Factors Affecting the Temperature Variation Rate of Bamboo during High-frequency Heating

Liang Ji,[a] Yanhe Liu,[b,c,]* Jianbo Zhou,[d,e,]* Yongjie Lei,[d,e] and Haiyun Feng [d,e]

High-frequency electromagnetic fields refer to electromagnetic waves with frequencies ranging from 100 kHz to 300 MHz. High-frequency medium heating has the advantages of uniform heating, rapid energy consumption, and environmental protection. While it has a wide range of applications, the use of high-frequency dielectric heating in the bamboo industry is rare. Understanding the influence of bamboo temperature rise rate in high-frequency heating could promote bamboo industry development. In this work, curved bamboo was tested with high-temperature energy for continuous heating. The influence of moisture content of bamboo, sample thickness, and high-frequency processing power on temperature rise rate were studied. The results showed that the water content of bamboo affected the temperature rise rate. The effect of high-frequency heating was highest when the moisture content of bamboo was close to 11%. The thickness of sample had little effect on the temperature rise rate, but the high-frequency power had a significant effect on the temperature rise rate. The temperature rise rate of the lower and higher frequency power levels increased slowly and was close to constant. The heating power was 11 kW, and the temperature rise rate was the highest.

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Contact information: a: China Forestry Press, Beijing, China, 100032; b: Central South University of Forestry and Technology School of Materials Science and Engineering, Changsha, Hunan, China, 410004; c: Market Supervision Administration of Yeji District, Lu'an City, Anhui, China, 237431; d: Harbin Research Institute of Forestry Machinery, State Forestry and Grassland Administration, Harbin, China, 150086; e: Key Laboratory Forestry of Electrical and Mechanical Engineering State Forestry and Grassland Administration, Harbin, China, 150086;
** Corresponding authors: liuyanhe0@126.com; zhoujianbol@126.com*

INTRODUCTION

High-frequency medium heating uses electromagnetic internal heating (Lyng *et al*. 2006; Tubajika *et al*. 2007). Bamboo billet was placed between parallel metal plates. When the high-frequency generator is operating, high-frequency waves are formed between the positive and negative plates (Inoue and Yamamoto 2004). In the alternating electromagnetic field, the polarized molecules and water molecules in the bamboo are polarized in the direction of the electric field; they heat up with the violent vibration and friction of the electric field, which is used to evaporate water and increase the temperature (Huang *et al*. 2013). High-frequency dielectric heating technology has greatly improved the bamboo processing industry (Kamke 2004; Kavazovic *et al*. 2010).

Bamboo is a porous, low thermal conductivity, natural composite composed of cellulose, hemicellulose, lignin, and a small amount of organic and inorganic substances. When bamboo is heated by an outside source, the internal temperature rise rate is low

(Korai *et al*. 2011). Bamboo is a dielectric substance with free ions and bound ions. There are a large number of polar groups, such as hydroxyl groups, in the amorphous regions of the cell wall (Hansson *et al*. 2006; Huang *et al*. 2006). In addition, bamboo has a large amount of water. When exposed to fields, molecules in the bamboo undergo directional polarization, which causes the bamboo to heat rapidly. The temperature rise rate of the high-frequency medium heating is determined by the dielectric constant and loss factor of the bamboo (Oloyede and Groombridge 2000; Zhao and Turner 2000; Koňas 2008). A higher dielectric constant and loss factor results in a higher rate of temperature increase. Because the dielectric constant of water is 30 to 40 times that of dry bamboo, the content and form of moisture in the bamboo is the main factor affecting the temperature rise rate of the high-frequency medium heating (PerrKe and Turner 1997). At high electric field density, when the moisture content of bamboo is 9% to 12%, the dielectric constant and loss coefficient are higher as the water content increases, but the temperature rise rate is lower. As the water content increases to the range 12% to 15%, the dielectric constant and loss coefficient increase, and the temperature rise rate increases slowly. For a wood moisture content of 9%, curved bamboo can be heated to 60 °C in 190 s under high-frequency heating. It can reach 76 °C in 260 s, and the temperature can also affect the dielectric constant of wood. When the water content is low, the dielectric constant increases with increasing temperature during heating. However, for bamboo with a high water content, since the medium relaxation frequency is close to the relaxation frequency of free water, the dielectric constant decreases with increasing temperature (Evon *et al*. 2014). When the temperature of the bamboo with different water content reaches a certain level, it may cause a change in the temperature rise rate.

