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CONVECTIVE HEAT AND MASS TRANSFER DURING VACUUM DRYING PROCESS

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

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ABSTRACT

Vacuum drying is now widely used in wood industry. However, drying defects remains a major problem because of the water migration rates inner wood is much lower than that at wood surface, as a result, the moisture gradient between wood surface and inner wood is steep, and the drying stress will damage the wood structure. What's more, the water removal rate from the inner regions of the wood can be calculated by weighing the wood throughout the drying process, while the evaporation ability at the wood surface is related to environmental conditions, thus, knowing the water evaporation at certain vacuum drying conditions is very important. In this paper, the convective heat and mass transfer coefficients were studied at temperatures of 35, 50, 65, and 80°C and at absolute pressures of 0.02, 0.05, 0.08, and 0.1MPa during the vacuum drying process. Results showed that the higher the temperature, or the lower the absolute pressure applied, the higher the water evaporation rate was. The convective mass transfer coefficient decreased as temperature increased and increased with decreasing absolute pressure. The convective heat transfer coefficient decreased along with decreasing absolute pressure at a constant temperature. Convective mass transfer coefficient and convective heat transfer coefficient models were established to simulate experimental results. This paper could provide guidance to choose the appropriate drying conditions based on the water evaporation rates under and the water migration rates inner wood under different vacuum drying conditions.

KEYWORDS: Evaporation rates; convective mass transfer coefficient; temperature difference; convective heat transfer coefficient; vacuum drying.

INTRODUCTION

Wood, the main raw material for the furniture, building, and woodworking industries, must be dried after it is felled (Zhang et al. 2005). 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 used throughout the entire manufacturing process (Zhang and Liu 2006; He et al. 2012). Vacuum drying is now widely used in many fields including wood drying, sludge drying, and food drying. Compared to traditional wood drying methods, vacuum drying can significantly shorten the drying time and reduce drying defects, especially for thicker lumber (Abdullah et al. 2012; He et al. 2013). However, checking (both on the surface and internally) remains a major problem for wood vacuum drying processes, especially at high drying temperatures, as a steep moisture gradient forms within the surface layer of samples. This is because the water migration rates inner wood is much lower than that at wood surface and an insufficient amount of moisture moves from the center of the piece to its surface during the vacuum drying process (Avramidis et al. 1994; Li et al. 2009).

One way to decrease the steep moisture gradient and avoid the drying defects is to make the water evaporation rate at the wood's surface similar to that of the inner wood (He et al. 2010). Generally, the water migration rates inner wood is only impacted by wood physical characteristics under certain drying conditions (Mulet et al. 1999), and the water removal rate from the inner regions of the wood can be calculated by weighing the wood throughout the drying process (Li et al. 2009), whereas the evaporation rate at the wood surface is related to environmental conditions such as the absolute pressure, temperature, and velocity of the drying medium. Therefore, knowing the water evaporation rates at certain vacuum drying conditions could is very important for decreasing the drying defects. Many experiments have been conducted regarding the water removal rate from the inner wood during the drying process (Torres et al. 2011; Nadi et al. 2012; Redman et al. 2012; Chaiyo and Rattanadecho 2013) and the temperature distribution through the inner wood (Liu et al. 2014). However, there have been no known studies of the evaporation ability under vacuum drying conditions, a parameter closely related to drying defects.

The purpose of the study was to evaluate the convective heat and mass transfer characteristics under different vacuum drying conditions and the result could provide guidance to choose the appropriate drying conditions for wood vacuum drying.

MATERIAL AND METHODS

Material and equipment

Distilled water, provided by JIALEJIE Water Co., Ltd, Beijing, China, was taken as material. A scheme of the experimental set-up of the vacuum drying system is presented in Fig. 1. This vacuum dryer (Shanghai Laboratory Instrumental Works Co., Ltd., Shanghai, China) consists of nine parts, including a pressure controller, a vacuum pump, and a pressure meter to control pressure to within 0.002 MPa. The apparatus supports absolute pressures ranging from 0.096 to 0.1 MPa (ambient pressure). The specimens can be automatically weighed by the weight sensor, at the interval of 5 s, during the drying process. The gas valve can be used to return the drying chamber to the ambient pressure when the chamber needs to be opened.

The air velocity is controlled by PWM (pulse width modulation) and is measured with a hot-wire anemometer such that it can be maintained at a constant velocity of 2 $m.s^{-1}$. The temperature monitor controls the temperature according to the setting value. Finally, the heat generator consists of two sets of heat generators capable of temperatures up to 200°C. The water bath can automatically heat distilled water from room temperature to 300°C with a controlling accuracy of 0.2°C.

