Heat Transfer Characteristics during Superheated Steam Vacuum Drying of Poplar

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Abstract

Superheated steam vacuum drying shows major advantages in terms of reducing the boiling point of water and speeding up the drying process, but to our knowledge, no researcher has addressed the effects of drying conditions on heat transfer characteristics during superheated steam vacuum drying of wood. In this study, we did so using fast-growing poplar. Temperatures inside the wood were measured and the convective heat transfer coefficients calculated under temperature conditions of 35°C, 55°C, and 70°C and absolute pressures of 0.03, 0.06, and 0.1 MPa. The results of our subsequent analysis showed that the ultimate temperatures inside wood increase alongside increasing absolute pressure at the set temperature conditions and are lower than that of the drying medium. In addition, we found that convective heat transfer coefficients increase as absolute pressure increases at the set temperatures and also increase as temperature increases at set absolute pressure conditions. We then established a convective heat transfer coefficient model based on the experimental results. The findings presented here may provide theoretical guidance for maximizing the available advantages of superheated steam vacuum drying and choosing appropriate drying schedules for poplar in future applications.

All manner of wood, which is the raw material most commonly used for furniture, building, and woodworking industries, must be dried after it is felled (Zhang et al. 2005). To this effect, wood drying is one of the most important steps in wood product manufacturing. In fact, the drying process consumes roughly 40 to 70 percent of the total energy used throughout the entire wood product manufacturing process (Zhang and Liu 2006, He et al. 2012). Compared with traditional wood drying methods, superheated steam vacuum drying (i.e., drying under vacuum with superheated steam) shows sizeable advantages in reducing the boiling point of water, speeding the drying process, and allowing wood to be dried at a lower temperature, which has a positive effect on its mechanical properties (Abdullah et al. 2012, Pang and Dakin 1999, Pang and Pearson 2004). The evaporation rates of water on the wood surface increase as absolute pressure decreases during the drying process (He et al. 2010), whereas the heat transportation ability decreases as absolute pressure decreases because air in the drying cabinet has been moved away, density of the medium becomes lower at low absolute pressure conditions, and heat does not reach the wood as readily under low pressures (Zhang and Qiao 1992). Temperatures play an important role in wood drying; thus, the primary objective of optimizing a heat-based wood drying process is to enhance heat transportation ability (thereby enhancing drying rate.) Many studies have investigated mass and heat transfer during the superheated steam vacuum drying of various materials (Defo et al. 2004, Devahastin et al. 2004, Li and Lee 2008, Chen et al. 2012, Redman et al. 2012, Chaiyo and Rattanadecho 2013, Liu et al. 2014). To our knowledge, however, there have been no prior studies on the effects of drying conditions on heat transfer characteristics, although they are a very important parameter during the superheated steam vacuum drying of wood.

The purpose of the present study was to evaluate heat transfer characteristics under different vacuum drying conditions to provide theoretical guidance for making better use of superheated steam vacuum drying. The findings of this study may also assist future researchers and developers in choosing appropriate drying schedules for poplar.

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Materials and Methods

Materials

Poplar (*Populus tomentosa*) sapwood specimens were provided by Landbond Furniture Co. Ltd., Shandong, China. The dimensions of the test specimens were 150 mm in length (longitudinal direction) by 100 mm in width (radial direction) by 60 mm in thickness (tangential direction), with initial moisture content of 100 ± 5 percent (according to GB/T 1931-2009; Zhao et al. 2009). To simulate a real-world production process, all the end cross sections of specimens were blocked by covering them with epoxy resin, and the specimens were placed in a customized incubator with internal dimensions of 150 by 100 by 60 mm. The faces of all specimens (except one, with dimensions of 150 by 100 mm) were covered by the internal wall of the incubator.

Equipment

The vacuum drying system included temperature and pressure controls, through which the temperature and the pressure of the drying medium could be controlled automatically with an accuracy of 0.01°C and 0.002 MPa, respectively. The data collection system included temperature sensors (used to calculate accurate inner wood temperatures automatically), a digital inspection instrument, and a computer. Superheated steam was produced by a steam generator.

Experimental methods and procedures

Experiments were carried out at three different temperature levels (35°C, 55°C, and 70°C) and three different absolute pressure levels (0.03, 0.06, and 0.1 MPa). Thermocouple locations are shown in Figure 1; layer 1 marks the outer layer, layer 2 the secondary layer, and layer 3 the central layer. In each experimental unit, superheated steam was injected into the vacuum drier before vacuum drying, and the temperature value acquisition process was complete when temperatures inside the samples became constant.

