. The minimum and the maximum values were 8.59 g/h and 33.60 g/h, respectively, at the ultrasound frequency of 20 kHz, while the minimum and the maximum values, compared with those treated by ultrasound with the frequency of 20 kHz, were increased by 99.1% and 26.3%, respectively, at the ultrasound frequency of 28 kHz. This result was found because more cavitation bubbles were generated at high-frequency conditions, enhancing water migration in the boundary layer (Ying 1990). Additionally, the water migration rates increased with increasing temperature and decreasing absolute pressures; these results are consistent with previous reports by other researchers (Davidovic *et al.* 2006; Li *et al.* 2009; He *et al.* 2013).

Mass Transfer Coefficient within the Boundary Layer

The mass transfer coefficient represents the ability of water to leave the wood surface during the drying process (Incropera 2011). It can be calculated by Eq. 1 (Welty *et al*. 2009),

$$k = \frac{N}{(c_s - c_\infty)A} \tag{1}$$

where k is the mass transfer coefficient within the boundary layer (m s^{-1}); N is the water migration rate within the boundary layer (mol s^{-1} m^2); A is the wood surface area (m^2); c_s is the water vapor concentration at the wood surface (mol m^{-3}); and c_∞ is the water vapor concentration in the drying medium (mol m^{-3}). The quantity c_s can be obtained from Eq. 2,

$$c_s = \frac{P_s}{RT} \tag{2}$$

where P_s is the saturation pressure at the corresponding temperature (Pa); T is the temperature (K); and R is the gas constant.

Combining Eqs. 1 and 2 and the saturation pressures at corresponding temperatures (Zhang and Qiao 1992), the mass transfer coefficients within the boundary layer were obtained and are shown in Figs. 5 to 7.

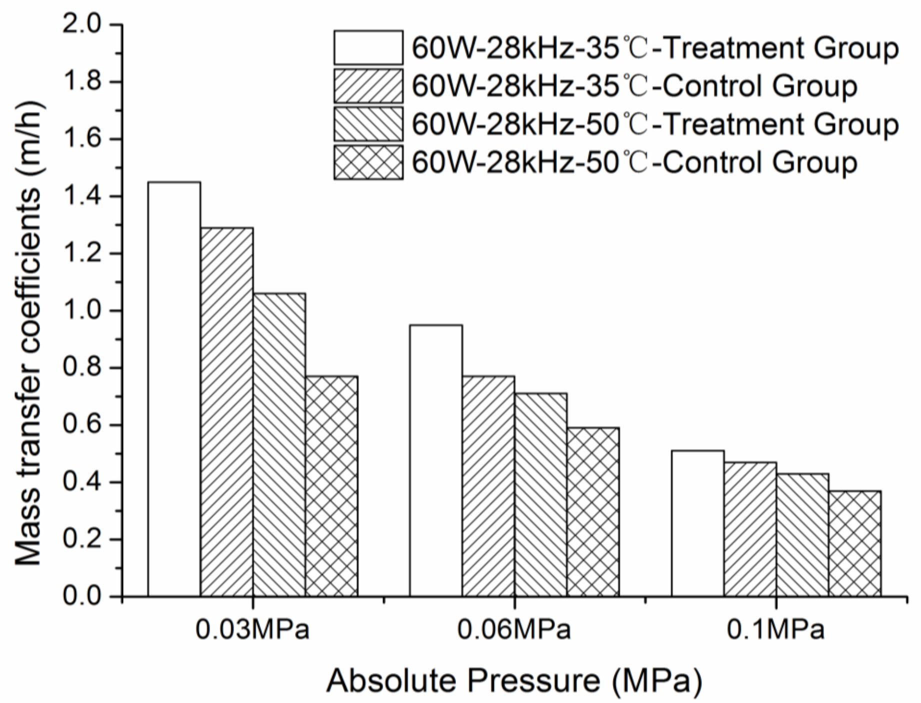

Fig. 5. Mass transfer coefficients within boundary layer at the ultrasound power of 60 W and the frequency of 28 kHz at different temperature conditions

Figures 5 to 7 show that, compared with those of the control group, the mass transfer coefficients within the boundary layer for specimens treated with ultrasound were much higher. Ultrasound markedly increased the mass transfer coefficients under all conditions.