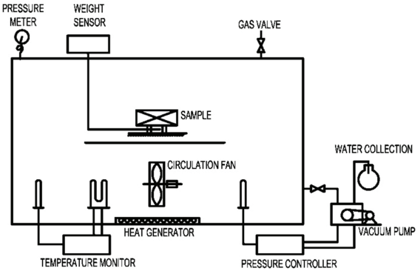

Fig. 1: Scheme of experimental set-up of the hot air ultrasound assisted vacuum dryer.

Methods and procedures

During this experiment, the convective mass transfer coefficient and convective heat transfer coefficient were examined at temperatures of 35, 50, 65, and 80°C, absolute pressures of 0.02, 0.05, 0.08, and 0.1 MPa, and an air velocity of 2 m.s^{-1}.

The air velocity remained constant (Zhang et al. 2005). The experimental steps were as follows:

1) The weight module was installed in the vacuum dryer, and the inner temperature of the vacuum dryer was set to 35°C.
2) When the temperature inside the vacuum dryer reached 35°C, a tray filled with water ata temperature of 35°C was put on the weight module.
3) Temperature sensors were installed in the vacuum dryer (three of which were immersed) to calculate the water temperature; three others were installed to calculate the temperature of the drying medium.
4) The absolute pressure of the vacuum dryer was set to 0.02 MPa, at which point the vacuum pump was started.
5) Temperature measuring instruments and the weighing system began to work when the absolute pressure in the vacuum dryer reached 0.02 MPa; all data were automatically.
6) Followed by steps 1) to 5), Similar process were done at the temperature of 50, 65 and 80°C, respectively, and at the absolute pressure of 0.05, 0.08 and 0.1 MPa, respectively.

RESULTS AND DISCUSSION

Water evaporation rate during vacuum drying process

The water evaporation rates at different conditions are showed in Tab. 1.

Tab. 1: Water evaporation rates.

		P (MPa)			
		0.1	**0.08**	**0.05**	**0.02**
T (°C)	35	15.02	16.50	17.10	22.80
	50	30.68	31.66	34.69	43.91
	65	48.00	52.12	58.93	72.53
	80	76.13	90.06	100.20	107.09

It was found that water evaporation rates increased along with the increase of temperature at the same absolute pressure condition. The water evaporation rates increased by 61.11 gram per hour when the drying temperature was raised from 35 to 80°C at the absolute pressure of 0.1 MPa. There were corresponding increases of 73.56, 83.10, and 84.29 gram per hour when the absolute pressures were 0.08, 0.05 and 0.02 MPa, respectively. The results can be mainly attributed to the increasing pressure differences between water and the drying medium. Such differences constitute the main drying force for evaporation during the drying process (Siau 1984),and the higher the temperature, the lager the pressure difference is (Welty et al. 2009). What's more, the kinetic energy of a water molecule increases with the increase of temperature, and it will enhance water evaporation (Chen and Wu 2007). Moreover, Tab. 1 also shows that the lower the absolute pressure applied, the higher the water evaporation rates will be when the temperature is constant. The water evaporation rates decrease by 7.78 gram per hour when the absolute pressure varies from 0.02 to 0.1 MPa at the temperature of 35°C, and those decrease by 13.23, decrease by 24.53 and decrease by 30.96 gram per hour when temperatures are 50, 65 and 80°C, respectively. This phenomenon mainly can be attributed to the decreasing vapor density inside the vacuum dryer at the low absolute pressure condition, which will increase the moisture gradient and enhance water evaporation.

The convective mass transfer coefficient

The convective mass transfer coefficient represents the ability of water evaporation during the drying process (Incropera et al. 2011). It could be calculated by Eq. 1 (Welty et al. 2009),

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

where: k - the convective mass transfer coefficient (m.s^{-1}),
N - the water evaporation rate (mol.s^{-1}.m^{-2}),
A - the evaporation area on liquid surface (m^2),
c_s - water vapor concentration at liquid surface (mol.m^{-3}),
c_∞ - the water vapor concentration in drying medium (mol.m^{-3}).

The value of cs can be obtained from Eq. 2,

$$c_s = \frac{P_s}{RT} \cdot \frac{P}{P_0} \tag{2}$$

where: P_s - the saturation pressure at corresponding temperature (Pa),
P - the absolute pressure inside vacuum dryer (Pa),
P_0 - the atmospheric pressure (Pa),
T - the temperature (°C),
R - the gas constant.

