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MODEL CONSTRUCTION AND MICROWAVE PREHEATING EXPERIMENTS USING FIBERBOARD

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ABSTRACT

Microwave heating is a new type of pre-heating for fiberboard mats. Compared to conventional heating, microwave heating is faster and the surface and interior are evenly heated, thus avoiding the phenomenon of premature hardening of the surface layer of the fibreboard mats. In this paper, the heat transfer law of microwave preheated fiberboard mats was analyzed, and a thermodynamic model of fiberboard microwave heating was established. Furthermore, a microwave preheating simulation was established through COMSOL software; the temperature distribution of the fiberboard after microwave heating was analyzed and the reliability of the simulation model was verified through experiments. The temperature changes of fibers in the two preheating methods were compared by direct contact preheating experiment and microwave preheating experiment. Microwave preheating is more efficient than direct contact preheating, and more uniform temperature distribution in fiberboard mats. The core layer temperature is higher than the surface layer temperature, which can shorten the preheating time. By comparing the COMSOL model with the test, the model can basically reflect the temperature change law of microwave preheating, and the temperature of each layer of the slab is more uniform in the model simulation process.

The heating law of the fiberboard was obtained, which provided a theoretical reference for the industrialized microwave preheating of fiberboard.

KEYWORDS: Fiberboard, microwave, thermal radiation, COMSOL.

INTRODUCTION

In order to increase the production efficiency of fiberboard and improve the quality of the fiberboard, the fiberboard mat must be preheated before entering the hot press. The pre-heating temperature is generally controlled at around 80□ in order to prevent the early curing of the urea-formaldehyde resin adhesive. Microwave heating is a new type of preheating method for fiberboard mat. Fiberboard is a composite material made from wood or other plant fibers, with synthetic resins added, under heated and pressurised conditions. In the manufacturing process, the pre-heating temperature and hot pressing temperature of the fiberboard mat, as well as the compression density and hot pressing pressure are very critical and many scholars have conducted research on this aspect.

Hata et al. (1990) developed and experimentally verified a thermal model for heating man-made mats by adding steam to the hot pressing process. The results showed that the time required for the intermediate layer to reach 100°C decreases as the moisture content increases. Carvalho and Costa (1998) developed a mathematical model of heat and moisture transfer in the hot pressing process of MDF. The model establishes a three-dimensional non-stationary problem including heat transfer between the hot press and the board, and analyses the effects of temperature, moisture content and vapour pressure gradients on the physical properties of the system. The theoretical model can be used to predict the variation of temperature, moisture content, vapour pressure and relative humidity with time, which is of great interest for the adjustment of the hot pressing process parameters. Zombori (2001) developed a relationship between process parameters and the final properties of boards during the hot pressing of OSB. The model simulates the formation of OSB based on Monte Carlo simulation techniques to reproduce the spatial structure of the bedding layer. The model also predicts the variation of several pore volume fractions within the board during the consolidation process. Thoemen et al. (2003) proposed a model for the thermal compression of fibreboard. The model is able to simulate the changes in temperature, moisture content, vapour and gas pressure, bond strength, density and the overall heat and gas flow patterns during the hot pressing of fibreboard. Garcia et al. (2005) established a relationship between panel permeability as a function of density by measuring data related to temperature, gas pressure, density and permeability of the panels during hot pressing. Thoemen et al. (2006) investigated the vertical density distribution and the development of internal stresses in man-made mats during hot pressing and developed a rheological model. The model explains the heat and mass transfer and the binder curing change pattern during the pressing process. Rofii et al. (2014, 2016) explored the temperature variation of mats during hot pressing by testing the temperature variation of the surface and core layers of man-made slabs with different raw materials and different slab densities. In 2021, Kazushige Murayama, an academic at the Forestry and Forestry Research Institute of Japan, and Kensuke Kukita, a professor at Shizuoka City University (Murayama et al. 2021) analysed the variation curves of mat centre temperature with time and the variation curves of steam pressure with time for different surface moisture content and FCF ratios.

