# Preheating Model of High-temperature Setting of *Pinus sylvestris* var. *mongolica* Litv. Wood

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Large-section boxed-heart square timber is prone to surface and radial cracks during the drying process. A high-temperature setting pretreatment could prevent cracking in boxed-heart timber. The pretreatment process is primarily determined by the preheating time. To determine the preheating time of the test material, a mathematical model for the internal temperature distribution of Mongolian pine (*Pinus sylvestris* var. *mongolica* Litv.) boxed-heart square timber in the preheating stage was established by the finite element method. The model viability was verified by tests that showed that the model simulation results were stable and non-fluctuating. For the prediction error of the temperature change, the early-period error was large, while the later predicted values and measured values tended to be consistent. For the prediction error of the temperature distribution, the core-layer error was smallest, while that of the surface layer was greatest. For the prediction error of the preheating time, greater preheating temperatures exhibited greater error, and the minimum error was 10 min, at 90 °C. Overall, the predicted values were close to the measured values and can be referenced for subsequent pretreatment process research.

*Keywords: Mongolian pine; Finite element; Preheating time; Pretreatment; Drying set*

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## INTRODUCTION

Wooden structures are desirable because they are made of natural materials, which are environmentally friendly and generally save energy (Guo *et al*. 2009). In recent years, the wood construction industry has rapidly developed, and great amounts of timber require efficient, fast, and high-quality drying (Liu *et al*. 2017). Due to anisotropic shrinkage, large-section boxed-heart square timber is prone to the development of surface and radial cracks during drying. Although surface cracks do not greatly affect the mechanical properties, these cracks may detract aesthetically, decreasing the commercial value of the wood. The majority of boxed-heart timber contains juvenile wood and pith, and the water migration distance from the core layer to the surface layer is high, resulting in longer drying time (Katagiri *et al*. 2007). To reduce the cracking and the drying time of boxed-heart timber and increase the drying quality and efficiency, various pretreatment methods have been proposed.

Some scholars have employed high-frequency vacuum drying (Lee *et al*. 2010), microwave drying (Harris *et al*. 2008), or smoke drying (Ishiguri *et al*. 2001) to prevent the surface cracks on wood. A few researchers have used hot pressing (Matsumoto *et al*. 2012) to prevent the surface cracks on boxed-heart timber. However, these techniques have not produced satisfactory results, as the treated wood still has surface cracks. The use of high-temperature setting pretreatment to control the drying cracks of boxed-heart timber has attracted widespread attention. Hermawan *et al*. (2012) performed a high-temperature low-humidity setting pretreatment of 200-mm- thick and 220-mm-thick sugi (*Cryptomeria japonica* D. Don) and found that a pretreatment temperature of 135 °C for 10 h or 150 °C for 7 h could effectively prevent surface cracks on the wood. Katagiri *et al*. (2007) used 120-mm-thick sugi to investigate the effects of different treatment temperatures on the surface deformation of wood. The results showed that the extent of surface cracking at the 120 °C treatment temperature was less than that at the 80 °C treatment temperature after the wood was dried. These studies show that high-temperature setting pretreatment could effectively prevent cracks on boxed-heart timber.

The pretreatment process is primarily the determination of the preheating time. Reasonable control of preheating time is important for high-quality and energy-efficient wood drying. Generally, the formulation methods of preheating time mainly include the actual measurement method (obtained by test) (Gu 1984) and the theoretical method (obtained by heat conduction equation) (Cai 2005). The actual measurement method is more accurate, but it requires multiple experiments to determine, and the operation is cumbersome and time-consuming. The theoretical method is convenient, but the precision cannot be guaranteed. The simulation prediction method combines the advantages of the above two methods and is one of the effective methods for preheating time formulation (Zhao *et al*. 2015). In this study, Mongolian pine (*Pinus sylvestris* var. *mongolica* Litv.) was used as the research object, and the finite element method was employed to establish a two-dimensional temperature field model inside wood at the preheating stage. The model was verified by tests. It was expected that this study could provide a theoretical basis for the reasonable implementation of high-temperature setting pretreatment processes.

## EXPERIMENTAL

### Preheating Model Building

*Geometric model*

Finite element simulation software (COMSOL Multiphysics 5.2a, COMSOL, Inc., Burlington, MA, USA) was used to simulate the preheating process of the specimen. As shown in Fig. 1, the geometric model was drawn at a 1:1 ratio of the wood cross-section.

