

Thermal Responses of Woods Exposed to High Temperatures Considering Apparent Thermo-Physical Properties

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Abstract: It is well known that the use of woods as construction materials can embody carbon content of structural members, which can enhance the urban sustainability. However, due to the combustibility of wood, its current application is restricted. To broaden the application of wood, its thermal responses exposed to fire (high temperature) is investigated in this study. Firstly, the wood kinetic parameters are determined by coats-redfern method using thermal gravimetric (TGA) data. Secondly, the density and thermal conductivity are obtained from parallel and series models. Thirdly, the specific heat capacity formula is presented considering latent and decomposition heat, which can be directly determined by differential scanning calorimetry (DSC). Finally, the one-dimensional nonlinear heat transfer model with apparent thermo-physical properties is proposed. The four-sided heating experiment of Laminated Veneer Lumber (LVL) is carried out to investigate the temperature filed. The results show that the proposed model can predict the thermal responses of timber structures subjected to fire and high temperatures precisely.

Keywords: Apparent thermo-physical properties; decomposition; evaporation; heat transfer; finite element method

Notation

M: the mass;

 $M_{v,e}$: the mass of pre-evaporation (virgin material);

 $M_{f,e}$: the mass of wood after evaporation;

 $M_{v,d}$: the mass of wood before decomposition;

 $M_{f,d}$: the mass of wood after decomposition;

A: the frequency factor;

Ea: the activation energy;

n: the reaction order;

subscript *e* and *d*: the evaporation and thermal decomposition, respectively;

R: the gas constant (8.314 J/molK);

 β : the heating rate;

*C*_e: the latent heat;

 C_{d} : the decomposition heat;

 $f_{\rm e}$: the mass fraction of un-evaporated;

 f_d : the mass fraction of un-decomposed;

n: the outward normal direction of the wood surface;

 T_{∞} : the fire temperature measured in the furnace;

 h_{conv} : the convection coefficient;

 σ_{Boltz} : the Stefan-Boltzmann constant;

 ε_{emis} : the emissivity.

1 Introduction

Wood is a kind of renewable, carbon sequestrated and environmental friendly material, which is widely used in civil engineering, transportation and energy fields. Recently, the Chinese government actively encourages the development of prefabricated buildings, involving prefabricated concrete structures, prefabricated steel structures and prefabricated timber structures [1-12]. However, wood is easily flammable. When the temperature rises, the physical and chemical changes of the wood will occur [13-14]. There are two stages in the deterioration of wood quality: At 20~120°C, the moisture begin to evaporate. At 200°C~400°C, wood is decomposed into char, tar and volatile gases and the mass drops remarkably. The schematic diagram of wood subjected to high temperature is shown in Fig. 1. The char layer is fragile, which cannot provide resistance to applied loads. Therefore, the poor high temperature performance of wood seriously hindered the development of timber structures. The heat transfer models for wood under high temperatures were frequently reported in the past years [15-17]. Shen et al. [15] found that the moisture in the wood began to evaporate as the temperature exceeds 100°C. The moisture will flow to outside of the wood and inner regions. It is slow up to 240°C and end to 320°C. Park et al. [16] conducted the pressure calculations, which revealed that the internal pressure was different at different furnace temperatures. Blasi et al. [17,18] studied the heat and mass transport phenomena. Meanwhile, the primary and secondary reactions were solved by use of implicit finite difference equations. Authors analyzed the category and output of pyrolysis products, and the influences of the heating rate, temperature and pressure, content/composition of raw materials and inorganic substances on the pyrolysis reaction were also evaluated in the pyrolysis stage. Zhang et al. [19] substituted the apparent thermal parameters of wood introduced in the European standard [20] into the finite element software ANSYS to simulate the performance of wood with three surfaces exposing to fire. Compared with the test results, the accuracy of the proposed model was verified. Janssens [21] established a model considered four factors, involving dry density of the wood, moisture content of the wood, lignin content of the wood and char contraction. In the meantime, a set of thermodynamic parameters considered the change of temperatures were developed. Fredlund [22] proposed a model to analyze the basic physical process of heating wood. The model was capable of treating transient temperature and moisture states in both uncharred and charred portions of the cross-section. The thermal properties of wood at high temperature depend on the thermal physical properties such as mass/density, specific heat capacity and thermal conductivity. However, the thermo-physical properties were obtained by fitting method based on test results in the existing models. This approach has its limitations. In addition, the evaporation latent heat and decomposition heat in the existing models were often treated as heat source term, and the specific heat capacity was actual specific heat of the material. In fact, the specific heat capacity measured by differential scanning calorimetry (DSC) was the apparent specific heat rather than real specific heat [23,24]. The apparent heat capacity can be directly implanted into the heat transfer model to consider the lateral and decomposition heat. Furthermore, the published literatures on the thermal analysis of wood were often focused on the activation energy and the frequency factor of the pyrolysis, while the reaction order was usually pre-assumed [25-27]. Hence, to address the mentioned issues, the coats-redfern [28] method was used to calculate the kinetics parameters of water evaporation and thermal decomposition based on TGA and DSC test results. Based on the results of kinetic results and mix rules, the apparent thermo-physical model was presented. Finally, the one-dimensional nonlinear heat conduction model of cross grain and rift grain can be obtained. The validity and accuracy of the proposed