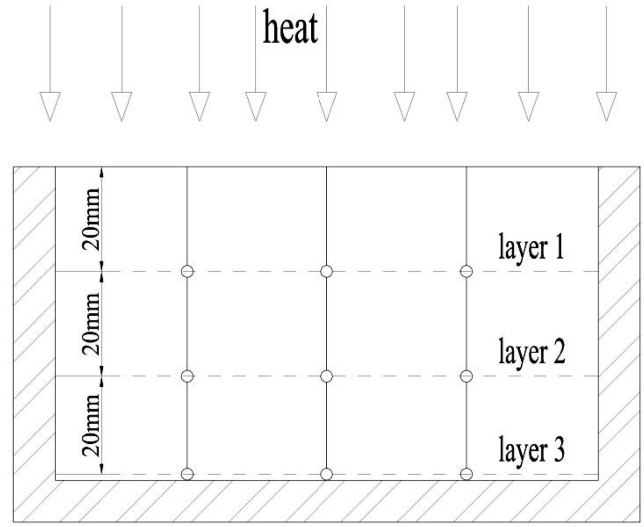


Figure 1.—Temperature sensor distribution diagram.

Results and Discussion

Influence of environmental conditions on wood temperatures

Wood temperature variation over time at environmental temperatures of 35°C, 55°C, and 70°C and absolute pressures of 0.03, 0.06, and 0.1 MPa are shown in Figures 2 through 4. Temperatures inside samples increased with time at the beginning and then rising rates decreased gradually until the temperature became constant. The time for temperatures inside the samples to become constant was different under different conditions: the higher the drying temperature applied, the shorter the time until stability was reached. It took 300 min for wood temperatures to become constant when the temperature of the drying medium was 35°C and 200 and 150 min at temperatures of 55°C and 70°C, respectively. This phenomenon may have been caused by the temperature differences between dying medium and poplar samples, which was larger when the temperature of the dying medium was high and smaller when the temperature of drying medium was low.

In addition, the ultimate temperatures of inner wood increased as absolute pressure increased at certain temperatures. Specifically, these temperatures were 29.1°C, 32.6°C, and 36.8°C at absolute pressures of 0.03, 0.06, and 0.1 MPa, respectively, at a drying medium temperature of 35°C. They were 49.3°C, 51.4°C, and 53.2°C at absolute pressures of 0.03, 0.06, and 0.1 MPa, respectively, at a drying medium temperature of 55°C, and they were 61.7°C, 64.7°C, and 69.1°C at absolute pressures of 0.03, 0.06, and 0.1 MPa, respectively, when the drying medium temperature was 70°C. Heat transfer capacity decreases as absolute pressure decreases, where air density is low and heat is less readily transferred to the wood; as a result, the wood sample temperature was low under low absolute pressure conditions. Further, ultimate temperatures inside the wood could not reach those of the drying medium at lower absolute pressure conditions.

Wood drying rates increase as absolute pressure decreases during vacuum drying (Mottonen 2006, Chen and Lamb 2007, Hermawan et al. 2013), so to secure the appropriate drying rates at a certain temperature, reasonable pressure must be applied. Compared with conventional wood drying, drying rates can be improved using vacuum conditions by

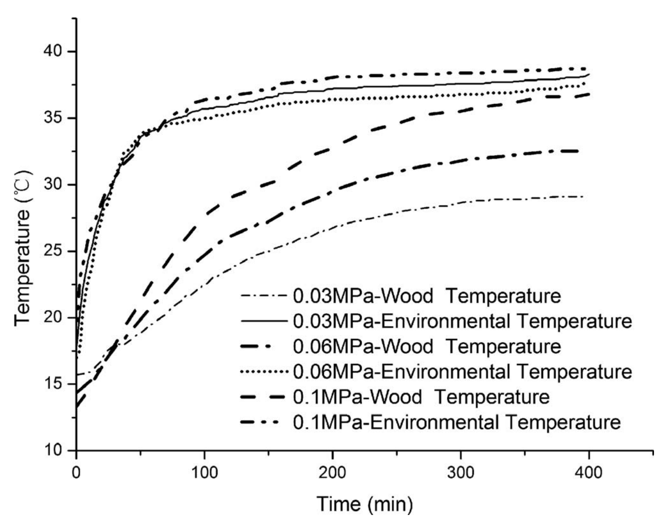


Figure 2.—Temperature variations of the inner wood along with pressure and time at 35°C.

