IMPROVEMENT SCHEME AND VERIFICATION OF HIGH-FREQUENCY HEATING UNIFORMITY OF WOOD

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Abstract. This study was based on the finite element method to construct a simulation model of high-frequency heating temperature field. In the model, bending length and angle of top plate were changed upward. Heating uniformity of the test material was then analyzed under different conditions (bending length and angle) to identify the optimal improvement scheme and carry out the experimental verification. Results showed that when the bending length and angle of top plate were 200 mm and 45°, respectively, the heating uniformity was obtained. From the experimental analysis, temperature variation of the test material was less after improvement, which effectively improved the heating uniformity. Comparison of changes in the electromagnetic field distributions between plates before and after improvement revealed an increase in distribution uniformity with temperature uniform index from 0.631 to 0.811. This indicated that the electromagnetic field distribution after improvement was more uniform with ideal heating effect. Improvement in the bending length and angle of top plate changes the distribution of electromagnetic fields between the plates and then enhances temperature distribution uniformity of wood during high-frequency heating.

Keywords: Finite element, wood, high-frequency, temperature distribution.

INTRODUCTION

Wood high-frequency vacuum drying (WHFVD) is characterized by its fast drying, low energy consumption, and less environmental pollution (Wang 2013). In the early 1970s, it was studied and developed in the former Soviet Union, the United States, Japan, and other countries. It has been increasingly valued by the wood drying industry (Kong 2018). During the drying process, the temperature distribution inside the wood would affect the driving force of water migration and determine the drying speed of wood, distribution of MC, and drying quality such as cracking and thermal degradation (Cai 2007). However, the internal temperature distribution of wood during high-frequency heating is uneven (Lin et al 1997), and the control of uniformity is one of the biggest problems of WHFVD technology (Chai 2018a). Therefore, it is of great significance to improve the uniformity of temperature distribution inside wood during high-frequency heating.

Koumoutsakos et al. (2001) systematically studied the mechanism of moisture and heat

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transfer in wood during high-frequency vacuum drying. Li (2010) conducted a series of high-frequency vacuum drying experiments on Japanese cedar, poplar, and larch and discussed suitable high-frequency vacuum drying process benchmark for poplar and larch in plantation. Jia (2015) investigated heat and mass transfer mechanism of Mongolian pine timber with pith during high-frequency vacuum drying process along the fiber direction and established a one-dimensional heat and mass transfer mathematical model. Rabidin and Seng (2017) explored the drying characteristics of 30-mm and 50-mm-thick kekatong under high-frequency vacuum and conventional drying. Other scholars have also extensively examined the thermal mass migration, process benchmarks, and mathematical models of WHFVD. However, the research on the uniformity of high-frequency heating is rarely reported.

In this work, the high-frequency heating simulation model of wood was established, the top plate was adjusted in the model, then the best improvement scheme was analyzed, and the feasibility of the solution was verified. The main contents were as follows: 1) the finite element method was used to construct the simulation model of high-frequency heating temperature field of wood, 2) the bending length and angle of the top plate were changed to obtain the best improvement scheme, and 3) the feasibility of the improved scheme was verified by experiments.

MATERIALS AND METHODS

Model Development

The high-frequency heating process was simulated by finite element simulation software (COMSOL5.2a) (COMSOL Multiphysics, Burlington, MA). The geometric model was constructed according to the actual structural size of the high-frequency drying device (YASUJIMA Co., Ltd., Ehime, Japan) that includes a drying tank (640 [diameter] × 1350 [depth] mm), parallel top and bottom plates (1000 × 400 × 1.3 mm), and test material (500 × 120 × 120 mm). The test material was placed at the geometric center between the top and lower plate. The drying tank was set to an electrically insulated state, and the initial temperature of all objects in the model was set to 23°C at room temperature. Other characteristic parameters of the materials involved in the model are shown in Table 1.