Bamboo is a porous material composed of ducts and wood fibers. When a porous material such as bamboo is heated under the electric field generated by the high-frequency generator, the surface of the bamboo has the largest electromagnetic wave energy density, and the electromagnetic wave can penetrate to the center of the bamboo (Mati-Baouche *et al*. 2012; Kochetkova *et al*. 2013). When it penetrates inward, the electromagnetic wave energy decreases exponentially. The medium releases energy. The thickness of the electromagnetic wave penetration high-frequency electric is limited; the depth of penetration depends on the frequency of the electromagnetic wave, and the thicker bamboo load requires a lower frequency for deep penetration (Sakai *et al*. 2003).

To achieve rapid and uniform heating of bamboo under high-frequency electric field, it is necessary to determine the appropriate heating method. This study explored the influence of moisture content, thickness, and high-frequency power on the temperature rise rate of bamboo (Antti *et al*. 2000; Resch 2003).

EXPERIMENTAL

Materials and Equipment

These bamboo samples were from Hailihong Bamboo Industry Co., Ltd. in Yiyang City, Hunan Province. The raw material was local *Phyllostachys edulis*, which was 3 to 5 years old. The water content of the raw materials was approximately 30%. After being segmented, broken, rough milled, and dried, it was finely milled into 440 mm high, 41 mm wide, and 5 mm thick bamboo pieces. These samples were immediately wrapped in plastic film and stored in a cool room to prevent moisture loss. Table 1 lists the size and number of experimental materials. The experimental equipment was comprised of a GJ-15-6B-I type high-frequency generator and GJB-PI-51B-JY type high-frequency hydraulic machine of Jiyuan Electric Co., Ltd., Shijiazhuang Development Zone, Hebei Province, China. The high-frequency generator has a power of up to 15 kw for continuous or intermittent heating. The laboratory equipment comes with a system that records changes in heating time and temperature of the recorded material. Figure 1 shows a schematic diagram of a high-frequency generator and a hydraulic press, as well as the locations for measuring the internal temperature of bamboo (bamboo shown in green). During the test, the frequency was maintained at 6.78 MHz. A hydraulic press matching 0.3 m × 0.5 m parallel plate was used to maintain the stability of bamboo between two parallel plates. The temperature was continuously monitored and recorded using a fiber optic temperature sensor (YT-PL-01-3000, Photon Control, Inc., Burnaby, BC, Xi'an).

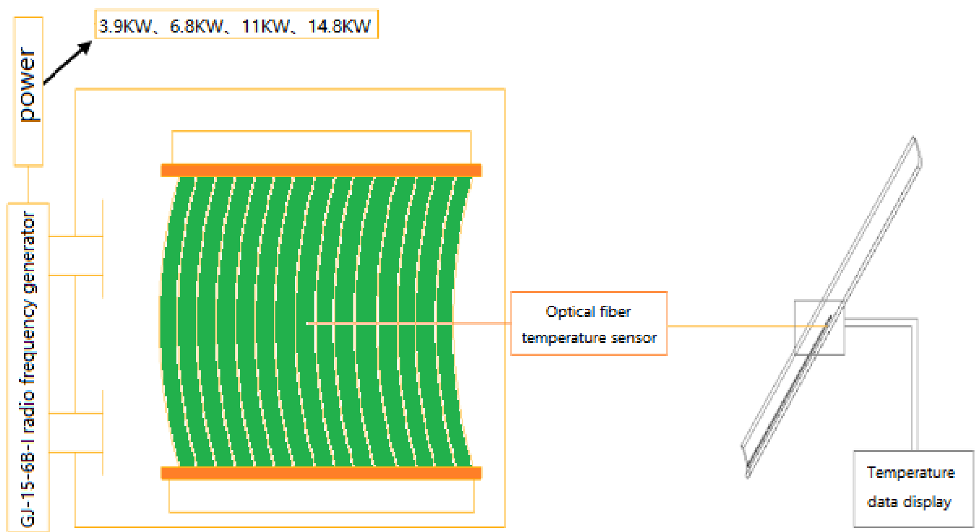

Fig. 1. Schematic diagram of the high-frequency device and the internal temperature measurement position of the bamboo

