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A Study on the Distribution and Time Dependent Change of Wood Temperature by Solar Radiation[*1]

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ABSTRACT

The fluctuation of physical properties in wood or wood composites is an important subject when the materials in building and construction. Sorption and desorption occur in wood when exposed to the open air, and the temperature distribution in wood can fluctuate as a result of changes in environmental temperature, solar radiation, humidity, and wind velocity. In this study, the temperature difference and fluctuation caused by outdoor environment among different wood species were analyzed using a numerical method. The effect on the process of heat transfer in wood caused by environmental factors was investigated using 1-dimensional partial differential equation with real boundary and initial conditions. The experimental data have been used to check the accuracy of programming code. Through analysis, it was found out that density and moisture content have a negative effect on thermal diffusivity of wood.

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

1. INTRODUCTION

The significant presence of wood in buildings, the energy design of wood frame buildings and the evaluation of their energy performance depends in part on thermal properties of wood products. Thermal properties of wood are well documented by many researchers (Avramidis *et al.*, 1992; Peter, 1977; Siau, 1995). TenWolde *et al.* (1988) researched heat properties of wood and wood panel products used in buildings. They derived linear equations for thermal conductivity and specific heat of solid wood and wood panels as a function of density and moisture content. When wood is used in outside wall of a building, the heat transfer behavior in it will fluctuate as a result of changes in environmental temperature, solar radiation, humidity, and wind velocity. Although heat and mass transfer characteristics of drying is well documented (Dedic, 2000; Olek *et al.*, 2003), heat transfer behavior of wood as affected by real outdoor environment is poorly understood.

In contrast, the analysis of heat and mass transfer behavior in related to the real outdoor environment is well developed in building de-

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Table 1. Status of the samples

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

partment. Sami (2003) considered periodic conditions which including temperature and solar radiation to measure heat behavior of walls and roofs. Tsilingiris (2002) studied the unsteady state of heat conduction in building walls which used the finite difference method. His research included development of a simulation model suitable for investigating the dynamic behavior of structural wall elements, under the effect of the time dependent drying function of solar radiation and ambient temperature.

Based on the thermal properties of wood and thermal analysis of buildings, in this study, the effect in process of heat transfer in wood caused by outdoor environment was investigated using 1-dimensional partial differential equation with real boundary and initial condition.

2. MATERIALS and METHODS

2.1. Materials

More than 3 years natural conditioned wood was chosen. Selection was depended on density and moisture content. The status of samples is shown in Table 1.

2.2. Methods

All of species were made in two work pieces. One was used for thermocouple attaching and the other for weighting. All of the sample surfaces were coated by oil-based paint except one surface that was exposed to the open air. The five painted surfaces were insulated by Styrofoam. The purpose of these treatments was to simulate the condition of 1-dimensional heat and mass transfer. All of the exposed surfaces were tangential section.

Samples with large differences in density (cedrela and willow) were coated with black water borne paint on their exposure surface in order to fix the value of emissivity (0.95).

Thermocouples were adhered to the sample surface, center and bottom. The adhesion method of thermocouples on the surfaces and bottoms were fixed with aluminum tape, and the center had a hole drilled and fixed with glue. The emissivity of aluminum tape is only 0.03. Aluminum tape can reflect solar radiation to decrease effect of the surface temperature by itself. So we can assume temperature of sample surface and aluminum tape is equal to each other. In order to diminish influence of thermocouple adhesion treatment on temperature of center and bottom, the three measuring points were not leave in the same line. A simplified schematic of analysis model is shown in Fig. 1.

Each temperature data was measured and recorded in real time during the experiment. Samples were weighed in 3 hours intervals. So we can record amount of sorption moisture from the exposed surface. From amount of sorption moisture, we can calculate heat of

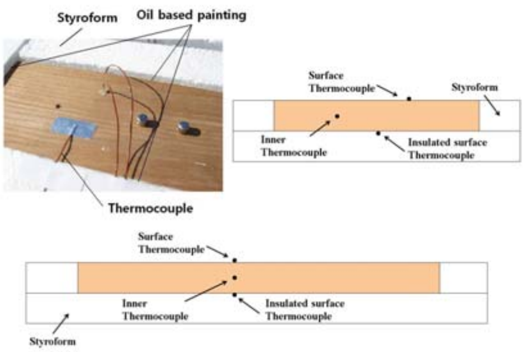

Fig. 1. Simplified schematic of analysis model.

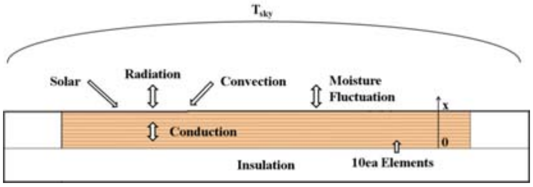

Fig. 2. Divided element and heat transfer phenomena.

vaporization. During the experiment, weather data including solar radiation, humidity, temperature, and wind velocity were downloaded from the Gwanju Regional Meteorological Administration.

