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Thermal constants of wood during the heating process measured with the laser flash method

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Abstract The thermal diffusivity, specific heat, and thermal conductivity of 13 species of wood were measured by means of the laser flash method to investigate the thermal properties of wood during the heating process. The temperature ranged from room temperature to 270°C in air or under vacuum. The thermal diffusivity varied little during the heating process up to 240°C. The values in air were larger than those under vacuum. There was a linear relation between the specific heat and the ambient temperature, and the specific heat under vacuum was larger than that in air at high temperature. The thermal conductivity increased with density and the ambient temperature. To discuss the effects of the atmospheric conditions on the thermal constants of wood, a theoretical model of thermal conductivity was proposed and its validity examined, where the wood was assumed to be a uniformly distributed material composed of cell walls and air.

Key words Thermal diffusivity · Heat capacity · Thermal conductivity · Laser flash method · Heating process

Introduction

The thermal constants are thermal diffusivity $\alpha(\mathrm{m^2 \cdot s^{-1}})$, specific heat $c(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$, and thermal conductivity $k(\mathrm{W \cdot m^{-1} \cdot K^{-1}})$. Thermal diffusivity α is defined as

$$\alpha = \frac{k}{\rho c} \tag{1}$$

where $\rho(\mathrm{kg \cdot m^{-3}})$ is the density of the solid. The thermal constants of wood are generally measured in the steady state, and measurements at high temperature are difficult. Consequently previous studies mainly targeted the properties at room temperature.[1-5]

The thermal constants during the heating process are important for analyzing the combustibility and fire endurance of wood. Moreover, these studies are expected to give significant clues for clarifying the mechanism of the property change in the charring process. Previous studies on the relations between the ambient temperature and the thermal constants of wood were mainly performed below 100°C. In this temperature range it has been found that specific heat and thermal conductivity increase in proportion to the temperature, and the thermal diffusivity is assumed to be constant.[1,4] So far, there have been few reports for temperatures above 100°C, although Ouchi[6] measured the thermal conductivity of wood up to 300°C.

The laser flash method enables us to measure the thermal constants at high temperatures and under vacuum conditions, as they are measured in an unsteady state within 1 s. This affords the possibility of obtaining information about the thermal properties in the cell wall. The laser flash method is defined by a Japanese Industrial Standard (JIS R 1611),[7] where the laser pulse is applied to a circular specimen with a 10 mm diameter and 1–2 mm thickness, the rear face temperature is measured, and the thermal constants are calculated. Parker et al.[8] measured the thermal diffusivity by the laser flash method for the first time in 1961; and the thermal constants of metals, ceramics, and many other materials have been measured by this method. In regard to the application of this method to wood specimens, Uesugi et al.[9] compared the thermal diffusivity of earlywood with that of latewood, and Murata and Sadoh[10] reported the heat absorption and the transfer in softwoods and their knot surfaces. However, there have been no reports on the measurement of thermal constants

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of wood during the heating process and under vacuum conditions.

In this study, the thermal constants of wood specimens were measured by means of the laser flash method in the range of room temperature to 270°C in air or under vacuum conditions. To discuss the effects of the specimen's density and the atmospheric condition, a theoretical model of thermal conductivity was proposed and its validity examined, where the wood specimen was assumed to be uniformly distributed material composed of cell walls and air.

Theory

Siau[3] proposed a microscopic model of the wood with rectangles composed of the cell wall and the lumen (i.e., a single wall model) and presented a theoretical equation of the thermal conductivity of the wood based on the equation for calculating the thermal resistance of a parallel multilayer material. Although the effects of the air in the lumen and the density of wood were considered in his model, a factor had to be introduced because the model was too microscopic and the entire width of the cross wall was not effective for conduction because of nonuniformity. Accordingly, his theoretical equation became complicated.