model was verified through the available test results. The proposed model can predict the thermal responses of timber structures subjected to fire and high temperatures precisely.



Figure 1: Wood subjected to high temperature

2 Thermal Kinetics Analysis

2.1 Thermogravimetric and DSC Tests

The Douglas fir was ground into powders and then passed in 125 mesh (0.1 mm) sieve for thermal analysis. Sample masses were 5 ± 0.1 mg. The thermogravimetric experiments were conducted with 409 Jupiter® STA synchronous thermal analyzer at modern analysis center in Nanjing Tech University. Nitrogen was purged into crucible. The scanning temperature was from 40°C to 600°C, and the heating rate was 10 K/min. The moisture contents of Douglas fir were 6%, 12% and 18%, respectively. The DSC 200F3 produced by NETZSCH company was used to measure specific heat capacity. Hot disk TSP2500 was used to measure thermal conductivity. The samples were cut into 30 mm × 30 mm × 15 mm, and 15 mm is the direction of measurement. Thermal conductivity parallel and perpendicular to fibers of 0%, 6%, 12% and 18% moisture content Douglas fir were measured, respectively.

2.2 Thermogravimetric and DSC Test Results

Figs. 2(a) and 2(b) show the results of thermogravimetric (TG) tests. "TGA 6%", "TGA 12%" and "TGA 18%" represent the TG test results of Douglas fir with 6%, 12% and 18% moisture content, respectively. The sample mass reduced slightly between 40°C and 150°C due to the moisture evaporation. The transition zone was from 150°C to 200°C. The curves show that there was no obvious changes during this temperature range. However, the mass reduced sharply due to the thermal decomposition from 200°C to 400°C. At 400°C, the mass reduced to roughly 20% of the virgin material. The test results also demonstrated that the smaller the moisture content, the smaller the mass loss between 40°C and 180°C. But it can be concluded that the decomposition was hardly affected by the moisture content of woods.



Figure 2: Thermo gravimetric curves at different moisture contents

Fig. 3 shows the DSC test results. "DSC 6%", "DSC 12%", "DSC 18%" represent the DSC test results of Douglas fir with 6%, 12% and 18% moisture content, respectively. There were two distinct peaks from 40°C to 150°C and from 28°C to 420°C, which were consistent with the water evaporation and the thermal decomposition stage of TG tests. The values of the specific heat were seriously affected by moisture content in the water evaporation stage. The higher water content led to a larger the specific heat, while the thermal decomposition was slightly affected by moisture content. The peaks of DSC 6%, DSC 12% and DSC 18% in the water evaporation stage were 3.6 kJ/(kg·K), 4.7 kJ/(kg·K) and 5.8 kJ/(kg·K), respectively. The peak at the thermal decomposition was about 3.7 kJ/(kg·K). Obviously, as the wood heats up, the temperature of the wood increased slowly because water can absorb heat in the water evaporation stage.