Model Application

As shown in Fig 1, the bending length (150, 200, and 250 mm) and angle (30, 45, and 60°) of the top plate were respectively changed upward to improve the distribution of electromagnetic field between the plates, thereby the purpose of improving temperature distribution uniformity was achieved in the test material. The simulated high-frequency heating of test material was carried out under the same condition, comparing the heating uniformity of different schemes to get the best improvement plan.

During the simulation, the temperature uniformity index (TUI) was estimated to evaluate the heating uniformity of the stack. TUI is defined as (Chai 2018a):

$$\mathrm{TUI} = \frac{\int_{V_{\mathrm{vol}}} |T - T_{\mathrm{ave}}| \mathrm{d}V_{\mathrm{vol}}}{(T_{ave} - T_{\mathrm{initial}})V_{\mathrm{vol}}},$$

where V_{vol} is the volume of stack (m^3) and T and T_{ave} represent the maximum temperature and the average temperature of the stack (°C), respectively.

The smaller the TUI, the better the uniformity of high-frequency heating. The minimum value of TUI is zero, which indicates that the temperature distribution of the stack is uniform.

Verification of Improvement Plan

Test materials. Mongolian pine timber (*Pinus sylvestris* var. *mongholica* Litv.) with pith was used as test object. The uniform and no defect sample was selected and processed into 120 mm × 120 mm × 500 mm size. The initial MC was measured to be 45%. A specimen was

Table 1. Physical properties of the material in the model.

Physical properties	Pine	Air	Plate electrode	Tank
Density (kg/m^3)	558	1.2	2700	7850
Specific heat (kJ/[kg·°C])	2104	1200	900	475
Thermal conductivity (W/[m·°C])	0.1073	0.025	238	44.5
Dielectric constant	26.4	1	—	—
Loss factor	0.17	0	—	—

used for each test and the test heating temperature was set to 65°C. The test was stopped when the predetermined temperature was reached. Accurately weighing 4 g of $CoCl_2 \cdot 6H_2O$ powder, an aqueous solution with 2% concentration was prepared. The test paper was immersed in $CoCl_2$ aqueous solution, and the immersion time was 10 min until the test paper showed uniform pink color and then taken out.

Temperature distribution before and after improvement. To verify the improvement of wood heating uniformity, the change in temperature distribution in the width direction of test material and the temperature variations among the center of the test material and its length, width, and thickness before and after the improvement were calculated.

In the model, thirty temperature probe points were uniformly preset along the width direction of the test material to detect the temperature distribution changes in the width direction before and after improvement.

To evaluate variations in temperature difference between the center of test material and its length, width, and thickness before and after improvement, seven probe points were preset along the center, length, width, and thickness of wood (Fig 2). Under the same conditions, each time a piece of the test material was selected and then the test of high-frequency heating was respectively performed before and after improvement.

Electromagnetic field distribution variation between plates before and after improvement. To qualitatively determine the uniformity of high-frequency field in the drying chamber, $CoCl_2$ test paper was used to display the temperature field distribution in the drying chamber (Han 2007).

Under normal conditions, the main component of $CoCl_2$ powder is $CoCl_2 \cdot 6H_2O$ in pink color.

