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Theoretic discussion on the way and driving forces of moisture migration in wood during vacuum drying

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Theoretic discussion on the way and driving forces of moisture migration in wood during vacuum drying

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ABSTRACT

Most of parameters in conventional drying cannot explain a lot of phenomena appeared in vacuum condition, so it is necessary to further explore the moisture migration way and driving forces in wood under vacuum condition. For the water movement channel in wood is very narrow, the characteristic of heat and mass transfer in wood is similar to that in microscale. This article applies theory of liquid nucleate boiling in microscale, combines with wood structure, deduces the vessel's critical radius of wood if the normal nucleate boiling of water in wood could occur under 60°C, 70°C, 80°C, 90°C, 100°C and 0.01MPa, 0.02MPa respectively, and finally comes to a conclusion that: Because the radius of vessels, tracheid, and pit which are main passageway for water getting out of wood when wood drying are much smaller than the smallest critical radius, therefore the microchannel in wood is smaller than the "evaporation space" and there is no normal nucleate boiling but fictitious boiling phenomenon exist when wood vacuum drying. There also is a certain degree of pressure pulse during the process of water nucleation throughout the drying, which not only prevent from the producing of larger cluster but also drives the moisture inside wood moving out; and the low pressure in the vacuum drying and small channel in wood lead water coming out in the form of bubble during vacuum drying, and the radius of bubble is very small, which make its water potential is higher than that of conventional drying, as a result, the drying rate in vacuum condition is much faster than that in conventional.

Keywords: microscale, critical radius, pressure pulse, moisture migration, vacuum drying, water potential, cluster

1. INTRODUCTION

Various approximate mathematical models such as Fick diffusion model, vapor pressure gradient model, Luikov model, Siau model and Watiker model etc. have been introduced to describe the form of moisture movement in wood during the drying process (Yi *et al.* 2005). Among these models, the Fick diffusion model is only applicable to isothermal condition (Siau 1984), vapor pressure gradient model and Luikov model regard water potential as driving force (Thomas *et al.* 1980), Siau model regards chemical potential as driving force. In fact, the chemical potential and water potential of wood moisture are just two different expressive ways, they are the same in essence for water in wood during drying process, so water potential can be used as driving force for vapor phase and liquid phase which includes bound water and free water in wood (Siau 1984). Though all the models give certain explanations to the internal moisture movements of wood during drying process, there are a lot of wood drying methods, each of which has its own

features, especially the wood vacuum drying, lots of parameters of conventional drying could not explain many phenomena appeared during the vacuum condition, so it is necessary to further explore the internal moisture migration way and drying forces in wood under vacuum condition. So far, microscale heat transfer theory has been applied in many fields such as nanofabrication, micro-sensors, micro-actuators and other micro-electro-mechanical system design process, but rarely seen in the wood drying process. Research of Peng *et al.* (Peng *et al.* 1994, Peng *et al.* 1996) showed that the existence of gas bubble generated in the internal or the heating surface of liquid not only depended on superheat and nucleation site, but also the dimension of the liquid itself, they also proposed two hypothetical concepts, namely "vaporization space" and "fictitious boiling " and a physical model, termed "interphase fluctuation propagation and superposition theory". As the water migration channel is very narrow in wood, thus, the heat and mass transfer characteristics in wood was consistent with that in microscale.

In order to better explain the phenomena appeared during vacuum drying process, this paper regarded water potential as driving force for moisture migration in wood during the vacuum drying process, studied on the forms of the internal moisture movement during the vacuum drying process based on the microscale heat transfer theory, compared vacuum drying with conventional drying, and explored the reason why vacuum drying rate was faster than that of the conventional drying.