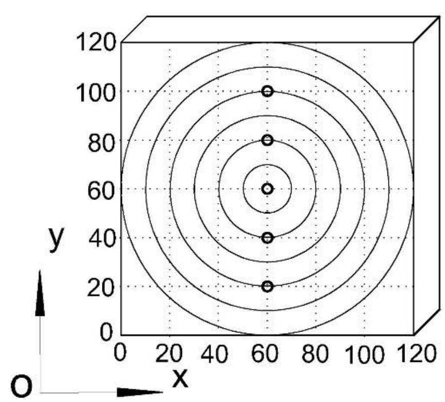


**Fig. 1.** The probe locations of the geometric model (dimensions in mm). From top to bottom, the locations of the probes were (60 mm, 100 mm), (60 mm, 80 mm), (60 mm, 60 mm), (60 mm, 40 mm), and (60 mm, 20 mm).

Five temperature probes were preset at coordinates (60 mm, 100 mm), (60 mm, 80 mm), (60 mm, 60 mm), (60 mm, 40 mm), and (60 mm, 20 mm), *i.e.*, uniformly along the thickness direction of the sample. The test material properties and moisture content (MC) were assumed to be evenly distributed.

*Governing equations*

Referring to Fourier second heat transfer theorem, the energy governing equation for the preheating phase of the test material is as follows (Eq. 1),

$$\rho_s c_w \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) \tag{1}$$

where $T$ is the wood temperature (°C), $\rho_s$ = 600 kg/m$^3$ is the basic density of the wood (kg/m$^3$, GB/T 1933 2009), $c_w$ is the specific heat of the wood (J/(kg·°C), $c_w = 2000 + 8.71M + 4.98T$ (Steinhagen and Lee 1988), where $M$ is the moisture content), $t$ is time (s), $\lambda$ is the thermal conductivity of the wood (W/(m·°C), $\lambda$ = 0.4615exp(0.8113$M$)*exp(-608.6/($T$+273.15)) (Zhao *et al*. 2016), and $x$ and $y$ are the distances between the thickness and width of wood cross-section (m).

*Initial and boundary conditions*

At $t = 0$ (initial time), it was assumed that the cross-section temperature distribution of the test material was uniform (Eq. 2),

$$T(x, y) = T_0 \tag{2}$$

where $T_0$ = 23 °C is the initial temperature of the test material.

The width ($x = L$ = 120 mm) and thickness ($y = H$ = 120 mm) correspond with the boundary conditions of the wood surface (Eq. 3 and 4),

$$\lambda \frac{\partial T}{\partial x} = h(T_e - T) \tag{3}$$

$$\lambda \frac{\partial T}{\partial y} = h(T_e - T) \tag{4}$$

where $h$ is the surface heat transfer coefficient ($h$ = 9.6 W/(m$^2$·°C)) (Pordage and Langrish 1999), and $T_e$ is the environment temperature (°C).

When $x = 0$ and $y = 0$, the temperature boundary conditions of the wood core layer (assuming an adiabatic surface) are as follows (Eq. 5 and 6):

$$\frac{\partial T}{\partial x} = 0 \tag{5}$$

$$\frac{\partial T}{\partial y} = 0 \tag{6}$$

*Meshing and solving model*

The “normal” mesh size was used in the research model to improve the calculation efficiency while ensuring computational accuracy; the meshing is shown in Fig. 2. The solid heat transfer module of the finite element simulation software was chosen for the solution.

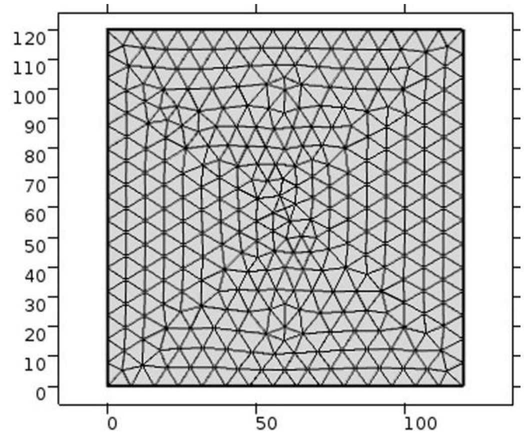


**Fig. 2.** Mesh generation (dimensions in mm)

## Preheating Model Verification

Mongolian pine specimens with similar material properties and no clear defects (such as cracking, decay, or deformation) were selected. The initial MC was 60%. The Mongolian pine was processed into 500 mm × 120 mm × 120 mm (longitudinal × tangential × radial) boxed-heart square timber.

