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Nonisothermal moisture movement in wood

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Abstract In order to analyze the effect of temperature gradient on moisture movement during highly intensive drying, such as microwave-vacuum drying, the profile of the temperature and moisture content in sealed wood whose opposite faces were subjected to temperature gradient for a short time was measured. The ratio of the moisture content (MC) gradient to the temperature gradient (dM/dT) was calculated and the factors influencing moisture movement under nonisothermal conditions were discussed. The results indicate that moisture moved in wood from the warm surface to the cold one even if opposite faces of the sealed wood assembly were exposed continuously to different but constant temperatures for a short period. The moisture content on the cold surface was higher than that on the warm surface. The moisture content gradient opposite to the temperature gradient was established, and the dM/dT was below $0.9\%/^{\circ}\text{C}$. The temperature in the sample and the distance from the hot surface of the sample was strongly linearly correlated. With an increase in temperature, initial moisture content and experimental time, the dM/dT was significantly increased.

Keywords nonisothermal moisture movement, temperature gradient, moisture content gradient, wood

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1 Introduction

Wood drying is a complex industrial operation involving coupled heat and mass transfer, so it is very essential to utilize a mathematical model based on the mechanisms of heat and mass transfer for predicting the drying time and the distribution of temperature and moisture within wood, and realize the optimal control of the entire drying process. Over the years, the mechanism of moisture movement through wood has been extensively studied because of its fundamental importance in understanding the behavior of wood during processing and some theoretical models have been proposed (Mujumdar, 1987; Ni et al., 1999; Tien and Mujumdar, 2001; Yi et al., 2003a, 2003b). In convective hot air drying, people generally agree that the diffusion model based on Fick's second law of diffusion can be used to quantify nicely the drying process of wood. In the model, the flow of heat and the flow of mass through have been treated essentially as independent processes without considering the coupling between mass and heat flow. That is to say, the mass transfer due to temperature gradient (known as thermal diffusion or Soret effect) and the heat transfer due to moisture gradient (known as Dufour effect) have not been taken into account in the Fick's model. However, the traditional Fick's model failed in giving nice result for quantifying the drying process of wood during highly intensive drying, such as microwave drying, high frequency drying and microwave-vacuum drying. So, many researchers suggested that in order to analyze the mechanism of moisture movement in wood, such as microwave-vacuum drying, the effect of temperature gradient on moisture movement should be taken into consideration (Perre and Turner, 1999; Demirel and Sandle, 2001; Joseph and Peralta, 2001; Jumah and Raghavan, 2001; Hartnett and Minkowycz, 2002). However, different opinions have been expressed concerning the significance of temperature gradient on moisture movement in wood. Some researchers believe that the moisture transfer due to temperature gradient is so small in wood that it can be ignored in practice, and even do not accept the concept of thermal diffusion (Bramhall, 1979; Nelson, 1986).

In the past few decades, some studies have been con-

ducted to investigate whether thermal diffusion occurs or not, and the effect of thermal diffusion to moisture movement in wood (Choong, 1963; Quarles and Erickson, 1990; Peralta and Skaar, 1993). Studies have shown that thermal diffusion does exist in wood subjected to constant temperature gradient over a period of time (beyond 5 weeks), and the magnitude of thermal diffusion was related to temperature and moisture content (*MC*) of wood. The experiments required long time periods to achieve moisture equilibrium such that very few samples were analyzed and insufficient data were generated to thoroughly investigate the various theories of thermal diffusion. And, the whole drying process of wood during highly intensive drying is so rapid and intense, which can be computed by the order of hours or even minutes. There were few reports published concerning thermal diffusion in wood exposed to constant temperature gradient for short time periods.

The main purpose of this project was to investigate the temperature and moisture distribution in wood subjected to constant but different temperature for a short time, analyze the factors influencing thermal diffusion, and calculate the magnitude of thermal diffusion. At the same time, the research results would be beneficial to present a theoretical basis for explaining the mechanism of moisture movement and establishing a mathematical model of wood microwave-vacuum drying.

