The Transverse Thermal Conductivity Coefficients of Some Hardwood Species Grown in Turkey

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Abstract

Thermal conductivity values for ash, oak, silver wattle, poplar, and beech were measured. Thermal conductivity coefficients of the wood species were determined for radial and tangential directions at four different moisture conditions, ranging from 0 to 22 percent moisture content (MC). Equations predicting thermal conductivities of the wood species according to the MC are proposed in the tangential and radial directions. The thermal conductivity test was performed with a quick thermal conductivity meter based on the ASTM C1113-99 hot-wire method, and measurements were carried out at a room temperature of 20°C to 24°C. The effect of density and porosity on thermal conductivity was also investigated. Results showed the behavior of all wood species studied is quantitatively similar. Thermal conductivity increased with increasing MC. Tangential thermal conductivity values within the MC range of 0 to 22 percent changed from 0.089 to 0.147 W/m-K for poplar, 0.127 to 0.222 W/m-K for beech, 0.113 to 0.202 W/m-K for ash, 0.142 to 0.290 W/m-K for silver wattle, and 0.130 to 0.219 W/m-K for oak. Tangential thermal conductivity was similar to radial thermal conductivity. Radial thermal conductivity was 1.08 times tangential thermal conductivity for poplar, 1.01 times for beech, 1.06 times for ash, 0.95 times for silver wattle, and 1.03 times for oak, respectively. The data are useful when calculating the energy required to kiln-dry lumber and predicting the thermal insulating qualities of log homes made from the species.

Wood has many applications in areas that require good insulating properties. For example, the significant presence of wood and wood products in buildings, the energy design of wood frame buildings, and the evaluation of their energy performance depend in part on the thermal properties of wood products (TenWolde et al. 1988). In addition, information on thermal conductivity of wood and its relationship to other wood properties is of interest from the standpoint of kiln-drying operations, gluing of wood, preservation of wood, hot pressing of wood-based composites, wood thermal degradation, and other processes in which wood is subject to a temperature change (Sanyal et al. 1991, Gu 2001, Gu and Zink-Sharp 2005).

In all materials, continuous random vibrations of molecules are noticed. The temperature of the material is a measure of these vibrations. When an amount of heat is added to an insulating material, such as wood, it is partially used to increase its internal energy, as manifested by a rise in its temperature. The energy transfer from molecule to molecule and the thermal agitation of the molecules on the application of heat energy are characterized by the material's thermal conductivity (Sanyal et al. 1991). Thus, thermal conductivity is a measure of the thermal energy flow through a unit thickness of a material under a temperature gradient. The measure usually reported is a proportionality factor used to link the temperature gradient to the thermal energy flow through an area. Under steady-state conditions, the relationship among the variables is known as Fourier's law (Simpson and TenWolde 2003, Rice and Shepard 2004):

$$q = -kA\frac{dT}{dx} \tag{1}$$

where

k = thermal conductivity coefficient (W/m-K),
q = heat flux (W),
A = area through which thermal energy flows (m^2),
dT = temperature difference across the sample (°K), and
x = sample thickness (m).

The ability of a material to conduct heat as a result of transmitting molecular vibrations from one atom or molecule to another varies greatly depending upon the chemical nature of the material and its gross structure or texture. Wood is an anisotropic, porous material with

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complicated cellular and macroscale structural features (Gu and Hunt 2007). The unique structure of wood explains the anisotropic nature of its physical properties, such as thermal conductivity. Previous studies found that the thermal conductivity of wood varies with the direction of heat flow with respect to the grain, with specific gravity (SG) with defects, and with extractives. The thermal conductivity of wood increases with density, moisture content (MC), and temperature (Rowley 1933, Wangaard 1940, MacLean 1941, Suleiman et al. 1999, Fotsing and Takam 2004, Gu and Zink-Sharp 2005). In addition to structure, species, and growing conditions, wood MC and temperature have a significant effect on heat and mass transfer (Gu and Hunt 2007). Conductivity in the longitudinal direction was found to be approximately 1.5 to 2.8 times higher than the transverse conductivity. The ratio is generally larger for dry wood than for moist wood (Wangaard 1940, MacLean 1941, TenWolde et al. 1988, Suleiman et al. 1999). Tangential thermal conductivity of wood is usually somewhat smaller than radial conductivity. According to Steinhagen (1977), the ratio of tangential to radial conductivity appears to be determined primarily by the ray cell volume in hardwoods and by the latewood volume in softwoods.

