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RESEARCH ARTICLE

Fundamental characteristics of microwave explosion pretreatment of wood I. properties of temperature development

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Abstract In this study, the effects of microwave radiation intensity, radiation time and initial wood moisture content (MC) on the properties of temperature development in *Eucalyptus urophylla* wood samples during the microwave explosion pretreatment have been investigated using a new microwave pretreatment equipment. The results show that 1) with the increase of microwave radiation intensity and a decrease in initial wood MC, both the average temperature and its rate of increase in wood rise rapidly; 2) with an increase in microwave radiation time, the average temperature of wood clearly increases, while the rate of increase in temperature shows a decline. In the microwave explosion pretreatment, the temperature development curve presented two patterns of variation: i) a sharp increase in temperature − a constant temperature − a slow warm-up and ii) a sharp increase in temperature − a rapid decline in temperature − a slow warm-up.

Key words microwave, pretreatment, temperature, wood

1 Introduction

Microwave explosion pretreatment as a novel technology for wood modification has been evaluated in recent years for different purposes by several scientists. The main process of the microwave explosion pretreatment includes treating green wood in a high intensive microwave electromagnetic field over a very short time. The moisture inside wood vaporizes quickly and the water steam creates a large internal vapor pressure within wood cells. Under high internal pressure the weaker elements of wood structures, such as thin-walled cells and pit membranes, are ruptured to form many pathways for easy transportation of liquids and vapors through wood, which can be used to increase permeability and the rate of drying in hardwoods, improve drying quality and even produce new composite products.

Torgovnikov and Vinden (2000, 2001) reported that after high intensive microwave treatment, the volume of eucalyptus (*Eucalyptus urophylla*) lumber could be increased by 13.4%, the absorption of preservative could be increased 10–14 times, the modulus of elasticity of wood decreased by 12–17%, the qualified rate of wood drying increased by more than 5% and the drying rate increased 5–10 times. They developed three types of wood microwave treatment equipment, with operating frequency in two bands of 0.922 and 2.45 GHz, two rated microwave input power levels of 60 and 300 kW and 1 to 3 microwave sources. The maximum dimensions of pretreated wood are as follows: length 4.7 m, width 200 mm and thickness 300 mm (Torgovnikov and Vinden, 2004, 2005, 2006). Harris et al. (2008) found that there was a significant reduction in surface checking both in the number and depth of messmate stringy-bark microwave-modified boards, compared to control boards. In addition, some new composite products can be made from wood modified by high intensive microwave energy and then impregnated with resin (Simon et al., 2007). Liu et al. (2005) treated larch wood with high intensive microwaves under different radiant intensities and times. The results showed that under suitable conditions of microwave treatment, the permeability of larch wood can be significantly improved without noticeably decreasing the MOR and MOE of the wood. The radial parenchyma and some pit membranes were ruptured and microscopic cracks were formed in cell walls. Zhou et al. (2009) presented some methods to pretreat eucalyptus wood by high intensive microwaves from the aspect of stress relaxation and damage of microscopic structures of wood. They pointed out that the rate of drying and quality of eucalyptus wood in subsequent conventional hot-air drying could be greatly improved after the wood was pretreated by microwaves, given the proper pretreatment process, without significantly affecting the mechanical properties of treated wood.

These previous studies indicate that microwave pretreatment is a novel technology with a good pros-

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pect for applications; however, the technology is not yet widely accepted in the wood processing industry. This can be largely explained by insufficient knowledge of the complex interactions between material and process parameters during microwave pretreatment, except for production costs. Recently, some studies on the mechanism of microwave pretreatment have been conducted by Li et al. (2005) and Zhou et al. (2009). However, only a limited number of research results on this subject have been reported so far.