2 Materials and methods

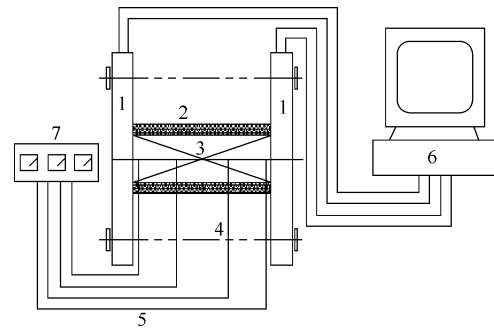
2.1 Material and sample preparation

Masson pine (*Pinus massoniana*) collected from Liuzhou City, Guangxi Province, was used for all the experiments in this study. Standard radial board with a thickness of 30 mm and a length of 2,000 mm, was slowly dried to below fiber saturation point (about 25%) in air, then the test samples of 24 mm×24 mm×24 mm were prepared. All samples except for those used to investigate the effect of *MC* on thermal diffusion were placed into a sealed glass bottle for one and a half month until they reached uniform initial *MC*.

2.2 Experiment and procedure

The experimental setup (Fig. 1) mainly consists of a heating system made of two independent bathing establishments and clamp device, four couples of NiCr-NiSi thermocouple with a diameter of 1 mm and an accuracy of 0.1°C, and a temperature data acquisition system.

The samples were sealed on all six faces with a resin sealer and aluminum foil overlay and heat-insulated at the four edges to prevent moisture and heat exchange with the surrounding environment. After the resin had cured (placed into a sealed glass bottle for two days), 4 holes with a depth of 12 mm were drilled in each sample in a direction perpendicular to the direction of moisture movement on tangential



1 bathing establishment, 2 insulating layer, 3 wood sample, 4 clamp device, 5 thermocouple, 6 computer, 7 data acquisition system

Fig. 1 Schematics diagram showing the setup for nonisothermal experiment

surface, and then the thermocouples were inserted into the holes for monitoring the temperature distributions in the samples. The slot between specimen and thermocouple was sealed with silicon resin, and four edges were coated with heat-insulated material (polythene), then the sample was clamped between two bathing establishment wherein opposing radial faces of the specimen were subjected to different but constant temperature (the temperature is higher in the left than that in the right).

The temperature readings at 4 different locations were recorded during the experiment every hour until the experiment was finished. After the final temperature readings at the four different thermocouple locations had been taken, the sample was quickly removed from the test assembly, the six faces test samples were then sawn to remove the resin sealer and foil layers, and cut into 11 or 12 halves with a sharp knife in the direction of moisture movement or heat conduction (tangential direction) from cold surface to warm surface. All of the halves were immediately weighted to the nearest 0.000,1 gram in an electric balance, and the distance from the new surface split by the sharp knife to the warm surface was measured. All wafer samples were placed in the oven at $103\pm 2^\circ\text{C}$ for at least 48 h to obtain the oven-dry weight, and the initial *MC* of each wafer sample was calculated. Three replications were performed for each experiment. Further information on the experimental procedures was detailed in Li and Zhang (2005).

3 Theoretical background

Skaar and Siau (1981) proposed an equation based on a gradient of activated moisture content to describe steady-state bound water diffusion in the transverse direction. Compared with Fick's law of diffusion, the equation is expressed with an additional term for thermal diffusion (Siau and Babiak, 1983; Siau and Jin, 1985). They considered that the moisture movement through wood in hygroscopic range involved two driving forces: moisture movement due to *MC* gradient and moisture movement due to temperature gradient. The equation can be expressed as:

$$J = -\frac{K_m M}{RT - M \partial E_b / \partial M} \left[\frac{E_b}{T} \frac{dT}{dX} + \frac{RT - M \partial E_b / \partial M}{M} \frac{dM}{dX} \right] \quad (1)$$

where J is flux ($\text{g}/(\text{cm}^2 \cdot \text{s})$), K_m bound-water conductivity coefficient based on an MC gradient ($\text{g}/(\text{cm} \cdot \text{s} \cdot \%)$), M moisture content (%), T Kelvin temperature (K), R universal gas constant ($8.37 \text{ J}/(\text{mol} \cdot \text{K})$), E_b activation energy of bound water (J/mol).