Experimental Method

A TESTO-606-1 moisture meter produced by Detu Instrument Co., Ltd. was used to measure the moisture content of bamboo slices. The measurement was replicated 5 times to take the average value. The true moisture content of bamboo slices was tested using the drying method, and the true moisture content was equal to the ratio of the quality difference of bamboo slices before and after drying to the quality of bamboo slices after drying. However, there was a difference between the measured value and the true value, especially when the water content gradient was low. To reduce experimental error, the relationship between them was described by experimental results. There was a linear relationship between the measured value and the true moisture content. As shown in Fig. 2, the experimental material for the bamboo material was curved bamboo. Before the experiment, the bamboo material was removed from the cooling chamber to measure the water content. All bamboo materials were divided into different water contents. The specimens were separated and wrapped with a plastic film. The moisture content of each bamboo piece was measured before and after the experiment. When studying the effect of water content on the temperature rise rate of curved bamboo, the thickness of the bamboo sample selected in this study was 40 mm, the average bamboo water content was 9, 11, 13, or 15%, and the high-frequency power was controlled at 10.5 KW. The moisture content was taken out from the cooling chamber, and all sheets were separated according to the measured moisture content and wrapped with a plastic film.

The moisture content of each plate was measured before and after the experiment, and the test was repeated 3 times for each moisture content. When studying the effect of the thickness of curved bamboo on the temperature rise rate, the bamboo material with a thickness of 20, 30, or 40 mm was selected to dry the moisture content of the bamboo to 12%, and the high-frequency power was controlled at 10.5 kW. The test was repeated three times for each thickness. The bamboo material with a thickness of 40 mm was selected to dry the water content of the bamboo to 11%, and the high-frequency power was controlled at 3.9, 6.8, 11, and 14.8 kW. The test was carried out three times at each power level.

