J Wood Sci (2016) 62:356–362
DOI 10.1007/s10086-016-1557-4

ORIGINAL ARTICLE

Investigation of thermal conductive properties of structural timbers at low temperature region using solid carbon dioxide as a chilling agent

BaekYong Choi[1] · **Tsuyoshi Yoshimura**[1]

Received: 20 January 2016 / Accepted: 25 March 2016 / Published online: 22 April 2016

Abstract Knowledge of the thermal conductive properties of wood at low temperatures aids the development and optimization of the application of a lethal cold temperature treatment for drywood termites. The present study investigates the relationship between the thermal conductive properties of wood at low temperatures and important factors, namely, the microstructural and anisotropy of wood using two types of solid carbon dioxide as a chilling agent. The results indicate that the thermal conductive properties of wood at low temperatures are mainly affected by the composition and morphological properties of wood (i.e., density/ratio of earlywood and latewood, proportion of heartwood and sapwood, pattern of growth ring). In particular, thermal conductive properties are mainly dependent on the pattern of the growth ring itself at low temperatures.

Keywords Freezing remedial drywood termite treatment · Thermal conductive properties · Solid carbon dioxide

Introduction

Drywood termites may be eradicated by a lethal cold temperature treatment as an alternative to the use of pesticides and fumigants. The first investigation on using a lethal cold temperature treatment for drywood termite control was a study applying liquid nitrogen into wall voids to create temperatures below the critical thermal minimum of drywood termites [1]. Thereafter, several other studies have reported the high efficacy of lethal cold temperature treatments under laboratory and field conditions [2, 3]; however, none of these studies investigated the relationship between the thermal conductive properties of wood at low temperature and the various factors affecting these properties. Knowledge of the thermal conductive properties of wood at low temperatures can aid the development and optimization of the application of a lethal cold temperature treatment for drywood termites.

High interest of energy performance [4–6] and fire resistance [7] of wooden structure buildings led to measurements of the thermal conductive properties of wood in past decades. Due to past research interest, most of the measurements of the thermal conductive properties on wood were made at high temperatures. Thermal conductive properties can be categorized into three groups: thermal conductivity, thermal diffusivity, and specific heat capacity [6, 8], which are the most important parameters for simulating the thermal behavior of wood [5]. The thermal conductive properties of wood are dependent on a number of factors. Some of the most important factors are density, porosity and anisotropy [9, 10]. There is general agreement that the thermal conductive properties of wood are mainly dependent upon the cell components which are aggregated into tissue-independent phases [11, 12]. Eventually, more cell components exist as the density of wood increases. The thermal conductivity of the cell components in wood has been described in detail by many other researchers. The major cell components of wood are cellulose and hemicellulose, which usually account for 65–75 % of the wood dry weight and 18–35 % of the lignin [13], and they are generally more thermally conductive than air [14–16]. Meanwhile, porosity is another obstacle to the thermal

✉ BaekYong Choi
baekyong_choi@rish.kyoto-u.ac.jp

[1] Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

conduction of wood, due to the low thermal conductivity property of air, which fills the cellular substance with voids before the fiber saturation points. The anisotropy of the structure, a key characteristic of wood, and physical properties have been extensively discussed under low thermal properties by several researchers. Wood is a lignocellulosic material mainly comprising long-chain linear polymers (cellulose, hemicelluloses, and lignin), minor amounts of extractives and inorganic compounds [13]. These components are combined and mainly aligned with the longitudinal axis of the cell. Given the anisotropic nature of wood, thermal conductivity is approximately 2–3 times higher in the longitudinal direction than in the transversal [17–19], but it is not significantly different between the radial and tangential directions [5, 20]. All three parameters are strongly influenced above the fiber saturation point (FSP) and can vary by as much as 100 % depending on the moisture content [21]; however, the moisture content of timber in service is well below the FSP. Therefore, it does not correspond with the pronounced change in the thermal conductive properties of wood because the thermal conductivities of water vapor and air are very similar [11].