E_b decreases approximately linearly with MC between values of 5% and 25%, which can be calculated as (Siau, 1984):

$$E_b = 9,200 - 70M \quad (2)$$

Substituting Eq. (2) into Eq. (1), it produces:

$$J = -\frac{K_m M}{RT + 70M} \left[\frac{9200 - 70M}{T} \frac{dT}{dX} + \frac{RT + 70M}{M} \frac{dM}{dX} \right] \quad (3)$$

As shown in Fig. 1, when a steady-state condition is attained in wood subjected to constant temperature gradient, the profiles of moisture and temperature in wood are established and will remain constant with time, and the net moisture flux is 0. There will be no further net moisture flux in wood since the moisture flow from the left to the right due to temperature gradient will be offset by moisture flow from the right to the left due to moisture gradient. So Eq. (3) can be abbreviated as:

$$\frac{dM}{dT} = -\frac{9200 - 70M}{\frac{RT^2}{M} + 70T} \quad (4)$$

According to Eq. (4), in the hygroscopic range (and $M \neq 0$), keeping the equilibrium of temperature and moisture in wood exposed to constant temperature gradient for a long time, the value of dM/dT at different locations in samples is not equal to 0, which indicates that the temperature gradient in wood can cause moisture movement (thermal diffusion), and the direction of temperature gradient is opposite to that of the MC gradient. That is to say, moisture can move through wood from high to low MC zones if a reverse temperature gradient of sufficient magnitude is maintained in the wood.

4 Results and discussion

Considering the fact that the period of highly intensive drying methods, such as microwave-vacuum drying and high frequency drying is usually less than 12 h, the experimental time in this study is set for 12 h except for the samples used to measure the effects of experimental time on thermal diffusion. The moisture and temperature profiles in wood based on the experimental data are illustrated in Figs. 2, 3 and 4.

Experiments indicate that the new constant temperature field in wood whose opposite faces are subjected to constant but different temperatures will be established in about 1–2 h after experiments start because of rapid heat transfer. A strong linear relationship with correlation coefficient of at least 0.99 exists between temperature and distance from the warm surface (X) at different locations in all linear regres-

sion runs. The data of MC and distance were fitted exponentially or logarithmically due to the different experimental time. The results shown in these figures indicate that the MC increase with the decline of temperature from warm to cold surface. The direction of MC gradient is opposite to that of temperature gradient, which testifies to the occurrence of thermal diffusion in wood even if the samples were subjected to constant temperature gradient for only a short time. The magnitude of thermal diffusion can be obtained directly by taking the ratio of the derivatives dM/dX and dT/dX of the MC and temperature regression equations.

4.1 Effect of temperature on dM/dT

In order to investigate the effect of temperature on thermal diffusion, an experiment was carried out in which wood samples with an initial MC ranging from 15.24% to 15.57% were subjected to constant temperature difference (40°C) or the same temperature gradient but different cold side and warm side temperature ($62^\circ\text{C}/22^\circ\text{C}$, $72^\circ\text{C}/32^\circ\text{C}$, $82^\circ\text{C}/42^\circ\text{C}$) for 12 h. Figure 2 shows that at a higher temperature, there is a higher MC in the wood cold surface and lower MC in the wood warm surface, which results in a higher a moisture gradient within the wood. At the same time, with the increase of temperature, the temperature gradient nearly remains constant within samples. Thus, at a given MC , with the increase in temperature, the dM/dT ratio is higher and the thermal diffusion is more significant.