The preheating temperatures of the tests was set as 90 °C, 105 °C, and 120 °C, that is, the dry bulb temperature and wet bulb temperature were set as 90 °C, 105 °C, and 120 °C. The wood end was sealed with epoxy resin during the test to ensure that the heat was only transmitted laterally. At the center cross-section of the test material, five measuring points were uniformly preset in the thickness direction (Fig. 3). Holes were drilled on the side of the specimen with a 2-mm drill bit to a depth of 60 mm. Each measuring point was embedded with one of the thermocouples, and the locations where the sensors were in contact with the wood surface were coated with silica gel to ensure good sealing. The T-type thermocouple was buried in the sample, and the sample was placed in a DS-408 constant temperature and humidity kiln (YASELINE, Beijing, China) with the temperature and humidity set. The volume inside the drying kiln was 800 mm (width) × 850 mm (height) × 600 mm (depth). The temperature range was 0 °C to 150 °C, the temperature fluctuation was ±0.5 °C, and the wind speed was 2 m/s.

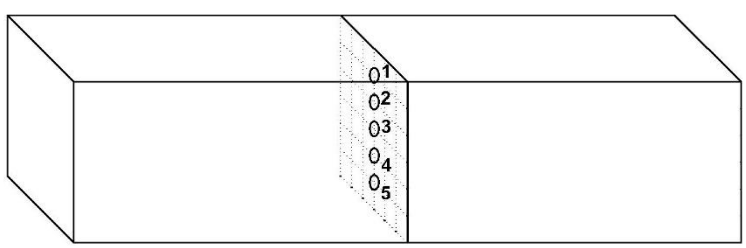


**Fig. 3.** Test material and measuring points: (1) upper-layer measuring point, (2) upper-middle-layer measuring point, (3) core-layer measuring point, (4) lower-middle-layer measuring point, and (5) lower-layer measuring point

When the sample center temperature reached the ambient temperature, the test was over, and the total preheating time was recorded. The wood temperature was measured using the T-type thermocouple by an NEC Remote Scanner Jr. DC3100 multi-point signal inspection instrument (Tokyo, Japan) (recorded every 1 min, with an instrument accuracy of 0.1 °C). The error between the predicted model and the measured temperature changes, temperature distribution, and preheating times were compared. Three sets of repetitive experiments were conducted to reduce accidental errors.

## RESULTS AND DISCUSSION

### Simulation Results

The sample was subjected to preheating simulation under different temperature conditions. The three sets of simulation results did not show different behaviors. To reflect the simulation results conveniently, the simulation results for the condition of 90 °C were selected for the explanation. As shown in Fig. 4, when the preheating temperature was 90 °C, the internal temperature field of the test material was simulated at different times in the preheating stage. The figure clearly shows the instantaneous temperature changes at various points inside the wood during the preheating phase. The internal temperature distribution of the wood always showed lower inner temperatures and greater outer temperatures, with the central temperature being the lowest and the corner temperature being the greatest. At the initial preheating time ($t$ = 0 min), the internal temperature distribution of the wood was uniform ($T_0$ = 23 °C). As the preheating progressed, the surface temperature increased first, with the temperatures at the corner positions changing the fastest.

The primary reason for this phenomenon is that the corner points were greatly affected by the environmental heat flux density. In the initial stages of preheating, the surface temperature change of the test material was primarily affected by the environment. This was especially the case for the corner points, which were affected by the ambient temperature on two side surfaces; hence, their temperatures changed rapidly. Thereafter, the heat gradually migrated from the surface layer to the core layer, causing the internal temperature to gradually increase. Then, the temperature difference gradually decreased and tended to be consistent until the sample temperature reached the ambient temperature ($T$ = 90 °C), and the preheating was stopped.

In theory, the model simulation results were stable and non-fluctuating. The results suggested that the model can simulate the change of the internal temperature distribution of wood at different times in the preheating stage. However, the simulation accuracy needed to be verified.

### Temperature Change Prediction Error Analysis

The predictions of temperature changes were based on the core layer temperature probe point. Therefore, to clearly reflect the trend of the temperature change prediction, only one curve of the core temperature probe point was adopted. The error curve of the measured and simulated temperature change (*error* = |*measured value* – *predicted value*|) is shown in Fig. 5. Of the different preheating temperature conditions, greater temperatures exhibited greater prediction errors.

The prediction error at 120 °C was the greatest, while the error was smallest at 90 °C. This phenomenon could be due to wood chemical composition changes at high temperatures, as the crystal structure of the wood changed, and the width and crystallinity of the crystallization zones increased (Cheng 2007).

