Experimental Measurements of Thermal Conductivity of Wood Species in China: Effects of Density, Temperature, and Moisture Content

Zi-Tao Yu Xu Xu Li-Wu Fan
Ya-Cai Hu Ke-Fa Cen

Abstract

Experimental measurements of thermal conductivity of wood were performed using the heat flow meter and transient plane source technique. The specimens were prepared from five species of both softwoods and hardwoods widely available and used in China, with a wide range of density and moisture content. The transverse thermal conductivity of ovendry specimens is presented as a function of density and temperature up to 90°C and is compared with that along the grain direction for two select species. The influence of moisture content up to 23 percent, which is below the typical fiber saturation point of wood, on the transverse thermal conductivity is presented as well. It is shown that the transverse thermal conductivity of wood increases with density, temperature, and moisture content. Linear correlating equations are proposed in terms of these factors.

Wood, a natural organic composite material that consists of cellulosic fibers and lignin, has a long history of use both as a solid fuel and as a construction material. A need exists, however, to know thermal properties of wood to understand and model heat transfer processes in wood and wood-based materials. For example, the energy design and evaluation of energy performance of wood-frame buildings partially rely on the thermal properties of wood and wood products (TenWolde et al. 1988). The analysis of combustion and pyrolysis of wood exposed to fire also demands the knowledge of thermal properties (Beall 1977, Ragland et al. 1991, Thunman and Leckner 2002). Thermal conductivity that represents quantitatively the ability of wood to conduct heat is of great significance in heat transfer modeling (Olek et al. 2003).

Measurement of thermal conductivity of wood dates back several decades (see, e.g., Wangaard 1940, MacLean 1941). The early experimental work was primarily performed using the steady-state, guarded hot plate method. Thereafter, transient techniques, such as the laser flash method (Harada et al. 1998), transient plane source technique (Suleiman et al. 1999), and transient hot wire method (Kol 2009), were developed. The main factors that significantly affect thermal conductivity of wood include density, temperature, and moisture content. Steinhagen (1977) and TenWolde et al. (1988) collected extensive data on thermal conductivity of wood from early experimental studies. Harada et al. (1998) measured thermal conductivity of both softwood and hardwood species in Japan under a heating process up to 270°C. Soon thereafter, Suleiman et al. (1999) measured thermal conductivity of the hardwood birch (*Betula alnoides*) grown in Sweden at 21°C and 100°C for both longitudinal and transverse directions. Samples obtained from the softwoods white pine (*Pinus strobus*) and red pine (*Pinus resinosa*) grown in the United States were measured by Rice and Shepard (2004) for two different moisture content levels. Ngohe-Ekam et al. (2006) reported their experimental measurements on thermal conductivity of

The authors are, respectively, Associate Professor, Inst. of Thermal Sci. and Power Systems, Dept. of Energy Engineering, Zhejiang Univ., Hangzhou, People's Republic of China (yuzitao@zju.edu.cn); Associate Professor, College of Metrological and Measurement Engineering, China Jiliang Univ., Hangzhou, People's Republic of China (xuxu@cjlu.edu.cn); Research Assistant, Dept. of Mechanical Engineering, Auburn Univ., Auburn, Alabama (lzf0002@tigermail.auburn.edu); Professor, Inst. of Thermal Sci. and Power Systems, Dept. of Energy Engineering, Zhejiang Univ., Hangzhou, People's Republic of China (huyacai@zju.edu.cn); and Professor, State Key Lab. of Clean Energy Utilization, Zhejiang Univ., Hangzhou, People's Republic of China (kfcen@zju.edu.cn).
This paper was received for publication in December 2010. Article no. 10-00075.

Forest Prod. J. 61(2):130–135.

tropical wood as a function of basal density. Recently, Kol (2009) measured transverse thermal conductivity of five hardwood species grown in Turkey with different moisture contents.

A literature survey, however, reveals a lack of experimental data on thermal conductivity of wood species grown in China and Southeast Asia. To extend the existing knowledge, this study measured and documented thermal conductivity of wood species that are widely available and used in China and investigated its variations with density, temperature, and moisture content.