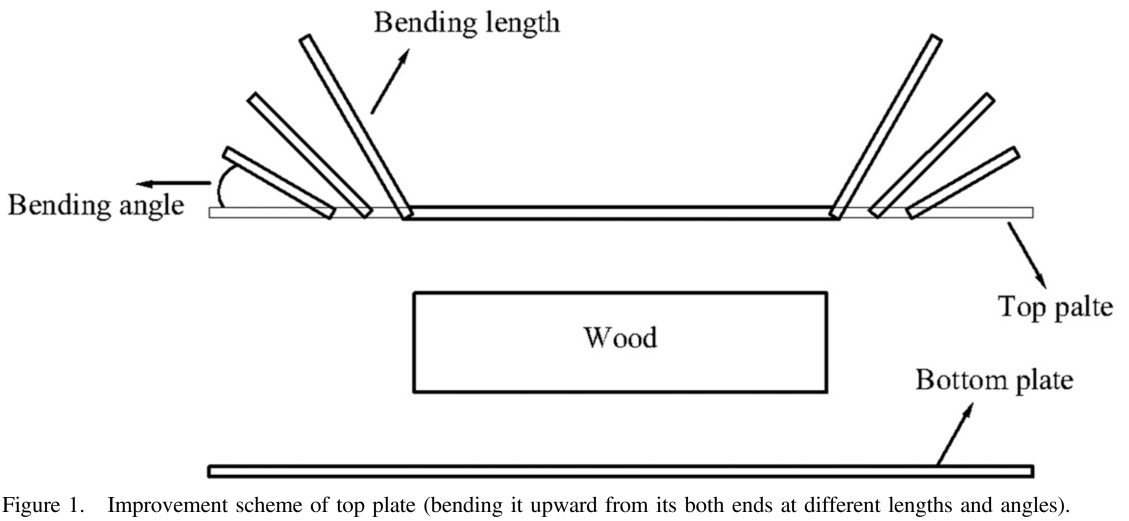

Figure 1. Improvement scheme of top plate (bending it upward from its both ends at different lengths and angles).

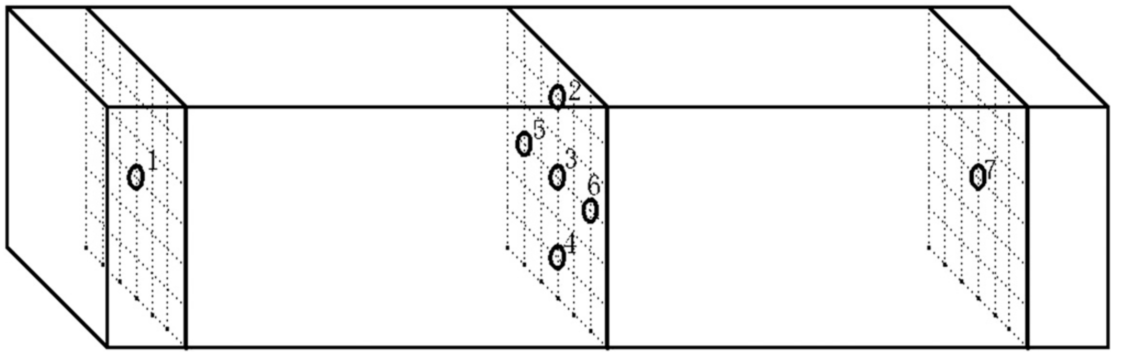

Figure 2. Test material and temperature measurement point (3 is the center measurement point, 1 and 7 are the length direction measurement points, 5 and 6 are the width direction measurement points, and 2 and 4 are the thickness direction measurement points).

When $CoCl_2 \cdot 6H_2O$ powder gradually loses water crystals because of heat, the color gradually changes from pink to magenta, blue–violet, and then blue. The higher the electromagnetic field density, the higher the temperature. Therefore, the high-frequency field strength of each part in the drying chamber can be judged based on color change.

The $CoCl_2$ test paper was placed in the middle of two dried flat woods. High-frequency heating was then respectively performed before and after improvement. As temperature reached to 65°C, the test paper was quickly taken out and photographed with a digital camera. Color change of the test paper was binarized through MATLAB to analyze the proportion of each color and estimate distribution uniformity of electromagnetic field.

Table 2. High-frequency heating uniformity analysis of simulation.

Test number	Angle	Length (mm)	TUI
1	0	0	0.112
2	60	250	0.071
3	60	200	0.056
4	60	150	0.069
5	45	250	0.064
6	45	200	0.044
7	45	150	0.058
8	30	250	0.067
9	30	200	0.051
10	30	150	0.059

RESULTS AND ANALYSIS

Determination of Improvement Plan

As shown in Table 2, the TUI decreased and then increased with both the bending length and bending angle. At a bending angle of 45° and a length of 200 mm, the TUI reached the smallest and high-frequency heating uniformity was 0.044. This showed that the TUI had large improvements compared with before improvement.