2. THE MOISTURE MIGRATION WAY IN WOOD DURING VACUUM DRYING

2.1 The Initial Changes of the Internal Moisture During Wood Vacuum Drying

During the wood vacuum drying process, as the environmental pressure is relative low, water could reach its boiling point at a relative low temperature. At the beginning, water molecular begin to experience cluster which is a material group assembled by some high energy particles though electronic coupling. From the perspective of molecular collision dynamics, the cluster process which is similar to the chemical reactions is a competitive process between aggregation and separation of water molecule (Liu *et al.* 2000). Based on Kwak's theory (Kwak *et al.* 1991), the cluster process could be simplified as the process of cluster adsorbing their surface activated molecules, if the cluster radius is r at time t , the radius increment is dr after time dt , and the volume increments are $4\pi r^2 dr$ (the surface layer of cluster), and the number of activated molecules are ,

$$N = 4\pi r^2 dr / V_m \quad V_m = \frac{4}{3}\pi \left(\frac{d_m}{2}\right)^3 \quad (1)$$

in which V_m and d_m are effective volume and effective diameter of activated molecules respectively.

At the same time, if the nucleation rate is J_{nc} per unit time and unit volume, the number of activated molecules at unit length along the radial direction during a give time dt are,

$$N = 4\pi r^2 (J_{nc} \times 1m) n_c dt = 4\pi r^2 J_s n_c dt \quad (2)$$

where n_c is the number of activated molecules of each cluster.

Because dr and dt are only two different expression way, thus, (1) is equal to (2), that is,

$$\frac{dr}{dt} = J_s n_c V_m \quad (3)$$

Because J_s is only related to temperature, thus,

$$\int_0^r dr = \int_0^t J_s n_c V_m dt \quad (4)$$

$$r(t) = J_s n_c V_m t \quad (5)$$

2.2 Pressure Changes During Water Molecule Nucleation Process in Wood Vacuum Drying

The cluster would compress its surrounding liquid with the increase of volume. To the surrounding liquid, Soave-Ridlich-Kwang equation which is suitable for calculating the polar substances, quantum fluids and saturated liquid density is applied to study on pressure changes (Chen *et al.* 2008), that is,

$$p = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)} \quad (6)$$

where,

$$a(T) = a_c \cdot \alpha(T) = 0.42748 R^2 T_c^2 / P_c \cdot \alpha(T) \quad (7)$$

$$b = 0.08664 R T_c / P_c \quad (8)$$

$$\alpha(T) = \left[1 + m \left(1 - T_r^{0.5} \right) \right]^2 \quad T_r = \frac{T}{T_c} \quad (9)$$

$$m = 0.480 + 1.574 \omega - 0.176 \omega^2 \quad (10)$$

ω is acentric factor

According the tables (Chen *et al.* 2008, $T_c=647.3$, $p_c=22.05$, $\omega=0.344$)

Combining eqs. (7) ~ (10) yields,

$$a(T)=0.924, b=0.21146 \times 10^{-4}$$

Thus, the pressure change is

$$\frac{\partial p}{\partial v} = -\frac{RT}{(V-b)^2} + \frac{a(T) \cdot (2V+b)}{[V(V+b)]^2} \quad (11)$$

$$V = \frac{4}{3} \pi r^3 = \frac{4}{3} \pi (J_s n_c V_m t)^3 \quad (12)$$

$$dV = 4\pi (J_s n_c V_m)^3 t^2 dt \quad (13)$$

$$\frac{\partial p}{\partial t} = \left[-\frac{RT}{(V-b)^2} + \frac{a(T) \cdot (2V+b)}{[V(V+b)]^2} \right] \cdot 4\pi(J_s n_c V_m)^3 t^2 \quad (14)$$

$$\int_{p^\infty}^p dp = \int_0^t \left[-\frac{RT}{(V-b)^2} + \frac{a(T) \cdot (2V+b)}{[V(V+b)]^2} \right] \cdot 4\pi(J_s n_c V_m)^3 t^2 dt \quad (15)$$

$$\Delta p = \frac{1}{3} \left[-\frac{RT}{(V-b)^2} + \frac{a(T) \cdot (2V+b)}{[V(V+b)]^2} \right] \cdot 4\pi(J_s n_c V_m)^3 t^3 \quad (16)$$