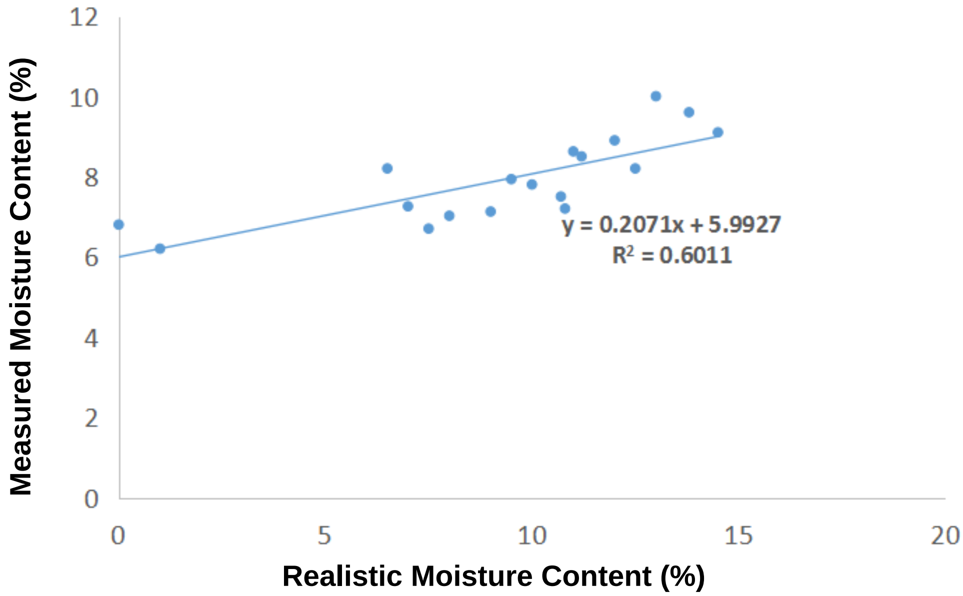

Fig. 2. Linear relationship between measured MC and real bamboo MC

Table 1. Specifications and Quantities of Materials Used in the Experiment

<table>
<tr><th>Test</th><th>Bamboo MC (%)</th><th>Bamboo Thickness (mm)</th><th>Power (kW)</th><th>Number of Experiments per Layer</th><th>Test Count</th><th>Number of Materials Required</th></tr>
<tr><td rowspan="4">Effect of water content on temperature rise rate</td><td>9</td><td rowspan="4">40</td><td rowspan="4">10.5</td><td rowspan="4">33</td><td rowspan="4">3</td><td>99</td></tr>
<tr><td>11</td><td>99</td></tr>
<tr><td>13</td><td>99</td></tr>
<tr><td>15</td><td>99</td></tr>
<tr><td rowspan="3">Effect of thickness on temperature rise rate</td><td rowspan="3">9</td><td>20</td><td rowspan="3">10.5</td><td rowspan="3">33</td><td rowspan="3">3</td><td>99</td></tr>
<tr><td>30</td><td>99</td></tr>
<tr><td>40</td><td>99</td></tr>
<tr><td rowspan="4">Effect of power level on temperature rise rate</td><td rowspan="4">11</td><td rowspan="4">40</td><td>3.9</td><td rowspan="4">33</td><td rowspan="4">3</td><td>99</td></tr>
<tr><td>6.8</td><td>99</td></tr>
<tr><td>11</td><td>99</td></tr>
<tr><td>14.8</td><td>99</td></tr>
</table>

RESULTS AND DISCUSSION

Effect of Water Content on Temperature Rise Rate

Based on the data obtained from multiple experiments, log, linear, and polynomial models were fitted using Origin software. The equations are shown in Table 2. The fitted data with the highest coefficient of determination (R^2), was selected, and the fitting curve is shown in Fig. 3 as a function of time. The fitting equation of the temperature rise rate is also shown in Table 2. Figure 4 shows the effect of moisture content of different curved bamboo on the temperature rise rate of bamboo core during high-frequency heating.

Figure 3 shows that when the bamboo material was in the range of 9 to 11%, the temperature rise rate of the curved bamboo sample became faster as the water content increased, and the temperature could be raised faster when the water content was higher. However, with an increase of water content to 11 to 15%, the temperature rise rate of the curved bamboo sample decreased compared with the water content of 11%, and it took more time to increase the temperature when the water content was higher.

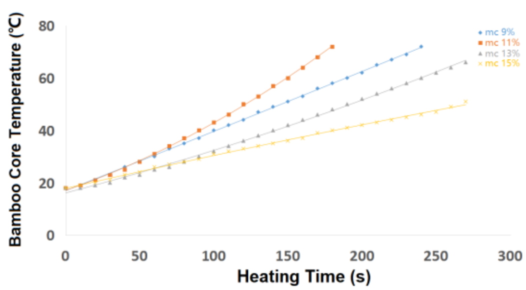

Fig. 3. Effect of moisture content of different curved bamboo on the temperature of bamboo core during high-frequency heating

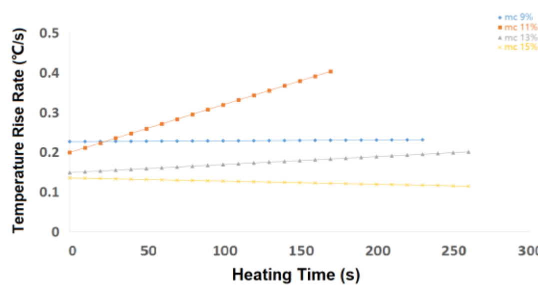

Fig. 4. Effect of moisture content of different curved bamboo on the temperature rise rate of bamboo core during high-frequency heating

Table 2. Data Fitting of Water Content Temperature Rise Rate of Different Curved Bamboos in High-frequency Heating