2.3. Analysis Methods

The heat and mass transfer process can be defined 1-dimensional as the sample treatment. The process of heat transfer in wood took into consideration radiation, convection, conduction, moisture sorption, and desorption. 1-dimensional unsteady state partial differential equation was used to describe the heat and mass transfer process with real boundary and initial conditions. In this study, wood is considered diffuse gray surface in order to regard both emissivity and absorbtivity as the same value. The heat transfer coefficient was determined by density and temperature. The amount of sorption and desorption were determined by weight change of samples.

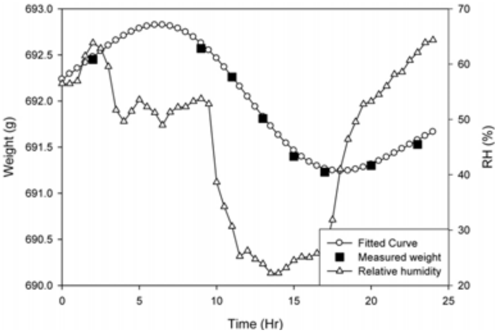

Fig. 3. Curve fitting of weight fluctuation (Chinese cedrela, November 11, 2006).

Fig. 2 shows the data of governing equation, boundary condition, and discretization. At x = 0, the sample was insulated by Styrofoam, and the gradient of heat flux was considered to be zero. The average temperature of sample at 12 p.m. was considered to be initial condition in each sample. Solar radiation, infrared sky radiation, convection and moisture fluctuation accompanying latent heat evaporation and condensation take place on the surface (x = L). As mentioned the amount of weight fluctuation was checked at 3 hours intervals, and the curve fitting method was used to simulate whole weight fluctuation. Fig. 3 illustrates the curve fitting results.

Equation 1 is the governing equation. Boundary conditions are shown in equations 2 and 3, while equation 4 reflects the initial condition.

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

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

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

Initial condition: $t = 0 : T = T_i$ (4)

Wh., I_S : radiation flux (W/m^2)
α : absorbtivity

ε : emissivity
σ : Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4)
T_s : surface temperature (K)
T : wood temperature (K)
E : latent heat of vaporization (J/kg)
W : weight (g)
t : time (s)

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

$$h_c = 16.21 V_s^{0.452} \tag{5}$$

Wh., h_c : heat transfer coefficient (W/m^{2}K)
V_s : wind velocity (m/s)

k is heat conductivity. k is determined by wood density and temperature (Harada *et al.*, 1998).

$$k = 0.00249 + 0.000145\rho + 0.000184 \times T \tag{6}$$

Wh., k: heat conductivity (W/m K)
ρ : wood density (kg/m^3)

In this study, we assumed the specific heat capacity was influenced by moisture content and temperature (Steinhagen *et al.*, 1988).

$$C_p = 2000 + 8.71 \times m + 4.98T \tag{7}$$

Wh., C_p : specific heat capacity (J/Kg K)
m : moisture content (%)
T : wood temperature (°C)

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

$$T_{sky} = 0.0522(T_\infty)^{1.5} + 273.15$$

Wh., T_∞ : environmental temperature (°C)

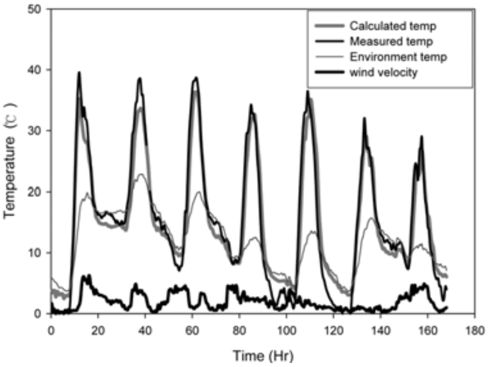

Fig. 4. Comparison between simulation results and experiment results (Chinese cedrela, surface temperature, November 8～14, 2006).

The finite difference method was used to solve the unsteady state and nonlinear governing equation. One of the steps of the finite difference method involves dividing the domain into a discrete one. In this study, the domain was divided into 10 elements (see Fig. 2) by fully implicit method. Afterwards, TDMA (tridiagonal 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 the simulation results, they were compared with experimental results. Fig. 4 shows the comparison of surface temperatures. As mentioned before, cedrela and willow coated by black water borne paint on their open air surface to fix the emissivity and absorptivity value.