Because the steam in cell cavities of wood with high moisture content (MC) (above fiber saturation point) is considered to remain in a saturated state and its pressure equals the saturated pressure at its corresponding temperature during microwave or radio frequency heating (Liu et al., 2006; Cai and Kazuo, 2007), understanding the temperature development of wood during microwave pretreatment is particularly important in order to explain correctly the internal pressure development relating to the deformation and damage of cell walls in wood cells. The motivation of this study was to investigate the temperature development of *E. urophylla* wood samples pretreated in a high intensive microwave electromagnetic field using the new microwave pretreatment equipment. Such an investigation could become the basis for further research of internal pressure development within wood and the mechanism of microwave explosion pretreatment.

2 Materials and methods

In order to investigate the temperature development during microwave explosion pretreatment, a series of experiments were carried out on green *E. urophylla* plantation wood samples with the following dimensions: 22 mm (width) × 22 mm (thickness) × 57 mm (length), using the new microwave pretreatment equipment, as shown in Fig. 1. It provides a maximum power output of 3 kW, operating at a frequency of 2450 MHz and an average microwave intensity of 50.32 $W \cdot cm^{-2}$ in the microwave heating cavity.

Before the experiment, all specimens were divided into three groups in order to examine the effect of microwave radiation intensity, radiation time and initial wood MC on temperature development. There are five experimental levels with eight samples at each level in each group. A hole 20 mm deep with a diameter of 1 mm was drilled at the center of the end surface along the longitudinal direction of each sample. The samples were fixed in the microwave heating cavity and then an optical fiber temperature sensor was inserted into the hole to monitor and measure the temperature inside the specimens. The samples were treated in the equipment by turning the microwave on for different microwave radiation intensities and durations. Temperatures of the wood samples were intermittently

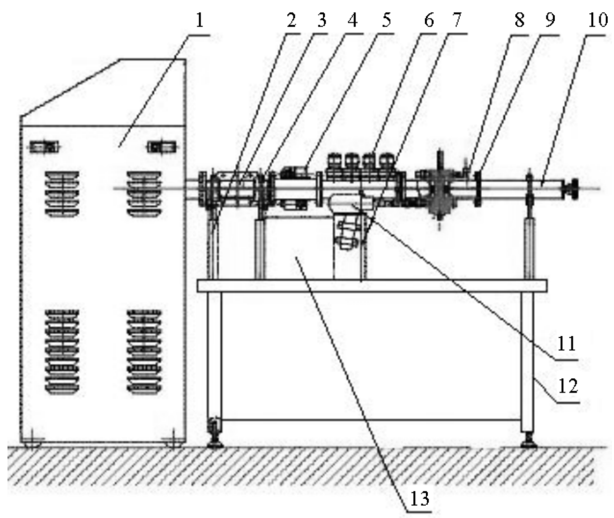

Fig. 1 Assembly diagram of microwave explosion pretreatment equipment. 1: microwave power source; 2 and 7: adjustable brackets; 3: water load; 4: microwave circumduction; 5: microwave coupling; 6: microwave modulator; 8: heating cavity; 9: bolt; 10: high powered short circuit plunger; 11: hot-air circulation system; 12: bracket; 13: electronic control cabinet.

auto-collected by the computer every second until the experiment was completed. Seven replications were carried out at each experimental level.

3 Results and discussion

3.1 Effect of microwave radiation intensity on temperature development

Figures 2 and 3 present the effect of microwave radiation intensity on temperature development and the rate of increase in temperature of wood with a moisture content of 70–80%, pretreated in a high intensive microwave field at five different microwave radiation levels (0.3, 0.4, 0.5, 0.6 and 0.7 A) and the same radiation time (80 s). In this study, the radiation intensity of the microwave equipment was adjusted by control of the input current. From the figures, it can be seen that the higher the microwave radiation intensity used on the pretreated wood, the higher the average final temperature of wood and the greater the rate of temperature increase. When the microwave radiation intensities were 0.3, 0.4, 0.5, 0.6 and 0.7 A, the average final temperatures and rates of increase in temperature of the eight samples were 111.9, 116.3, 118.5, 130.5, 138.8°C and 1.111, 1.170, 1.194, 1.344, 1.448 $°C \cdot s^{-1}$, respectively. An analysis of variance also showed that the effect of microwave radiation intensity on the average final temperature and rate of increase in temperature was significant. The reason for this is that with the increase of microwave radiation intensity more thermal energy, converted from mi-

