THERMAL AND DIELECTRIC PROPERTIES OF PINE WOOD IN THE TRANSVERSE DIRECTION

Hamiyet Şahin Kol

In this paper, the thermal conductivity and dielectric parameters for pine [*Pinus sylvestris* (L.)] woods were determined in transverse directions for moisture conditions from oven-dry to 22 percent at a room temperature of 22 to 24 °C. Results indicate that the behaviors of thermal conductivity and dielectric parameters with moisture content and structural directions were similar. In general, the properties increased within the range studied with increasing moisture content. The radial values were similar to tangential values for both thermal conductivity and dielectric properties. The data presented here should be useful in most design problems where pine wood is subjected to microwave electric fields and heat changes.

Keywords: Thermal conductivity; Dielectric properties; Transverse direction; Pine wood

Contact information: a: Karabük University, Technical Education Faculty, Department of Furniture and Decoration Education, 78050, Karabük, Turkey, Tel.: +90 370 433 82 00/1239; fax: +90 370 433 82 04
**Corresponding author: hsahinkol@karabuk.edu.tr*

INTRODUCTION

In all materials continuous random vibrations of molecules are noticed. The temperature of the material is a measure of these vibrations. In an insulating material, such as wood, when amount of heat is added to the material, it is used, in part, in increasing the internal energy, manifested by a rise in its temperature. The passing on of the energy from molecule to molecule and the thermal agitation of the molecules on the application of heat energy is characterized by its thermal conductivity (Sanyal et al 1991). The amount of energy that can be stored in the material is related to its dielectric constant, and these attributes of an insulating material might be related to each other.

Information on thermal conductivity of wood and its relationship to other wood properties is of interest from the standpoint of kiln-drying operations, glueing of wood, preservation impregnation, hot pressing of wood based composites, wood thermal degradation, and other process in which wood is subjected to a temperature change (Sanyal et al 1991; Gu 2001; Gu and Zink-Sharp 2005).

The study of the dielectric properties of wood at microwave frequencies is useful for the application of microwave energy for heating, drying, and gluing of wood, as well as for diagnostic purposes, e.g. measuring the moisture content and thickness of lumber, detecting defects, checking strength characteristics, estimating surface roughness by a nondestructive electrical measurement (Martin et al 1987; Kabir et al 1998) All of these applications require a reliable knowledge of the dielectric properties of the wood species of interest (Şahin and Ay 2004).

A large amount of data on the dielectric properties of Turkish woods has been published (Şahin 2002). Also, a lot of work has been performed on other wood species (James and Hamill 1965; Tinga 1969; Peyskens et al 1984; Jain and Dubey 1988; Kabir et al 1997; Khalid et al 1999; Olmi et al 2000). The thermal conductivity of woods has also been studied extensively (TenWolde et al 1988; Gu 2001; Gu and Zink-Sharp 2005; Rice and Shepard 2004; Rowley 1933; Wangaard 1940; MacLean 1941; Suleiman et al. 1999).

This article summarizes the results of thermal conductivity and dielectric properties of pine wood (*Pinus sylvestris* (L.)) that are naturally grown and intensively used for industrial applications in Turkey. The effects of some parameters, e.g., moisture content and grain direction, on these properties are discussed. Because radial and tangential direction has been the most interesting topic for practical applications and wood drying process, the article is limited to that situation. The data are useful for calculating the energy use during drying, determining the density and moisture content etc. by a nondestructive technique, and estimating the thermal insulating properties of log homes produced from the wood species.

EXPERIMENTAL

Pinus sylvestris (L.) wood was obtained from the Gümüşhane region in Turkey. The average oven-dry density (δo) of the *Pinus sylvestris* (L.) wood was 0.470 g/cm^3.

For thermal conductivity measurements, a quick thermal conductivity meter based on the ASTM C 1113-99 hot-wire method was used. A variac (power supply) was used to supply constant electrical current to the resistance. The QTM 500 device is a product of Kyoto Electronics Manufacturing, Japan. The test samples were prepared by planing the surfaces and sawing into a rectangular shape 20 x 50 x 100 mm according to the procedure of ASTM C 177/C 518.