Experiments

Preparation of specimens

Five species of both softwoods and hardwoods were selected for a total of 10 wood species studied, as listed in Table 1. The origins of these wood species, all of which are widely available and used in China as construction and decoration materials, are also given. Except for the three hardwood lauan species (red lauan [*Shorea negrosensis*], yellow lauan [*Shorea kalunti*], and white lauan [*Pentacme contorta*]), all studied species were originally grown in China, covering an extremely broad area from the northernmost province (Heilongjiang) to southern provinces (Zhejiang, Fujian, and Yunan). Although lauan species have been planted in southern China for years, the available logs in the Chinese market are mainly imported from Malaysia and the Philippines.

Boards were sawn from portions of logs that were free of evident cracks, checks, and knots. Specimens were then prepared by planing the board surfaces and sawing into flat slabs with nominal dimensions of 100 by 100 by 10 mm^3. For each wood species selected, three ovendry specimens were prepared to measure the transverse thermal conductivity. As described by Siau (1984), ovendry samples were obtained using a drying temperature of 105°C for a sufficiently long time until a constant mass was attained. After heating at such temperature, both the free and bound water in wood was released, and the specimens were completely dry. The actual dimensions and mass of the samples were then measured precisely by using digital calipers (precision, ± 0.1 mm) and a digital scale (precision, ± 0.1 g), respectively. Consequently, apparent ovendry densities of the specimens were readily calculated, as given in Table 1.

Furthermore, for each of the two select species (i.e., the softwood masson pine [*Pinus massoniana*] and the hardwood red lauan), three ovendry specimens along the grain direction were prepared so that both longitudinal and transverse thermal conductivities could be measured. For two other select species (i.e., the softwood larch [*Larix gmelinii*] and the hardwood basswood [*Tilia yunnanensis*]), specimens with different moisture contents up to approximately 23 percent, which is below the typical fiber saturation point of wood, were prepared in such a way that the samples were conditioned at different relative humidity levels until an equilibrium moisture content had been reached (Kol 2009). This wetting process usually took 3 to 7 days, depending on the microstructures of the wood species. Both drying and wetting processes were monitored intermittently by weighing the samples being treated. At each moisture level, only one specimen was prepared for both species. To preserve any moisture from undesirable gain or loss, all of the treated specimens were stored in sealed glass jars until measuring.

Heat flow meter technique

In this study, thermal conductivity of ovendry specimens was measured by using the heat flow meter technique, which uses two calibrated heat flux transducers to measure the heat flux passing through the specimen that is placed between them. A steady-state, unidirectional heat flux is maintained by applying a given thermal gradient across the specimen. As given by Fourier's law (Siau 1984), thermal conductivity of the specimen is evaluated as

$$k = \frac{q''H}{\Delta T} \tag{1}$$

where k is the thermal conductivity (W/mK), q'' is the heat flux measured (W/m^2), H is the height of the specimen (m), and ΔT is the temperature difference (K).

An HFM 436/3 Lambda system (NETZSCH, Germany) based on the heat flow meter technique, which is designed for poorly conducting insulation materials that possess a low thermal conductivity up to 0.5 W/mK, was used. This instrument allows temperature-dependent measurements between 0°C and 100°C, and the typical repeatability is less than 5 percent. In addition, it accepts rectangular specimens with a maximum size of 300 by 300 by 100 mm^3. Because of the use of two heat flux transducers, the measurement times are typically within 20 minutes, providing a rapid means of measuring thermal conductivity.

Table 1.—Wood samples measured.