This article summarizes the results of thermal conductivity coefficients obtained for five hardwood species (ash, oak, silver wattle, poplar, and beech) naturally grown and intensively used for industrial applications in Turkey. The effects of some parameters (e.g., MC, grain direction, density, and wood species) on thermal conductivity are discussed. To our knowledge, no detailed information is available regarding the thermal conductivity of these species. This article discusses the influence of grain direction on the thermal conductivity in the radial and tangential directions because of their importance in the wood drying process. In addition, for practical building applications, the heat flow is primarily across the grain. The data about the wood species are useful for calculating the energy use during kiln-drying and for estimating the thermal insulating properties of log homes produced from the wood species. The data also allow comparison of the thermal conductivity values of wood species.

Materials and Methods

Thermal conductivity measurements were made using a QTM 500 device (Kyoto Electronics Manufacturing, Japan). The quick thermal conductivity meter based on the ASTM C1113-99 hot-wire method was used (ASTM International 2004a). Variac (power supply) was used to supply constant electrical current to the resistance. PD-11 box probe sensor (constantan heater wire and chromel–alumel thermocouple) was used. Measurement range was 0.0116 to 6 W/m-K. Measurement precision was 5 percent of reading value per reference plate. Reproducibility was 3 percent of reading value per reference plate. Measurement temperature was −100°C to 1,000°C (external bath or electric furnace for temperature other than room). Required sample size was 20 by 50 by 100 mm. Measuring time was standard (100 to 120 s).

The five hardwoods selected for thermal conductivity measurements were poplar (*Populus tremula*), oriental beech (*Fagus orientalis*), silver wattle (*Acacia dealbata*), ash (*Fraxinus excelsior*), and oak (*Quercus petreae*). The main criteria for this selection were the commercial importance of the timbers in the Turkish market and other factors that related to the wood itself, such as density and anatomical features.

The sample trees used for the present study were harvested in the Zonguldak and Karabük Forestry Districts, northwestern part of Turkey. From all species, five trees having approximately 35- to 50-cm breast height diameters ($d_{1.30}$) were selected as sample trees. With the aim of avoiding errors during sampling, extreme cases were taken into account, such as excessively knotty trees and those containing reaction wood or slope grain. Sections with a length of 1.5 m were cut between 1.30 and 2.80 m of tree height to obtain samples for thermal conductivity.

The test samples were obtained from the sapwood region of the 1.5-m sections. The test samples were prepared by planing the surfaces and sawing into a rectangular shape of 20 by 50 by 100 mm according to the procedure of ASTM C177/C518 (ASTM International 2004b). To determine the thermal conductivity values at different MCs, ranging from approximately 0 to 22 percent, samples were prepared in tangential and radial directions and were divided into four groups containing five specimens for each wood species. One group of samples (ovendry samples) was dried at 103°C ± 2°C for 24 hours, and the other three groups were conditioned at three different relative humidity levels (40%, 65%, and 93%) at 20°C until they reached equilibrium MC. By regular control of the weight, the samples that had already reached their equilibrium MC were selected. Before testing, each sample was checked on a tabletop to assess flatness, a factor that preliminary testing indicated was critical to consistent thermal conductivity values (Rice and Shepard 2004). The flat samples were measured and weighed, and then the measurements were carried out. Each sample was tested twice. After each test, each sample was reweighed and flipped 180 degrees, and the thermal conductivity was retested. Variations in values (>5%) in the readings between each side indicated that samples were warped or defective, and these samples were discarded. Weight data were taken before and after each measurement so that the MCs could be determined. The reported data are the averages of the two measurements, although little change was found between the two measurements.