The dielectric properties of the test materials were determined by means of a slotted waveguide and standing wave ratio meter (SWR meter). The apparatus is represented schematically in Fig. 1. The frequency used in this study was 2.45GHz. This frequency was chosen because of its importance in potential applications. The method was based upon Von Hippel’s transmission line method for low loss dielectric materials (Chatterjee 1988). The dimensions of the specimens were dependent on the inside dimensions of the waveguide section. The test specimens were bar-shaped and fitted exactly in the opening at the end of the waveguide, where contact between the specimen and the short circuit plate occurred. The dimensions of the specimens were as close as possible to 85.5 x 42.5 x 43.85 mm.

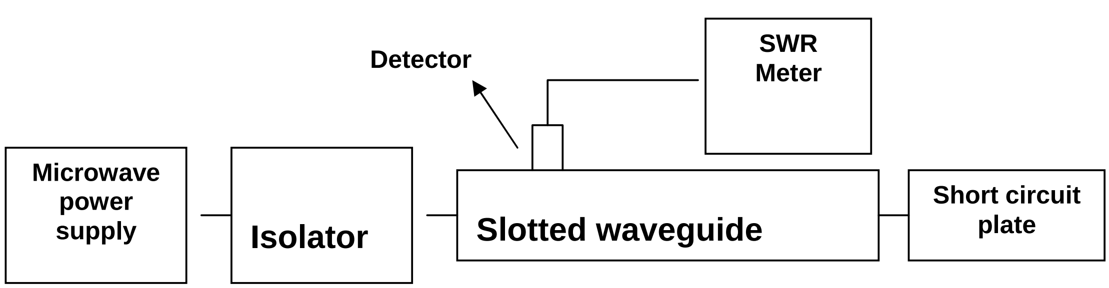

Fig. 1. Equipment used for the determination of the dielectric properties of the material

The test samples were obtained from the sapwood region. To determine the thermal conductivity and dielectric constant values at different moisture content, ranging from about 0% to 22%, 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 (oven-dry samples) was dried at 103° ± 2°C for 24 h, and the other three groups were conditioned at three different relative levels of 40%, 65% and 93%, at 20°C until they reached equilibrium moisture content. By regular control of the weight, the samples that had already reached their equilibrium moisture content were selected. Each sample was checked on a table-top to assess flatness prior to testing; a factor that preliminary testing indicated was critical to consistent values. The flat samples were measured, weighed and then the measurements were carried out. Weight data were taken before and after each measurement so that moisture contents could be determined. The measurements were made at room temperature (20°–24°C). After conducting the measurements, the samples were oven-dried at 103° ± 2°C for 24 h to determine the moisture content of the test samples at the time of measurement. The oven-dry specific gravity was determined after calculation of the oven-dry volume according to TS 2472. The microwave data were worked up with an ordinator after the dielectric characteristics of each sample were printed out.

RESULTS AND DISCUSSION

The average values of the dielectric properties at 2.45 GHz frequency and thermal conductivity of pine wood at different moisture contents in transverse directions are given in Table 1. The results are graphically presented in Fig. 2, which was obtained by testing different equations and taking the best fit to the experimental values. Second-order equations for dielectric properties and linear equations for thermal conductivities were used for curve- fitting the properties as a function of MC.

Table 1. Dielectric Constant (ε′), Loss Factor (ε′′), Loss Tangent (tanδ) and Thermal Conductivity (k) of Pine Wood [Pinus sylvestris (L.)] at Different Moisture Contents & Structural Directions; T=tangential, R=radial, ⊥=transverse directions.