In general, research into the heating of fiberboard has focused on the more traditional heating methods of direct heating and steam-assisted heating. Currently, most fiberboard enterprises in China still use the traditional hot plate contact heating method. During this hot-pressed fiberboard forming method, heat is transferred from the surface to the interior, so that there is a large temperature difference between the inside and outside the plate (Dömény et al. 2014, Ganguly et al. 2021). Its central layer is a lower temperature and has a lower curing degree of the aldehyde adhesive, which results in a decrease in the strength of the inner binding of the plate. It takes a long time for the heat to transfer from the surface to the inner portion of the plate, which severely affects the quality and yield of the plate (Harris et al. 2008, He et al. 2014). During contact heating, the hot plate first heats the surface of the mat, and then the heat is gradually transferred to the core layer, resulting in a temperature gradient throughout the mat. The surface is subjected to a higher temperature and amount of moisture. As a result, the amount of compression is relatively large, but the core layer is not as easily compressed, so a density gradient is generated in the direction of the thickness of the mat (Baettig et al. 2017, Liu et al. 2019, Gong et al. 2014). Compared with conventional heating, microwave heating is a completely different heating method from the perspective of heat transfer and mass transfer. Microwaves are a type of high frequency electromagnetic waves, which have four basic characteristics: volatility, high frequency, thermal characteristics, and non-thermal characteristics (Bogosanovic et al. 2010, Li et al. 2013, 2015). Microwaves, as an electromagnetic wave, also have wave-particle dichotomy. Microwave quantum energy is 1.99×10^{22} J to 1.99×10^{25} J. Microwaves can penetrate directly into the fiberboard in the form of electromagnetic waves, and through the microwave electromagnetic field and the interaction surface of the water molecules and other polar groups in the plate embryo. This quickly produces a large amount of heat, which achieves rapid heating of the mats. In recent years, many scholars have conducted a lot of research on the physical and chemical properties of microwaved fibers and the hot-pressing process of fiberboard (Li et al. 2008, Vinden et al. 2011).

He et al. (2017) used fast-growing artificial forest poplar wood as the research object and expounded the characteristics of the high-intensity microwave pretreatment in terms of the change of the temperature and humidity of the poplar. This revealed the mechanism of high-intensity microwave pretreatment of poplar wood and provided a scientific basis and theoretical support for follow-up research on the manufacturing technology of high-strength microwave pretreatments and high value-added functional wood composite materials (Baettig et al. 2017). Poonia et al. (2017) studied the effects of different microwave intensities and radiation times on the vertical air permeability of larch and birch using a homemade air permeability meter and showed that the vertical breathability of both woods considerably improved as the microwave intensity and processing time increased.

Ganguly et al. (2021) simulated the effect of microwave radiation on the internal temperature distribution of wood. The temperature distribution and migration law of the wood during microwave drying was studied via the analysis method. In addition, the diffusion law of moisture during the microwave drying process was studied, and a mathematical model of the heat transfer mass of microwave dried unsaturated porous medium was established. Microwave heating can be used to increase the air permeability of wood, improve drying quality, and provide favorable conditions for the preparation of novel wood-based composite materials (Gu et al. 2005, Xu et al. 2014).

In general, domestic and foreign scholars have performed more research on the physical and chemical properties of natural wood under the action of microwaves, but relatively few have performed research on microwave preheated fibers (Sanchez-Montero et al. 2018, Li et al. 2010, Yun et al. 2020). Therefore, combined with the characteristics of microwave heating, microwave rapid heating technology is used before the plate enters the continuous press (Bartholme et al. 2009, Gu et al. 2005). Through microwave heating, a temperature field opposite to conventional hot pressing is quickly established inside the board, which shortens the hot-pressing time, improves the yield and quality of the board, and reduces the amount of formaldehyde released from the board (Lazarescu et al. 2012, Mekhtiev et al. 2004). This method has important economic and social benefits in terms of the overall energy usage and emission reductions of the fiberboard industry.

Theoretical model

The theoretical basis of microwave heating is based on the theory of electromagnetic heat correlation, and its basic mechanism is based on Maxwell's equation and heat transfer equation. Microwave heating is a multiple physical coupling field that involves the thermal radiation of electric and magnetic fields in microwave ovens and the heat conduction of solid heating.

During the microwave heating process of fiberboard, microwaves can pass through wood fibers; as such, the primary form of heat absorption is thermal radiation. Heat comes from two aspects, the absorption of microwaves by the fiberboard mats and heat transfer between the mats. Therefore, by constructing a thermal radiation model of microwave heating and the related initial and boundary conditions, the temperature change in the fiber mats can be simulated during the heating process.