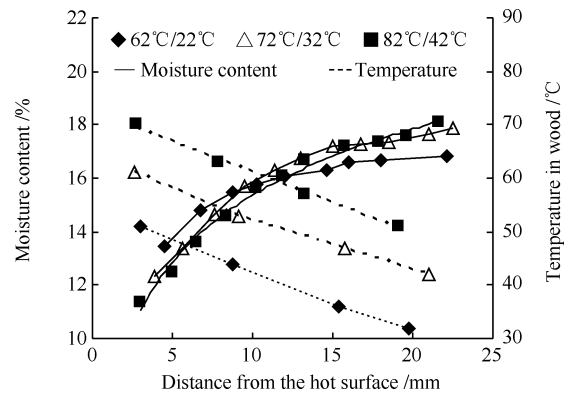


Fig. 2 Temperature and MC distributions in samples for different temperatures

For the different cold side and warm side temperature ($62^\circ\text{C}/22^\circ\text{C}$, $72^\circ\text{C}/32^\circ\text{C}$, $82^\circ\text{C}/42^\circ\text{C}$), the dM/dT ratios are 0.219, 1, 0.380, 6 and 0.435, 6%/°C, respectively, which shows temperature is an important factor affecting thermal diffusion. The reason for this is that at a higher temperature, a greater fraction of water molecules has enough energy to overcome the potential barrier that keeps them bound to a particular sorption site to move through wood (Choong, 1956), and the ratio of movement is directly proportional to the number of molecules with energy in excess of the bonding energy (Peralta and Skaar, 1993). Therefore, the thermal diffusion is more significant, and the dM/dT ratio

significantly increases with the increase of wood temperature at the same experimental condition.

4.2 Effect of MC on dM/dT

The distributions of temperature and moisture in samples with different initial MC , subjected to the same warm surface temperature (62°C) and cold surface temperature (22°C), is shown Fig. 3. From the figure, it can be seen that with the increase in initial MC , the difference of MC increases between near the warm surface and near the cold surface, but the temperature gradient remains constant. Thus, the thermal diffusion is more significant, and the dM/dT ratio is higher.

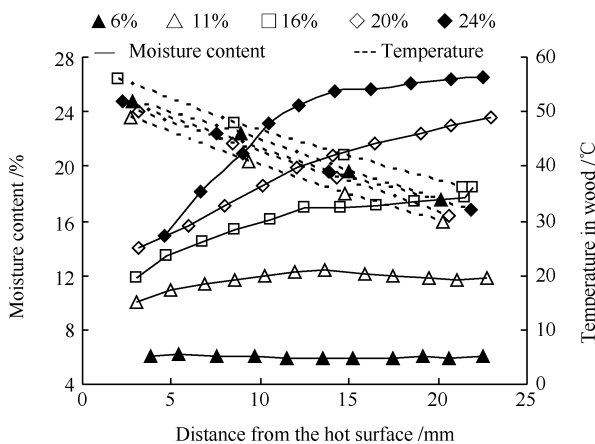


Fig. 3 Temperature and moisture content distributions in samples for different initial moisture contents

From Dent water sorption theory (Dent, 1977; Skaar, 1982; Zhao, 2002), sorption water within wood is presumed to be adsorbed in two forms, i.e., “primary” molecules adsorbed directly on primary sorption site (hydroxyl groups) with high binding energy within the cell wall, and “secondary” molecules adsorbed on secondary sites exhibiting lower binding energy. At low MC s below 10%, most of the sorption water molecules are primary molecules, which exhibits higher binding energy adsorbed tightly on primary sorption sites. Thus, it is very difficult for these water molecules to move through wood. In this experiment, the thermal diffusion almost cannot be found in samples whose initial MC is about 6%. With the increase in MC , the fraction of secondary sorption water with less binding energy will increase. Thus, at higher MC s, a greater fraction of sorption water molecules have enough energy to escape from sorption sites and move from the hot surface to the cold surface through wood, and a higher dM/dT ratio is achieved.