Species	Origin	Ovendry density (kg/m^3)
Softwoods (conifers)		
China-fir (*Cunninghamia lanceolata*)	Fujian, China	308.3
Korean pine (*Pinus koraiensis*)	Heilongjiang, China	378.6
Masson pine (*Pinus massoniana*)	Zhejiang, China	415.0
Scots pine (*Pinus sylvestris* var. *sylvestriformis*)	Heilongjiang, China	416.4
Larch (*Larix gmelinii*)	Heilongjiang, China	672.8
Hardwoods (angiosperms)		
Red lauan (*Shorea negrosensis*)	Imported from Malaysia	345.8
Yellow lauan (*Shorea kalunti*)	Imported from Malaysia	401.7
White lauan (*Pentacme contorta*)	Imported from Malaysia	436.9
Basswood (*Tilia yunnanensis*)	Yunnan, China	456.0
Birch (*Betula alnoides*)	Yunnan, China	613.8

Transient plane source technique

Although the heat flow meter technique is somewhat faster than the conventional guided hot plate method, it is still a steady-state method, and the typical measurement times of 20 minutes cannot be shortened. Therefore, this technique is not suitable for measuring moist wood specimens. When a thermal gradient is applied to a moist sample, a redistribution of the moisture takes place, leading to a transient heat flow that in turn confounds the measurement (TenWolde et al. 1988). In view of this, the recently developed transient techniques, which offer rapid measurements within several minutes or even seconds, appear desirable for measuring thermal conductivity of moist wood samples, because the moisture diffusion during the short heating period would be negligible.

In the present study, the measurements for moist specimens were performed on a TPS 500 Thermal Constants Analyzer (Hot Disk AB, Sweden) that is based on the transient plane source technique. The principle and data reduction of this technique were summarized by Suleiman et al. (1999) and are not herein duplicated. This instrument offers a simultaneous measurement of both thermal conductivity and diffusivity, although only the thermal conductivity data are presented. The applicable thermal conductivity range is between 0.03 and 100 W/mK, and the reproducibility is typically less than 2 percent. The measurement time is between 2.5 and 640 seconds. In addition, a controllable electric furnace was used to achieve measurement temperatures greater than room temperature. Once a desirable temperature had been attained, the moist samples were inserted into the furnace chamber, and the measurements were finished rapidly.

Experimental details

As mentioned, the ovendry specimens were measured using the heat flow meter technique, and the moist specimens were measured using the transient plane source technique. The accuracy and reproducibility of the instruments were assured by testing with stainless steel standard.

For each ovendry specimen, five measurements were performed at each of the temperatures of interest, and the average thermal conductivity was obtained with a standard deviation of less than 1 percent. The typical relative deviation among the three specimens for each of the select species was less than 3 percent. Furthermore, for the moist specimens, three measurements were conducted with a standard deviation of less than 5 percent. Although the variation of moisture content was not monitored during the measurements, this relatively small standard deviation indicates that the influence of the moisture redistribution was nearly negligible, because the three measurements were completed in a short period of several minutes. In the next section, average thermal conductivity at each of the data points will be presented without noting the local uncertainty. The ovendry density presented in Table 1 is also the average value among the three specimens for each species. The standard deviation for ovendry density is typically less than 3 percent.

Results and Discussion

Density dependence of ovendry wood

The transverse thermal conductivity of ovendry specimens as a function of the ovendry density is presented in Figure 1. Note that the data were measured at 30°C, which is higher than room temperature (~21°C). In Figure 1, the data points for ovendry specimens at room temperature, presented by TenWolde et al. (1988), and two empirical equations, proposed by TenWolde et al. (1988) and Harada et al. (1998), are given for comparison.

It is shown that thermal conductivity of wood increases with density, which is consistent with the relationship found by many other researchers. This is obvious in that for a given volume, as the density of wood increases, more fibril exists that is more conductive than air. Considering the effective media theory of composite materials, the effective thermal conductivity is therefore increased. A generic linear increasing tendency is observed for both softwoods and hardwoods; hence, there is no need to distinguish a wood species. For densities lower than 500 kg/m^3, the measured data agree well with those reported in the literature, whereas for the two data points at higher densities, the measured data are smaller. However, the data presented by TenWolde et al. (1988) are approximate and may vary from the actual values by as much as 20 percent.

The correlating equation, which has a coefficient of determination of 0.853, for the measured data is

$$k = 0.04409 + 0.0001278\rho \quad \text{for } 300\,\text{kg/m}^3 < \rho < 700\,\text{kg/m}^3 \tag{2}$$

where ρ is the ovendry density (kg/m^3). The three equations presented in Figure 1 may be interchangeable with reasonable accuracy when the density of interest is relatively low, although the present fitting curve has a smaller slope than those of the others.