The microwave heating effect is closely related to the dielectric constant of the heated dielectric material, so the thermal effects under the action of microwave electromagnetic fields are also different. A substance consisting of polar molecules can absorb microwave energy well. Water molecules are the best medium for absorbing microwaves, so substances containing water molecules can absorb microwaves. The other group consists of non-polar molecules, which rarely absorb microwaves, e.g., polytaphedrene, polypropylene, polyurethane, plastic products, glass, ceramics, etc. The microwaves can pass through these materials but cannot be absorbed. These materials can be used as containers or holders for microwave heating, or as sealing material.

While building the electromagnetic field and temperature distribution models, thermodynamics and Maxwell's electro-magnetic theory are the foundation of the simulation (Campanone et al. 2012, Nioua et al. 2017, Resch 2006).

Microwave heating is a kind of multi-physical coupled field, which involves the thermal radiation of electric and magnetic fields in microwave oven and the heat conduction of solid heating (Sugiyanto et al. 2010, Sethy et al. 2012, Tuhvatullin et al. 2019). The differential form of Maxwell's basic equation can be expressed as:

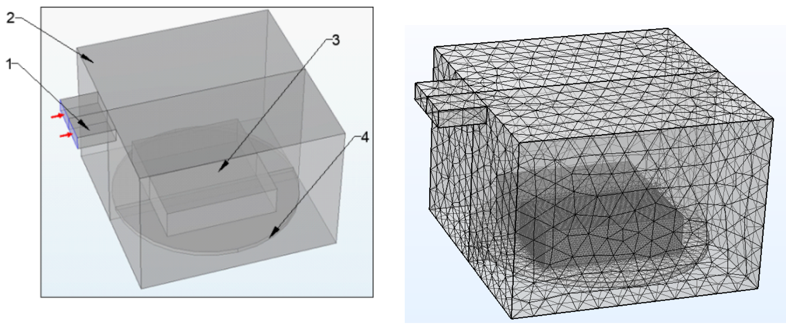
$$\begin{cases} \nabla \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t} \\ \nabla \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} = 0 \\ \nabla \cdot \vec{D} = \rho \end{cases} \qquad (1)$$

In Eq. 1 $\vec{E}$ is the electric field intensity, $\vec{H}$ is the magnetic field intensity, $\vec{B}$ is the magnetic induction intensity, $\vec{D}$ is the electric displacement, $\vec{j}$ is the current density, and ρ is the free charge density. According to Eq. 1, the distribution of the electromagnetic field inside the wood fibers can be calculated (Luo et al. 2014).

MATERIAL AND METHODS

COMSOL software simulation

The microwave heating model (Fig. 1a) was established using COMSOL software (COMSOL Multiphysics 5.6, COMSOL Inc., Stockholm, Sweden). The wall and waveguide of the microwave model are made of stainless steel, and the relevant parameters can be directly retrieved in the software. The meshing was divided into fiberboard mats as shown in Fig. 1b. The material setting of the fiberboard was based on the relevant parameters of poplar fibers with a moisture content of 10%, as used in the experiment (Tab. 1). The microwave heating power was set at 0.7 kW and 2.45 GHz, with a heating time of 70 s for the simulation analysis.



a) b)