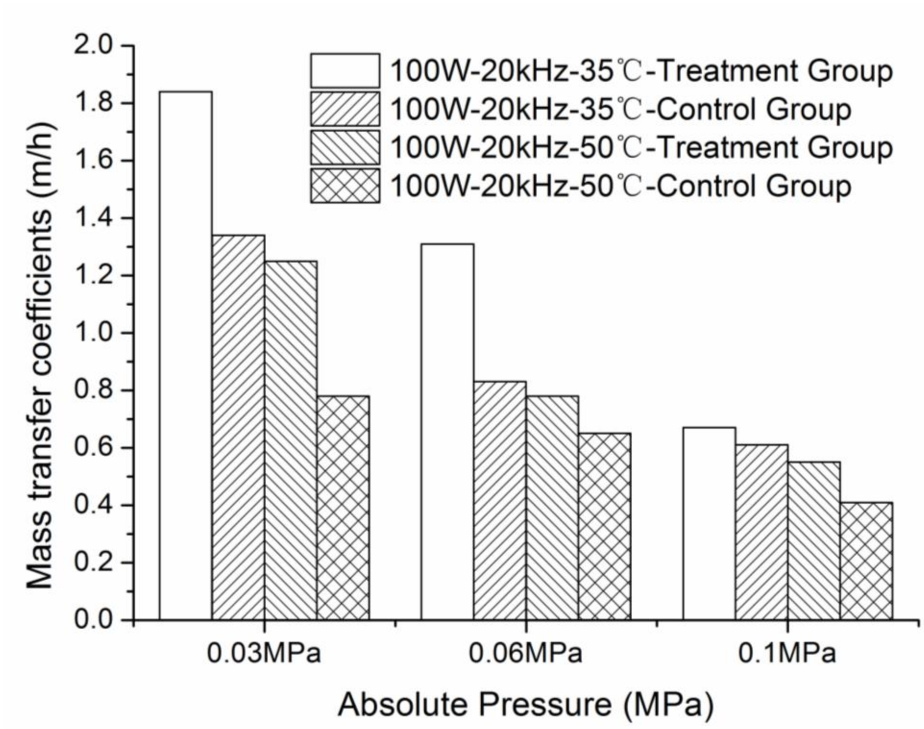

Fig. 6. Mass transfer coefficients within boundary layer at the ultrasound power of 100 W and the frequency of 20 kHz at different temperature conditions

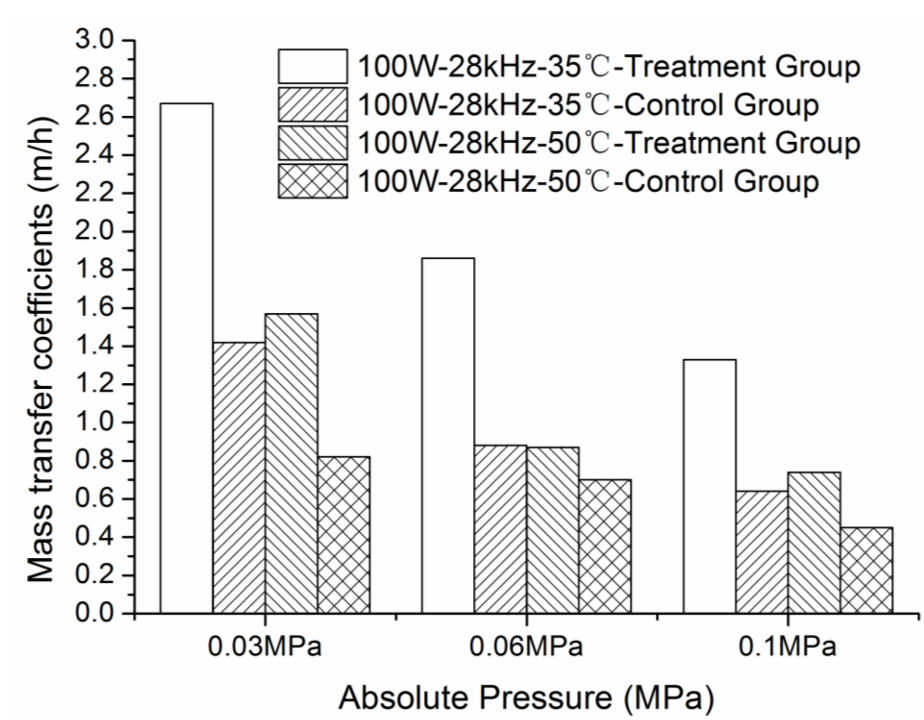

Fig. 7. Mass transfer coefficients within boundary layer at the ultrasound power of 100 W and the frequency of 28 kHz at different temperature conditions