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Figure 3: DSC curves at different moisture contents

2.3 Kinetic Equation for Water Evaporation and Decomposition

Based on the TG and DSC test results, 150°C can be considered as the boundary temperature of evaporation and pyrolysis. The factors, α_e and α_d , can be used to describe the degree of water evaporation and thermal decomposition, respectively.

$$\begin{cases} \alpha_{e} = \frac{M_{v,e} - M}{M_{v,e} - M_{f,e}}, 40^{\circ} \text{C} < \text{T} < 150^{\circ} \text{C} \\ \alpha_{d} = \frac{M_{v,d} - M}{M_{v,d} - M_{f,d}}, 150^{\circ} \text{C} < \text{T} < 700^{\circ} \text{C} \end{cases}$$
(1)

where *M* represents the mass; $M_{v,e}$, $M_{f,e}$, $M_{v,d}$ and $M_{f,d}$ represent the mass of pre-evaporation (virgin material), after evaporation, before decomposition and after decomposition, respectively. Because the mass remained almost unchanged during the transition zone (150°C~200°C), $M_{f,e}$ is equal to $M_{v,d}$.

Then α_e and α_d can be expressed by the Arrhenius equation,

$$\begin{cases} \frac{d\alpha_e}{dt} = A_e \exp\left(\frac{-Ea_e}{RT}\right) (1 - \alpha_e)^{n_e}, 40^{\circ} \text{C} < T < 150^{\circ} \text{C} \\ \frac{d\alpha_d}{dt} = A_d \exp\left(\frac{-Ea_d}{RT}\right) (1 - \alpha_d)^{n_d}, 150^{\circ} \text{C} < T < 700^{\circ} \text{C} \end{cases}$$
(2)

where A is the frequency factor, Ea is activation energy, n is the reaction order, (A, Ea and n called "kinetic parameters"); subscript e and d represent evaporation and thermal decomposition, respectively; R is the gas constant (8.314 J/molK).

To study the effects of heating rate, the Eq. (1) can be converted into:

$$\begin{cases} \frac{d\alpha_e}{dT} = \frac{A_e}{\beta} \exp\left(\frac{-Ea_e}{RT}\right) (1 - \alpha_e)^{n_e}, 40^{\circ}\text{C} < T < 150^{\circ}\text{C} \\ \frac{d\alpha_d}{dT} = \frac{A_d}{\beta} \exp\left(\frac{-Ea_d}{RT}\right) (1 - \alpha_d)^{n_d}, 150^{\circ}\text{C} < T < 700^{\circ}\text{C} \end{cases}$$
(3)

where β is the heating rate.

2.4 Calculation of Kinetic Parameters

In this study, the Coats-redfern classical method was used to calculate all the kinetic parameters. Rearranging and integrating the Arrhenius equations, Eq. (4) can be obtained,

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$$\int_{0}^{\alpha} \frac{d\alpha}{\left(1-\alpha\right)^{n}} = \frac{A}{\beta} \int_{0}^{T} e^{-\frac{Ea}{RT}} dT$$
(4)

The right hand side can be rewritten as,

$$\frac{A}{\beta} \int_{0}^{T} e^{-\frac{Ea}{RT}} dT = \left(\frac{ART^{2}}{\beta Ea}\right) \left(1 - \frac{2RT}{Ea}\right) e^{-\frac{Ea}{RT}}$$
(5)

The left hand side can be rewritten as:

$$\int_{0}^{\alpha} \frac{d\alpha}{(1-\alpha)^{n}} = \alpha + \frac{n\alpha^{2}}{2} + \frac{n(n+1)\alpha^{3}}{6} + \left(\frac{n(n+1)(n+2)\alpha^{4}}{24}\right) \dots$$
(6)

When the value of α was less than 0.3, the term α^2 and higher order terms can be neglected,

$$\alpha = \frac{ART^2}{\beta Ea} \left(1 - \frac{2RT}{Ea} \right) e^{-\frac{E}{RT}}$$
(7)

$$\ln\left(\frac{\alpha}{T^2}\right) = \ln\frac{AR}{\beta Ea} \left(1 - \frac{2RT}{Ea}\right) - \frac{Ea}{RT}$$
(8)

Hence, a plot of $\ln \frac{\alpha}{T^2}$ against $\frac{1}{T}$ for small value of α should be a straight line with a slope of $-\frac{Ea}{R}$ since $\ln \frac{AR}{\beta Ea} \left(1 - \frac{2RT}{Ea}\right)$ is sensibly constant. *Ea* can be easily calculated from the slope of the

straight line. Then the frequency factor can be obtained.