The aforementioned factors that significantly affect the thermal properties of wood were mostly determined by measuring the rate of heat flow at high temperatures (steady-state method); however, a literature review reveals limited information on the thermal conductive properties of wood at low temperatures. To expand the existing knowledge of the thermal conductive properties of wood at high temperatures, the present study investigates the relationship between the thermal conductive properties of wood at low temperatures and important factors, namely, the microstructural properties (density and porosity) and the anisotropy of wood using two types of solid carbon dioxide as a chilling agent. During this study the rate of heat flow could not be calculated; therefore, the thermal conductive properties of wood at low temperatures were defined as the cooling rate to the targeted critical thermal minimum (CT_{min}) of drywood termites (°C/min), the minimum core temperature (°C), and the duration of the temperature below CT_{min} (min).

Materials and methods

Wood materials

Special emphasis was placed on the selection of wood material. Accordingly, defect-free, normally grown wood materials were selected from four commonly used structural timbers in the Japanese wood market. As raw materials, four softwood species (moisture content ranged from 13 to 19 %), Japanese cedar (*Cryptomeria japonica* D. Don), Japanese cypress (*Chamaecyparis obtusa* ENDL.), Douglas-fir [*Pseudoitsuga menziesil* (Mirb.) Franco], and Sitka spruce [*Picea sitchensis* (Bong.) Carr.], air-seasoned for more than 5 years were used. The Japanese cypress and Sitka spruce specimens used in this study contained a considerable proportion of sapwood (≥50 %), whereas the other two species comprised either 100 % heartwood or a high proportion of heartwood (>75 %), respectively (Table 1).

Preparation of the test blocks

Wood blocks of Douglas fir were cut from the large diameter of wood based on small ring curvation, whereas most of the other wood species were cut from a moderate diameter, which had a partially tangential and partially radial larger ring curvation. The wood blocks were then conditioned at 20 ± 3 °C and 65 ± 5 % relative humidity for 8 weeks in a conditioning room until their weights stabilized. After the conditioning, the average values of the air-dried density were calculated for each block based on the air-dried masses and volumes. To estimate the porosity (r) of the wood blocks, the following equation given by Suleiman et al. [9] was used:

Table 1 Density, porosity, moisture content, growth ring and heartwood proportion measured and computed for the samples of the different blocks of wood in air-dry conditions (mean ± SE)

Species	Direction	MC (%)	Density (kg/m^3)	Porosity (r)	Growth ring (#)	Ring angle (°)	Heartwood/sapwood ratio (%)
Japanese cedar	Radial	21.7 ± 1.8	381 ± 9	0.746 ± 0.006	21.7 ± 1.8	22.4 ± 1.8	≥75
	Tangential	18.8 ± 1.6	358 ± 8	0.761 ± 0.006	18.8 ± 1.6	23.0 ± 2.3	≥75
Japanese cypress	Radial	14.8 ± 1.4	480 ± 15	0.680 ± 0.020	14.8 ± 1.4	61.8 ± 3.7	≥50
	Tangential	16.3 ± 0.7	474 ± 7	0.684 ± 0.005	16.3 ± 0.7	61.0 ± 3.6	≥50
Sitka spruce	Radial	16.8 ± 0.6	438 ± 9	0.708 ± 0.006	16.8 ± 0.6	62.2 ± 4.8	≥50
	Tangential	17.9 ± 0.4	439 ± 4	0.707 ± 0.003	17.9 ± 0.4	59.0 ± 3.1	≥50
Douglas fir	Radial	14.8 ± 1.4	564 ± 26	0.624 ± 0.017	14.8 ± 1.4	30.8 ± 1.5	100
	Tangential	16.3 ± 0.6	645 ± 9	0.570 ± 0.006	16.3 ± 0.6	29.0 ± 2.9	100