Temperature dependence of ovendry wood

In the literature, few studies have considered the temperature dependence of thermal conductivity of wood. For example, Steinhagen (1977) presented the variations of conductivity data for temperatures between –40°C and 100°C in the form of piecewise linear curves, but no data points were given. Harada et al. (1998) measured thermal conductivity of some Japanese wood species up to 270°C, but the variations below 100°C were not clearly revealed. Furthermore, Suleiman et al. (1999) measured birch samples

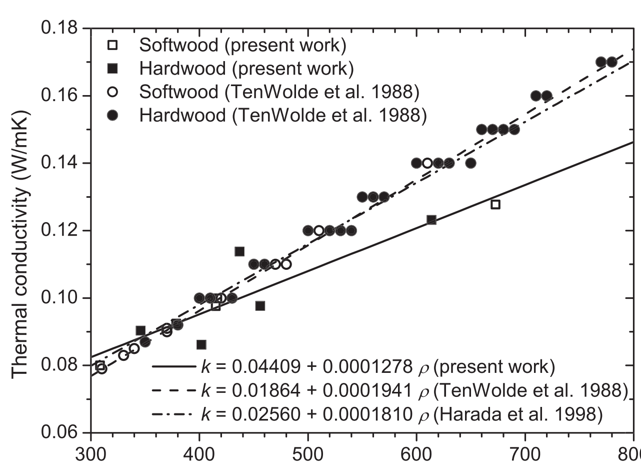

Figure 1.—Transverse thermal conductivity of wood at 30°C as a function of ovendry density.

grown in Sweden at both 21°C and 100°C, but only a single temperature point other than room temperature was reported. Therefore, to investigate the temperature dependence of thermal conductivity of wood below 100°C, measurements were conducted in the present study at temperatures between 30°C and 90°C, in 10°C increments. Note that this temperature range is out of the normal in-service temperature of wood and may reflect an early stage toward fire or pyrolysis.

In Figure 2, variations of transverse thermal conductivity as a function of temperature are compared for the five softwood species. It is shown that the thermal conductivity is proportional to temperature. For each wood species, the increase between 30°C and 80°C is almost linear. However, for Scots pine (*Pinus sylvestris* var. *sylvestriformis*), masson pine, and Korean pine (*Pinus koraiensis*) specimens, the thermal conductivity at 90°C is nearly identical to the corresponding value at 80°C, although the linear increasing trend remains for the other two species (China-fir [*Cunninghamia lanceolata*] and larch). The most relative increase at 80°C is 19.8 percent for Korean pine, whereas the smallest increase is 10.1% for China-fir.

As shown in Figure 2, the linear fitting curve for China-fir is less steep than the other curves, which are nearly parallel to one another. The correlating equations, all of which exhibit a coefficient of determination greater than 0.97, are as follows:

$$k = 0.07538 + 0.0001681T \quad \text{for China-fir} \tag{3}$$

$$k = 0.08124 + 0.0003695T \quad \text{for Korean pine} \tag{4}$$

$$k = 0.08653 + 0.0003521T \quad \text{for masson pine} \tag{5}$$

$$k = 0.08805 + 0.0003888T \quad \text{for Scots pine} \tag{6}$$

$$k = 0.1185 + 0.0003417T \quad \text{for larch} \tag{7}$$

where T is temperature (°C). These equations are valid for temperature between 30°C and 80°C and may be extended to room temperature and up to 100°C with reasonable accuracy.