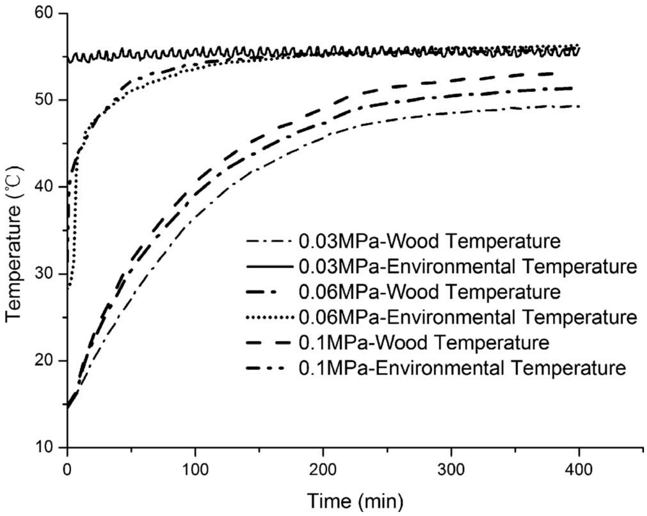


Figure 3.—Temperature variations of the inner wood along with pressure and time at 55°C.

controlling decreases in temperature caused by low pressure. Appropriate drying schedules can be defined by the lowest possible temperature and absolute pressure conditions that still provide desired results, which could save energy and truncate the drying cycle.

Convective heat transfer coefficients under different drying conditions

To obtain the convective heat transfer coefficients under different drying conditions, temperatures at specific locations inside the wood samples were measured and results are shown in Figure 5. Temperature differences among different places in one wood sample were slight ($P > 0.05$), suggesting that the heat transfer rates in the inner wood were very fast and that the wood could be considered an integrated whole; thus, its biot number (*Bi*) is less than 0.1 (Zhang and Nie 2000).

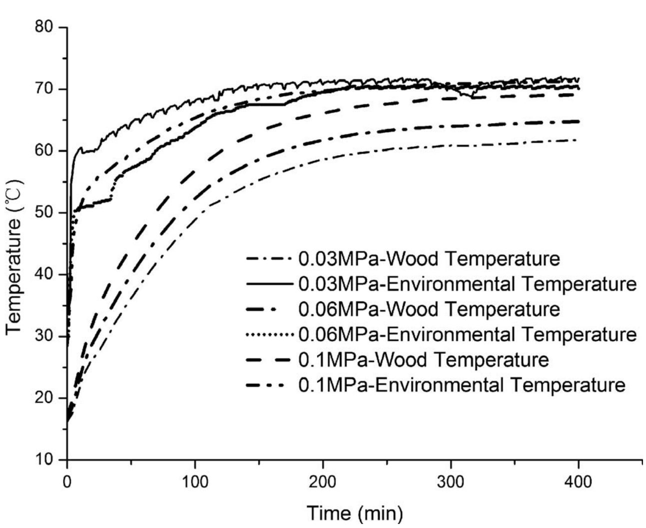


Figure 4.—Temperature variations of the inner wood along with pressure and time at 70°C.

According to Newton's cooling formula:

$$q = hA(T - T_\infty) \tag{1}$$

where q is power (W), h is convective heat transfer coefficient (W/[m^2·K]), A is area (m^2), T is the wood sample temperature (°C), and T_∞ is the drying medium temperature (°C).

By combining Equation 1 and the mass conservation law, when *Bi* is less than 0.1, we can draw Equation 2 (Zhang and Nie 2000):

$$hA(T - T_\infty) = -\rho V c_p \frac{dT}{d\tau} \tag{2}$$

where T is wood sample temperature (°C), ρ is wood sample density (kg/m^3), c_p is wood sample specific heat (J/[kg·K]), V is wood sample volume (m^3), and τ is time (s).