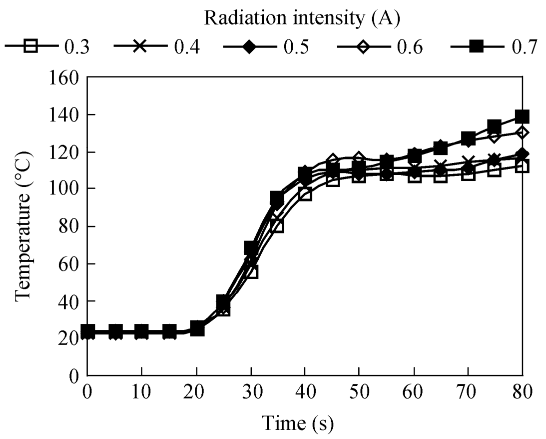

Fig. 2 Temperature curves of wood at different microwave radiation intensities

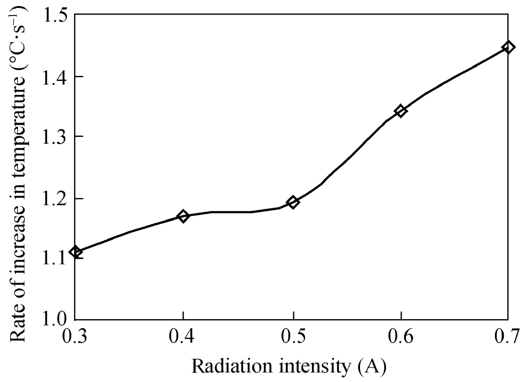

Fig. 3 Effect of microwave radiation intensity on rate of increase in temperature

crowave energy, can be used to increase the temperature in wood at the same time, which results in higher average final temperatures and rates of increase in temperature.

3.2 Effect of microwave radiation time on temperature development

The effect of microwave radiation time on temperature development and rate of increase in temperature of wood during microwave explosion pretreatment is shown in Figs. 4 and 5. Five microwave radiation time levels (40, 50, 60, 70 and 80 s) at the same microwave radiation intensity were used to pretreat wood with an initial moisture content of 70–80%. From Figs. 4 and 5, it can be seen that the longer the microwave radiation time, the higher the average final wood temperature. The rate of increase in temperature decreased in the first half of the treatment period (from 40–60 s) and remained almost constant during the last half of the period (from 60–80 s) of the microwave radiation time. In a previous study conducted in microwave drying, Li et al. (2008) found that the change of temperature during entire drying process could be divided into three periods: 1) a rapid warming-up drying period, in which most of the thermal energy, converted from microwave energy, is utilized for raising the temperature of wood; 2) a constant temperature period, in which the temperature remains relatively constant, where the absorbed microwave energy is balanced by energy losses associated with moisture evaporation and surface convection cooling; 3) a heating up period, in which the temperature of the wood rises gradually. In our study, the first 40 s after the start of the experiment belongs to the rapid warming-up period, where the temperature of the wood increased rapidly. Within the range of 40–60 s, the temperature of wood remained almost constant, which is similar to the constant temperature period in wood microwave drying. After 60 s, the temperature of the wood increased slowly, similar to the third stage in wood microwave drying. Therefore, in this study, for the entire microwave pretreatment process, the rate of increase in the temperature of wood decreased in the first half of the