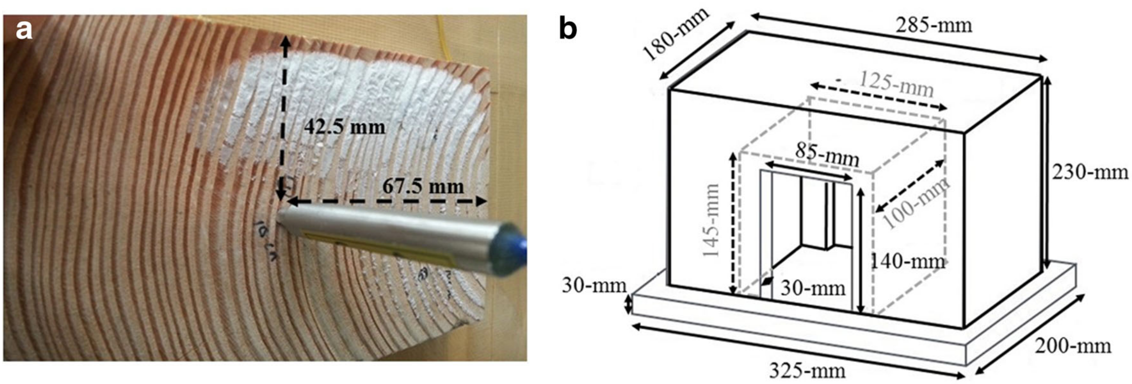

Fig. 1 **a** Instant temperature change of the wood block core on radial block. **b** Polystyrene insulation chamber

$$r = 1 - (\rho_{ave}/\rho_{th})$$

where ρ_{ave} = the average density of wood and ρ_{th} = the assumed theoretical density of a compact solid wood free from voids (1500 kg/m^3) [17].

Afterwards, when the moisture content of the wood blocks reached below the fiber saturation point (<30 %), they were cut into dimensions of 85(R) × 135(T) × 200-mm (L) for tangential blocks and 85(T) × 135(R) × 200-mm (L) for radial blocks. To measure the instant temperature change of the wood block cores, a 3.5-mm diameter hole (70-mm deep) was drilled into the blocks from each cutting edge for thermocouple insertion (Fig. 1a). A total of 20 replications (five replicates/dry ice forms/cutting directions) were prepared from each wood species. The average microstructural and anisotropy data are presented in Table 1.

Measurement procedures

The low thermal conductive properties of the wood blocks was determined using two types of dry ice forms (solid slabs and crushed small particles/snow; 1300 ± 50 g) in a specially designed polystyrene (JIS A-9511 [22]) insulation chamber (Fig. 1b). The insulation chamber was designed to maximize the heat transfer properties of solid carbon dioxide. During the test operation, the instant temperature change of the wood blocks tested were monitored with a thermocouple [3.5(ϕ) × 70-mm (L), JUST Co. Ltd, Tokyo, Japan] connected to a computer via a thermocouple interface and SoftThermo E830 software (Technol Seven, Tokyo, Japan) for 20 h at 15-min intervals.

Data analysis

To confirm the normality and homogeneity of the data variance, the Shapiro–Wilk test was used. In addition, an analysis of variance (ANOVA) was used to test for significant differences between the two factors (wood species and grain angles) and levels. When the null hypothesis ($P < 0.05$) was rejected, a comparison of means was performed employing a Tukey HSD (Honestly Significant Difference) test at 5 % of probability of error [23].

Results

Influence of microstructure (density and porosity) on thermal conductive properties