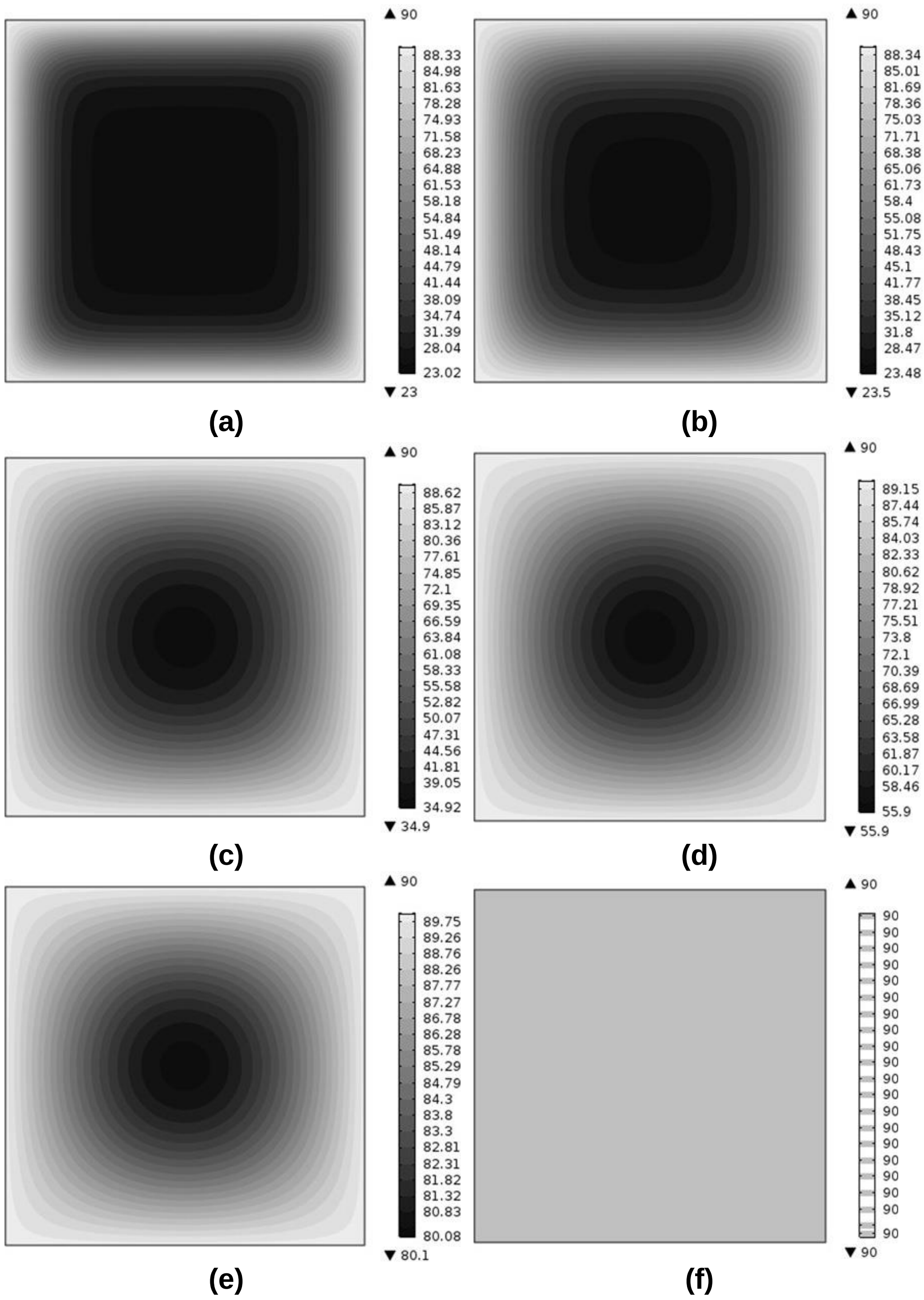


**Fig. 4.** Temperature field distribution (in °C) of test material at different times during preheating: (a) 15 min, (b) 45 min, (c) 90 min, (d) 180 min, (e) 360 min, and (f) 600 min

Through high-temperature steaming, the wood cell wall softened, the wood permeability increased, and the discharge of wood internal extractives was accelerated. Meanwhile, the hemicellulose itself had the characteristics of poor heat resistance and easy hydrolysis. Under the high-temperature treatment at 120 °C, part of the hemicellulose began to degrade, which had affected the physical and chemical properties of the wood. These changes were not taken into account in the model; only physical heat transfer was considered.

In the early stage of preheating, the simulation error was great, and the error then gradually decreased. The simulation and measured temperature tended to be consistent eventually. This result might be due to the differences in the material properties distributions of wood and uneven MC distributions. In subsequent model studies, the effects of wood material differences and MC distributions should be fully considered. Meanwhile, in the initial stage of preheating, many high-temperature water vapor molecules in the environment were liquefied and adsorbed on the wood surface, which caused the wood temperature to change greatly and made it unstable. As the preheating progressed, the wood temperature gradually increased and approached the ambient temperature. The molecular amount of water vapor in the environment gradually decreased, resulting in the relatively flat change of the temperature inside the wood.

