

A Study on the Distribution and Time Dependent Change of the Temperature in the Wood Affected by Solar Radiation

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ABSTRACT: The fluctuation of physical properties in wood or wood composites is an important subject when the materials are used as building materials. Sorption and desorption would be happened in wood when exposed to the open air, and the temperature distribution of wood will be fluctuated by environmental temperature, humidity, solar radiation, wind velocity, etc.

In this study, the temperature difference and fluctuation among different wood species were analyzed using numerical method. The effect in the process of heat transfer in wood caused by environment was investigated using 1-D partial differential equation with real boundary and initial conditions. The experimental data have been used to check the accuracy of programmed code. Through analysis, it was found out that density and moisture content have negative effect to the thermal diffusivity. The density is the main factor that influences heat transfer behaviour in wood.

Keywords: wood, solar radiation, temperature distribution, thermal diffusivity

NOMENCLATURE

I_s : radiation flux [W/m^2],
 α : absorbtivity
 ε : emissivity
 σ : Stefan-Boltzmann constant
[$5.67 \times 10^{-8} \text{W/m}^2 \text{K}^4$]
 T_s : surface temperature [K]
 T_{sky} : sky temperature [K]
 T : wood temperature [K]
 E : latent heat of vaporization [J/kg]
 W : weight [g]
 t : time [s]
 h_c : heat transfer coefficient [$\text{W/m}^2 \text{K}$]
 V_s : wind velocity [m/s]
 k : heat conductivity [W/m K]
 ρ : wood density [kg/m^3]
 m : moisture content [%]
 T_∞ : environmental temperature [K]

1. INTRODUCTION

During the process of using, the fluctuating properties happened in wood must be considered when selecting wood. Sorption and desorption will be happened in wood when exposing to the open air and the temperature distribution of wood will be fluctuated by environmental temperature, humidity, solar radiation, wind velocity, etc. Although heat and mass transfer characteristics of drying wood is well documented (Avramidis et al., 1992; Dedic, A, 2000; Olek et al., 2003), the study on heat transfer behaviour of wood consideration of real environment such as solar radiation, convection, etc is generally little understood. Therefore, the effect to

wood caused by real outdoor environment must be studied.

Nevertheless, in building department the analysis of heat and mass transfer behaviour depending on the real outdoor environment is well developed. TenWolde et al., (1988) researched heat properties of wood and wood composites which used in building construction. Sami(2003) considered periodic condition which including temperature and solar radiation to measure heat behaviour of walls and roofs. Tsilingiris(2002) studied to simulate the unsteady state of heat conduction in building walls which used finite difference method. In his research, development of simulation model suitable for the investigating of the dynamic behaviour of structural wall elements, under the effect of time dependent driving function of solar radiation and ambient temperature.

In this study, the effect in the process of heat transfer in wood caused by environment was investigated using 1-D partial differential equation with real boundary and initial conditions.

Wood conductivity, heat capacity and heat diffusion coefficient were influenced by density and moisture content. Coefficient of wood solar radiation emissivity and absorptivity are influenced by surface condition. All of these factors combine to influence heat transfer behaviour in wood.

2. MATERIALS AND METHODS

2.1 Materials

More than 3 years wood in natural condition was chosen. Selecting was depended on density and moisture content. The status of samples was showed in table 1.

Table 1. Status of the samples.

Species	Density (kg/m ³)	MC* (%)	Thickness (mm)
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Chinese cedrela (<i>Cedrela sinensis</i>)	798.5	10.9	30
Korean willow (<i>Salix koreensis</i>)	423.2	10.3	30
Douglas fir (<i>Pseudotsuga menziesii</i>)	529.9	27.6	24
Douglas fir (<i>Pseudotsuga menziesii</i>)	529.9	<3.0	24

*MC: moisture content

2.2 Methods

Each sample was made in two work pieces. One was used for thermocouple adhesion and another was used for weighing. All of the sample surfaces were coated by oil-based paint except one surface which exposed to the open air. The five painted surfaces were insulated by styrofoam. The purpose of these treatments was for the reason of simulation condition of 1D heat and mass transfer.

Samples with large differences in density (cedrela and willow) were coated by black water borne paint on their exposure surface in order to fix emissivity. As well known, sorption process happens on their surfaces. L, a, b values of the exposed surface were measured before experiment (table 2).

Table 2. L, a, b values of the sample.