The average cooling rates to the targeted critical thermal minimum (CT_{min}) of drywood termites (°C/min), minimum core temperature (°C), and duration of temperature below CT_{min} (min) of wood as a function of density and porosity are presented in Table 2. A positive correlation of thermal conductivity with density and porosity is shown to be partly coherent to the theory. For example, high energy is shown to be transferred through Douglas fir which had the highest density (602 ± 46.8 kg/m^3) and the lowest porosity (0.599 ± 0.031), which is consistent with the relationship found by other studies. Meanwhile, Japanese cedar, which had the lowest density (381.1 ± 9.4 kg/m^3) and the highest porosity (0.753 ± 0.010) in the group, also exhibited higher energy transfer through the wood. Despite the density and estimated porosity according to Table 2 and the fact that the wood species must have different thermal properties in terms of their thermal profiles, the cooling rate, minimum core temperature, and duration of those wood species showed no significant difference ($P < 0.0001$). Similarly, for the similar range of density and porosity of Japanese cypress (431.4 ± 11.9 kg/m^3; 0.712 ± 0.008) and Sitka spruce (438.1 ± 5.0 kg/m^3; 0.708 ± 0.003), the data showed significant differences in thermal properties at low temperatures. The mean cooling rate to target the critical thermal minimum (−21.3 °C) for Sitka spruce was −0.23 °C/min, whereas a cooling rate of only −0.19 °C/min was recorded from Japanese cypress.

Table 2 Results of the thermal conductive property measurements performed with the solid carbon dioxide as chilling agent for commonly used structural timber species in transverse directions (mean ± SE)

Species	Direction	Density (kg/m^3)	Porosity (*r*)	Cooling rate (°C/min)	Min. temperature (°)	Duration in CT_{min} temp. range (min)
Japanese cedar	Radial	381 ± 9	0.746 ± 0.006	−0.27 ± 0.00	−22.5 ± 0.7	490 ± 13
	Tangential	358 ± 8	0.761 ± 0.006	−0.26 ± 0.01	−25.2 ± 0.8	453 ± 22
Japanese cypress	Radial	480 ± 15	0.680 ± 0.020	−0.19 ± 0.00	−22.0 ± 0.6	180 ± 8
	Tangential	474 ± 7	0.684 ± 0.005	−0.19 ± 0.00	−21.6 ± 0.6	170 ± 6
Sitka spruce	Radial	438 ± 9	0.708 ± 0.006	−0.24 ± 0.01	−24.2 ± 0.3	420 ± 11
	Tangential	439 ± 4	0.707 ± 0.003	−0.23 ± 0.01	−23.3 ± 0.7	398 ± 8
Douglas fir	Radial	564 ± 26	0.624 ± 0.017	−0.27 ± 0.01	−26.4 ± 1.0	420 ± 11
	Tangential	645 ± 9	0.570 ± 0.006	−0.24 ± 0.01	−25.2 ± 0.9	490 ± 16

Furthermore, the results of Japanese cypress for other associated parameters, such as minimum core temperature and duration of temperature below CT_{min}, showed significantly higher and shorter results than Sitka spruce.

Influence of anisotropy on thermal conductive properties

According to the mean values of the thermal properties at the loading of 1300 g of solid carbon dioxide in bar form for both the tangential and radial direction, the cooling rate increased in the radial direction in Douglas fir but did not significantly differ for the other thermal properties of wood at low temperatures (minimum core temperature and duration of temperature below CT_{min}) compared with the tangential direction ($P < 0.0001$). The quickest cooling rates (−0.27 ± 0.1 °C/min) were obtained in the radial direction of Douglas fir and both transverse directions of Japanese cedar followed by tangential Douglas fir and both transverse directions of Sitka spruce (−0.23 ± 0.1 °C/min). The lowest values were obtained in both transverse directions in Japanese cypress as −0.19 ± 0.0 °C/min. For all wood species except Douglas fir, there was no significant difference in the cooling rate between the radial and tangential directions ($P < 0.0001$).

The increase in cooling rate and duration was similar to the order of the cooling rate. The lowest core temperature and the longest duration of the CT_{min} temperature range was obtained from Douglas fir in the radial direction, and the highest core temperature and the shortest duration was obtained from both transverse directions of Japanese cypress (Fig. 2).