Bamboo MC	Fitting Method	Curve Equation	Fit	Curve Equation Obtained after Derivation
9%	logarithm	$y = 20.648e^{0.0057x}$	$R^2 = 0.9679$	
	Linear	$y = 0.2283x + 16.803$	$R^2 = 0.9994$	
	Quadratic polynomial	$y=0.00001x^2+ 0.2257x + 16.902$	$R^2= 0.9994$	$y=0.00002x+ 0.2257$
11%	logarithm	$y = 18.622e^{0.0079x}$	$R^2 = 0.9915$	
	Linear	$y = 0.3067x + 13.926$	$R^2 = 0.9904$	
	Quadratic polynomial	$y=0.0006x^2+ 0.1984x + 16.994$	$R^2 = 0.9994$	$y = 0.0012x + 0.1984$
13%	logarithm	$y = 18.393e^{0.0051x}$	$R^2 = 0.9857$	
	Linear	$y = 0.1879x + 14.315$	$R^2 = 0.9952$	
	Quadratic polynomial	$y=0.0001x^2+ 0.1479x + 16.046$	$R^2 = 0.9984$	$y = 0.0002x + 0.1479$
15%	logarithm	$y = 20.023e^{0.0037x}$	$R^2 = 0.9711$	
	Linear	$y = 0.1184x+ 18.296$	$R^2 = 0.9974$	
	Quadratic polynomial	$y=-0.00004x^2+ 0.1298x + 17.803$	$R^2 = 0.9981$	$y=-0.00008x+ 0.1342$

When the water content of the curved bamboo was 11%, it took only 120 s to reach 50 °C. When the water content of the curved bamboo was 9%, it took 145 s to reach 50 °C. The temperature rise rate with high water content was very slow. When the moisture content of the curved bamboo was 15%, it took more than 260 s to reach 50 °C. The highest temperature rise rate occurred in the curved bamboo at a water content of about 11%.

Figure 4 shows that in the first 23 s, the curved bamboo with 9% water content had the fastest temperature rise rate, and with the increase of water content, the temperature rise rate increased slowly; with the heating time exceeding 23 s there was 11% water. The rate of temperature rise of curved bamboo with more than 9% moisture was in general the fastest. However, in detail the rate of temperature rise of curved bamboo with 9% moisture content was still faster than that of curved bamboo with either 13% or 15% moisture. The change in temperature rise rate can be attributed to dielectric relaxation, which is the result of a combination of temperature and moisture content on the dielectric properties of the bamboo. For the heating acceleration, the curved bamboo with 11% water content had the fastest heating acceleration and the temperature rise rate increased with the heating time. The water content was 9 to 11%, and the water content increased. The heating acceleration was gradually reduced, and the temperature rise rate gradually increased. As the water content was increased to the range 11 to 13%, the heating acceleration gradually decreased, and the temperature rise rate gradually increased. The water content increased by 13 to 15%. The temperature rise rate was gradually reduced.

Through analysis of variance, it was shown that the moisture content of bamboo had a significant effect on the temperature rise rate ($p<0.01$). When the water content was low, the higher the water content, the higher the dielectric constant of the bamboo and the higher the temperature rise rate. However, when the water content was large, the evaporation of free water consumed a large amount of heat, lowering the rate of temperature rise. In addition, the dielectric constant and loss factor of bamboo at high temperatures increased with increasing temperature.

Wu *et al*. (2020) found that there was a difference in the temperature rise rate between the core layer and the surface layer during the preparation of bamboo poplar composite materials by high-frequency hot pressing. At the beginning of hot pressing, the temperature rise rate of the surface layer was faster, but when the core layer reached 85 °C, the temperature rise rate of the core layer exceeded that of the surface layer. The temperature rise rate of the surface layer was close to a uniform temperature rise rate, while the core layer was variably heated (Wu *et al*. 2020). Yang *et al*. (2018) found that the drying rates of free water and bound water were consistent in the study of high-frequency vacuum drying of white wax wood square timber. The dehydration efficiency of high-frequency vacuum drying is related to the temperature of the wood, and the moisture content and drying quality after drying meet the requirements for Grade II timber in GB (Yang *et al.* 2018). Liu *et al*. (2018) used the RF/V drying method to dry the large-sized square timber of *Dalbergia bariensis* and *Dalbergia latifolia*. The moisture content distribution of wood after high-frequency vacuum drying is different from that of conventional drying. The moisture content of the surface layer is higher than that of the core layer, and the wood near the negative electrode plate has the highest moisture content (Liu *et al.* 2018). During the high-frequency heating process, the change in the dielectric properties inside the bamboo sample is another factor affecting the internal temperature. Bamboo contains a large amount of water. The dielectric constant and loss coefficient of water is much larger than that of dry bamboo. The moisture content and distribution in the bamboo determines the overall dielectric properties of the bamboo. The difference in dielectric properties of different parts of bamboo is mainly caused by uneven distribution of water in bamboo. At the moisture content below the saturation point of the bamboo fiber, the water is present in the form of bound water. The bound water is tightly bound to the polar group, and there is no rotation of the free water, resulting in a decrease in the loss coefficient. As the moisture content of bamboo increases, the number of polar molecules increases. This increases the loss factor, and therefore the temperature rise rate increases. In addition, the heat of adsorption may have an effect on the rate of temperature increase. When the water content of bamboo is low, the lower the water content, the greater the heat required due to the heat adsorption characteristics of the bamboo. This may be the reason why the high-frequency temperature rise rate is lower at low moisture content. At higher water contents, although increasing the water content leads to an increase in dielectric constant and dielectric loss angle. The combination of dielectric constant and dielectric loss angle results in low power deposition inside the bamboo at high moisture content because of high dielectric constant and small microwave penetration depth.