On the other hand, when the wood is considered as a uniformly distributed material consisting of cell walls and air (i.e., a macroscopic model), the thermal conductivity of a wood specimen in air with a void ratio x can be easily expressed as

$$k_{\mathrm{At},\rho} = (1 - x)k_{\mathrm{w}} + x \cdot k_{\mathrm{a}} \tag{2}$$

where $k_{\mathrm{At},\rho}$ is the thermal conductivity of wood with density ρ, and k_{w} and k_{a} are the thermal conductivities of the cell wall and the equivalent thermal conductivity of the air, respectively. The void ratio x is calculated as follows.

$$x = 1 - \frac{\rho}{\rho_{\mathrm{w}}} \tag{3}$$

where ρ ($\mathrm{kg{\cdot}m^{-3}}$) is the apparent density of wood, and ρ_{w}($\mathrm{kg{\cdot}m^{-3}}$) is the density of the cell wall. If we assume k_{w} and ρ_{w} are uniform regardless of the species, the theoretical equation for the thermal conductivity of wood in air is expressed as a simple equation of the density ρ. Empirically, the thermal conductivity of wood is assumed to increase in proportion to the density at room temperature, and this expression agrees with the empirical formula. If we assume that the lumen is insulated under vacuum conditions, the theoretical equation is expressed as

$$k_{\mathrm{Va},\rho} = (1 - x)k_{\mathrm{w}} \tag{4}$$

where $k_{\mathrm{Va},\rho}$ is the thermal conductivity of wood under vacuum.

Materials and methods

Laser flash method

The thermal constants were determined by the thermal constants measuring apparatus (Sinku-riko TC7000H system) according to the Japanese Industrial Standard (JIS R-1611).[7]

The thermal diffusivity $\alpha(\mathrm{m^2{\cdot}s^{-1}})$ was calculated by

$$\alpha = 1.37 \cdot \frac{L^2}{\pi^2 \cdot t_{1/2}} = 0.1388 \cdot \frac{L^2}{t_{1/2}} \quad \left(\mathrm{m^2{\cdot}s^{-1}}\right) \tag{5}$$

where L is the thickness of the specimen, and $t_{1/2}$ is the half-time for the rear face of the specimen to reach half of the maximum rear face temperature rise $\Delta T_{\max}$.

The specific heat $c(\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}})$ was calculated from the maximum rear face temperature rise $\Delta T_{\max}$. This is based on the assumption that the energy absorption at the surface is constant. The energy absorption Q is expressed by

$$Q = c \cdot L \cdot \rho \cdot \Delta T_{\max} \tag{6}$$

The specimens were heated by an electric furnace. The rate of temperature increase was $8°\mathrm{C{\cdot}min^{-1}}$. The thermal constants of the specimens were measured after the atmosphere stabilized at the expected temperature both in air and under vacuum. In the measuring system, vacuum conditions were achieved using oil rotary and oil diffusion pumps.

Specimens

Thirteen species of wood (Table 1) were used for the experiments at room temperature. For the experiments during the heating process, five species of wood – hiba (*Thujopsis dolabrata* Sieb. and Zucc. var. *hondai* Makino), hinoki (*Chamaecyparis obtsusa* (Sieb. and Zucc.) Endl.), kiri (*Paulownia tomentosa* Steud.), buna (*Fagus crenata* Bl.), and akagashi (*Quercus acuta* Thunb.) – were used. The hiba specimens were measured at 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, and 270°C. The other four species were measured at 20°, 90°, 150°, 180°, 210°, and 240°C. One or two replications were performed for each specimen and temperature.

Each specimen was in the shape of a circular plate with a diameter of about 10 mm and a thickness of 1 mm. The radial or tangential surface of wood was irradiated with the laser pulse. The laser pulse can easily penetrate porous materials such as wood. To avoid this problem, the specimens were thinly painted with silver paste. Moreover, carbon black was sprayed on both sides of the specimens to improve the absorption of the laser energy and the accuracy of temperature measurement using the noncontact thermometer.