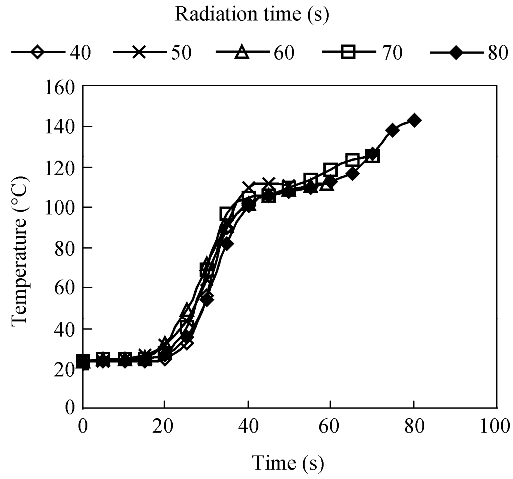

Fig. 4 Temperature curves of wood as a function of microwave radiation time

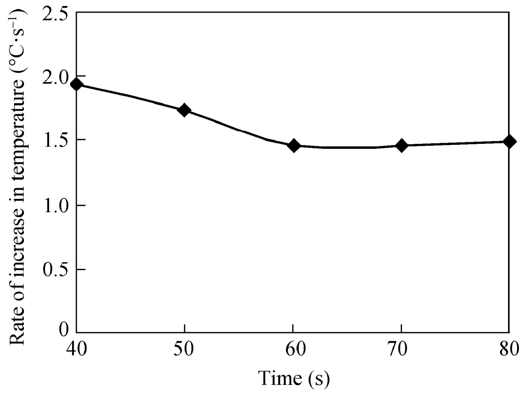

Fig. 5 Effect of microwave radiation time on rate of increase in temperature

period (from 40–60 s) and remained constant during the second half of the period of microwave radiation time. With microwave radiation times of 40, 50, 60, 70 and 80 s, the average final temperatures and rates of increase in temperature of the eight samples were 101.7, 110.6, 111.6, 125.8, 142.9°C and 1.945, 1.733, 1.456, 1.452, 1.488 °C·s^{-1}, respectively. Here as well, the analysis of variance showed that the effect of microwave radiation time on the average final temperature and rate of increase in temperature was significant.

3.3 Effect of initial moisture content on temperature development

A series of experiments were carried out to investigate the effect of initial MC on temperature development and rates of increase in the temperature of wood pretreated in a high intensive microwave field. In these test series, 40 green wood samples with an initial MC of about 100% were conditioned to five different levels, i.e., to about 20%, 40%, 60%, 80% and above 80% before the experiment. The microwave radiation intensity was 0.7 A and the length of treatment 60 s. The experimental results are presented in Figs. 6 and 7. It can be seen that the final average temperature and rate of increase in temperature increase with the decrease in initial MC of wood samples. This can be explained by the fact that at the same microwave radiation intensity and time, the higher the initial MC of wood, the lower the thermal energy absorbed per unit mass of moist wood, i.e., the average final temperature and rate of increase in temperature decrease. When the initial MC of samples were 23.87%, 41.35%, 62.59%, 84.31% and 97.38%，the average finial temperature of the samples were 181.0, 159.2, 136.3, 119.6, 114.3°C and the rates of increase in temperature were 2.631, 2.269, 1.890, 1.611, 1.520 °C·s^{-1}. And again, the analysis of variance showed that the effect of the initial MC of wood on the average final temperature and rate of increase in temperature was significant.

Our investigation also found that there are two different types of temperature development after the first 20 s of microwave power being switched on during the microwave explosion pretreatment (see Fig. 8). The first one, shown as type 1 in Fig. 8, can be divided into three periods: 1) a brief period of a rapid rise in temperature of the wood, because most of the thermal energy, converted from microwave energy, is mainly utilized for raising the temperature of the wood samples rather than for the evaporation of water; 2) a constant temperature period, in which a pretreatment process with a constant wood temperature is established and almost all of the thermal energy, converted from microwave energy, is used for evaporation of water; 3) a final warming-up period, in which some water is removed from wood, the microwave energy is used for evaporation of residual water and a slight increase in the temperature of wood. The second temperature development, shown as type 2 in Fig. 8, also consists of three periods: a period of rapid increase in temperature, a period of rapid deceleration in temperature and a final warming-up period. The first is the major type, with a probability of occurrence above 70% in our study. Compared with type 1, a very significant period of a rapid decrease in temperature is shown in type 2. The reason for this may be that the moisture inside wood vaporized quickly, the water steam created a large internal vapor pressure in wood cell lumens and formed a high tensile stress in cell