Species	L	a	b
Chinese cedrela (<i>Cedrela sinensis</i>)	23.87	0.03	-0.26

Korean willow (<i>Salix koreensis</i>)	23.67	0.01	-0.33
Douglas fir (<i>Pseudotsuga menziesii</i>)	68.47	11.50	23.70

Thermocouples were adhered to sample surface, center and bottom. The adhesion method of thermocouple on the surfaces and bottoms were used aluminum tape to fix and middle point was drilled a hole and fixed in glue. Each temperature data was measured and recorded in real time during the experiment. Simplified schematic of analysis model is shown in figure 1(a&b). Samples used for weighting were weighted in 2 or 3 hours interval. During the experiment, weather data like solar radiation, humidity, temperature and wind velocity were downloaded from Gwangju regional meteorological administration.

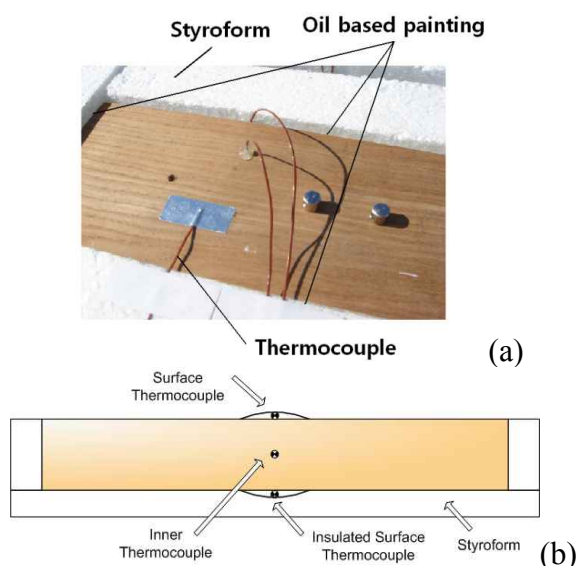


Figure 1. Simplified schematic of analysis model.

2.3 Analysis Methods

As mentioned before, the samples were insulated in five surfaces by oil based paint and styrofoam and one surface was exposed to open air. The process of heat transfer in wood was taken considered radiation, convection, conduction, moisture sorption and desorption. 1-D unsteady state partial differential equation was developed to describe heat transfer process with real boundary and initial conditions. It was considered that samples were diffuse gray surfaces in order to regard both of the emissivity and absorptivity as the same values. Heat transfer coefficient was determined by wind velocity and the conductivity of wood was determined by density and moisture content. The amount of sorption and desorption were determined by weighing samples.

Figure 2 shows the information of governing equation, boundary condition and discretization. At $x=0$ it was insulated by styrofoam that gradient of heat flux was considered to be zero. Average temperature of sample in 12 pm was considered to be initial condition in each sample. Solar radiation, infrared sky radiation, convection and moisture fluctuation accompany with latent heat of evaporation and condensation take place in surface($x=L$). The amount of weight fluctuation was checked in 2 or 3 hours interval, so we used curve fitting method to simulate the whole weight fluctuation. Figure 3 shows curve fitting results.

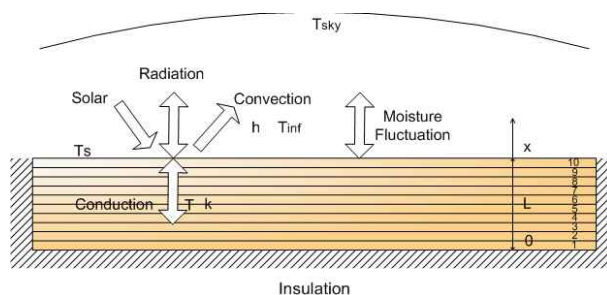


Figure 2. Heat and mass transfer process and divided element.

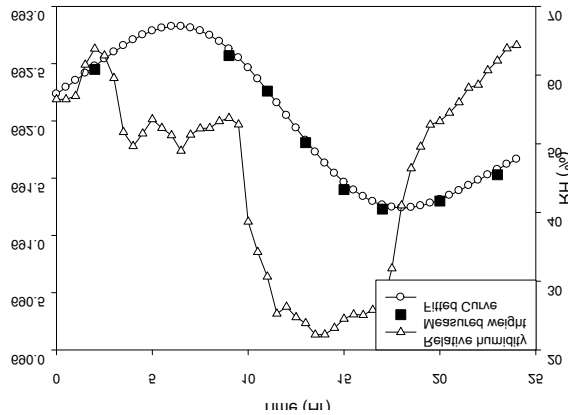


Figure 3. Curve fitting of weight fluctuation.