Results and discussion

Specific heat at room temperature

The specific heats of wood specimens are considered to be constant irrespective of species or density, and the value

Table 1. Wood materials tested

Species	Thickness (mm)	Density ($kg \cdot m^{-3}$)
Softwood		
Hinoki (*Chamaecyparis obtsusa* (Sieb. and Zucc.) Endl.)	1.2	360
Hiba (*Thujopsis dolabrata* Sieb. and Zucc. var. *hondai* Makino)	1.0–1.4	375
Redwood (*Sequoia sempervirens* Endl.)	1.0	391
Akamatsu (*Pinus densiflora* Sieb. and Zucc.)	1.1	424
Karamatsu (*Larix leptolepsis* Gord)	0.9	504
Hardwood		
Kiri (*Paulownia tomentosa* Steud.)	1.0	286
Hannoki (*Alnus japonica* Steud.)	1.1	378
Buna (*Fagus crenata* Bl.)	1.1	488
Onigurumi (*Juglans soeboldiana* Maxim.)	1.1	583
Aodamo (*Fraxinus lanuginosa* Koidz.)	1.1	636
Keyaki (*Zelkova serrata* Makino)	0.9	728
Mizunara (*Quercus mongolica* Torcz. var. *grosserrata* Rehd. and Wils.)	1.1	788
Akagashi (*Quercus acuta* Thunb.)	1.0	965

Thicknesses and densities are given as average values

$1.25 \times 10^3 J \cdot kg^{-1} \cdot K^{-1}$ is reported in chronological scientific tables.[11] To confirm whether similar results could be obtained using the laser flash method, the specific heats in air and under vacuum conditions were calculated. When the specific heat of the akamatsu specimen at room temperature in air (specimen A) was assumed to be $1.25 \times 10^3 J \cdot kg^{-1} \cdot K^{-1}$, the specific heats of the other specimens (specimen B) were calculated according to

$$c_B = c_A \times \frac{\Delta T_{A,max}}{\Delta T_{B,max}} \times \frac{\rho_A}{\rho_B} \tag{7}$$

where the subscripts A and B denote the values for specimen A and specimen B, respectively. The results are shown in Fig. 1. Although the values were scattered, the specific heats at room temperature are roughly constant regardless of the species, density, and the presence of air. Consequently, we adopted $1.25 \times 10^3 J \cdot kg^{-1} \cdot K^{-1}$ as the specific heat of wood at room temperature.

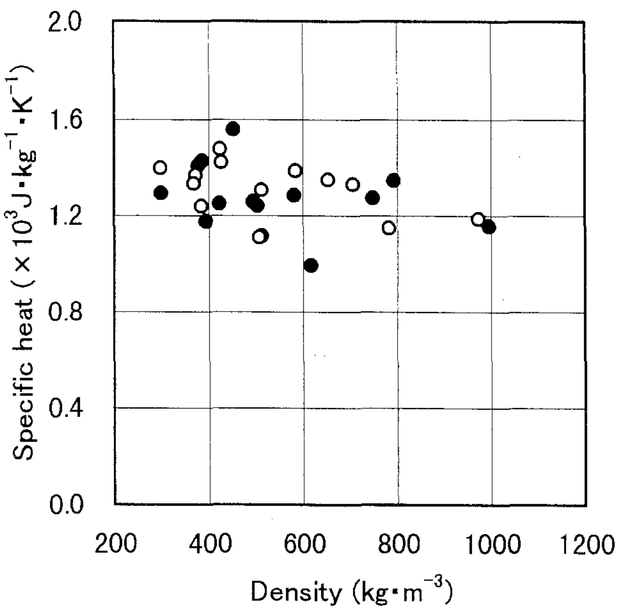

Fig. 1. Effects of density and air on specific heat at room temperature. *Filled circles*, measured in air; *open circles*, measured under vacuum

Thermal conductivity at room temperature

The thermal conductivities of the specimens were calculated using Eq. (1). The results are shown in Fig. 2. It is clear that the thermal conductivity increases in proportion to the density, and the values in air are larger than those under vacuum conditions.

There have been many studies on the thermal conductivity of wood in air. Urakami and Fukuyama,[4] for example, reported the relation between density and thermal conductivity, $k_{At,\rho,R}$, in a direction perpendicular to the grain of wood at room temperature as follows:

$$k_{At,\rho,R} = 0.0174 + 1.86 \times 10^{-4} \rho \quad \left(W \cdot m^{-1} \cdot K^{-1}\right) \tag{8}$$

where the subscript R denotes the value at room temperature. This regression line for Eq. (8) on the data is shown in Fig. 2. The measured values of $k_{At,\rho,R}$ were almost on this line, and the validity of the thermal conductivity obtained by the laser flash method was confirmed.