When the maximum reaction rate occurred at temperature T_m , the derivative of Eq. (3) gives,

$$\frac{Ea\beta}{RT_m^2} = An(1-\alpha)_m^{n-1} \cdot \exp\left(\frac{-Ea}{RT_m}\right)$$
(9)

Substituting Ea into Eq. (9), reaction rate can be obtained.

2.5 Dynamic Parameter Analysis Results

Tab. 1 shows the results of kinetic parameters of evaporation and decomposition. According to Eq. (1), the mass M can be expressed as:

$$M = \begin{cases} M_{v,e} - \alpha_e \left(M_{v,e} - M_{f,e} \right), 20 < T < 150^{\circ} C \\ M_{v,d} - \alpha_d \left(M_{v,d} - M_{f,d} \right), 150 < T < 700^{\circ} C \end{cases}$$
(10)

Figs. 4(a) and 4(b) presents the mass loss curves with different heating rates at the water evaporation and the whole stages. "C-R 6%", "C-R 12%", "C-R 18%" represent the calculation results of Douglas fir with 6%, 12% and 18% moisture content, respectively. It can be found that the predicted values agreed well with test results.

Dynamic model	Conversion Rate	Eae(J/mol)	$A_{\rm e}({\rm min}^{-1})$	ne	Ead(J/mol)	$A_{d}(\min^{-1})$	nd
Coats-redfern	6%	97018	$2.9 imes 10^{14}$	2.89	96744	4.9×10^7	1.86
	12%	101766	$2.7 imes 10^{15}$	3.05	100227	$1.1 imes 10^8$	2.32
	18%	111692	7.1×10^{32}	3.41	107416	602×10^{8}	2.77

Table 1: Results of kinetic parameters

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(b) The whole stages

Figure 4: Comparison between TGA and calculation results

3 One-Dimensional Heat Transfer Model

3.1 Apparent Thermo-Physical Properties

According to the mix rule, the wood can be considered as the combination of the virgin material (before water evaporation), dry materials (after evaporation and before decomposition) and char (after decomposition), respectively. The apparent density of wood can be denoted by parallel model:

$$\rho = (1 - \alpha_e)\rho_v + \alpha_e(1 - \alpha_d)\rho_d + \alpha_e\alpha_d\rho_c$$
(11)

where subscript v, d, c represents the state of before evaporation, after evaporation and decomposition, respectively.

The apparent thermal conductivity can be expressed by Eq. (12),

$$\frac{1}{k} = \frac{(1-\alpha_e)}{k_v} + \frac{\alpha_e(1-\alpha_d)}{k_d} + \frac{\alpha_e\alpha_d}{k_c}$$
(12)

For apparent specific heat capacity considering latent heat and decomposition heat,

$$C_{p} = C_{p,v} f_{e} + (1 - f_{e}) \cdot f_{d} C_{p,d} + (1 - f_{d}) \cdot (1 - f_{e}) C_{p,c} + \frac{d\alpha_{e}}{dT} \cdot C_{e} + \frac{d\alpha_{d}}{dT} \cdot C_{d}$$
(13)

where C_e and C_d represent latent heat and decomposition heat, respectively, which can be obtained from DSC tests; f_e and f_d represent mass fraction of un-evaporated and un-decomposed, respectively, which can be calculated by Eq. (14):

$$f_{e} = M_{v,e} / \left[M_{v,e} + M_{f,e} \alpha_{e} / (1 - \alpha_{e}) \right]$$

$$f_{d} = M_{v,d} / \left[M_{v,d} + M_{f,d} \alpha_{d} / (1 - \alpha_{d}) \right]$$
(14)

The temperature-dependent thermo-physical parameters can be obtained by substituting conversion degrees listed in Tab. 2 into the Eq. (2).

Moiatura	0	2	2	Cross grain			C	C
content	$\rho_{\rm v}$ (kg/m ³)	$\rho_{\rm d}$ (kg/m ³)	$\rho_{\rm c}$ (kg/m ³)	$k_{ m v} = W/m \cdot K$	$k_{\rm d}$ W/m·K	$k_{\rm c}$ W/m·K	L _e kJ/kg	kJ/kg
6%	495	467	72	0.198	0.207	0.105	108	188
12%	524	467	76.5	0.213	0.207	0.105	153	225
18%	551	467	99	0.290	0.207	0.105	223	201

Table 2: Thermo-physical parameters used in model

Figs. 5 to 7 show the normalized apparent density, thermal conductivity and specific heat capacity, respectively. The predicted results were compared with Janssens model, Eurocode 5 and Fredlund model, respectively. It can be found that the proposed model can be used to reasonably describe the temperature-dependent thermo-physical properties.