Equation 1 is the governing equation. Boundary conditions were as shown in equation 2 and 3, and equation 4 is initial condition.

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) \quad (1)$$

Boundary condition:

$$x = 0: \quad k \frac{\partial T}{\partial x} = 0 \quad (2)$$

$x = L$:

$$k \frac{\partial T}{\partial x} - \alpha I_s = -h_c (T_s - T_\infty) - \varepsilon \sigma (T_s^4 - T_{sky}^4) - \frac{E}{A_s} \cdot \frac{dw}{dt} \quad (3)$$

Initial condition:

$$t = 0: \quad T = T_i \quad (4)$$

h_c is heat transfer coefficient. In this study it was determined by wind velocity (Loveday et al., 1996).

$$h_c = 16.21 V_s^{0.452} \quad (5)$$

k is heat conductivity. k is determined by wood density and wood temperature (Harada et al., 1988).

$$k = 0.00249 + 0.000145 \rho + 0.000184 \times T \quad (6)$$

In the governing equation, the specific heat capacity of C_p was influenced by moisture content and temperature (Avramidis et al., 1992).

$$C_p = \frac{-135.014 + 4.598 \times T + 41.8m}{1 + 0.01m} \quad (7)$$

The sky temperature was calculated by equation 8 (ASHRAE, 1999).

$$T_{sky} = 0.0552 (T_\infty)^{1.5} \quad (8)$$

Finite difference method was used to solve the unsteady state and nonlinear governing equation. The first step of the finite difference method is dividing the domain into discrete one. In this study, the domain was divided into 10 elements and 11 nodes (figure 3) by fully implicit method. After that, TDMA (tri-diagonal matrix algorithm) was used to solve the discretised equation.

3. RESULTS AND DISCUSSION

3.1 Simulation Verification Using Experiment Results

In order to verify the accuracy of simulation results, simulation results were compared with experimental results. Cedrelas were chosen which coated by black water-borne painting on their surface in order to fix value of emissivity (0.95). Figure 4 shows the comparison results of surface temperature.

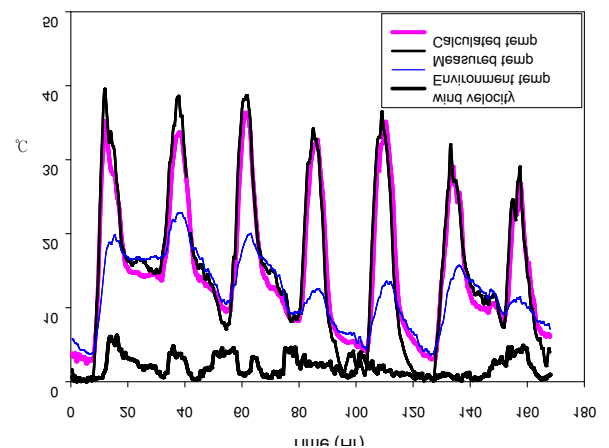


Figure 4. Comparison between simulation results and experiment results. (Chinese cedrelas, surface temperature, November 8-14, 2006.)

The difference between simulation and experimental results was less than 6%. The biggest gap of them was happened during the night. From the theory of radiation, the surface temperature in night should be similar to the environmental temperature. But, surface temperature was much lower than calculated one in experiment. It is mainly caused by cooling effect. It can be observed sample surfaces were wetted by dew before sunrise.

3.2 Tendency of Heat Behavior Depending on Samples' Condition

3.2.1 Heat Behavior Depends on Density

Simulation results were used to analyze heat behavior of the whole samples. The samples which differ only in density presented different heat transfer behavior. Heat conductivity mainly depends on density. When density is high the value of conductivity is high, while the value of heat diffusivity is in inverse proportion to the value of density and heat conductivity. It is the main reason that sample with high density has slower movements in heat transfer. From figure 5 it can be seen that heat transfer behavior of high density sample delay in sample with low density. At the same time the largest difference between them was 1.74°C and it happened in 17:00~18:00.