The values in air were larger than those under vacuum owing to the effect of the air. In air, the heat is transmitted though wood by a combination of heat conduction and convective heat transfer of the cell wall and air, whereas under vacuum conditions the heat transfer by air disappears and the thermal conductivity of wood is diminished. Therefore the difference between $k_{At,\rho,R}$ and $k_{Va,\rho,R}$ is believed to increase for the lower density wood specimen. To examine the proposed theory for its validity at room temperature, the values of ρ_w, $k_{w,R}$, and $k_{a,R}$ [i.e., $\rho_w = 1560 kg \cdot m^{-3}$, $k_{a,R} = 0.0256 W \cdot m^{-1} \cdot K^{-1}$, and $k_{w,R} = 0.308 W \cdot m^{-1} \cdot K^{-1}$, which was calculated from Eq. (8)] were substituted into Eqs. (2)–(4);

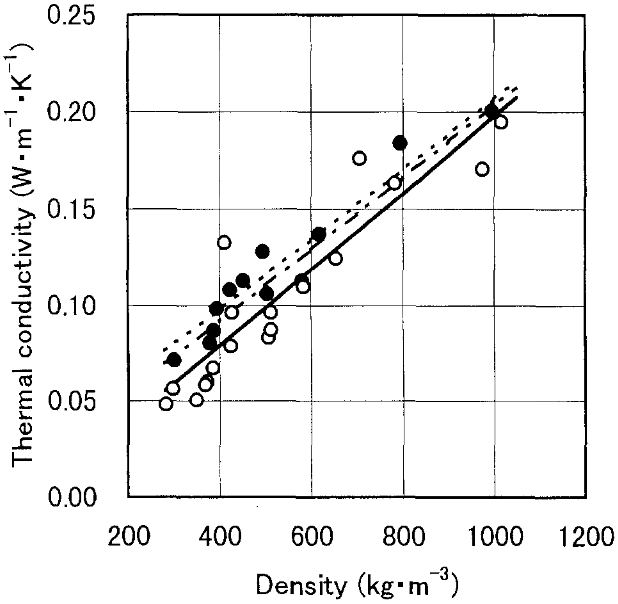

Fig. 2. Effects of density and air on thermal conductivity at room temperature. *Filled circles*, measured in air; *open circles*, measured under vacuum; *alternate long and short dashed line*, regression line calculated by Urakami and Fukayama[4]; *broken line*, theoretical line in air; *solid line*, theoretical line under vacuum

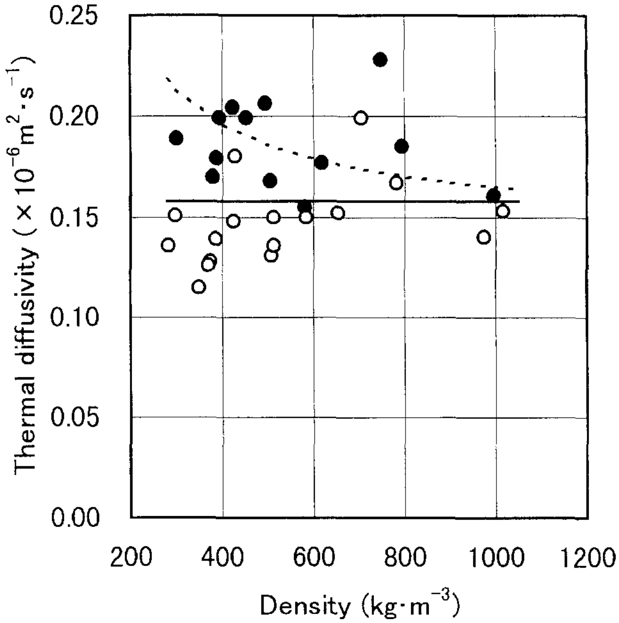

Fig. 3. Effects of density and air on thermal diffusivity at room temperature. *Filled circles*, measured in air; *open circles*, measured under vacuum; *broken line*, theoretical line in air; *solid line*, theoretical line under vacuum