For the five hardwood species, the temperature dependence of transverse thermal conductivity is presented in Figure 3. Similar to the softwoods, the almost-linear increasing trend is observed for hardwoods between 30°C and 80°C. The linear fitting equations, all of which possess a coefficient of determination greater than 0.97, are expressed as

$$k = 0.08283 + 0.0002437T \quad \text{for red lauan} \tag{8}$$

$$k = 0.078 + 0.0002532T \quad \text{for yellow lauan} \tag{9}$$

$$k = 0.1044 + 0.0002859T \quad \text{for white lauan} \tag{10}$$

$$k = 0.08635 + 0.0003695T \quad \text{for basswood} \tag{11}$$

$$k = 0.1114 + 0.00037T \quad \text{for birch} \tag{12}$$

Except for birch, which has the greatest density among the hardwoods tested, the thermal conductivity becomes nearly unvaried when the temperature is further increased to 90°C. The greatest relative increase at 80°C is 18.5 percent for basswood, whereas the smallest relative increase is 11.7 percent for white lauan. In summary, for both softwoods and hardwoods, the temperature dependence is nearly linear between 30°C and 80°C. Over this 50°C temperature difference, the relative increase of transverse thermal conductivity is between 10 and 20 percent, which is greater than the 10 percent increase for every 50°C indicated by Steinhagen (1977).

The anisotropy of thermal conductivity of wood is presented for the two select species (the softwood masson pine and the hardwood red lauan) in Figure 4. It is shown that at constant temperatures, the longitudinal thermal conductivities for both species are nearly identical, although more significant differences are present for the transverse direction. In addition, the temperature dependence of longitudinal thermal conductivity is much weaker than that of transverse conductivity; that is, the longitudinal thermal conductivity is nearly independent of temperature, especially for red lauan (hardwood). Therefore, the ratio of longitudinal to transverse thermal conductivity becomes smaller with increasing temperature. The average ratios over different temperatures are found to be 1.71 and 1.87 for masson pine (softwood) and red lauan (hardwood),

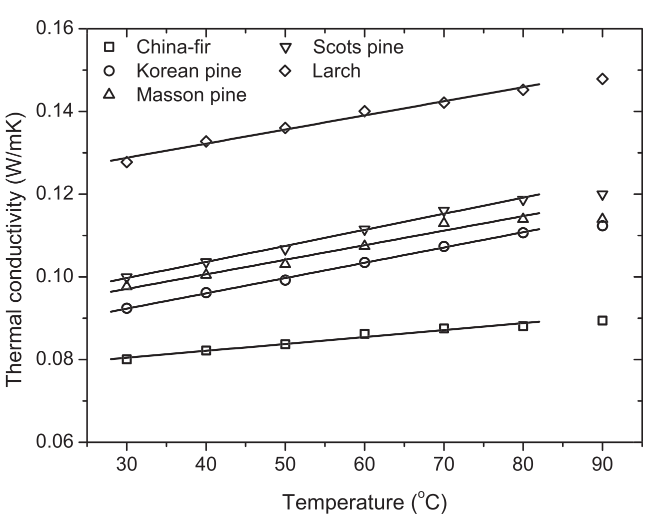

Figure 2.—Transverse thermal conductivity of softwood species as a function of temperature.

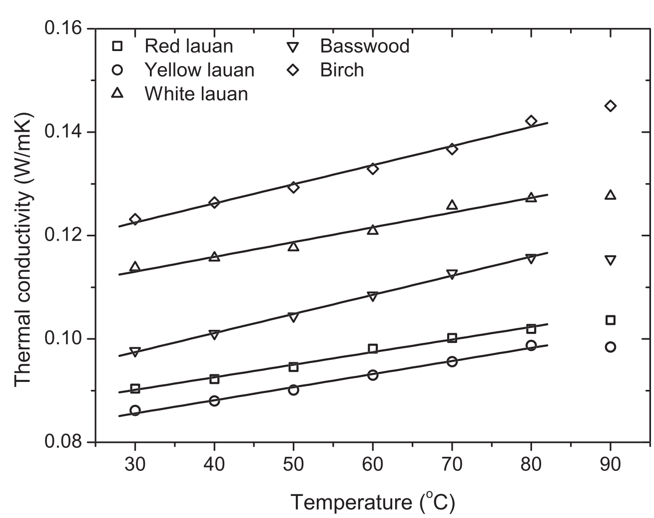

Figure 3.—Transverse thermal conductivity of hardwood species as a function of temperature.