Effect of Thickness on Temperature Rise Rate

Based on the data obtained from multiple experiments, log, linear, and polynomial models were fitted using Origin software. The equations are shown in Table 3. The coefficient of determination (R^2) was used to select the equation that best fit the data. The obtained fitting curve was derived with respect to time, and the fitting equation of the temperature rise rate was obtained. Figure 5 shows the effect of thickness of different curved bamboo on the temperature of bamboo core during high-frequency heating. Figure 6 shows the effect of thickness of different curved bamboo on the temperature rise rate of bamboo core during high-frequency heating. When the thickness of the curved bamboo was 40 mm, the temperature had to be applied for 260 s when the temperature reaches 40 °C, and the required time was not only longer than for the curved bamboo with a thickness of 30 mm, but also much longer than the curved bamboo with a thickness of 20 mm, which is due to the arc shape.

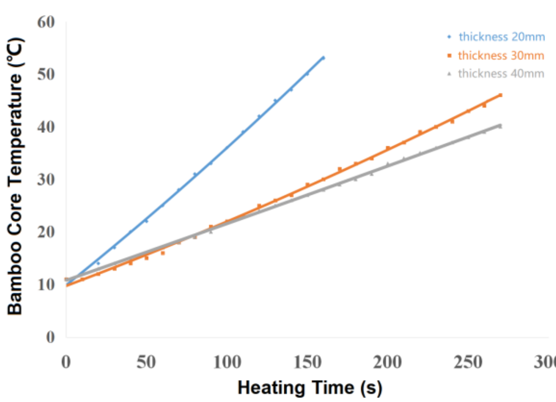

Fig. 5. Effect of thickness of different curved bamboo on the temperature of bamboo core during high-frequency heating

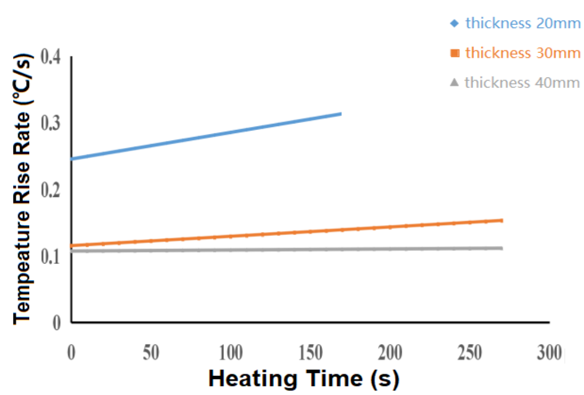

Fig. 6. Effect of thickness of different curved bamboo on the temperature rise rate of bamboo core during high-frequency heating

Table 3. Data Fitting of the Temperature Rise Rate of Different Curved Bamboo Thickness in High-frequency Heating