By means of Eqs.1 and 2, along with the experimental data, the convective mass transfer coefficient were obtained, and the values are shown in Tab. 2.

Tab. 2: Convective mass transfer coefficient under different condition.

		P (MPa)			
		0.1	**0.08**	**0.05**	**0.02**
T(°C)	35	0.032	0.044	0.073	0.245
	50	0.029	0.037	0.065	0.204
	65	0.022	0.030	0.054	0.167
	80	0.019	0.028	0.050	0.133

It demonstrates that the convective mass transfer coefficient decreased along with the increase of temperature, and increased with the decrease of absolute pressure. It increased from 0.032 to 0.245 m.s^{-1} at the temperature of 35°C, increased from 0.029 to 0.204 m.s^{-1} at the temperature of 50°C, increased from 0.022 m.s^{-1} to 0.167 at the temperature of 65°C, and increased from 0.019 to 0.133 m.s^{-1} at the temperature of 80°C when the absolute pressure was changed from 0.1 to 0.02 MPa.

To predict the convective mass transfer coefficient at different drying conditions, the relationship among the convective mass transfer coefficient, temperature and absolute pressure was established based on the experimental results, which was showed in Eq. 3,

$$\begin{aligned} k = & -4.033\times10^{-2} + 2.103\times10^{-3}t + 4.814\times10^{-3}P - 4.55\times10^{-5}t^2 \\ & -1.583\times10^{-5}/P^2 - 5.344\times10^{-6}t/P + 2.716\times10^{-7}t^3 + 1.194\times10^{-6}/P^3 \quad R^2=0.99 \\ & -1.071\times10^{-6}t/P^2 + 1.338\times10^{-7}t^2/P \end{aligned} \tag{3}$$

where: *k* - the convective mass transfer coefficient (m.s^{-1}),
t - the temperature in vacuum drier (°C),
P - the absolute pressure (MPa).

Eq. (3) shows that the correlation coefficient is 0.99, which indicates that this equation could simulate the experimental results very well and could be used to predict the convective mass transfer coefficient at different drying conditions.

Water temperature variation at different conditions

To study the water temperature variation at different conditions, temperatures of water and drying medium are shown in Fig. 2. It shows that water temperature decreased at the beginning stage of drying process, while it reached a constant value at the final stage. These results can be explained based on an understanding that water absorbs energy, which will decrease water temperature during the vaporization process at the beginning stage. However, water temperature remains invariant when energy absorbed from the drying medium is equal to that for water vaporization. Moreover, Fig. 2 also indicates that water temperatures at the last stage increased along with the increase of absolute pressure. The temperatures were 29.6, 31.9 and 33.46°C at the pressures of 0.02, 0.05, and 0.1 MPa respectively when the temperature of drying medium was 35°C. The temperatures were 39.5, 39.9, and 42.1°C at the pressures of 0.05, 0.08, and 0.1 MPa, respectively, when the temperature of drying medium was 50°C. The temperatures were 47.2, 51.6, and 53.1°C at the pressure of 0.02, 0.05, and 0.08 MPa, respectively, when the temperature of drying medium was 65°C. The temperatures were 54.6, 66.3, and 67.6°C at the pressure of 0.02, 0.08, and 0.1 MPa respectively when the temperature of drying medium is 80°C. These results can be attributed to the fact that, in comparison with a low absolute pressure condition, the water vaporization process, which will take energy away, takes place more slowly when the absolute pressure is high (Li et al. 2011).