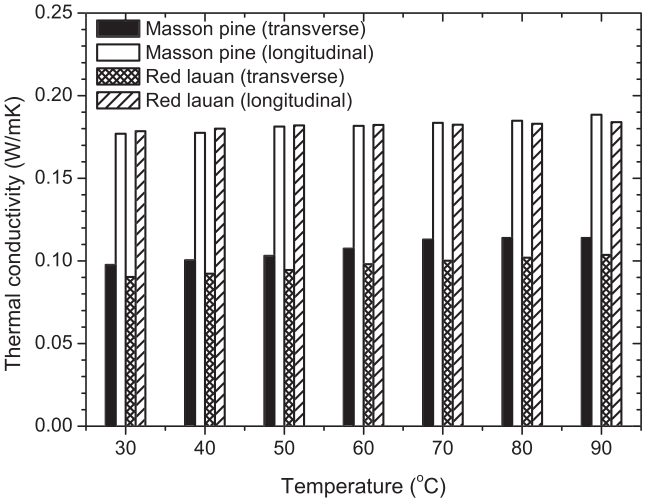

Figure 4.—Comparison of thermal conductivity of wood between transverse and longitudinal directions.

respectively. These values are consistent with the range of 1.5 to 2.8 reported in the literature (TenWolde et al. 1988).

Combined effects of moisture content and temperature

As an example for softwood species, transverse thermal conductivities of larch specimens at different moisture content levels (6.7% [air dry], 9.7%, 12.6%, 19.1%, and 22.9%) are presented in Figure 5. All of these moisture content levels are below the nominal fiber saturation point of wood (~30%), which is defined as the moisture content that corresponds with pronounced changes in the mechanical and physical properties of wood (Siau 1984). In other words, the thermal properties of wood begin to change as a function of moisture content when it is below the fiber saturation point (TenWolde et al. 1988). Also note that the moisture condition of wood in service is normally below the fiber saturation point. Therefore, thermal conductivity of wood above the fiber saturation point is of little practical interest.

Because of the presence of more water, which is more conductive than fibril and air, the thermal conductivity increases proportionally as the moisture level is increased. At constant moisture content levels, thermal conductivity increases nonlinearly with temperature. Although the nonlinearity is insignificant at relatively lower moisture content levels, the fitting curves are apparently in the form of a quadratic equation when the moisture content is high. On the other hand, five different moisture content levels (8.7% [air dry], 12.6%, 15.8%, 19.7%, and 22.2%) were studied for basswood specimens. As presented in Figure 6, the increase of thermal conductivity with temperature becomes generally linear for this hardwood. It is noted that for two of the intermediate moisture content levels (12.6% and 15.8%), the fitting curves are slightly nonlinear and are better expressed as a quadratic equation with a negative quadratic coefficient. At similar moisture content levels, the difference of the increasing trends between softwood and hardwood species might be attributed to microstructures/anatomy of wood, which in turn leads to different distributions of water in wood.

In Figure 7, the data presented in Figures 5 and 6 are collected in such a way that the variations of thermal conductivity with moisture content are shown explicitly. At constant temperatures, thermal conductivity increases linearly with moisture content. Two empirical equations for moist wood at room temperature are shown in Figure 7. The equation proposed by MacLean (1941) is

$$k = 0.02376 + (0.0002001 + 0.000004031\text{MC})\rho \quad \text{for MC} < 40\% \tag{13}$$

where MC is moisture content, and the equation proposed by TenWolde et al. (1988) is

$$k = 0.01864 + (0.0001941 + 0.000004064\text{MC})\rho \quad \text{for MC} < 25\% \tag{14}$$

Note that Equations 13 and 14 are in the form of a binary equation that relates thermal conductivity of wood to its ovendry density and moisture content. For the wood specimens studied, the original binary equations have been reduced by substituting the corresponding known ovendry