2.3 Critical Dimension Calculation When Normal Nucleate Boiling Occurs During Drying

2.3.1 Calculation of propagation velocity of pressure field when water clustering

Following the SRK equation (Chen *et al.* 2008), the state equation of water inner wood can be described as follows :

$$p = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)} \quad (6)$$

Therefore, the propagation velocity of pressure field is

$$c^2 = \frac{dp}{d\rho} = \left(\frac{V}{V-b} \right)^2 \cdot RT - \frac{2Va(T) + ba(T)}{(V+b)^2} \quad (17)$$

2.3.2 Determination of constants of pressure disturbance model

According to nucleation dynamics theory (Frenkel *et al.* 1946), the nucleation rate of cluster with n particles is

$$J_n = N \cdot D_n \cdot Z_f \cdot \exp\left(-\frac{F_n}{KT}\right) \quad (18)$$

where,

N is particle density, $Z_f = \left[-\frac{1}{2\pi KT} \left(\frac{\partial^2 F_n}{\partial n^2} \right) \right]^{1/2}$ is non-equilibrium factor,

D_n is collision rate between water molecule and cluster A_n ,

F_n is free energy of cluster

$D_n = \frac{1}{4} \beta \bar{v} \bar{n} A_n$ β is volumetric coefficient \bar{v} is mean velocity of molecular

$\bar{v} = \left(\frac{8KT}{\pi m} \right)^{1/2} \exp\left(-\frac{\Delta H_f}{RT_f}\right)$ ΔH_f is dissolution enthalpy

$\bar{n} = N \cdot \exp\left(\frac{\Delta H_{vap}}{RT}\right)$ \bar{n} is activated molecule density, ΔH_{vap} is Vaporization Enthalpy

According to Lienhard and Kanimi (Lienhard *et al.* 1981),

$$\frac{F_n}{KT} \cong 13.0 \quad (19)$$

While the density N of typical liquid molecules is equal to $10^{21}/\text{cm}^3$ and $D_{nc}Z_f$ is equal to $10^7/\text{s}$, thus,

$$J_{nc} = N \cdot D_n \cdot Z_f \cdot \exp\left(-\frac{F_n}{KT}\right) = 10^{21} \cdot 10^6 \cdot 10^7 \cdot e^{-13} = 2.26 \times 10^{28} \quad (20)$$

Suppose the liquid molecules arrangement is a face-centered cubic structure (Zhang *et al.* 2006), so,

$$\frac{\pi}{6} d_m N = V_m N = 0.7045 \quad (21)$$

and

$$V_m = 0.7045 \times 10^{-27} \text{ m}^3 \quad (22)$$

Supposed that the radius of the moisture migration pipeline within wood is r during the drying process, the time that pressure pulse δp reflecting back to cluster can be estimated to be

$$\tau \propto \frac{2r}{c} \quad (23)$$

When τ is less than the nucleation time τ_i ($\tau_i=10\mu\text{s}$ (Skripov 1974)), pressure pulse δp would stop from the producing of larger cluster, thus, the critical radius (CR) of pipeline when there is no nucleation is

$$r \leq \frac{1}{2} c \tau_i \quad (24)$$

The pressure chosen in the wood vacuum drying process were 0.01MPa and 0.02MPa and the temperatures were 50°C, 60°C, 70°C, 80°C, 90°C and 100°C respectively, V was got from tables (Chen *et al.* 2007), and n_c is equal to 10. Combining eqs. (16)~(24), a series of dates in table 1 were got,

Table 1 : The critical radius (CR) of pipeline, propagation velocity of pressure field and pressure pulse value table