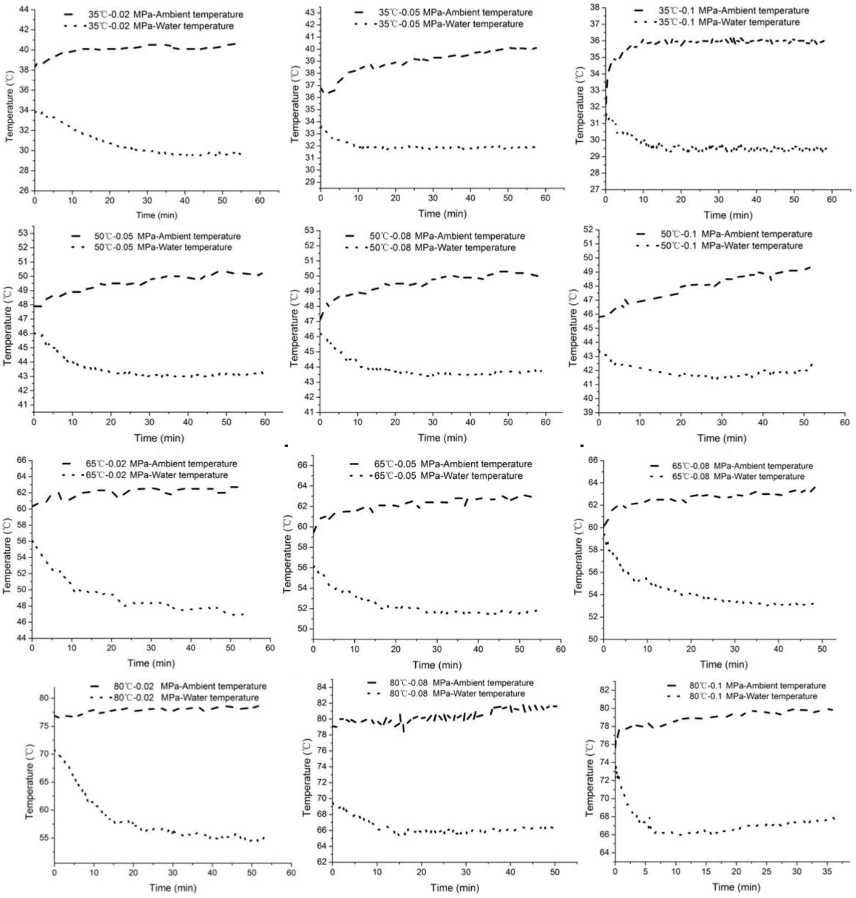

Fig. 2: Ambient temperature and water temperature under different condition.

The differences between the water temperatures at the last stage and that of dying medium are shown in Tab. 3. The results showed that the differences increased along with the decrease of absolute pressure. They increased by 4.17 at the temperature of 35, by 6.43°C at the temperature of 50, by 5.68°C at the temperature of 65, and by 11.69°C at the temperature of 80°C when the absolute pressure was varied from 0.1 to 0.02 MPa. What's more, the differences increased along with the increase of dying temperature.

Tab. 3: Differences between ambient temperature and water temperature.

		P (MPa)			
		0.1	**0.08**	**0.05**	**0.02**
T(°C)	35	6.50	7.20	8.18	10.67
	50	7.17	9.66	10.05	13.50
	65	9.51	10.33	11.31	15.19
	80	12.16	15.24	17.84	23.85

They increased by 5.66°C at the absolute pressure of 0.1 MPa, by 8.04°C at the absolute pressure of 0.08 MPa, by 9.66°C at the absolute pressure of 0.05 MPa, and by 13.18°C at the absolute pressure of 0.02 MPa when the dying temperature was varied from 35 to 80°C. This was mainly because the lower the absolute pressure applied, the faster the water vaporization rates will be, and the more energy will be taken away.

Convective heat transfer coefficient

The above results indicate that the differences between the water temperatures at the last stage and that of dying medium were different under various conditions. Therefore, the convective heat transfer coefficient should be involved to study the heat transfer ability at different conditions.

According to the Newton cooling formula, as shown in Eq. 4 (Zhang and Qiao 1992),

$$q = hA(T - T_\infty) \tag{4}$$

where: q - power (W),
h - convective heat transfer coefficient (W/(m^2•K)),
A - the area, (m^2),
T - the water temperature (°C),
T_∞ - the drying medium temperature (°C).

Combined with the mass conservation law, Eq. can be obtained,

$$hA(T - T_\infty) = -\rho V c_p \frac{dT}{d\tau} \tag{5}$$

where: T - water temperature (°C),
ρ - water density (k.m^{-3}),
cp - water specific heat (J/(kg•K))
V - water volume (m^3),
τ - time (s).

Energy obtained from heat convection is used for water evaporation for the reason that the water temperature is constant at the last stage. Thus:

$$hA(T - T_\infty) = m\gamma \tag{6}$$

Therefore:

$$h = \frac{m\gamma}{A(T - T_\infty)} \tag{7}$$

where: h - convective heat transfer coefficient (W.m^{-2}·K),
m - the evaporation capacity (g.s^{-1}),
γ - latent heat of vaporization (J.g^{-1}).

Combined with differences between temperature of drying medium and water, water evaporation rates and latent heat of vaporization, the convective heat transfer coefficient was obtained, and the results are shown in Tab. 4.

Tab. 4: Convective heat transfer coefficient under different conditions.