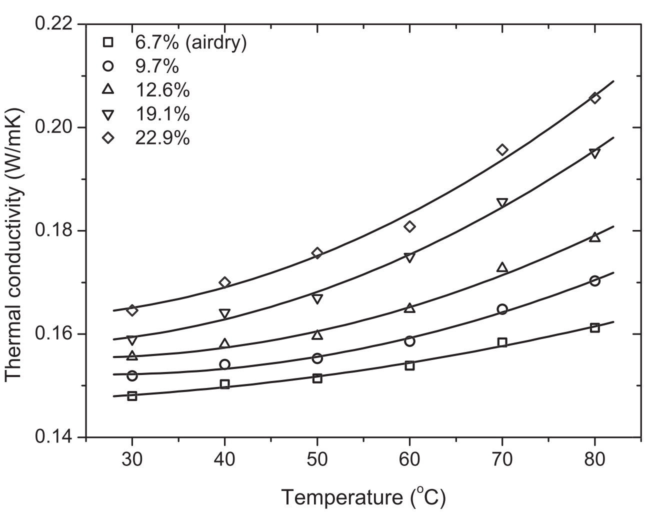

Figure 5.—Transverse thermal conductivity of larch at different moisture content levels.

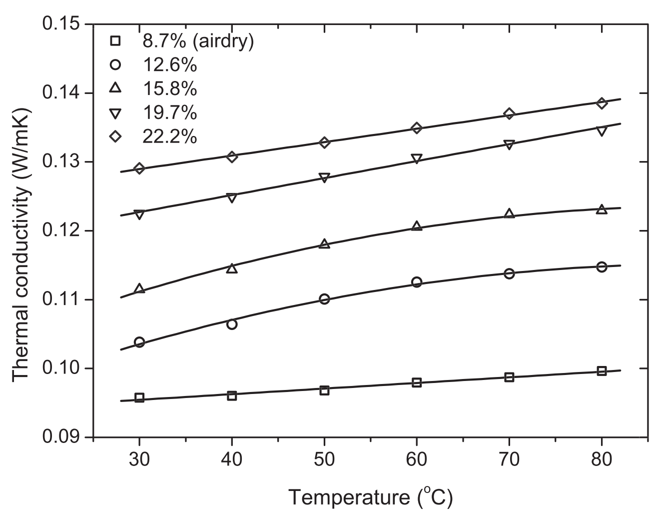

Figure 6.—Transverse thermal conductivity of basswood at different moisture content levels.

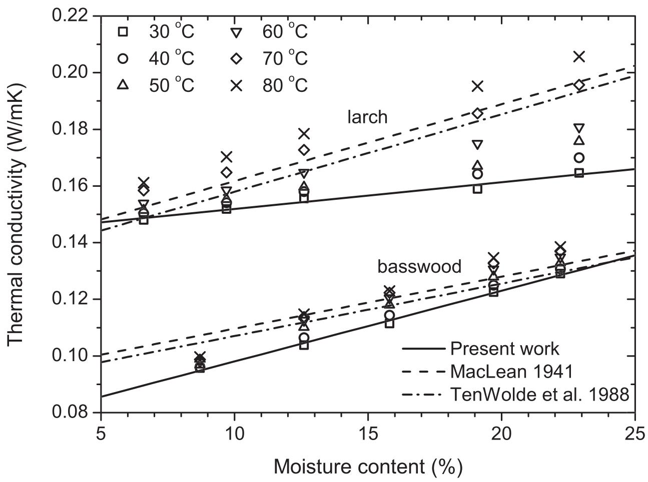

Figure 7.—Transverse thermal conductivity of wood as a function of moisture content at different temperatures.

densities. The linear fitting curves for the present data at 30°C, which is close to room temperature, are depicted as well for comparison. The equation, which is free of density, for larch is

$$k = 0.1425 + 0.094\mathrm{MC} \quad \text{for MC} < 25\% \qquad (15)$$

with a coefficient of determination of 0.972. In this case, the slopes of the two empirical equations proposed in the literature are greater than the slope in Equation (16). Concurrently, the linear regression equation for basswood is

$$k = 0.0731 + 0.2497\mathrm{MC} \quad \text{for MC} < 25\% \qquad (16)$$

with a coefficient of determination of 0.996. The slope in this equation becomes slightly greater than those in Equations 14 and 15. In general, the two empirical equations predict thermal conductivity with acceptable accuracy for a wide range of density and moisture content. However, for the specific wood species studied, the correlating equations proposed by the present study would lead to more accurate predictions.