The measurements were made at a room temperature of 20°C to 24°C. After conducting the measurements, the samples were oven-dried at 103°C ± 2°C for 24 hours to determine the MC of the test samples at the time of measurement. The ovendry SG was determined after calculation of the ovendry volume according to TS 2472 (Turkish Standards Institution 1976).

Wood is a porous material, and porosity affects the thermal properties. The porosity r can be estimated using the calculation

$$r = 1 - (\delta_{\text{ave}}/\delta_{\text{th}}) \tag{2}$$

where

δ_{ave} = the average apparent density of the sample, and

δ_{th} = the assumed theoretical density of a compact solid wood free from voids; this value is assumed to be 1,500 kg/m^3 (Kollmann and Côté 1968).

Results and Discussion

The average thermal conductivity values of five wood species at different MCs in the tangential and radial directions are given in Table 1. Linear equations of the type $k = a \times \mathrm{MC} + b$ were used for curve-fitting the thermal conductivity as a function of MC for five wood species, where a and b are constant values that depend on wood species. The curves shown in Figure 1 were obtained by testing different equations and taking the best fit of the experimental values. The equations and the measure of variation (R^2) for the lines in Figure 1 are given in Table 2. Analysis of variance (ANOVA) results for the effects of wood species and directions on thermal conductivity are given in Table 3.

The results indicate that the thermal conductivity increases with increasing MC within the range studied. This trend was similar for the five wood species. This result can be explained by considering the combination of two facts. First, as moisture in wood increases, the amount of water molecules within the wood matrix increases. The thermal conductivity of water molecules is higher than that of wood, so a trend of increased thermal conductivity of wood is expected. Furthermore, as the MC increases, the space between the molecules increases, which gives greater molecular mobility and, thus, more energy transportation results (Gu 2001). The increase of thermal conductivity with MC was also observed by Gu and Hunt (2007), Wangaard (1940), and MacLean (1941).

The second important result of this research is the relationship between structural direction and thermal conductivity of wood. From Figure 1, it appears that a slight difference in thermal conductivity values exists between the radial and tangential directions and that the radial values are somewhat higher than the tangential ones. However, this distinction is insignificant statistically (Table 3). Radial thermal conductivity was 1.08 times tangential thermal conductivity for poplar, 1.01 times for beech, 1.06 times for ash, 0.95 times for silver wattle, and 1.03 times for oak. The influence of grain orientation on thermal conductivity has been proved by several scientists. Wangaard (1940), Suleiman et al. (1999), and Steinhagen (1977) pointed out that radial conductivity may be higher than tangential conductivity and that the ratio of the tangential to radial conductivity is primarily determined by the volume of the ray cell in hardwoods.

According to the ANOVA results, the effect of wood species on thermal conductivity was significant (Table 3). Considering the whole range of MCs, the highest thermal conductivity was obtained with silver wattle and the lowest with poplar. Beech and oak had similar thermal conductivity values (Fig. 1). The porosity and SG of the wood species are given in Table 1. The general trends of the porosities and SGs of the wood species are identical to those of the thermal conductivity values.

The differences in the transverse thermal conductivity among wood species are related to one or more of their specific characteristics. Among these, the unique microstructure of each species and the inherent chemical composition and density may be decisive. The available data have permitted analysis of a relationship between the thermal conductivity and wood SG. Figure 2 shows the relationship between SG (disregarding the wood species) and the transverse thermal conductivity at different MCs. Figure 2 shows the values obtained by testing different equations as best fit to the experimental values (Table 4). The transverse

Table 1.—Thermal conductivity coefficients of poplar, oriental beech, European ash, silver wattle, and oak woods at different MCs and structural directions.[a]