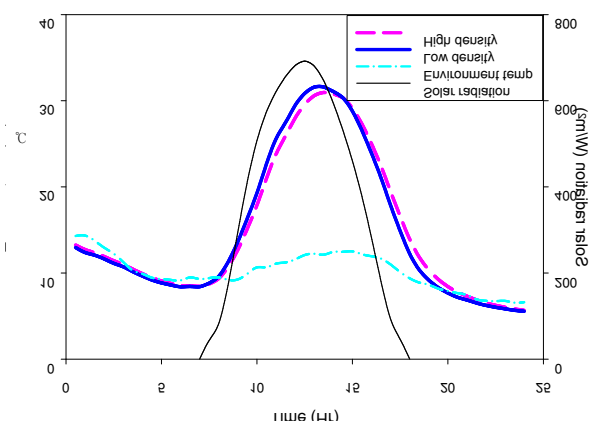


Figure 5. Computer simulation results between high density and low density. (Chinese cedrela, back temperature, November 11, 2006.)

3.2.2 Tendency Depends on Moisture Content

Same species with different moisture content samples have different value of specific heat capacity. Heat capacity mainly depends on moisture content. Sample with high moisture content has high value of heat capacity. The value of heat diffusion coefficient was proportioned to the value of heat capacity. So sample with high moisture content had slower movements in heat transfer than the low moisture content one. Figure 6 is the comparison result of samples in different moisture content. From the figure, it can be seen that heat transfer behaviour of high moisture content sample delay in sample with low moisture content. In the same time the largest difference between them was 0.73°C and it happened in 17:00~18:00. In this samples' simulation, values of emissivity and absorptivity were determined by inverse method. Simulation results were compared with experimental results and determined the value of emissivity and absorptivity until the adjusted results closed to experimental results.

Comparing different density case and moisture content case, results showed that density influenced heat transfer behaviour much more than moisture content.

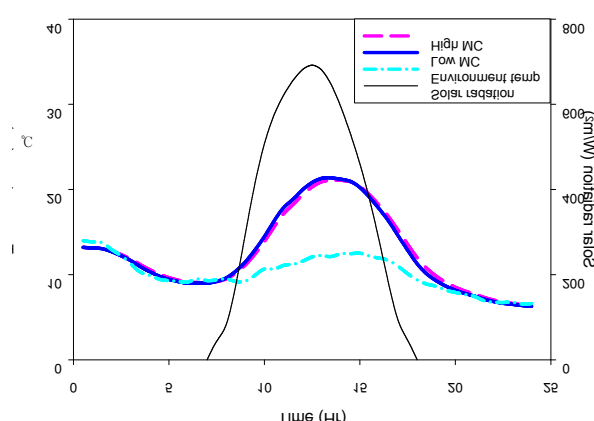


Figure 6. Computer simulation data between high and low MC. (Douglas fir, Back temperature, November 11, 2006.)

3.2.3 Thermal Exchange between the Testing Surface and the Sky

The trend of the sample surface temperature, outdoor air and the sky temperature are shown in figure 7. Throughout the whole day, the difference between the surface temperature and sky temperature varied from 4.9°C to 23.7°C, whereas the difference between the air temperature and sky temperature was from 5.7°C to 11.5°C.

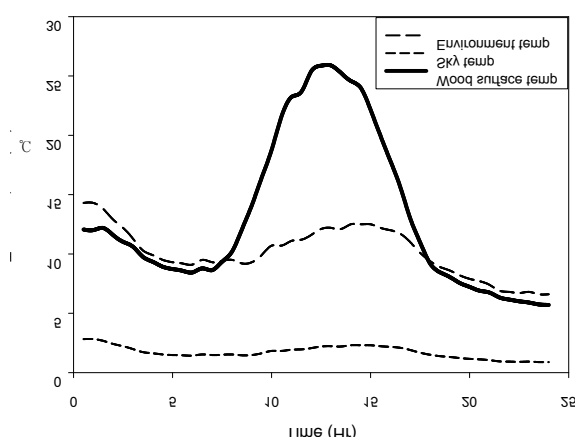


Figure 7. Temperature of sample surface, environment and sky temperature on a clear day.

One significant point emerges from the figure 7 is whatever the solar radiation conditions, the infrared heat flow is always leaving the sample surface ($T_s > T_{sky}$). During the day time sample surface cooled both by convection of air and by infrared sky radiation, whereas during the night the sample surface is heated by convection of the outdoor air and is cooled by infrared sky radiation (Olivetti et al., 2003).

4. CONCLUSION

The effect to the process of heat transfer in wood caused by environmental condition was investigated using 1-D partial differential equation with real boundary and initial conditions. The experimental data was used to check the accuracy of

programmed code. It was found out that density and moisture content have negative effect to the thermal diffusivity. Also, it was shown that the most important factor is density compared with the other factors.

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