Influence of solid carbon dioxide form on thermal conductive properties

Figure 3 compares the thermal conductive properties (cooling rate, minimum core temperature, and duration of temperature below CT_{min}) obtained in both the tangential and radial directions from two different solid carbon dioxide forms in this study. It appears that crushed small particles/snow solid carbon dioxide increases the thermal conductive properties of the wood species tested. The rate of convection heat transfer were obtained using Newton's law of cooling equation. The mean value of 0.146 W/m^2 were generated by crushed solid carbon dioxide, whereas 0.138 W/m^2 was generated by solid carbon dioxide slabs. This phenomenon might be caused by the faster sublimation of small particle/snow which extracts the heat energy from the immediate surroundings resulting in extreme cooling compared with solid carbon dioxide slabs. Consequently, the crushed form of solid carbon dioxide increased the cooling rate by a minimum of 9.9 % to a maximum of 28.9 %, the minimum core temperature by a minimum of 7.7 % to a maximum of 10.6 %, and the duration by a minimum of 8.8 % to a maximum of 17.0 % compared with solid slabs.

Discussion

Based on the theory of the thermal conductive properties of wood, higher densities and lower porosities increase the thermal conductive properties of wood [9, 14]. However, in contrast with the thermal conductive properties of wood at high temperature, few discrepancies were observed at low temperatures.

The results indicate that the thermal conductive properties of wood at low temperature are mainly affected by the composition and morphological properties of wood (i.e., density/ratio of earlywood and latewood, proportion of heartwood and sapwood, pattern of growth ring). In Fig. 1a, the cross-section photo reveals a clear frost variation where high energy is shown being transferred first through the latewood ring and then across into the earlywood ring. In the latewood of softwood, thick cell walls