and the values of $k_{\mathrm{At},\rho,\mathrm{R}}$ and $k_{\mathrm{Va},\rho,\mathrm{R}}$ were calculated for arbitrary density ρ. The theoretical equations for $k_{\mathrm{At},\rho,\mathrm{R}}$, $k_{\mathrm{Va},\rho,\mathrm{R}}$ were as follows, and the relations are plotted in Fig. 2.

$$k_{\mathrm{At},\rho,\mathrm{R}} = 0.0256 + 1.81 \times 10^{-4}\rho \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right) \tag{9}$$

$$k_{\mathrm{Va},\rho,\mathrm{R}} = 1.97 \times 10^{-4}\rho \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right) \tag{10}$$

The theoretical values showed good agreement with the experimental values, and the validity of the theory at room temperature was confirmed.

Thermal diffusivity at room temperature

The thermal diffusivities at room temperature are shown in Fig. 3. The theoretical values of the thermal diffusivity calculated from the above equations are also shown in Fig. 3. Although the experimental values were slightly scattered, the values under vacuum conditions were smaller than the values in air. According to Fig. 3, the theoretical model explains the tendency of the experimental results; that is, the theoretical model shows that the values in air decrease with density, and those under vacuum conditions are almost the same for the different species and smaller than the values measured in air.

Heat capacity during the heating process

The heat capacities of kiri, hiba, hinoki, buna, and akagashi during the heating process are shown in Fig. 4. The heat capacities during the heating process were calculated from

$$c_{\mathrm{T}} = c_{\mathrm{R}} \times \frac{L \cdot \rho_{\mathrm{R}}}{L \cdot \rho_{\mathrm{T}}} \times \frac{\Delta T_{\mathrm{max,R}}}{\Delta T_{\mathrm{max,T}}} \quad \left(\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}\right) \tag{11}$$

where the subscripts R and T denote the values at room temperature and at temperature T, respectively, and c_{R} was taken to be $1.25 \times 10^3\,\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$. The differences between species were small, and the following regression formulas were obtained.

In air:

$$c_{\mathrm{At,T}} = 1200 + 2.45 \times T \quad \left(\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}\right) \quad (n = 37,\ r = 0.64) \tag{12}$$

Under vacuum:

$$c_{\mathrm{Va,T}} = 1100 + 7.72 \times T \quad \left(\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}\right) \quad (n = 44,\ r = 0.88) \tag{13}$$

where T is the ambient temperature (°C), and its range is from room temperature to 240°C; n is the number of specimens; and r is the correlation coefficient. The specific heat at 20°C was taken to be $1.25 \times 10^3\,\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$. It is known that the specific heat of wood increases linearly with the temperature for temperatures less than 100°C. It was found that this tendency continued up to 240°C; above this temperature the specimens pyrolize rapidly.

Although $c_{\mathrm{At,R}}$ and $c_{\mathrm{Va,R}}$ were almost the same at room temperature, the values $c_{\mathrm{Va,T}}$ were larger than those for $c_{\mathrm{At,T}}$ during the heating process. This phenomenon depends on the effect of the air. Generally in air, the higher the temperature, the larger is the heat loss from the specimen. In the case of a porous material such as wood, it is