Improvement Plan Verification

Changes in temperature distribution before and after improvement. Figure 3 shows the changes of temperature distribution in the width direction of test material before and after improvement. The temperature distribution along the width direction tended to low values in the uniform index on both sides but high in the middle. When compared with data obtained before improvement, the temperature distribution of the test material looked relatively uniform in the width direction after improvement.

Figures 4 and 5 show comparison of temperature difference between center measurement point and length and width direction measurement points before and after improvement. In high-frequency heating for 0-6 min, the difference between the temperature difference before and after improvements looked not very obvious. After that,

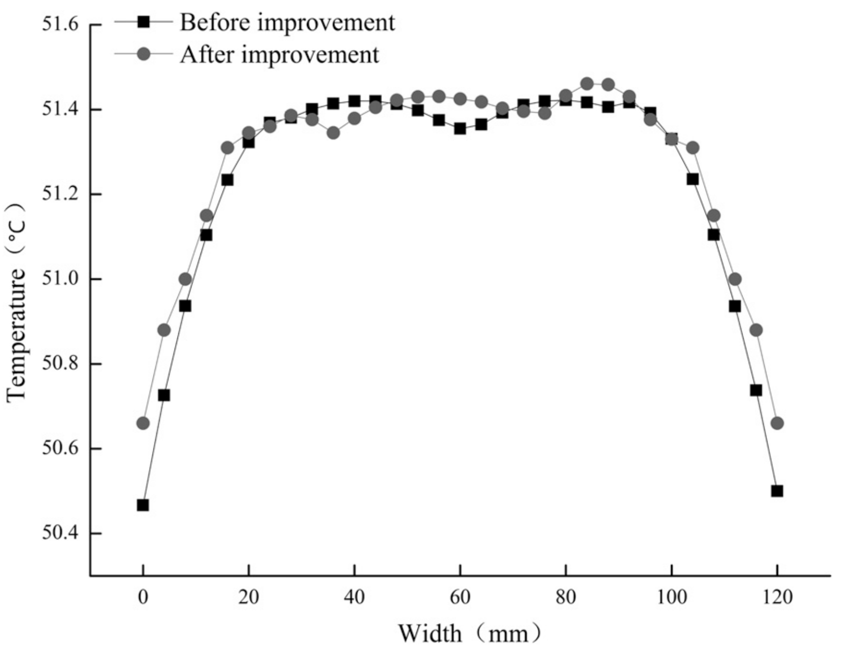

Figure 3. Temperature distribution in the width direction of test material before and after improvement.

as heating time increased, the difference in temperature difference gradually enhanced. Figure 6 indicates changes in the temperature difference of the center measurement point and thickness direction measurement point before and after improvement with time. In high-frequency heating for 0-2 min, the difference between temperature before and after improvements