Bamboo Thickness	Fitting Method	Curve Equation	Fit	Curve Equation Obtained after Derivation
20 mm	logarithm	$y = 12.561e^{0.0099x}$	R^2 =0.9668	
	Linear	y=0.2711x + 9.1961	R^2 =0.9981	
	Quadratic polynomial	$y=0.0002x^2+0.2451x+9.8462$	R^2 =0.9988	y =0.0004x + 0.2451
30 mm	logarithm	$y = 11.799^{e0.0055x}$	R^2 =0.9767	
	Linear	y =0.1345x+ 8.8842	R^2 =0.997	
	Quadratic polynomial	$y=0.00007x^2+0.1152x+9.718$	R^2 =0.9984	y=0.00014x+ 0.1152
40 mm	logarithm	$y = 12.681e^{0.0047x}$	R^2 =0.974	
	Linear	y=0.1093x + 10.672	R^2 =0.9991	
	Quadratic polynomial	$y=0.000008x^2+0.107x+10.771$	R^2 =0.9991	y=0.000016x+ 0.107

As shown in the Fig. 6, the temperature rise rate of the center of the curved bamboo of 20 mm thick was always higher than the temperature rise rate of the center of the curved bamboo of 30 to 40 mm, and the acceleration of 20 mm was also higher than the temperature rise rate of the center of the curved bamboo of 30 to 40 mm; The 30 mm heating acceleration was also always higher than the temperature rise rate of the curved bamboo center of 40 mm.

The temperature difference inside the bamboo was caused by the absorption capacity of high-frequency energy. Bamboo is an anisotropic material with great changes. Its dielectric properties vary with position. Therefore, bamboo has its own energy absorption capacity in different positions. The results show that the temperature rise rate of curved bamboo was affected by temperature. The smaller the thickness, the larger the temperature rise rate and the acceleration of heating. The smaller the thickness of curved bamboo, the closer the longitudinal section is to the rectangle, and the heat in the high temperature region of the plate can be passed more quickly to the low temperature area to achieve rapid temperature rise.

Effect of Power Level on Temperature Rise Rate

According to the data obtained from multiple experiments, the data were fitted by software to the logarithmic, linear, and polynomial equations, which are shown in Table 4. The data with the highest coefficient of determination was selected based on the obtained fitting value R^2, and the fitted curves are plotted in Fig. 7. At the same time, the obtained fitted curve was derived for time, and the fitted equation of the temperature rise rate was obtained.

Figure 7 shows the effect of different heating power on the temperature of bamboo core during high-frequency heating. Figure 8 shows the effect of different heating power on the temperature rise rate of bamboo core during high-frequency heating.

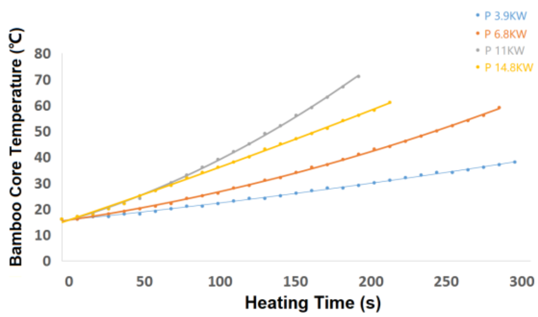

Fig. 7. Effect of different heating power on the temperature of bamboo core during high-frequency heating

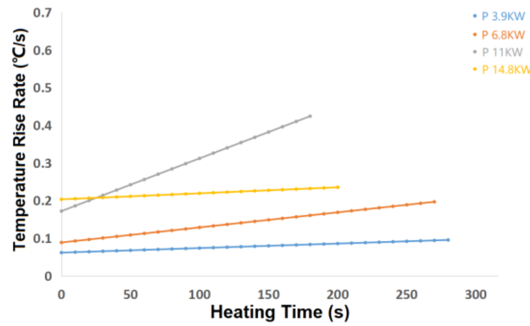

Fig. 8. Effect of different heating power on the temperature rise rate of bamboo core during high-frequency heating

Table 4. Data Fitting of Different High-frequency Heating Power to the Temperature Rise Rate of Curved Bamboo