				Thermal conductivity coefficients (W/m-K)							
				0% MC		8% MC		12% MC		22% MC	
Wood species	SG	Porosity[b]	Direction[c]	Mean (SD)[d]	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Populus tremula	0.385	0.743	k_T	0.089 (0.011)	0.073–0.103	0.107 (0.004)	0.102–0.112	0.126 (0.004)	0.122–0.133	0.147 (0.002)	0.145–0.150
			k_R	0.097 (0.001)	0.950–0.980	0.115 (0.004)	0.109–0.120	0.129 (0.005)	0.123–0.136	0.148 (0.002)	0.144–0.150
Fagus orientalis	0.666	0.556	k_T	0.127 (0.005)	0.122–0.134	0.171 (0.005)	0.167–0.179	0.191 (0.003)	0.188–0.197	0.222 (0.005)	0.215–0.229
			k_R	0.130 (0.004)	0.124–0.135	0.169 (0.006)	0.163–0.178	0.194 (0.004)	0.188–0.199	0.224 (0.002)	0.222–0.227
Fraxinus excelsior	0.568	0.621	k_T	0.113 (0.003)	0.108–0.115	0.148 (0.016)	0.127–0.164	0.171 (0.009)	0.159–0.181	0.202 (0.005)	0.197–0.207
			k_R	0.123 (0.004)	0.116–0.127	0.140 (0.005)	0.133–0.147	0.197 (0.008)	0.186–0.206	0.216 (0.009)	0.208–0.230
Acacia dealbata	0.753	0.498	k_T	0.142 (0.019)	0.121–0.156	0.197 (0.013)	0.183–0.208	0.238 (0.015)	0.214–0.250	0.290 (0.015)	0.272–0.301
			k_R	0.136 (0.011)	0.128–0.149	0.191 (0.022)	0.158–0.216	0.214 (0.010)	0.203–0.224	0.285 (0.005)	0.279–0.290
Quercus petreae	0.643	0.571	k_T	0.130 (0.005)	0.123–0.134	0.159 (0.007)	0.153–0.171	0.191 (0.008)	0.179–0.199	0.219 (0.003)	0.215–0.223
			k_R	0.134 (0.002)	0.131–0.137	0.176 (0.004)	0.172–0.180	0.186 (0.009)	0.176–0.199	0.225 (0.006)	0.215–0.230

[a] Data collected at 20°C to 22°C; number of samples measured (n) was 5.
[b] Porosity is defined by Equation 2 by using the corresponding listed SG ($n = 5$).
[c] k_T = thermal conductivity coefficient in tangential direction, k_R = thermal conductivity coefficient in radial direction.
[d] Mean = arithmetic mean, SD = standard deviation.