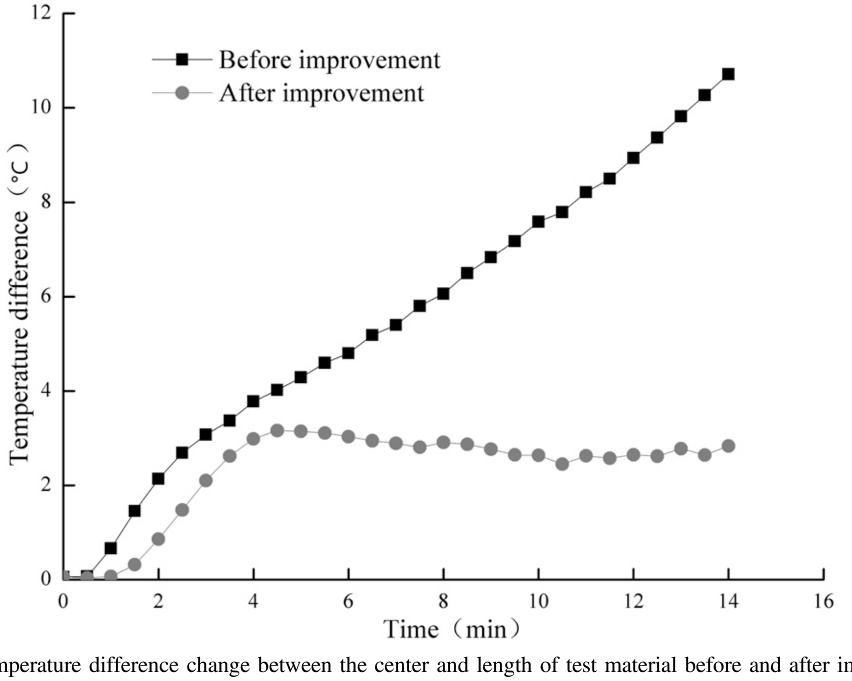

Figure 4. Temperature difference change between the center and length of test material before and after improvement.

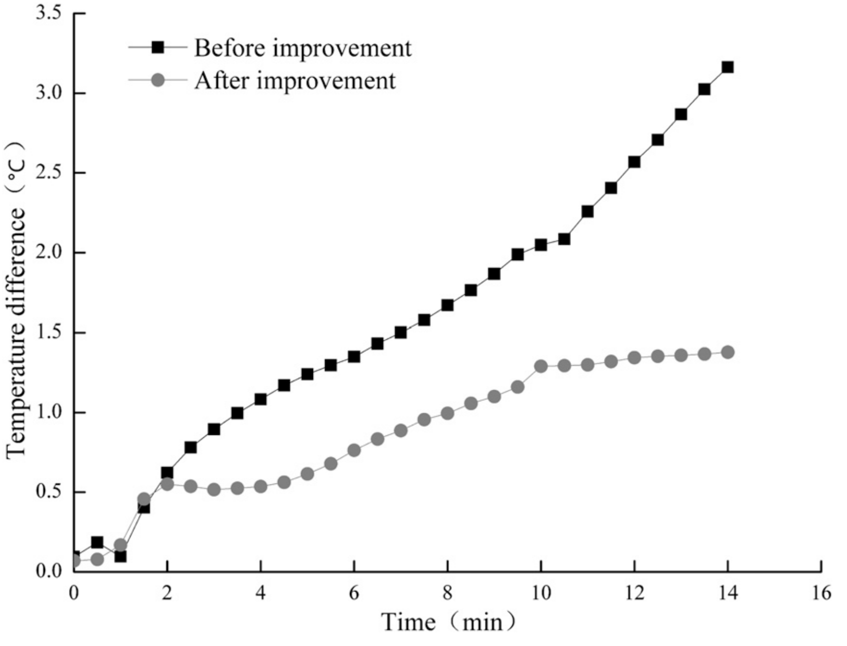

Figure 5. Temperature difference change between the center and width of test material before and after improvement.

appeared insignificant. Within 2-10 min, the improved temperature difference was higher than before improvement; however, with time migration after high-frequency heating for 10 min, the improved temperature difference was gradually lower than before improvement, and the purpose of improving temperature distribution uniformity was achieved.