Conclusions

Thermal conductivity of wood was measured experimentally by using the heat flow meter and transient plane source technique for ovendry and moist specimens, respectively. The specimens included five species for both softwoods (China-fir, Korean pine, masson pine, Scots pine, and larch) and hardwoods (basswood, birch, and red, yellow, and white lauan), which are widely available and used in China.

First, transverse thermal conductivity was presented as a function of ovendry density for ovendry specimens, and a linear correlating equation was obtained. Second, temperature dependence of transverse thermal conductivity of the ovendry specimens was presented up to 90°C. A nearly linear increasing trend was observed for each of the softwood and hardwood species between 30°C and 80°C. For the two select species (masson pine and red lauan), the ratios of longitudinal to transverse thermal conductivity were consistent with the range given in the literature. Finally, transverse thermal conductivity of two other select species (larch and basswood) at different moisture content levels up to approximately 23 percent was presented in different ways. At each moisture content level studied, a quadratic increase of thermal conductivity with temperature was observed for the softwood species (larch), whereas the trend for the hardwood species (basswood) was generally linear. Furthermore, at constant temperatures, thermal conductivity was shown to increase linearly with moisture content, and a correlating equation was proposed for each of the species tested.

Acknowledgments

The authors thank Ms. Li-Ping Shi and Mr. Liang Xu at NETZSCH Scientific Instruments Trading (Shanghai) Co. Ltd. for their assistance in conducting the experiments.

Literature Cited

Beall, F. C. 1977. Properties of wood during carbonization under fire conditions. *In:* Wood Technology: Chemical Aspects. I. S. Goldstein (Ed.). American Chemical Society, Washington, D.C. ACS Symposium Series. Vol. 43. Chap. 7, pp. 107–114.

Harada, T., T. Hata, and S. Ishihara. 1998. Thermal constants of wood during the heating process measured with the laser flash method. *J. Wood Sci*. 44:425–431.

Kol, H. Ş. 2009. The transverse thermal conductivity coefficients of some hardwood species grown in Turkey. *Forest Prod. J*. 59:58–63.

MacLean, J. D. 1941. Thermal conductivity of wood. *Heat. Piping Air Cond*. 13:380–391.

Ngohe-Ekam, P. S., P. Meukam, G. Menguy, and P. Girard. 2006. Thermophysical characterization of tropical wood used as building materials: With respect to the basal density. *Constr. Build. Mater*. 20: 929–938.

Olek, W., J. Weres, and R. Guzenda. 2003. Effects of thermal conductivity data on accuracy of modeling heat transfer in wood. *Holzforschung* 57:317–325.

Ragland, K. W., D. J. Aerts, and A. J. Baker. 1991. Properties of wood for combustion analysis. *Bioresour. Technol*. 37:161–168.

Rice, R. W. and R. Shepard. 2004. The thermal conductivity of plantation grown white pine (*Pinus strobus*) and red pine (*Pinus resinosa*) at two moisture content levels. *Forest Prod. J*. 54:92–94.

Siau, J. F. 1984. Transport Processes in Wood. Springer-Verlag, Berlin. 245 pp.

Steinhagen, H. P. 1977. Thermal conductive properties of wood, green or dry, from –40° to +100°C: A literature review. FPL-9. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 10 pp.

Suleiman, B. M., J. Larfeldt, B. Leckner, and M. Gustavsson. 1999. Thermal conductivity and diffusivity of wood. *Wood Sci. Technol*. 33: 465–473.

TenWolde, A., J. D. McNatt, and L. Krahn. 1988. Thermal properties of wood and wood panel products for use in buildings. DOE/USDA-21697/1. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 40 pp.

Thunman, H. and B. Leckner. 2002. Thermal conductivity of wood—Models for different stages of combustion. *Biomass Bioenergy* 23: 47–54.

Wangaard, F. F. 1940. Transverse thermal conductivity of wood. *Heat. Piping Air Cond*. 12:459–464.