T(°C) \ P(MPa)	0.1	0.08	0.05	0.02
35	197.27	195.64	182.42	178.47
50	360.08	290.47	275.80	273.71
65	432.06	418.39	408.54	366.60
80	511.16	482.48	458.57	395.94

From Tab. 4, one can reach the conclusions that the convective heat transfer coefficient decreases along with the decrease of absolute pressure under the condition of constant temperature. This phenomenon is due to the decrease in heat transportation ability by the decrease of the medium density, which is low at the low absolute pressure condition. The convective heat transfer coefficient was decreased by 18.81 W.m^{-2}·K when the absolute pressure was decreased from 0.1 to 0.02 MPa at the temperature of 35°C. It was decreased by 86.37 W.m^{-2}·K at the temperature of 50°C, by 34.54 W.m^{-2}·K at the temperature of 65°C, by 144.56 W.m^{-2}·K at the temperature of 80°C at the same absolute pressure changes. Therefore, the variable quantity of convective heat transfer coefficient increased along with the increase of temperature at the same absolute pressure changes. What's more, the higher the temperature applied, the higher the convective heat transfer coefficient will be. The maximum values of the convective heat transfer coefficient were 511.15, 482.48, 458.57, and 395.94 W.m^{-2}·K. The minimum values of the convective heat transfer coefficient were 197.27, 195.64, 182.42, and 178.47 W.m^{-2}·K at the absolute pressure of 0.1, 0.08, 0.05, and 0.02 MPa, respectively.

To predict the convective heat transfer coefficient at different drying conditions, the relationship among the convective heat transfer coefficient, temperature, and absolute pressure was established based on the experimental results, which is shown as follows,

$$\begin{aligned} h = {} & 3209.07 - 15.38t + 2893.23\ln P + 0.392t^2 + 905.34(\ln P)^2 - 3.713t\ln P \\ & - 2.62\times10^{-3}t^3 + 91.885(\ln P)^3 - 0.738t(\ln P)^2 + 1.70\times10^{-3}t^2\ln P \end{aligned} \quad R^2=0.99 \tag{10}$$

where: h - the convective heat transfer coefficient (W/(m^2•K)),
t - the temperature in the vacuum drier (°C),
P - the absolute pressure (MPa).

Eq. (10) shows that the correlation coefficient was 0.99, which indicates that this equation could simulate the experimental result very well and could be used to predict the convective heat transfer coefficient at different vacuum drying conditions.

CONCLUSIONS

1. The higher the temperature, the lower the absolute pressure applied, and the higher the water evaporation rates will be. The water evaporation rates increased by 61.11 gram per hour when drying temperature was changed from 35 to 80°C at the pressure of 0.1 MPa, and those were 73.56, 83.10, and 84.29 g when the absolute pressure values were 0.08, 0.05, and 0.02 MPa, respectively, for the same temperature changes.
2. The convective mass transfer coefficient decreases along with the increase of temperature, and increases with the decrease of absolute pressure. It increased from 0.032 to 0.245 m.s^{-1} at the temperature of 35°C, increased from 0.032 to 0.245 m.s^{-1} at the temperature of 50°C,

increased from 0.022 to 0.167 m.s^{-1} at the temperature of 65°C, and increased from 0.019 to 0.133 m.s^{-1} the temperature of 80°C when the absolute pressure changed from 0.1 to 0.02 MPa.

3. Water temperature decreased at the beginning stage of drying process, while it approached to a constant at the last stage. The differences between the water temperatures at the last stage and that of dying medium increased along with the decrease of absolute pressure. It increased by 4.17 at the temperature of 35, by 6.43°C at the temperature of 50, by 5.68°C at the temperature of 65, and by 11.69°C at the temperature of 80°C when the absolute pressure was varied from 0.1 to 0.02 MPa.
4. The convective heat transfer coefficient decreased along with the decrease of absolute pressure at the constant temperature condition. It decreased by 18.81 W.m^{-2}·K when the absolute pressure was decreased from 0.1 to 0.02 MPa at the temperature of 35°C, decreased by 86.37 W.m^{-2}·K at the temperature of 50°C, decreased by 34.54 W.m^{-2}·K at the temperature of 65°C, and decreased by 144.56 W.m^{-2}·K at the temperature of 80°C at the same absolute pressure changes.
5. The convective mass transfer coefficient and the convective heat transfer coefficient models were established, and these equations could simulate the experimental results very well and could be used to predict heat and mass transfer characteristics. These two models could provide guidance to choose the appropriate drying conditions for wood vacuum drying.

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Zhengbin He*, Zijian Zhao, Yu Zhang, Huan Lv, Songlin Yi
Beijing Forestry University
Beijing Key Laboratory of Wood Science and Engineering
Beijing 100083
P.R. China
Corresponding author: hzbbjfu@126.com