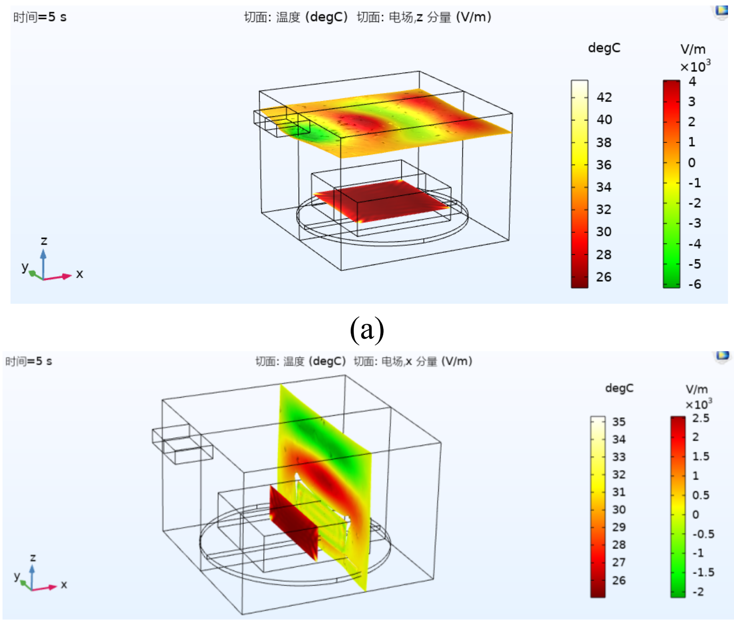
Fig. 1: a) Microwave heated fiberboard model, b) and grid-dividing graph (1- microwave waveguide, 2- microwave metal case, 3- fiberboard, 4- disc holder).

Tab. 1: The thermal physics coefficients of the fiberboard mat (Liu 2013).

Density of fiber mat ($kg \cdot m^{-3}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat capacity ($kJ \cdot kg^{-1}$)	Thermal diffusivity ($m^2 \cdot s^{-1}$)
150	0.236	1.755	0.206×10^{-6}
Note: The initial moisture content is 10%.			

Because microwaves are a type of electromagnetic waves, the simulation module of "frequency domain-transient, bidirectional coupling and electromagnetic heat" in the COMSOL software was chosen to solve this heating model. The frequency domain interface adds the TE10 mode because TE10 is the only propagation mode for frequencies between 1.92 GHz and 3.84 GHz. The microwave frequency was set to 2.45 GHz, and added transient research types to the solid heat transfer interface.

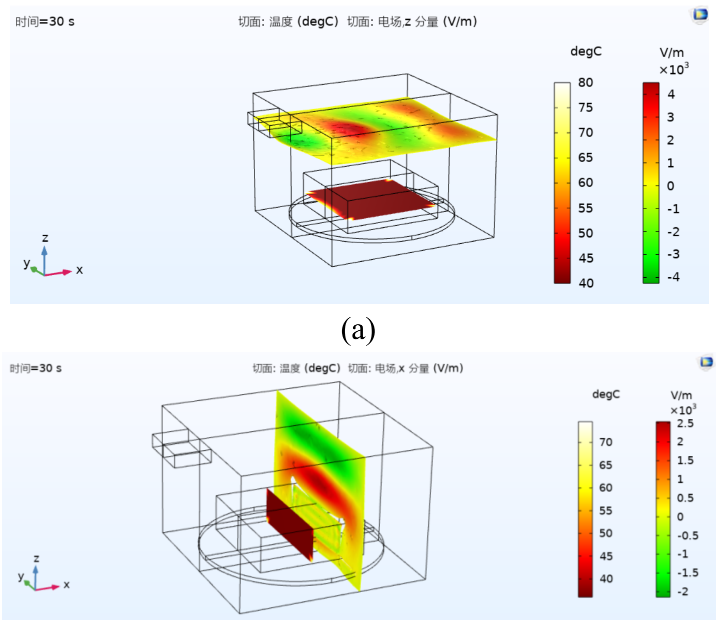
In order to match the test microwave oven setup, the side rectangle is defined as the inlet for loading the microwave (Fig. 1a). This mode was equivalent to a multi-port output microwave, heated using single-side radiation, which is a complex oscillation mode. The fiberboard acted as a resonator for the microwave field. The temperature variation and electric field distribution in fiber mat are very important during microwave heating. By using COMSOL software, the temperature during the reheating of the mat and the change in the electric field in the microwave oven are obtained (Figs. 2-4).



(a)

（b）

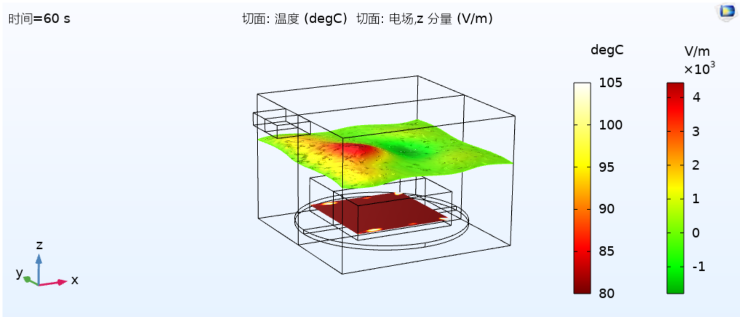
Fig. 2: a) Temperature (°C) and Z- direction electric field distribution (V/m) of fiber mat after heating for 5 s, b) temperature (°C) and X- direction electric field distribution (V/m) of fiber mat after heating for 5 s.