To solve Equation 2, excess temperature ($\theta = T - T_\infty$) is involved, so Equation 2 should be rewritten as follows:

$$\frac{d\theta}{\theta} = \frac{hA}{-\rho V c_p} d\tau \tag{3}$$

We integrated both sides of Equation 3 and combined it with the known conditions under which T equals T_0 (the initial temperature of the wood sample) at the initial time. Equation 3 was then converted to Equation 4:

$$\ln\left(\frac{T - T_\infty}{T_0 - T_\infty}\right) = \frac{hA}{-\rho V c_p}\tau \tag{4}$$

Therefore,

$$h = \frac{-\rho V c_p}{A\tau} \ln\left(\frac{T - T_\infty}{T_0 - T_\infty}\right) \tag{5}$$

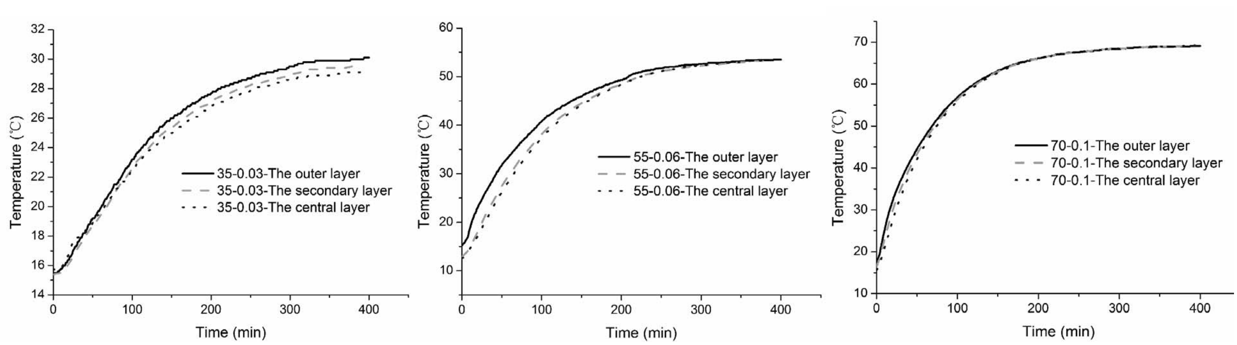
The convective heat transfer coefficients under different drying conditions were obtained by comparing experimental data and the calculation results of Equation 5 as shown in Table 1. We found that convective heat transfer coefficient increases as absolute pressure increases at certain temperatures, by 3.33 W/m^2·K at 35°C, 2.52 W/m^2·K at 55°C, and 7.95 W/m^2·K at 70°C when absolute pressure increases from 0.03 to 0.1 MPa. Table 1 also shows where the convective heat transfer coefficient similarly increases alongside temperature at a certain absolute pressure, by 6.24 W/m^2·K at 0.03 MPa, 6.68 W/m^2·K at 0.06 MPa, and 10.86 W/m^2·K at 0.1 MPa as temperature increased from 35°C to 70°C.

To predict the convective heat transfer coefficient under various drying conditions, the relationship among convective heat transfer coefficient, temperature, and absolute

Table 1.—Convective heat transfer coefficients under different conditions.

	Heat transfer coefficients (W/m^2·K) at different temperatures		
Pressure (MPa)	35°C	55°C	70°C
0.03	4.94	10.22	11.18
0.06	7.11	11.72	13.79
0.1	8.27	12.74	19.13

1.



2.

Figure 5.—Temperatures at different places of the inner wood under different drying conditions.

pressure can be established based on experimental results as follows:

$$h = \frac{1}{0.0424 + 5.03/t + 0.264P \ln P} \quad (6)$$

where h is the convective heat transfer coefficient (W/[m^2·K]), t is the temperature in the vacuum drier (°C), and P is the absolute pressure (MPa). Via Equation 6, we found that the correlation coefficient (R^2) was 0.97. This indicates that the equation simulated the experimental results very well and can feasibly be used to predict the convective heat transfer coefficient under different vacuum drying conditions.

Temperatures inside wood samples at different times and under different conditions can be determined by Equations 4 and 6, allowing appropriate temperature and absolute pressure to be optimized according to the wood temperature needed during the poplar drying process in practice. Appropriate drying schedule facilitates both energy and time efficiency during the poplar drying process.

Conclusions

The ultimate temperatures inside wood increase as absolute pressure increases at a set temperature, and at certain pressures, the ultimate temperature inside wood cannot reach that of the drying medium. Convective heat transfer coefficients increase as absolute pressure increases at set temperature conditions and increase alongside temperature at set absolute pressure conditions. We established a convective heat transfer coefficient model and used equations to simulate our experimental results very effectively, suggesting that the proposed model can be feasibly applied in practice to predict heat transfer characteristics. An accurate convective heat transfer coefficient allows an appropriate drying schedule to be determined, which can maximize the advantages of superheated steam vacuum drying of poplar and other wood materials.

Acknowledgments

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