For these samples with five different initial MC levels (6%, 11%, 16%, 20%, 24%), the dM/dT ratios are 0.011,2, 0.090,6, 0.356,9, 0.579,6 and 0.881,2%/°C, respectively. Therefore, the higher the average initial MC of wood is, the more significant thermal diffusion and the greater dM/dT ratio are.

4.3 Effect of experimental period on dM/dT

In order to know more about the effect of experimental time on temperature field, MC s filed and thermal diffusion, an experiment was carried out in which wood samples with an initial MC from 13.18% to 13.70% were subjected to a constant temperature of about 62°C on one end of the sample and of about 22°C on the opposite end for 12 h, 24 h, 36 h and 48 h. As shown in Fig. 4, for the different experiment period, the temperature and distance (X) still keep a strong linear relationship, and the temperature at different locations within samples remains constant with time. This result reveals that a new constant temperature field can be established in a relatively short time due to fast heat conduction within samples when the two opposite faces of a sample are suddenly exposed to two different but constant temperatures. This experimental result agrees well with previous research (Peralta and Skaar, 1993). On the other hand, the moisture distributions will continue to change slowly with time. With the increase of the experimental period, the moisture distribution with a higher MC near the cold surface and a lower MC near the warm surface in the sample will be established, and the thermal diffusion is more significant. For the four different experimental periods (12, 24, 36 and 48 h), the corresponding dM/dT ratios are 0.161,6, 0.233,3, 0.246,8 and 0.350,4, respectively.

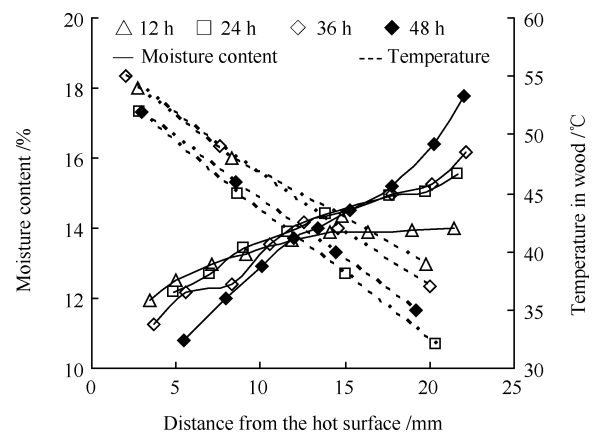


Fig. 4 Temperature and moisture content distributions in samples for different experimental periods

The regression analysis shows that the relationship between MC distribution within wood and the distance from the warm surface (X) will change from logarithmical to exponential form with the increase of the experimental period. For the experiment conducted within 24 h, the MC distribution within wood can be better fitted to a logarithmical equation, and the square of regression coefficient is above 0.96. For the experiment conducted for 48 h, the MC distribution within wood can be fitted to an exponential equation with a square of regression coefficient of 0.95.

5 Conclusions

On the basis of this work the following conclusions can be drawn:

1) Moisture can move through wood against the moisture gradient even if the samples were subjected to constant temperature gradient for only a short time. The direction of *MC* gradient is opposite to that of the temperature gradient, and the dM/dT is below $0.9\%/^{\circ}\text{C}$.

2) The new constant temperature profile in wood whose opposite faces are subjected to constant temperature gradient is reached within a short time of about 1–2 h. The temperature and distance from the warm side is strongly linearly correlated. However, the *MC* profile required very long periods to achieve a new steady-state condition, and the relationship between *MCs* at different locations and distance from the warm side changes from logarithmical to exponential form according to the experimental period.

3) The magnitude of thermal diffusion is closely related to the temperature, initial *MC* and experimental period. The thermal diffusion is more significant and the dM/dT ratio increases with the increase of temperature, initial *MC* and experimental period.

Only the effect of the three factors of temperature, wood initial *MC* and experimental period on thermal diffusion have been discussed in this work. The effect of other factors, such as temperature gradient, species and grain direction, on thermal diffusion will be discussed in the future.

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