The mass transfer coefficients were increased by at least 9%, and this increase was obtained in the conditions in which the ultrasound power was 60 W, the frequency was 28 kHz, the temperature was 35 °C, and the absolute pressure was 0.1 MPa. The mass transfer coefficients, at the most, increased by 111%, and such increases were obtained under conditions in which the ultrasound power was 100 W, the frequency was 28 kHz, the temperature was 35 °C, and the absolute pressure was 0.06 MPa. This may be attributed to the fact that ultrasound cavitation, ultrasound mechanical effects, and the successful generation and transmission of the sound pressure waves to a solid–gas system enhance mass transfer within the boundary layer (García-Pérez *et al.* 2006, 2007; Sabarez *et al.* 2012).

Moreover, from Fig. 5 to Fig. 7, it was also found that the mass transfer coefficients, both for specimens treated with ultrasound and the control group, increased with decreasing absolute pressure at set conditions. The mass transfer coefficients, compared with that at 0.1 MPa, increased by 184% and 147% when the ultrasound power was 60 W and the frequency was 28 kHz at a pressure of 0.03 MPa, increased by 175% and 127% when the ultrasound power was 100 W and the frequency was 20 kHz at a pressure of 0.03 MPa, and increased by 101% and 112% when the ultrasound power was 100 W and the frequency was 28 kHz at a pressure of 0.03 MPa, at temperatures of 35 and 50 °C, respectively. This result might be due to the fact that the cavitation threshold decreases with a decrease in absolute pressure; therefore, the ultrasound cavitation is more likely to be generated under low-pressure conditions (Li and Yin 1995; Wang and Niu 2008). In addition, Figs. 5 to 7 also showed that the mass transfer coefficient increased with increasing ultrasound power and frequency applied. The mass transfer coefficients were 1.45, 0.95, and 0.51 m/h, respectively, at the ultrasound power of 60 W, while they were 2.67, 1.86, and 1.33 m/h, respectively, at the ultrasound power of 100 W when the ultrasound frequency was 28 kHz, the temperature was 35 °C, and the pressures were 0.03, 0.06, and 0.1 MPa, respectively. The mass transfer coefficients were 1.25, 0.78, and 0.55 m/h, respectively, at the ultrasound frequency of 20 kHz, while they were 1.57, 0.87, and 0.74 m/h, respectively, at the ultrasound frequency of 28 kHz when the ultrasound power was 100 W, the temperature was 50 °C, and the pressures were 0.03, 0.06, and 0.1 MPa, respectively. This phenomenon might be due to the fact that the ultrasound effect has a close relationship with ultrasound intensity; the ultrasound intensity increases with increasing power (Crum 1995), and the ultrasound cavitation increases along with increasing ultrasound frequency (He 2014).

CONCLUSIONS

1. Ultrasound markedly increased the water migration rates within the boundary layer. Compared with the control group, the water migration rates increased, and the minimum and maximum increase amplitude were 7.7% and 110.1%, respectively. Moreover, the water migration rates increased with increasing ultrasound power and frequency.
2. The mass transfer coefficients within the boundary layer for specimens treated with ultrasound were much higher than those of the control group. The mass transfer coefficients increased by 9% to 111% with ultrasound.
3. The mass transfer coefficients increased with decreasing absolute pressure at set conditions. The mass transfer coefficient increased from 101% to 184% with a decrease in pressure from 0.1 MPa to 0.03 MPa.

4. The mass transfer coefficient increased with increasing ultrasound power and frequency applied. The minimum and maximum mass transfer coefficients were 0.51 m/h and 1.45 m/h at the power of 60 W, while those were 1.33 m/h and 2.67 m/h, respectively, at the ultrasound power of 100 W. The minimum and maximum mass transfer coefficients were 0.55 m/h and 1.25 m/h at the frequency of 20 kHz, while those were 0.74 m/h and 1.57 m/h, respectively, at the ultrasound frequency of 28 kHz.

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