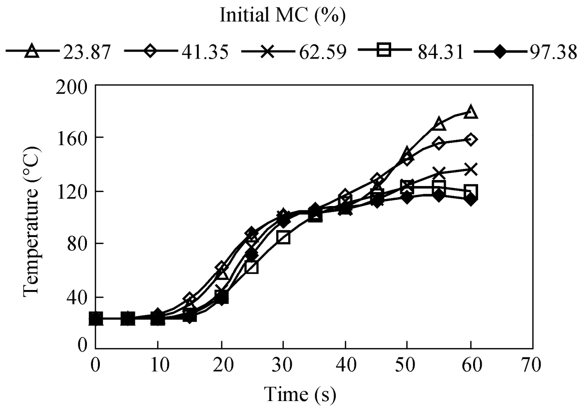

Fig. 6 Temperature curves of wood with different initial MC

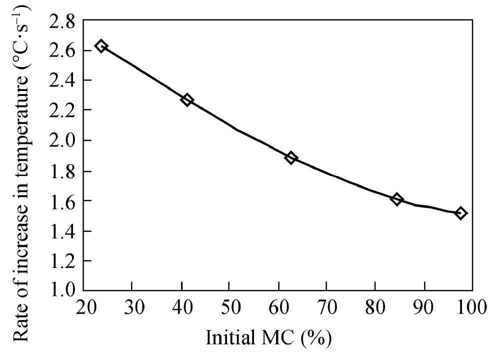

Fig. 7 Effect of initial MC on rate of increase in temperature

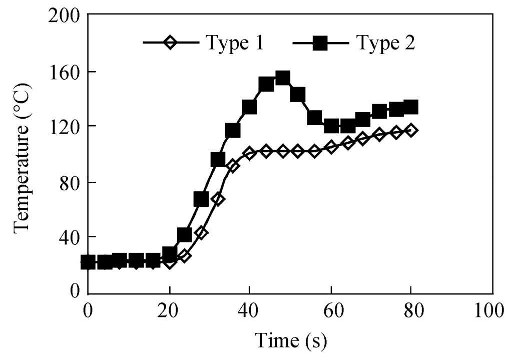

Fig. 8 Pattern of temperature change of wood during microwave explosion pretreatment

walls or intercellular layers.

When the tensile stress in cell walls or intercellular layers was higher than its tensile strength, some cracks generated in cell walls and intercellular layers and formed new pathways for easy transportation of liquids and vapor. The vapor inside the wood was quickly emitted and the internal steam pressure and its corresponding saturated temperature in wood decreased rapidly. Therefore, the temperature of the turning point between the periods of rapid increase in temperature and its rapid decrease can be seen as a critical temperature to form checks in wood samples.

4 Conclusions

In our study, a series of experiments were conducted to investigate the effect of microwave radiation intensity, radiation time and initial wood MC on temperature development of *E. urophylla* wood samples, using new microwave pretreatment equipment during microwave explosion pretreatment. The results show i) the higher the microwave radiation intensity and the lower the initial wood MC, the higher the average final temperature and rate of increase in the temperature of wood samples; ii) the longer the microwave radiation time, the higher the average final temperature and the lower the rate of increase in temperature; iii) analyses of variance have shown that the effect of microwave radiation intensity, radiation time and initial wood MC on the average final temperature and rate of increase in the temperature of wood was statistically highly significant; iv) temperature development presented the following two patterns: a rapid increase in temperature − a period of constant temperature − a period of slowly heating up; the second pattern shows first a period of a sharp increase in temperature − a period of rapidly decelerating temperature − a slow period of heating up. The temperature at the turning point between the period of rapidly increasing temperature and the period of rapid decrease in temperature can be seen as a critical temperature to form checks in wood samples.

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