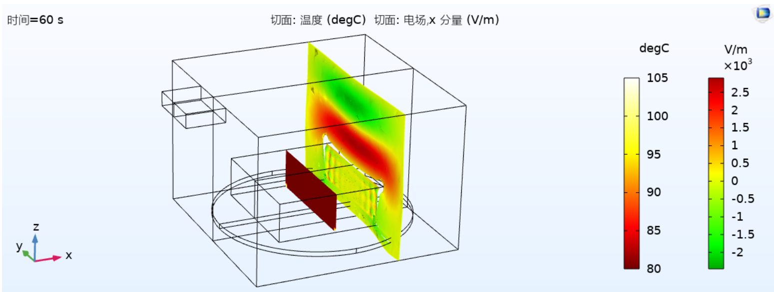
(a)

(b)

Fig. 3: a) Temperature and Z- direction electric field distribution of fiber mat after heating for 30 s, b) temperature and X- direction electric field distribution of fiber mat after heating for 30 s.



(a)



(b)

Fig. 4: a) Temperature and Z- direction electric field distribution of fiber mat after heating for 60 s, b) temperature and X- direction electric field distribution of fiber mat after heating for 60 s.

Fig. 2a shows the temperature distribution of the fiberboard after 5 s of horizontal heating and the electric field of the Z component in the microwave oven. Fig. 2b shows the temperature distribution of the vertical surface of the fiberboard after microwave heating for 5 s and in the microwave oven. Figs. 3 and 4 show the temperature inside the fiber mat after heating for 30 s and 60 s. The fiberboard is warmer near the microwave oven waveguide, and the temperature is relatively balanced in the rest of the place. As can be seen from the figure, microwave preheating fiberboard has more uniform heat than traditional fiberboard contact preheating. Uniform heating of the fibers is very conducive to the curing of the fiber glue in the subsequent hot pressing process. At the same time, it avoids large thermal stresses during hot pressing, so that the fiberboard shape size temperature and the bond is firm.

Materials

In order to compare the heating effect of direct contact heating and microwave heating, this study set up two heating methods double plate direct heating and microwave heating. An microwave oven and hot-press was used, and their basic parameters are listed in. Tabs. 2 and 3; Moisture content 10% fiber mats, digital display thermocouples, video cameras, etc.

Tab. 2: The parameters of the microwave.

Model	Power supply	Frequency	Rated power	Box material
P70F20CN3P	220 V 50 Hz	2450 MHz	700 W	304 Stainless steel

Tab. 3: The parameters of the hot-press.

Model	Power supply	Rated power	The temperature of the upper pressure plate	The temperature of the lower pressure plate
BY101X1/10	380 V, 50 Hz	16 kW	100°C	100°C

(a) (b)

Fig. 5: a) fiber mat heated simultaneously by upper and lower hot pressing plates, b) fiber mat heated by microwave.

Methods

In order to measure the heating effect of fiber mats in different heating methods, the temperature changes of fiber mats in double plate heating for 3 min, and microwave heating for 70 s were recorded. Since the microwave heating temperature changes rapidly, the microwave heating 5 s, 10 s, 15 s, 20 s, 25 s, 30 s, 35 s, 40 s, 45 s, 50 s, 55 s, 60 s, 65 s,70 s these time nodes and the temperature measurement at different heights in the center of the fiberboard blank are measured. Its specific location is shown in Fig. 6.