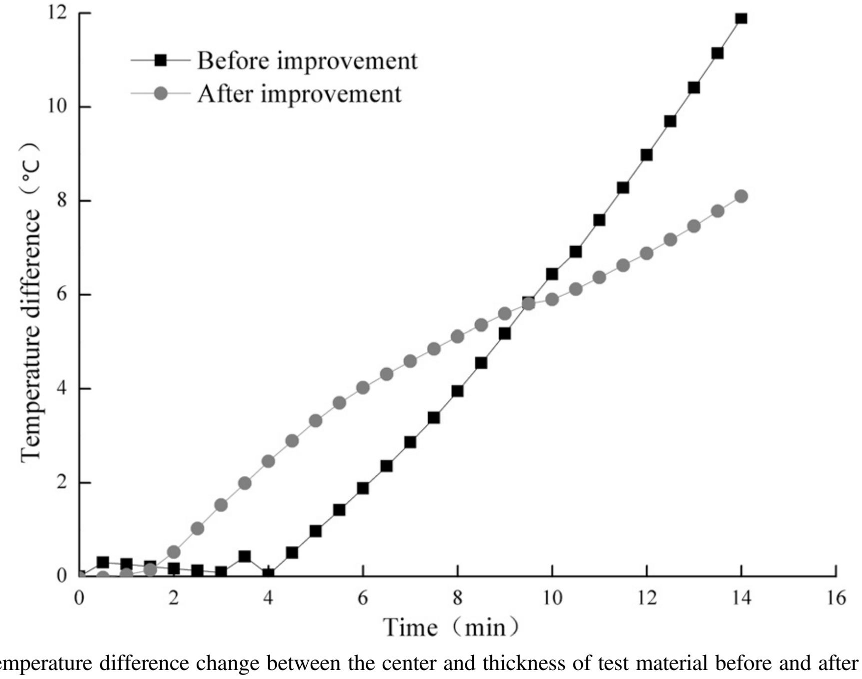

Figure 6. Temperature difference change between the center and thickness of test material before and after improvement.

It took 14 min for high-frequency heating to reach the predetermined temperature. The temperature difference between the center measuring point and the length, width, and thickness direction measuring points reduced by 7.6°C, 1.7°C, and 3.4°C before and after improvement, respectively. The temperature difference significantly declined along the length direction followed by the thickness and width direction. This was because the bending length and angle of top plate were changed, and the electromagnetic field distribution inside the sample was effectively changed to make its distribution more uniform so that the temperature difference between the center of sample and its length, width, and thickness direction was reduced.

Variation in electromagnetic field distribution between plates before and after improvement. After the test paper was treated with $CoCl_2$ solution (Fig 7), it became pinkish white. On the left, it is the image of high-frequency heating and binarization processing before improvement. On the right, it is the image of high-frequency heating and binarization processing after improvement. After high-frequency heating, the heated portion of the test paper changed from pink to blue. From the center to the edge of the test paper, the color gradually deepened. This was related to the electric field edge effect (Huang et al 2015; Chai 2018b), causing higher electromagnetic field densities at the corners when compared with the center, resulting in uneven heating. As shown in Fig 8 (TEC 1987), the electric field was evenly distributed when the plates were unloaded. On application of load, the electric field lines bent inward near the edge of the plate. Thus, the electric field lines were concentrated at the corners of the sample with higher density than in the central area. The color ratio of the test paper after heating was binarized by MATLAB. Heat-receiving areas of the test paper before and after improvement were recorded having the uniform indexes of 0.631 and 0.811, respectively. It suggested more uniform electromagnetic field distribution between plates with more ideal heating effect after