As shown in Fig. 5, it can be found that as the temperature increased, the relative densities decreased. From 100°C to 200°C, the density radios calculated by the proposed model and Eurocode 5 showed a significant reduction from the initial state, which were around 90% of its initial state. The density calculated by Fredlund model reduced to 85% of its initial state. Because of thermal decomposition, they all dropped dramatically until the thermal decomposition was finished. After thermal decomposition, the predicted density radio was slightly lower than those of other models.



Figure 5: Evolutions of temperature-dependent relative density

As shown in Fig. 6, the proposed model shows a two-stage downward trend. Janssens pointed that before 350°C, the thermal conductivity declined with the increase in temperature, while after 350°C, the thermal conductivity raised with the increase in temperature. Eurocode 5 measured the thermal conductivity of woods at 20°C, 200°C, 350°C and 500°C, respectively. Within the 600°C, the thermal conductivity did not occur significant change with the increase in temperature. Fredlund indicated that the thermal conductivity bluff type drop occurred at 300°C.

As shown in Fig. 7, there was two distinct peaks at 75°C and 325°C, respectively. It is worth noting that the gauge at 100°C to 120°C heat capacity suddenly increased to 13.6 kJ/(kg·K). Janssens and

Fredlund used the same specific heat capacity model. At 250° C ~ 400° C, the specific heat obtained from proposed model is obviously higher than that other models.



Figure 6: Evolutions of temperature-dependent apparent thermal conductivity



Figure 7: Evolutions of temperature-dependent apparent specific heat capacity

3.2 Governing Equations and Boundary Conditions

According to Fourier's law, the one-dimensional unsteady heat conduction equation can be expressed as:

$$\rho C_{p} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k_{x} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{y} \frac{\partial T}{\partial y} \right)$$
(15)

The initial temperature distribution at t = 0 is described by

$$T(x, y, z, t)|_{t=0} = T_0(x, y, z, t)$$
(16)

where $T_0(x, y, z, t)$ is the ambient temperature of the considered specimen.

The heat fluxes exchange heat with the exposed surfaces of the wood sample by convection and radiation, which can be expressed by means of the following boundary conditions:

$$-k_{i}\frac{\partial T}{\partial n} = h_{conv} \times (T - T_{\infty}) + \sigma_{Boltz} \times \varepsilon_{emis} \times (T^{4} - T_{\infty}^{4}), i = x, y, z$$
(17)

where *n* represents the outward normal direction of the wood surface; T_{∞} represents the fire temperature measured in the furnace; h_{conv} , σ_{Boltz} and ε_{emis} are convection coefficient the Stefan-Boltzmann constant and the emissivity, which were equal to 25 W/(m²·K), 5.67 × 10⁻⁸ W/(m²·K⁴) and 0.8, respectively [8].

4 Experimental and Numerical Verification

4.1 Experimental Program

LVL panel specimen of 60 mm thick, 146 mm width and 1000 mm long were used to measure temperature by Thi [23]. The moisture content of the samples was 12%, and the corresponding initial density was 570 kg/m³. In the direction of height and width, the sample was exposed to fire on four sides. The temperatures at various locations across the thickness were measured using a series of K-type thermocouples, which were embedded at depths of 5 mm and 15 mm along the perpendicular directions (horizontal for the short dimension and vertical for the long dimension), as shown in Fig. 8. Figs. 9(a) and 9(b) display LVL sample and custom-made furnace. The temperature regression curve of furnace can be expressed as:

$$T = \begin{cases} 102.857t + 30.0 < t < 7\\ 750.7 < t < 50 \end{cases}$$
(18)

where T is the temperature Regression curve of furnace (°C), and t is time (min).



Figure 8: One quarter of the cross-section of the specimen





(a) LVL sample (b) custom-made furnace Figure 9: LVL sample and custom-made furnace [28]

4.2 Finite Element Model

The finite element program ANSYS was used to analyze the temperature distribution of the timber beams exposed to four-side fire. Because only one quarter of the cross-section of the specimen was modeled, the heat transfers of sides subject to fire and the surrounding components layer were assumed to

be heat thermal radiation and heat convection. The plane element 55 was used to model the distribution of temperature field of any section along the beam's longitudinal direction, while the surface effect element SURF151 was used to model the section sideline of the thermal radiation. The initial temperature was 30°C, and the furnace temperature was the temperature regression curve.