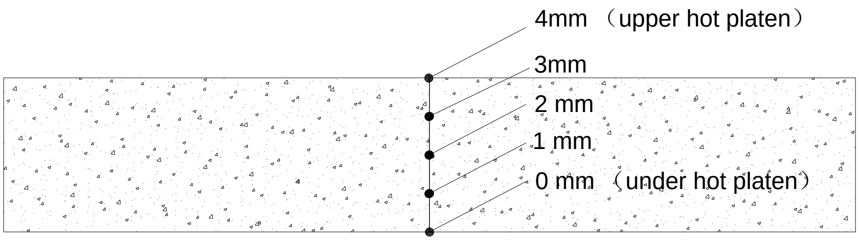


Fig. 6: The position of the fiber mat temperature measurement points.

RESULTS AND DISCUSSION

In order to study the temperature change of the fiber mat, the average of the 5 measurements was taken as the final measurement by repeating the test on 5 fiber mats. The actual temperature curves of the fiber mats in different heating methods and the COMSOL simulation curves are shown in Fig. 7 and Fig. 8a,b compares the simulation and test of the COMSOL software, and the simulation is basically consistent with the effect of the actual microwave heating.

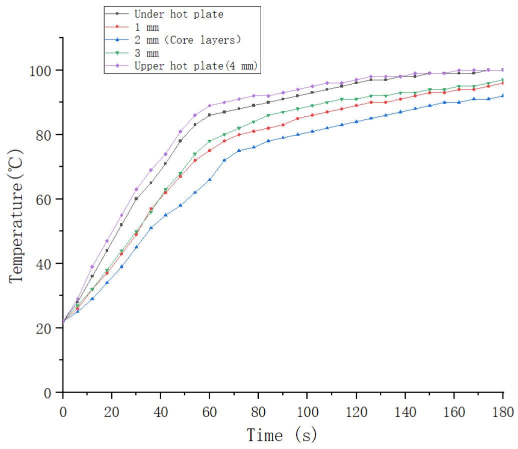


Fig. 7: Heating the fiber mat on both sides of the upper and lower hot press plates.

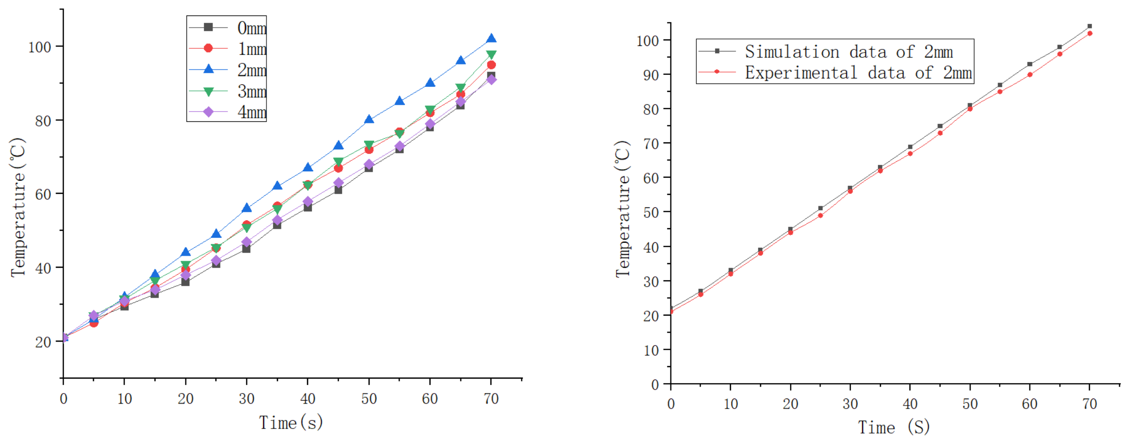


Fig. 8: a) Microwave heated fiber mats, b) microwave simulation temperature in the middle (at 2 mm) of fiber mat compared with test temperature.

From the comparison results, it is clear that microwave preheating is much more efficient than direct contact heating, and the temperature distribution of the fiberboard slab is more uniform. The temperature of the surface layer of fibers rises fastest with direct contact heating and the heat is transferred from the surface layer to the core layer, resulting in a temperature gradient. If the thickness of the board is too large, the resin bonding agent at the core layer of fibres may not reach the required temperature during the subsequent hot pressing process, thus reducing the static flexural strength of the board. Microwave preheating of fiberboard slabs is more effective because it is electromagnetic radiation heating and is uniformly heated everywhere, with the central temperature being higher than the surface temperature.