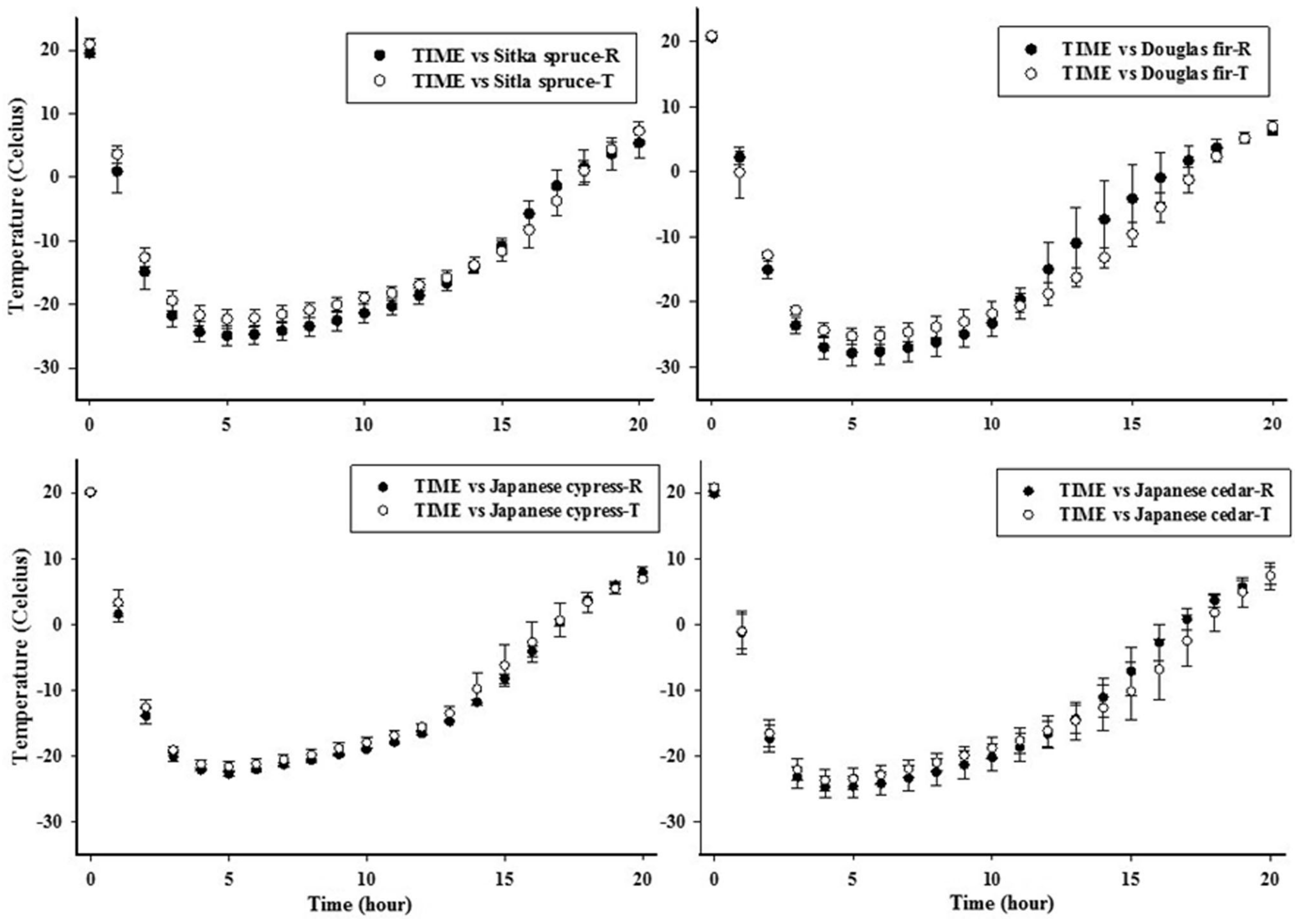

Fig. 2 Comparison of the thermal conductive properties values obtained in both tangential and radial direction using solid carbon dioxide slabs

with a small lumen increase the thermal conductive properties because heat transfers mainly through cell walls [18]. By contrast, earlywood has thin walls with larger cell lumens. Below the FSP, these cell lumens are mostly filled with air, which consequently decreases the thermal properties of wood due to the low thermal properties of air [16]. A study of the thermal conductive properties below the FSP by Gu et al. [18] also revealed that the percentage of latewood substantially affects the thermal conductive properties of wood. For example, for spruce, the densities of early wood and late wood differ by three factors [5].

Thermal conductive properties may also be responsible for the differences between heartwood and sapwood. The higher proportions of heartwood of Douglas fir (100 %) and Japanese cedar (>75 %) recorded higher thermal conductive properties, which may indicate that the chemical substances in heartwood increase the thermal conductive properties. MacLean and others [9, 24, 25] deduced that chemical substances in the heartwood such as tannin, resin or oil possibly increase the thermal conductive properties.

The effect of anisotropy on the thermal conductive properties of wood is a highly controversial topic. Some scientists claim that the thermal conductive values in the radial direction are higher than in the tangential direction [5, 17, 26], whereas others report the same thermal conductive properties in both transverse directions [8, 9, 20]. However, most importantly, the thermal conductive properties are mainly dependent on the pattern of the growth ring itself at low temperatures. In the case of Douglas fir, the thermal conductive properties in the radial direction are higher than in the tangential direction. However, in contrast with Douglas fir, similar thermal conductive properties in the tangential and radial directions were obtained for moderate-diameter wood, which comprises partly tangential and partly radial directions. Consequently, this combination of both transverse directions influences the anisotropic factor of the thermal conductive properties in this study. Furthermore, the orientation of the microfibrils strongly affects the thermal conductive properties. A number of other studies have reported that the thermal conductive properties of wood increase with increasing ring angle which is influenced by the microfibril angle in the S2 layers of the cell walls [5, 26, 27].