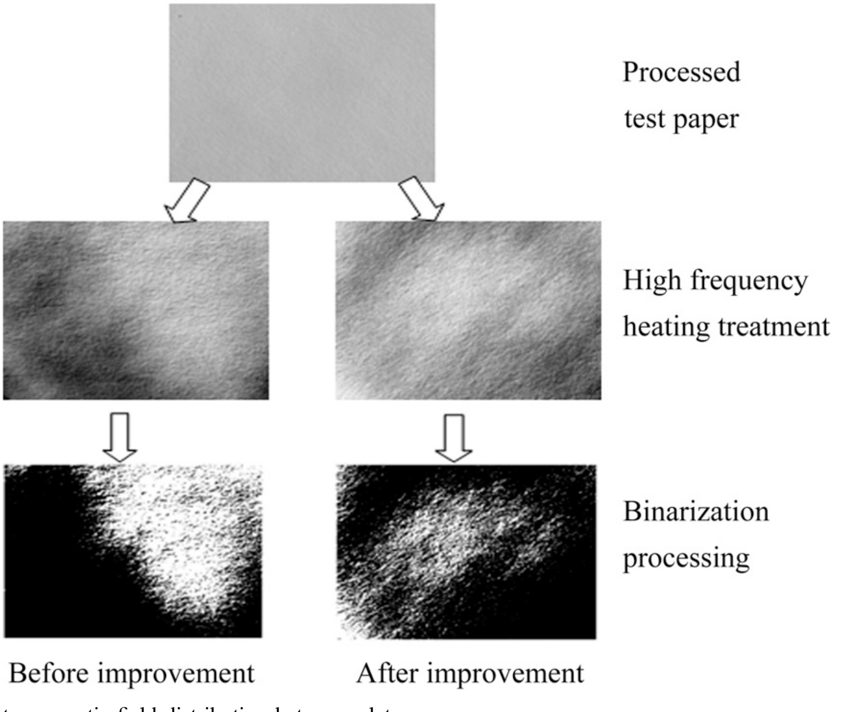

Figure 7. Electromagnetic field distribution between plates.

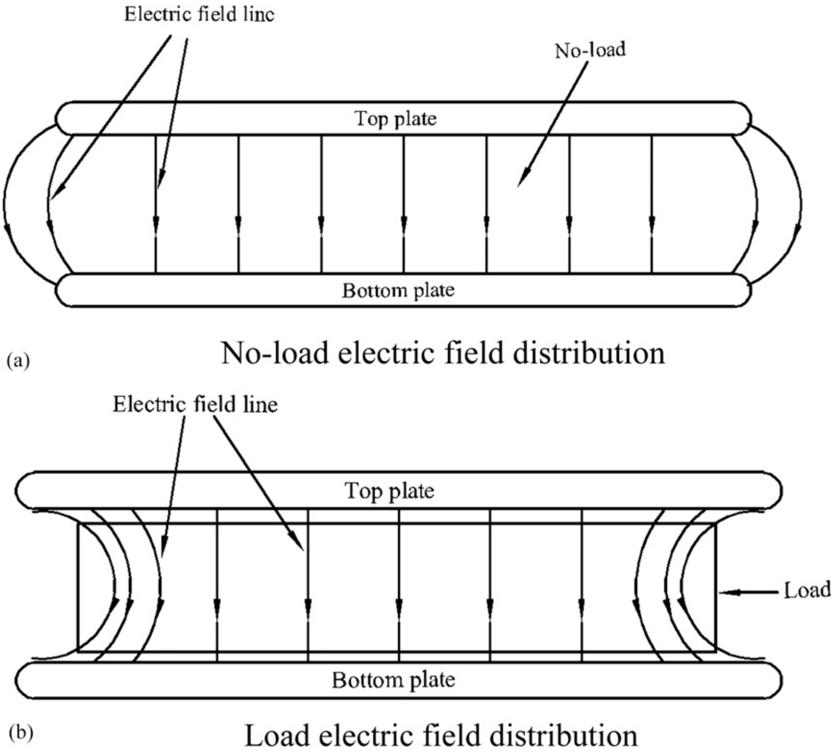

Figure 8. Electric field line distribution between plates (TEC 1987).

improvement, thus proving the view of changes in temperature distribution before and after improvement.

CONCLUSION

The finite element method was used to construct the simulation model of high-frequency heating temperature field. The model revealed that bending angle of 45° and length of 200 mm induced the best results. Through test verification, the temperature distribution was more uniform after improvement. The binarized image processing by MATLAB estimated the proportions of heated area of the test paper before and after improvement to 0.631 and 0.811, respectively. This indicated that the uniform electromagnetic field distribution was achieved after improvement with optimal heating effect. In general, the improved scheme can effectively improve the uniformity of wood temperature distribution in the process of high-frequency heating, and it can provide basic data and theoretical basis for optimizing wood drying quality.

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