Power	Fitting Method	Curve Equation	Fit	Curve Equation Obtained after Derivation
3.9KW	logarithm	$y = 16.01e^{0.0031x}$	$R^2 = 0.9942$	
	Linear	$y = 0.0781x + 14.647$	$R^2 = 0.9947$	
	Quadratic polynomial	$y = 0.00006x^2 + 0.0615x + 15.422$	$R^2 = 0.9979$	$y = 0.0001x + 0.0615$
6.8KW	logarithm	$y = 15.97e^{0.0048x}$	$R^2 = 0.9957$	
	Linear	$y = 0.155x + 12.2$	$R^2 = 0.9864$	
	Quadratic polynomial	$y = 0.0002x^2 + 0.0884x + 15.197$	$R^2 = 0.9994$	$y = 0.0004x + 0.0884$
11KW	logarithm	$y = 16.257e^{0.0082x}$	$R^2 = 0.9919$	
	Linear	$y = 0.2979x + 11$	$R^2 = 0.9861$	
	Quadratic polynomial	$y = 0.0007x^2 + 0.1717x + 14.786$	$R^2 = 0.9991$	$y = 0.0014x + 0.1717$
14.8KW	logarithm	$y = 17.462e^{0.0064x}$	$R^2 = 0.9745$	
	Linear	$y = 0.2195x + 14.13$	$R^2 = 0.9983$	
	Quadratic polynomial	$y = 0.00008x^2 + 0.2029x + 14.684$	$R^2 = 0.9987$	$y = 0.0016x + 0.2029$

When the curved bamboo with a water content of 11% was heated at a high-frequency power of 3.9 kW, 260 s was required when the temperature reached 35 ℃. The time required was much longer than other power levels due to the insufficient nature of the energy supply of this power level. When heating at a power of 11 kW, it took only 165 s to reach 61 ℃, but when the RF power was 14.8 kW, it took 210 s to reach 61 ℃. The faster the rate of temperature rise, the lower the rate of temperature rise with power up in the power of 11 to 14.8 kW.

Figure 8 shows that after heating for 25s, the temperature rise rate was the fastest under the power of 11 kW, and as time passed, the temperature rise rate gradually rose and the temperature rise acceleration was basically stable at a fixed value; at the same time, at the power of 14.8 kW, at the beginning 25s, the temperature rise rate of 14.8 kW was higher than the temperature rise rate of 11 kW. After 25s, the result was the opposite. The temperature rise rate of 14.8kW was lower than the temperature rise rate of 11 kW, and the longer the time, the greater the difference between the two temperatures. Below 11 kW, as the power increased, the temperature rise rate and the heating acceleration gradually increased. High-frequency power levels significantly affected the high-frequency temperature rise rate. The higher the high-frequency power level at a certain level, the higher the temperature rise rate. As the high-frequency power increased, the average power density also increased. The medium per unit volume absorbed more energy and kept the temperature rise rate at a higher level.

CONCLUSIONS

1. In the high-frequency heating process, the moisture content of bamboo significantly affected the temperature rise rate ($p<0.01$). When the moisture content of bamboo was close to 11%, the high-frequency temperature rise rate was the highest. The temperature rise rate was 0.0012 °C/ s; the temperature rise rate of the 41 mm thick bamboo at 15% moisture content was -0.00008 °C / s, and the power was 10.75 kW. When the water content was low, the high-frequency temperature rise rate increased with the increase of the moisture content of the bamboo. When the water content was high, the temperature rise rate decreased with the increase of the moisture content of the bamboo.
2. Thickness had little effect on the rate of temperature increase. The results show that the smaller the thickness, the greater the temperature rise rate and the acceleration of the heating, and the temperature rise rate and acceleration of 20 mm increased rapidly with the continuation of high-frequency heating.
3. The high-frequency power level significantly affected the temperature rise rate of bamboo ($p<0.01$). At the beginning of heating, the temperature rise rate with a low power level was very low. As the high-frequency heating continued, the temperature rise rate of the high power level was constantly rising. In particular, the power rate of 11 kW was the highest. However, as the high-frequency heating continued, the temperature rise rate of the lower and higher frequency power levels rose slowly and were nearly constant.
4. This study obtained a mathematical model for the effects of moisture content, sample thickness, and high-frequency power level of bamboo with the highest degree of fit on bamboo core temperature and temperature rise rate through fitting experimental data. The model was able to effectively reflect the relationship between parameters and temperature changes and can provide technical reference for future high-frequency hot pressing of bamboo.

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