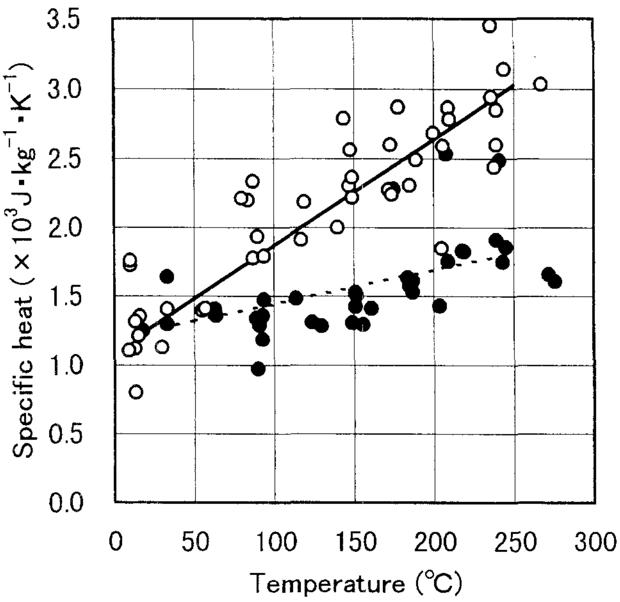

Fig. 4. Relation between temperature and specific heat. *Filled circles*, measured in air; *open circles*, measured under vacuum; *broken line*, regression line in air; *solid line*, regression line under vacuum

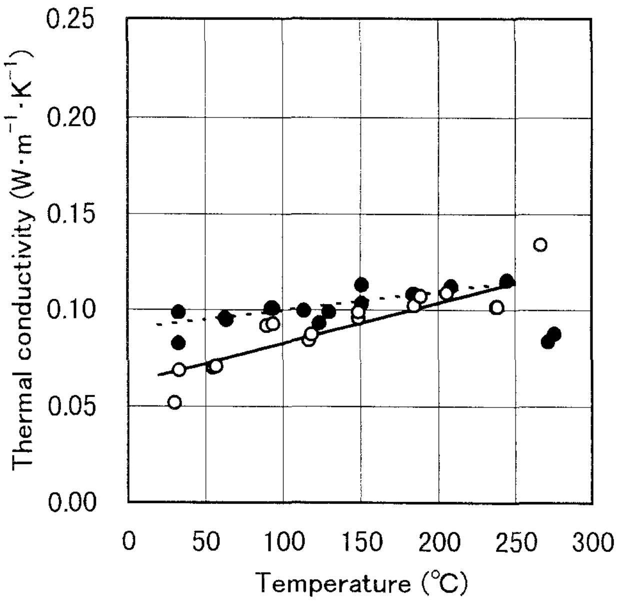

Fig. 5. Relation between temperature and thermal conductivity of hiba. *Filled circles*, measured in air; *open circles*, measured under vacuum; *broken line*, regression line in air; *solid line*, regression line under vacuum

thought that the effect of the heat loss from the lumen is significant.

Thermal conductivity during the heating process

The thermal conductivity of hiba during the heating process is shown in Fig. 5. There were linear relations between the thermal conductivity of the wood and the ambient temperature both in air and under vacuum. Considering these results in relation to the above discussion, we can assume that the thermal conductivity of wood is correlated with its density and the ambient temperature. We analyzed the relations between the three parameters using multiple regression analysis and obtained the following results.

In air:

$$k_{\mathrm{At},\rho,\mathrm{T}} = 0.00249 + 0.000145\rho + 0.000184T \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right)\left(n = 37,\ R^{*2} = 0.76\right) \tag{14}$$

Under vacuum:

$$k_{\mathrm{Va},\rho,\mathrm{T}} = -0.0237 + 0.000208\rho + 0.000361T \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right)\left(n = 44,\ R^{*2} = 0.76\right) \tag{15}$$

where R^{*2} is the coefficient of determination adjusted by the degrees of freedom and a temperature range of room temperature to 240°C. Although the coefficients of determination were slightly low, it was found that the values for $k_{\mathrm{At},\rho,\mathrm{T}}$ and $k_{\mathrm{Va},\rho,\mathrm{T}}$ could be estimated from multiple regression formulas.

We found (above) that the thermal conductivity at room temperature could be explained by the theoretical model. We now consider whether the theoretical model also applies to thermal conductivity during the heating process. Here, the thermal conductivities of the cell wall in air and under vacuum were calculated from the results of hiba specimens and were compared. If Eq. (4) holds at ambient temperature, the thermal conductivity of the cell wall at T under vacuum $k_{\mathrm{Va,w,T}}$ can be obtained from the data of the hiba specimens. The regression formula between $k_{\mathrm{Va,w,T}}$ and T was determined to be

$$k_{\mathrm{Va,w,T}} = 0.291 + 0.000836T \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right) \quad \left(n = 14,\ r = 0.93\right) \tag{16}$$

where the thermal conductivity at 20°C was taken to be $0.308\,\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$ to correlate with the value at room temperature.