0.01MPa					0.02MPa				
T[°C]	V[m ³ /kg]	C[m/s]	CR[μm]	δp*10 ⁹ [Pa]	T[°C]	V[m ³ /kg]	C[m/s]	CR[μm]	δp*10 ⁹ [Pa]
50	15.16	51.83	259.16	197.53	---	---	---	---	---
60	15.64	52.63	263.14	191.34	60	7.797	52.6269	263.13	771.22
70	16.11	53.41	267.06	185.75	70	8.038	53.411	267.06	746.11
80	16.58	54.18	270.92	180.48	80	8.277	54.1838	270.92	724.15
90	17.06	54.95	274.73	175.29	90	8.515	54.9457	274.73	703.62
100	17.53	55.7	278.49	170.59	100	8.751	55.6972	278.49	684.52

It can be seen from table 1 that the critical radius which varies in the range of 259.16~274.13 μm increased as temperature increased, while pressure hardly influence the critical radius. The pressure pulse which could drive the moisture inside wood moving out also exist during wood vacuum drying.

Wood is a complex porous material. Vessels, tracheid, and pit are main passageway for water getting out of wood during drying process. The existing researches (John 1984) indicate that the vessel diameter of most broadleaved tree varies from 20 to 100 μm ; tracheid diameter in the range of 20~30 μm and pit diameter is much smaller. All of these values are much smaller than the smallest critical radius which is about 259.16 μm , therefore the microchannel in wood is smaller than the “evaporation space” and there is no normal nucleate boiling but fictitious boiling phenomenon existing when wood vacuum drying.

3. STUDY ON THE MOISTURE EVAPORATION OF TIMBER BOUNDARY LAYER DURING THE VACUUM DRYING PROCESS

Water potential can be used as driving force for vapor phase and liquid phase which includes bound water and free water in wood (Siau 1984)

$$\psi_s = \psi_1^0 + \frac{RT}{18\text{cm}^3 / \text{mol}} \text{Lnh} \quad (25)$$

$$\psi_1^0 = 23.77t + 0.018t^2 \quad (26)$$

where,

t is centigrade temperature, ψ_1^0 is saturated vapor pressure potential of pure water ,

h is relative vapor pressure, R is equal to 1.987cal/mol

There may be boiling phenomenon only when the temperature reaches 100°C in conventional drying, while in the vacuum condition, because the actual pressure is below atmospheric pressure, in the case of a relatively low temperature, the moisture could easily reach boiling point. Even though there will not normal nucleate boiling occur internal wood during drying process because the microchannel in wood is much smaller than the “evaporation space”, when the moisture moves to the wood surface, as the vaporization space increases greatly, a large number of water bubbles appeared in an instant. Saturation vapor pressure is only related to the temperature according to the equation of saturation vapor pressure (Siau 1984),

$$P_0 = 8.75 \cdot 10^7 \exp(-10400/RT) \quad (27)$$

According to the Laplace equation (Zhang *et al.* 2008), the internal pressure of bubble is,

$$P = P_0 + 2\gamma / r \quad (28)$$

where

γ is surface tension coefficient, r is radius of bubble

While the radius r of bubble is very small under vacuum condition which made h very high, so in the vacuum state, the water potential within the timber is far greater than the conventional drying's, which leads to the vacuum drying rate much faster than that of conventional drying.

4. CONCLUSION AND DISCUSSION

(1) Because the microchannel in wood is much smaller than the critical radius which is one of the most important factors to induce normal nucleate boiling, therefore there is no normal nucleate boiling but fictitious boiling phenomenon existing when wood vacuum drying.

(2) There is a certain degree of pressure pulse during the nucleation process internal wood during the drying process, which drove the moisture inside the wood moving to the outside.

(3) Because the pressure was low during the vacuum drying process, when the moisture moves to the wood surface, as the vaporization space increases greatly, a large number of water bubbles with small radius and high water potential appeared in an instant, making the vacuum drying rate much faster than that of conventional drying.

(4) Only theoretical derivation has been done in this paper, experimental study should be done in the future.

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