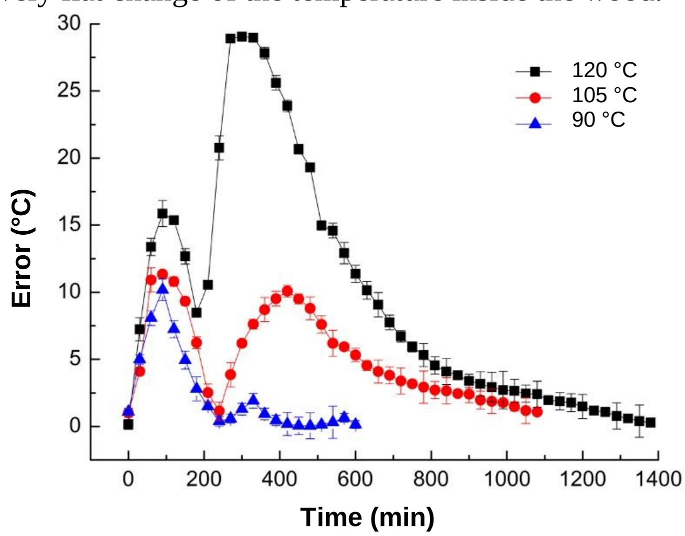


**Fig. 5.** The error curves of temperature change prediction

## Temperature Distribution Prediction Error Analysis

The error curves of temperature distribution prediction while reaching the setting preheating temperature are presented in Fig. 6.

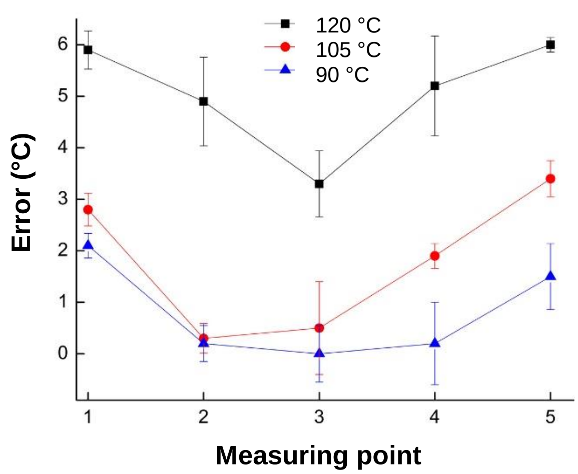


**Fig. 6.** The error curves of temperature distribution prediction while reaching the setting preheating temperature

As the preheating temperature increased, the temperature distribution prediction error also increased. Along the cross-section of the wood, from top to bottom, the error first decreased and then increased, and the prediction error of the core layer was less than that of the surface layer. This result is attributed to the uneven distribution of the material properties of boxed-heart square timber. During the experiment, the heat transfer efficiencies of different parts were quite different, resulting in an uneven final temperature distribution. The temperature control of the experimental equipment fluctuated ± 0.5 °C. From the surface layer to the core layer, the heat transfer process proceeded slowly. When the core layer reached the predetermined temperature, the surface layer might have been at a slightly greater temperature than the predetermined temperature.

### Preheating Time Prediction Error Analysis

The comparison between the simulated and measured preheating times is shown in Table 1. As the preheating temperature increased, the time prediction error also increased. When the preheating temperature was 120 °C, the error was up to 54 min. When the preheating temperature was 90 °C, the error was at least 10 min. Overall, the predicted values were close to the measured values and can be referenced for subsequent pretreatment process research.

**Table 1.** Prediction Time Error

| Group | Preheating Temperature (°C) | Preheating Time (min) | Simulated Time (min) | Error (min) |
|---|---|---|---|---|
| 1 | 120 | 1356 | 1410 | 54 |
| 2 | 105 | 1050 | 1080 | 30 |
| 3 | 90 | 590 | 600 | 10 |

## CONCLUSIONS

1. A two-dimensional mathematical model of the internal temperature distribution of wood in the preheating stage was established. A verification test was performed.
2. Under different preheating temperature conditions, greater temperatures exhibited greater prediction errors. The model had high error in the early stage and high precision in the later stage.
3. In general, the model simulation results were stable and non-fluctuating. The predicted values were close to the measured values and can be referenced for subsequent research of pretreatment processes. The preheating model could provide the basic data and theoretical basis for optimizing wood drying quality.

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