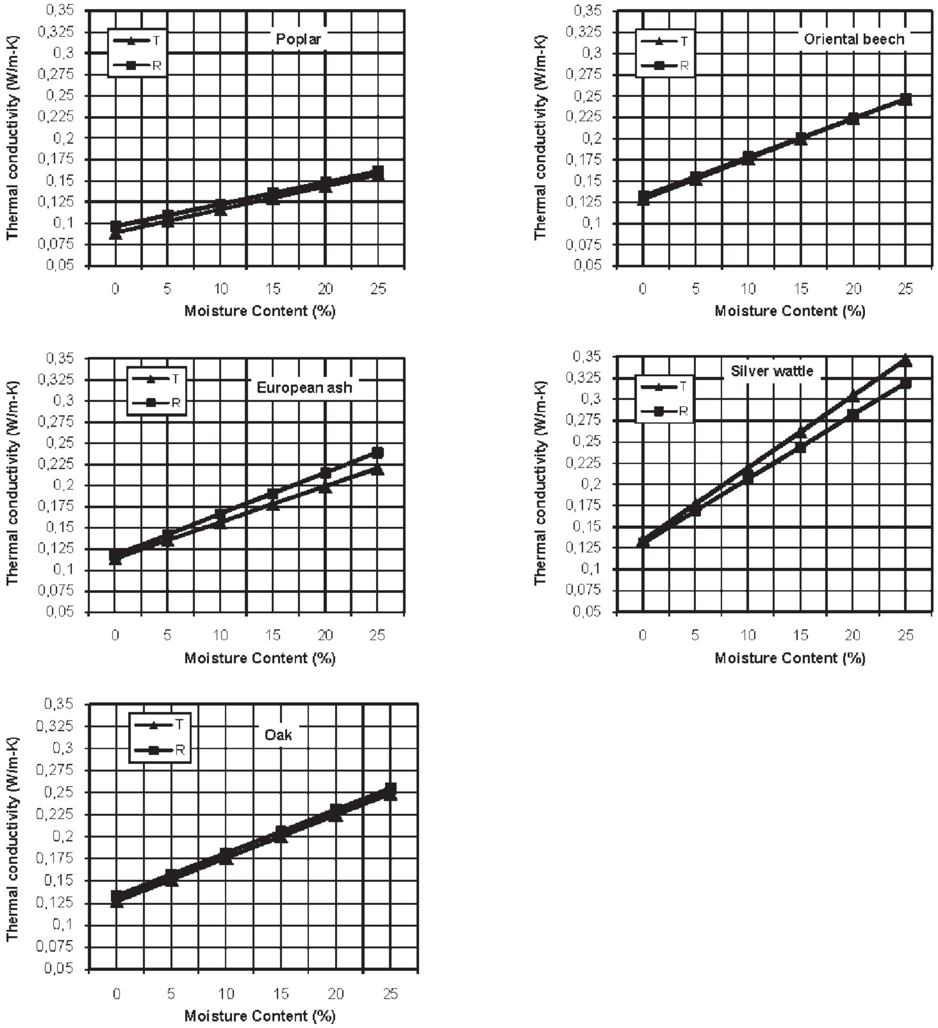

Figure 1.—Thermal conductivity of poplar, beech, silver wattle, ash, and oak as a function of MC for the transverse direction.

thermal conductivity is highly correlated ($R^2 = 0.80$ to 0.86) to the SG of wood and increases linearly with increasing SG. The most proper relationship was the form $k = a \times \mathrm{SG} + b$, where a and b are coefficients, the values of which depend on wood species. The model-predicted transverse thermal conductivity values for wood with an SG of 0.250 to 0.750 g/cm^3 and an MC from 0 to 22 percent are given in Table 5.

The observations confirm the data found in the literature on this subject. Suleiman et al. (1999) found a positive linear relationship between the density and the thermal conductivity at 20°C to 100°C for birch wood. Wangaard (1940), MacLean (1941), and Siau (1984) reported a consistent relationship between thermal conductivity and SG. Rice and Shepard (2004) reported that the general trend

Table 2.—Regression equations of the type $k = a \times MC + b$ *between thermal conductivity (*k*) and MC.*[a]

Wood species	Direction[b]	R^2	F	Significance	Parameter estimates	
					b	a
Populus tremula	T	0.90	169.696	1.331E−10	0.0886	0.0027
	R	0.95	312.184	8.088E−13	0.0961	0.0026
Fagus orientalis	T	0.98	750.152	3.993E−16	0.1286	0.0047
	R	0.98	798.803	2.296E−16	0.1321	0.0046
Fraxinus excelsior	T	0.93	240.130	7.469E−12	0.1137	0.0043
	R	0.92	201.493	3.233E−11	0.1174	0.0049
Acacia dealbata	T	0.89	151.776	3.301E−10	0.1342	0.0085
	R	0.94	262.578	3.517E−12	0.1305	0.0075
Quercus petreae	T	0.94	293.167	1.382E−12	0.1270	0.0049
	R	0.96	483.064	1.879E−14	0.1328	0.0049

[a] The independent variable is MC.
[b] T = tangential, R = radial.

Table 3.—ANOVA results.