This pattern is similar to that studied by Vinden et al. (2011) and Luo et al. (2014). Vinden et al. (2011) used microwaves to modify sleepers for experimental studies, through the cross-section of the sleeper and along the length of the temperature measurement shows that the overall temperature distribution of microwave heating is uniform, the centre of the sleeper temperature is higher than the surrounding temperature (Fig. 9).

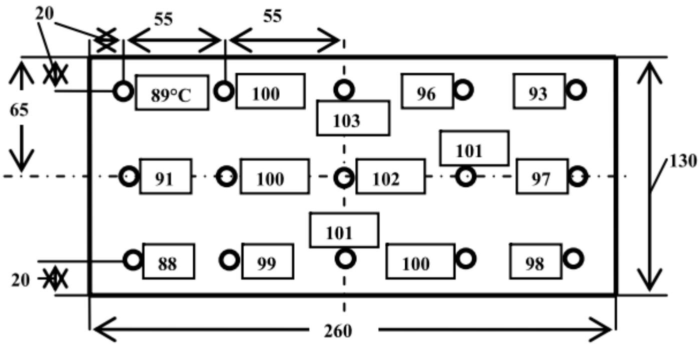


Fig. 9: Temperature distribution in the sleeper cross section (Vinden et al. 2011).

Luo et al simulated the temperature changes inside the wood by analysing the basic principles and theories of microwave heating of the wood in different microwave heating methods. The results are shown in Fig. 10, where the temperature in the centre of the wood is higher than the surface temperature by microwave heating.

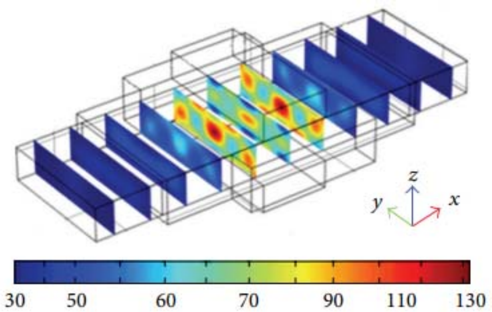


Fig. 10: The multisections temperature (□) distribution within wood heated by microwave (Luo et al. 2014).

CONCLUSIONS

Preheating methods for fiberboard mats are analyzed and discussed. The advantages and laws of microwave preheating are highlighted, and theoretical and practical references are provided for the microwave preheating process of fiberboard. Microwave preheating of fiberboard slabs is very different from contact heating in terms of how the heat is transferred. In contact heating, the heat is transferred from the surface layer of the fiberboard mats into the core layer, so there is a large uneven temperature distribution. Whereas with contact heating the fiberboard slab takes longer in the heat transfer process due to heat dissipation when the heating plate is set at 100□. Microwave heating is radiation heating and the heat is mainly transferred in the form of electromagnetic waves. During the microwave heating process, the distribution of the electric field changes with time. Microwave preheating of slabs is much more efficient than direct heating, and its advantages are even more obvious as it can be used to preheat slabs of greater thickness due to its strong penetrating power.

Combining microwave heating and fiberboard mats thermal correlation parameters, the changes in mat thickness and temperature during microwave heating are discussed.

The changes in fiber temperature and electric field during microwave preheating are elucidated, and the differences between microwave preheating and direct contact heating are experimentally compared, thus verifying the reliability of the simulation model and providing a theoretical reference for fiberboard mats microwave preheating.

The changes in fiberboard mats temperature and electric field during microwave preheating are elucidated, and the differences between microwave preheating and direct contact heating are experimentally compared, thus verifying the reliability of the simulation model and providing a theoretical reference for fiberboard mats microwave preheating.

A simulation model for microwave heating of fiberboard mats plates was established using COMSOL software and the relevant parameters of the model were determined according to the experimental requirements. By applying microwave thermal radiation, the temperature change pattern of the fiberboard mat in the microwave environment was obtained. Compared with direct contact heating, microwave heating is a deep heating of the object.

By scientifically selecting the fiberboard mats temperature at the centre of the layer at different heights for repeated experiments and comparing the experimental data with the simulated data, it was found that the heating profiles analysed by the COMSOL simulations were in general agreement with the actual situation.

It is worth noting that, due to the high power of industrial microwaves, the microwave cavity must be strictly sealed to prevent microwave leakage in order to prevent radiation to humans.

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