The results have shown that the thermal conductive properties of wood at low temperatures are mainly

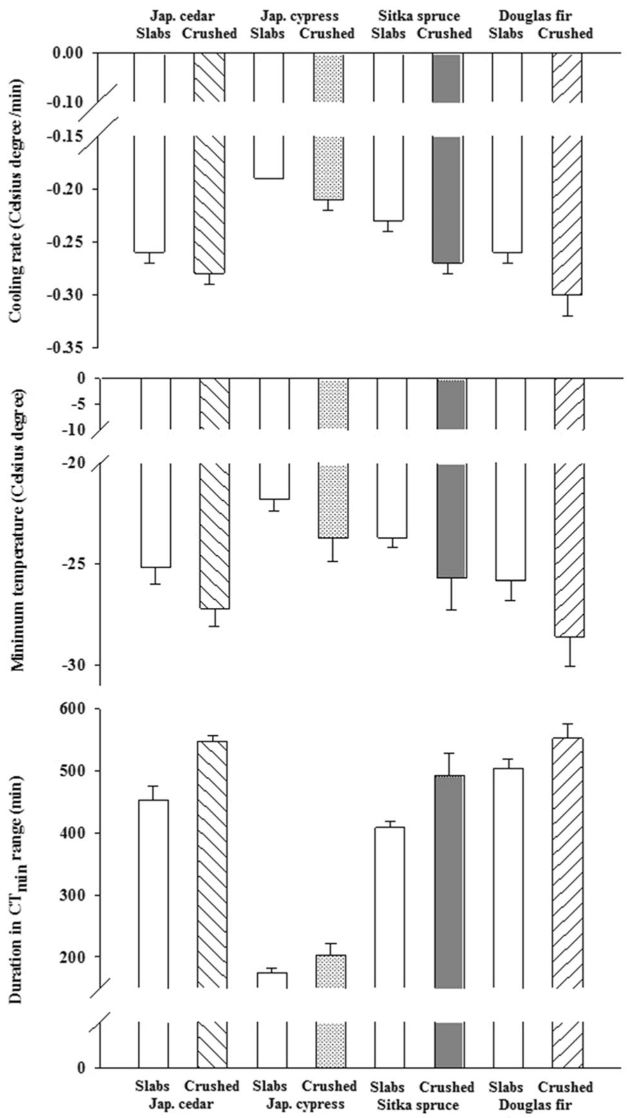

Fig. 3 Comparison of the thermal conductive properties values obtained in two type of solid carbon dioxide form

dependent on the hierarchical organization of wood. Therefore, to establish a model that can predict the thermal conductive properties at low temperatures, the thermal conductive properties of the cell wall material are required in future studies. In addition, the effect of knots, checks, and other defects on structural timber must be studied because these defects have a tendency to increase the thermal conductive properties of wood. Finally, in addition to the three parameters above, the probe location strongly influenced the results, due to the localized temperature measurement and the influence of heterogeneities. Hence, the probe location must be carefully selected to eliminate the influence of heterogeneities and also to increase the number of probe locations to encompass the temperature measurement of the entire sample in future study. Overall, as remedial drywood termite treatments using solid carbon dioxide are developed to kill them inside timber, we are certain that the results obtained demonstrate the high capability of the application.

Acknowledgments The authors are gratefully thankful to Shuichi Tami and Seiichi Shinzato (Dainaga cork Co., Ltd.) for technical assistance on the development and optimization of the application, and John NR Ruddick (University of British Columbia) for his comments on the manuscript.