Properties		Moisture content (%)			
		0	8	12	22
Dielectric parameters (at 2.45 GHz)	ε′T	1.60	1.82	2.01	2.79
	ε′R	1.59	1.84	2.00	2.69
	ε′⊥	1.60	1.83	2.005	2.74
	ε′′T	0.042	0.144	0.274	0.539
	ε′′R	0.036	0.134	0.246	0.539
	ε′′⊥	0.039	0.139	0.26	0.539
	tanδT	0.025	0.081	0.127	0.185
	tanδR	0.022	0.070	0.118	0.185
	tanδ⊥	0.024	0.076	0.123	0.185
Thermal conductivity (W/m-K)	kT	0.098	0.108	0.139	0.167
	kR	0.107	0.112	0.145	0.174
	k⊥	0.102	0.110	0.142	0.171

Data collected attemperature 20-24°C

Dielectric properties

The results indicate that the dielectric properties increased with rising moisture content within the range studied. In order to explain this phenomenon, the combination of two facts has to be considered. One the hand, as the moisture content increases from the oven-dry condition, the polar components of the cell wall and cellulose get more freedom of rotation, leading to higher dielectric behavior. On the other hand, water is characterized by high dielectric values, and with increasing moisture content, the amount of water within the wood matrix increases (Torgovnikov 1993; Peyskens et al. 1984).

The increase of dielectric constant with the increase in moisture content up to 28% was also observed by James and Hamil (1965), Peyskens et al. (1984), Kabir et al. (1997), Jain and Dubey (1988), James (1975, 1977), and Tinga (1969).

From Figure 2 it appears that the radial dielectric properties were relatively similar to tangential ones. The observations confirm the data found in the literature on this subject (Peyskens et al. 1984; Kabir et al. 1997).