The equivalent thermal conductivity of the air at T was calculated from the known thermal properties of the air[12] as follows.

$$k_{\mathrm{a,T}} = 0.0243 + 0.0000722T \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right) \tag{17}$$

As mentioned, because there is heat loss in the high temperature air, the thermal conductivity calculated from Eqs. (4), (16), and (17) did not agree with the experimental values. It is necessary to introduce the coefficient μ to correct for the effect of the heat loss. Because the rate of the $c_{\mathrm{At,R}}$ increase against T was about one-third that of $c_{\mathrm{Va,R}}$ and the thermal conductivity is expressed by $k = \alpha{\cdot}\rho{\cdot}c$ from Eq. (1), we set $\mu = 0.33$. Thus the thermal conductivity of the cell wall in the high-temperature air $k_{\mathrm{At,w,T}}$ is given by

$$k_{\mathrm{At,w,T}} = 0.291 + 0.000836 \times \mu \times T \quad \left(\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}\right) \tag{18}$$

The experimental values and those calculated from Eqs. (2), (17), and (18) are compared in Fig. 6. Both sets of values

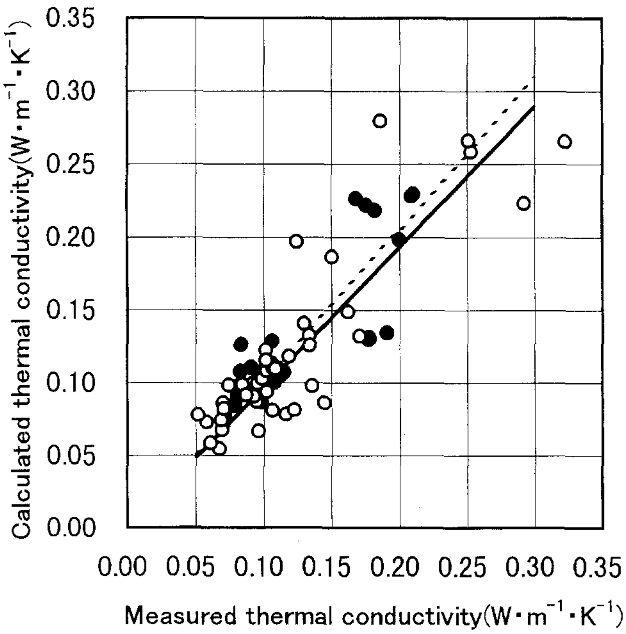

Fig. 6. Relation between the measured and calculated thermal conductivities from room temperature to 240°C. *Filled circles*, values in air; *open circles*, values under vacuum; *broken line*, regression line in air; *solid line*, regression line under vacuum