Source	Sum of squares	df	Mean square	F	Significance
Wood species	0.177	4	0.044	29.337	0.000
Direction	0.000	1	0.000	0.187	0.666
Wood species × direction	0.002	4	0.001	0.395	0.812
Total	6.260	200			

is thermal conductivity increases as SG increases, although this is not predicted by Fourier's law and is not consistent for small changes in SG. Wood transfers heat via convection and conduction, and SG effect may be related to the porosity of the wood. Voids resulting from porosity serve as scattering centers for phonons, and the voids take up a fraction of the heat conduction volume of the material, leading to a lower thermal conductivity. The presence of other heat conduction obstacles in addition to voids, such as rays and cell boundaries, could also affect the conduction process (Suleiman et al. 1999). Therefore, it can be claimed that the differentiation of thermal conductivities of wood species found in this study is strongly related to the SG. Although the SG of oak was lower than that of beech wood, the transverse thermal conductivity of oak was somewhat higher than that of beech (Table 1). This specific result for oak wood may be explained by the chemical content of oak, because Venkateswaran (1974) also mentioned that variation in the chemical components of woods results in variation in the thermal conductivities of woods.

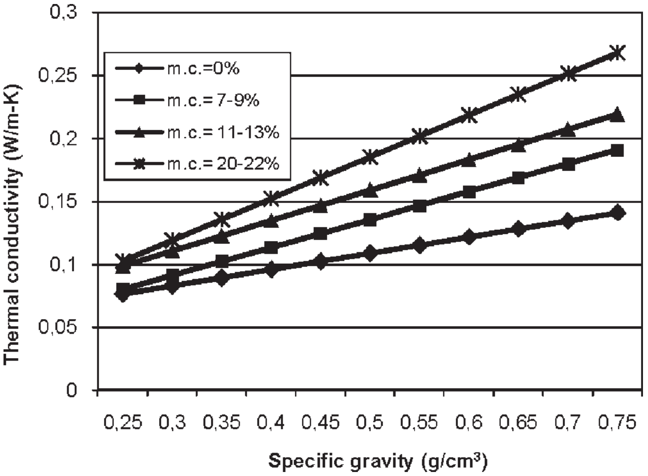

Figure 2.—Thermal conductivity as a function of SG at four ranges of MC for the transverse direction.

Table 4.—Regression equations of the type k = a × *SG* + b *between transverse thermal conductivity* (k) *and SG.*[a]

MC (%)	R^2	F	Significance	Parameter estimates b	 a
0	0.80	194.447	1.67E−18	0.0444	0.1288
7–9	0.88	341.046	1.89E−23	0.0250	0.2211
11–13	0.82	224.204	1.03E−19	0.0382	0.2412
20–22	0.86	294.998	3.92E−22	0.0202	0.3303

[a] The independent variable is SG.

Table 5.—Model-predicted transverse thermal conductivity coefficients as a function of SG at four moisture ranges.

SG (g/cm³)	MC 0%	 8%	 12%	 22%
0.250	0.077	0.080	0.099	0.103
0.300	0.083	0.091	0.111	0.119
0.350	0.089	0.102	0.123	0.136
0.400	0.096	0.113	0.135	0.152
0.450	0.102	0.125	0.147	0.169
0.500	0.109	0.136	0.159	0.185
0.550	0.115	0.147	0.171	0.202
0.600	0.122	0.158	0.183	0.218
0.650	0.128	0.169	0.195	0.235
0.700	0.134	0.180	0.207	0.251
0.750	0.141	0.191	0.219	0.268

Conclusions

The MC, SG, and wood species affected the thermal conductivity. The transverse thermal conductivity increased with increasing MC and SG. The tangential thermal conductivity was similar with the radial thermal conductivity. Considering the whole range of MCs, poplar and silver wattle manifested the lowest and highest thermal conductivity values, respectively. Beech and oak had similar thermal conductivity values. To reach optimum results, it is important to be aware of the influence of these variables. With regard to the gluing, drying, and hot pressing operations of wood, emphasis must be put on the thermal conductivity of the material to be treated. Also, knowledge of this value allows estimation of the thermal insulating properties for log homes manufactured from the species.

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