4.3 Comparison between Predicted and Test Results of the Temperature Distribution Field

The temperature distributions at different fire-exposure times (5, 15, 25 and 30 min) are shown in Fig. 10. The superposition of heat fluxes of the two sides (vertical and horizontal) at the corners leads to much higher temperature in that region. The temperature in the vertical direction was higher than the temperature in the horizontal direction because the thickness was smaller in the horizontal direction than that in the vertical direction.

Fig. 11 displays the comparison of the predicted temperatures as a function of fire-exposure time at different depths along the vertical directions. It can be observed that Eurocode 5, Janssens, Fredlund and proposed model all can predict the trend of the temperature. The correlation coefficient between the test values and the simulated values of each model was calculated. In Fig. 8(a), the correlation coefficient of the proposed model, Janssens, Eurocode 5 and Fredlund are 0.987, 0.991, 0.986 and 0.992, respectively. In Fig. 8(b), the correlation coefficient of the proposed model, Janssens, Eurocode 5 and Fredlund are 0.987, 0.991, 0.986 and 0.992, respectively. In Fig. 8(b), the correlation coefficient of the proposed model, Janssens, Eurocode 5 and Fredlund are 0.998, 0.971, 0.989 and 0.980, respectively.

In Fig. 8(a), the proposed model, Janssens and Fredlund models can predict the temperature more accurately than Eurocode 5 when the temperature is below 400°C. The Eurocode 5, however, seems to slightly underestimate the temperature fields at the depth of 5 mm and 15 mm along the vertical directions. It can be attributed to its specific heat at $100^{\circ}C$ ~120°C, corresponding to the drying process. At the water evaporation process, Eurocode 5 need to absorb more heat. The simulation value obtained from Janssens's model was slightly higher than the test value because of low specific heat value at moisture evaporation and decomposition. The proposed model and Fredlund model can more accurately simulate the temperature change of wood under high temperature.



(a) Time $t = 5 \min$



(d) Time t = 30 min Figure 10: Distribution of temperature at different fire-exposure times



Figure 11: Experimental and predicted time-temperature profiles in vertical direction

4.4 The Effect of Moisture Content on the Temperature Distribution

Figs. 12-14 show the normalized apparent density, thermal conductivity and specific heat capacity with different moisture contents, respectively. The effect of moisture content on the temperature distribution was simulated by the finite element program ANSYS. Fig. 15 displays the temperature distribution field with different moisture contents along the vertical direction. It can be found that the lower moisture content of wood can lead to a slower increase in temperature. At the evaporation stage, the difference of temperatures with different moisture contents become larger, while at the thermal decomposition stage, the gap gradually diminished.



Figure 12: Evolutions of temperature-dependent relative density



Figure 13: Evolutions of temperature-dependent apparent thermal conductivity



Figure 14: Evolutions of temperature-dependent apparent specific heat capacity



Figure 15: The Comparison between Calculation Results of the Temperature with different moisture content

5 Conclusion

In this paper, the one-dimensional nonlinear heat transfer model considered the apparent thermo-physical properties of wood was presented. The model was validated by the four-side heating experiments. The main conclusions are concluded as follows:

(1) The Arrhenius equation was used to describe the processes of evaporation and thermal decomposition. Coats-redfern method was used to calculate kinetic parameters. The analytical results agreed well with the TG results.

(2) Based on the Fourier heat conduction law, the one-dimensional nonlinear heat transfer model considered the apparent thermal parameters was established. Well agreement was found between the test and simulated results.

(3) The time-dependent temperature distributions as well as thermo-physical properties can be estimated with this model. Moreover, the proposed model for calculating apparent thermo-physical properties have clear physical meanings.

(4) The effect of moisture content on thermo-physical properties was serious at the water evaporation. The latent heat at the water evaporation of 18% moisture content was twice as large as the latent heat of 6% moisture content. But it has no effect at the thermal decomposition. The lower the moisture content of wood, the slower the temperature rise when wood is subjected to high temperature.

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