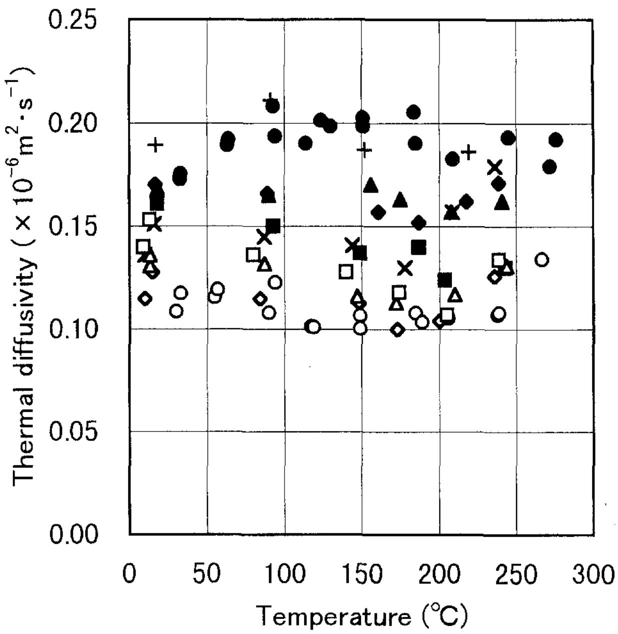

Fig. 7. Relation between temperature and thermal diffusivity. *Pluses*, kiri in air; *crosses*, kiri under vacuum; *filled circles*, hiba in air; *open circles*, hiba under vacuum; *filled rhombuses*, hinoki in air; *open rhombuses*, hinoki under vacuum; *filled triangles*, buna in air; *open triangles*, buna under vacuum; *filled squares*, akagashi in air; *open squares*, akagashi under vacuum

showed good agreement. Consequently, if the heat loss is corrected for, the theoretical model for thermal conductivity is valid for high temperatures up to 240°C in air.

Thermal diffusivity during the heating process

The values for thermal diffusivity during the heating process of kiri, hiba, hinoki, buna, and akagashi are given in Fig. 7. It is evident that there is little change in the thermal diffusivity during the heating process up to 240°C both in air and under vacuum. However, differences between the species were observed. The mean values and their 95% confidence limits are illustrated in Fig. 8, which indicates that the lower-density wood specimens have larger thermal diffusivities in air, whereas there is little difference between the species under vacuum. The theoretical thermal diffusivity tendency illustrated in Fig. 3 was also supported by these results. Although the thermal diffusivity under vacuum calculated from the theoretical model is constant, according to Fig. 8, there is a tendency for the thermal diffusivity under vacuum to increase slightly with the density. Further study is necessary to clarify this point.

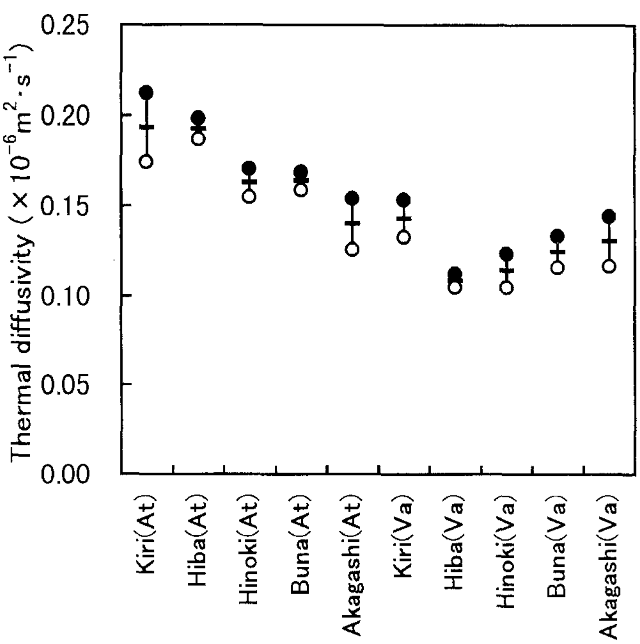

Fig. 8. Population mean of thermal diffusivity (95% confidence limits). *Filled circles*, upper confidence limit; *open circles*, lower confidence limit; *minuses*, average value; (*At*), measured in air; (*Va*), measured under vacuum

Conclusions

The thermal constants of wood specimens were measured by means of the laser flash method at room temperature and during the heating process up to 270°C, and the atmospheric conditions in air or under vacuum. The effects of atmospheric conditions on thermal constants were discussed; a theoretical model of the thermal conductivity was proposed and its validity examined. The results can be summarized as follows.

1. At room temperature, the specific heat of wood is uniform regardless of species or atmospheric conditions.

During the heating process there was a linear relation between specific heat and the ambient temperature, and the specific heat under vacuum was larger than that in air.

2. The thermal conductivity increased with the density and the ambient temperature. The theoretical model explained the thermal conductivity at room temperature effectively. During the heating process, it is necessary to correct for the effect of heat loss.

3. The thermal diffusivities under vacuum conditions were smaller than those in the air, and these values varied little in the heating process up to 240°C. This tendency was also explained effectively by the theoretical model.

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