The difference between simulation and experimental results was less than 6%. The biggest gap occurred during the night. From the theory of radiation, it is known that the surface temperature at night should be similar to the en-

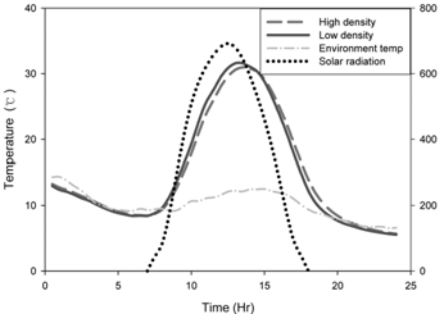

Fig. 5. Computer simulation results between high density and low density (Chinese cedrela, back temperature, November 11, 2006).

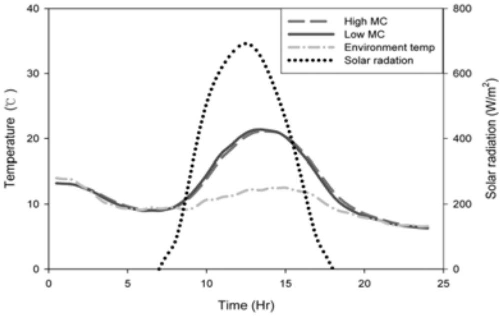

Fig. 6. Computer simulation data between high MC and low MC (Douglas fir, back temperature, November 11, 2006).

vironmental temperature. However, the measured surface temperature was much lower than the calculated one at night. This is mainly caused by the cooling effect. Sample surfaces were observed to have been wetted by dew before sunrise.

3.2. Density-Dependent Heat Behavior

Simulation results were used to analyze heat behavior of the whole samples. The samples which differ only in density exhibited different heat transfer behavior. From Fig. 5, it can be seen that heat transfer behavior of a high density sample is delayed in a sample with low density. Heat conductivity mainly depends on density (equation 6). From the equation 1, $\frac{k}{\rho C_p}$ is the value of heat diffusivity. Though the conductivity increased with the density, the resultant value of diffusivity is largely influenced by density rather than conductivity. It means diffusivity inverse to density. This is the main reason why a sample with high density has slower temperature movement in heat transfer.

3.3. Moisture - Dependent Heat Behavior

The same species with different moisture contents have different values of specific heat capacity. Heat capacity mainly depends on moisture content (equation 7). A sample with high moisture content has a high value of the heat capacity. Fig. 6 illustrates the comparison results of samples with different moisture content. From the Figure, it can be seen that heat transfer behavior of the high moisture content sample is delayed in the sample with low moisture content. Obviously, the value of heat diffusion coefficient ($\frac{k}{\rho C_p}$) was inversely proportional to the value of heat capacity. In this sample's simulation, values of emissivity and absorptivity are hard to determine. So we used inverse method. The value of emissivity and absorptivity were determined until the adjusted results mirrored the experimental results. The adjusted value of Douglas fir's emissivity and absorptivity was 0.4.

3.4. Thermal Exchange between the Testing Surface and the Environment

The relationship between sample surface temperature, ambient temperature, and the sky temperature are shown in Fig. 7 Throughout the day, the difference between the surface temper-

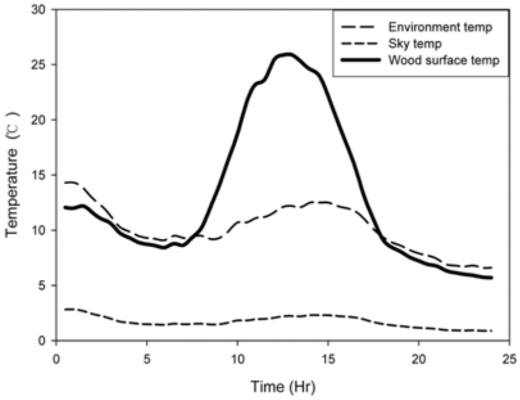

Fig. 7. Temperature of sample surface, environment and sky temperature on a clear day (Chinese cedrela, surface temperature, November 11, 2006).

ature and sky temperature varied from 4.9°C to 23.7°C, whereas the difference between the ambient temperature and sky temperature was from 5.7°C to 11.5°C.

One significant point emerging from Fig. 7 is regardless the solar radiation conditions, the infrared heat flow always leaves the sample surface ($T_s > T_{sky}$). During the daytime, sample surface heated by solar radiation. Also, 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 ambient air and is cooled by infrared sky radiation (Oliveti *et al.*, 2003).

4. CONCLUSION

Wood conductivity, heat capacity, and heat diffusion coefficient were influenced by density and moisture content. In this study, the effect to the process of heat transfer in wood caused by environment condition was investigated using 1-dimensional partial differential equation with real boundary and initial conditions. The experimental data was used to check the accuracy of the programming code. From this study we can find density and moisture content have a negative effect to the thermal diffusivity. Also, we can make an observation of thermal exchange between wood and environment.

ACKNOWLEDGEMENT

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