References

1. Forbes C, Ebeling W (1986) Update: liquid nitrogen controls drywood termites. IPM Pract 8(8):1–4
2. Rust M, Plaine EO, Reierson DA (1995) Laboratoty evaluation of low temperature for controlling drywood termites. Report prepared for the California Structural Pest Control Board. Department of Entomology, Univerity of California Riverside, Riverside, CA
3. Lewis VR, Haverty MI (1996) Evaluation of six techniques for control of the western drywood termite (Isoptera: Kalotermitidae) in structures. J Econ Entomol 89(4):922–934
4. Lagüela S, Bison P, Peron F, Romagnoni P (2015) Thermal conductivity measurements on wood materials with transient plane source technique. Thermochim Acta 600:45–51
5. Sonderegger W, Hering S, Niemz P (2011) Thermal behaviour of Norway spruce and European beech in and between the principal anatomical directions. Holzforschung 65(3):369–375
6. Bouguerra A, Ait-Mokhtar A, Amiri O, Diop M (2001) Measurement of thermal conductivity, thermal diffusivity and heat capacity of highly porous building materials using transient plane source technique. Int Commun Heat Mass Transfer 28(8):1065–1078
7. Clancy P (2001) Advances in modelling heat transfer through wood framed walls in fire. Fire Mater 25(6):241–254
8. Steinhagen HP (1977) Thermal conductive properties of wood, green or dry, from −40 to +100 °C: a literature review. General technical report GTR-FPL-9. USDA Forest Service, Forest Products laboratory, Madison, Wisconsin, pp 3–23
9. Suleiman B, Larfeldt J, Leckner B, Gustavsson M (1999) Thermal conductivity and diffusivity of wood. Wood Sci Technol 33(6):465–473
10. Mauranen A, Ovaska M, Koivisto J, Salminen L, Alava M (2015) Thermal conductivity of wood: effect of fatigue treatment. Wood Sci Technol 49(2):359–370
11. Eitelberger J, Hofstetter K (2011) Prediction of transport properties of wood below the fiber saturation point—a multiscale homogenization approach and its experimental validation: part I: thermal conductivity. Compos Sci Technol 71(2):134–144
12. Dupleix A, Kusiak A, Hughes M, Rossi F (2013) Measuring the thermal properties of green wood by the transient plane source (TPS) technique. Holzforschung 67(4):437–445
13. Missio AL, Mattos BD, de Cademartori PH, Pertuzzatti A, Conte B, Gatto DA (2015) Thermochemical and physical properties of two fast-growing eucalypt woods subjected to two-step freeze–heat treatments. Thermochim Acta 615:15–22
14. Yu Z-T, Xu X, Fan L-W, Hu Y-C, Cen K-F (2011) Experimental measurements of thermal conductivity of wood species in China: effects of density, temperature, and moisture content. For Prod J 61(2):130–135
15. Dunlap F (1914) Density of wood substance and porosity of wood. J Agric Res 2:423–428

16. Asako Y, Kamikoga H, Nishimura H, Yamaguchi Y (2002) Effective thermal conductivity of compressed woods. Int J Heat Mass Transfer 45(11):2243–2253
17. Kollmann FF, Côte WA Jr (1968) Chapter 6: physics of wood. Principles of wood science and technology, vol I. Solid wood. Springer, Berlin, pp 160–285
18. Gu H-m, Zink-Sharp A (2005) Geometric model for softwood transverse thermal conductivity. Part I. Wood Fiber Sci 37(4):699–711
19. Wagner T, Götz S, Eska G (1994) Thermal conductivity of wood at low temperatures. Cryogenics 34(8):655–657
20. Simpson W, TenWolde A (1999) Chapter 3: Physical properties and moisture relations of wood. Wood handbook—wood as an engineering material. Forest Products Laboratory, Maidison, pp 15–20
21. Ragland K, Aerts D, Baker A (1991) Properties of wood for combustion analysis. Bioresour Technol 37(2):161–168
22. JIS A-9511 (2009) Preformed cellular plastics thermal insulation materials (in Japanese). Janpanese Stanard Association, Tokyo
23. Institute SAS (2013) PROC user's manual, version, 11th edn. SAS Institute, Cary
24. MacLean J (1941) Thermal conductivity of wood. Heat Pip Air Cond 13(6):380–391
25. Lacoste C, Basso M, Pizzi A, Laborie M-P, Celzard A, Fierro V (2013) Pine tannin-based rigid foams: mechanical and thermal properties. Ind Crops Prod 43:245–250
26. Niemz P, Sonderegger W, Hering S (2010) Thermal conductivity of Norway spruce and European beech in the anatomical directions. Annals of Warsaw University of Life Sciences–SGGW. For Wood Technol 72:66–72
27. Vay O, Obersriebnig M, Müller U, Konnerth J, Gindl-Altmutter W (2013) Studying thermal conductivity of wood at cell wall level by scanning thermal microscopy (SThM). Holzforschung 67(2):155–159