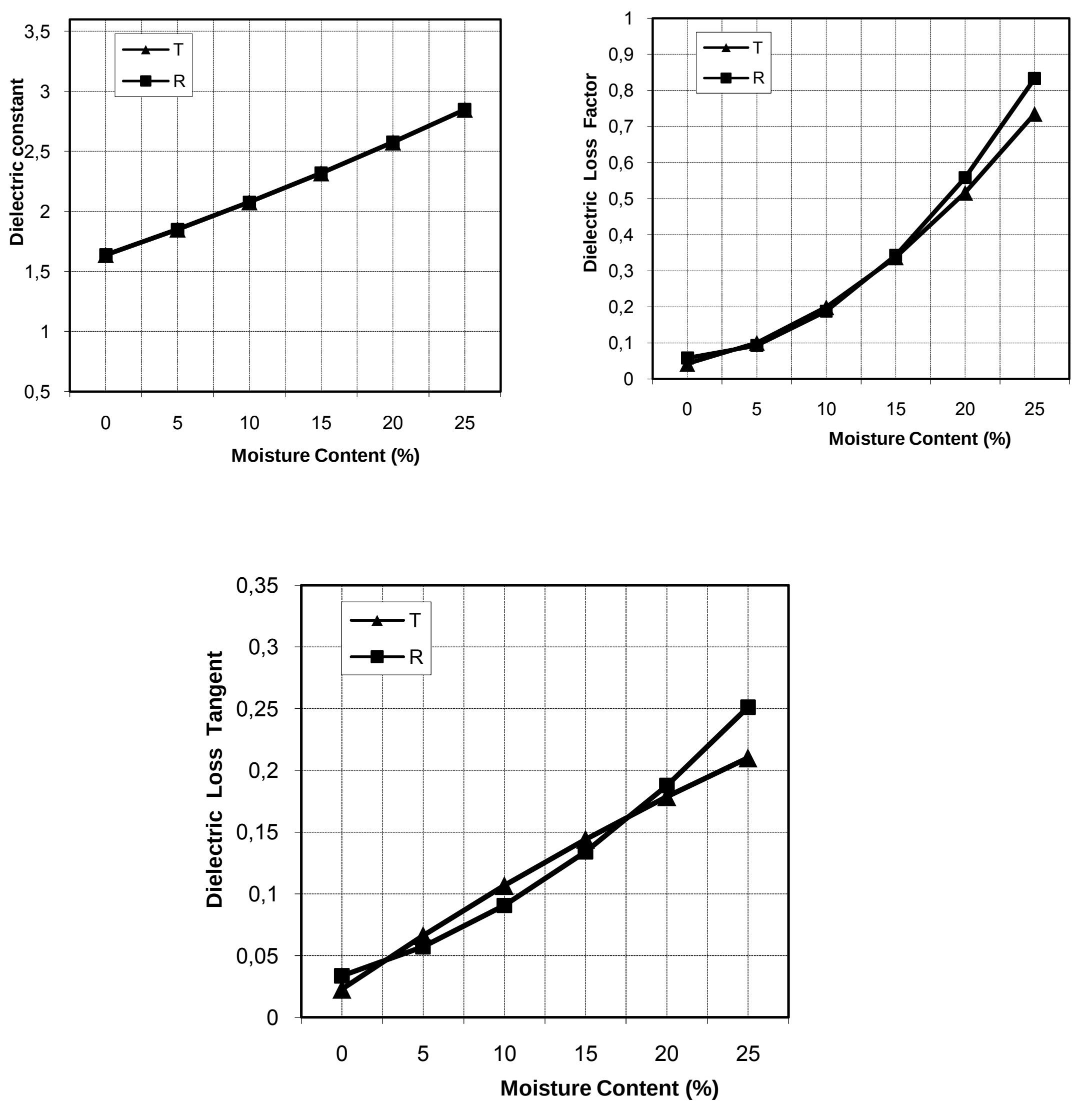

Fig. 2. Dielectric constant, dielectric loss factor and dielectric loss tangent of pine wood as a function of moisture content for transverse directions.

Thermal conductivity

The results indicate that the thermal conductivity increased with rising moisture content within the range studied (Fig. 3).

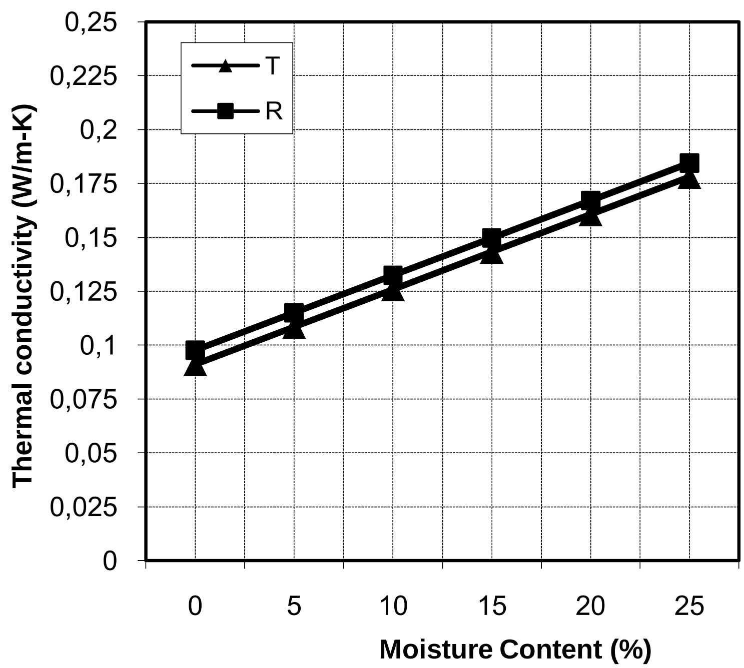

Fig. 3. Thermal conductivity of pine wood as a function of moisture content for transverse directions

This result can be explained by considering the combination of two factors. First, as moisture in wood increases, the amount of water molecules within the wood matrix increases. The thermal conductivity due to the water molecules is higher than that of dry wood, so a trend of increased thermal conductivity of wood with increasing moisture is expected. Furthermore, as the moisture content increases the space between the molecules in the wood solids increases, which give the greater molecular mobility, and then more energy transportation results (Gu 2001).

The increase of thermal conductivity with the increase in moisture content was also observed by Gu and Hunt (2007), Wangaard (1940), and MacLean (1941).

The result of this research is the relationship between the structural direction and the thermal conductivity of wood. According to this relationship the thermal conductivity of pine wood the radial values were somewhat higher than the corresponding tangential values (Fig. 3 and Table 1). However, this distinction is negligible on a statical basis. The influence of grain orientation on thermal conductivity has been proved by several scientists. Suleiman et al (1999) and Steinhagen (1977) pointed out that radial conductivity may be higher than tangential conductivity, and the ratio of the tangential to radial conductivity is primarily determined by the latewood volume in softwood .

CONCLUSIONS

1. The data presented here should be useful in most design problems where pine wood is subjected to microwave electric fields and heat change.
2. In general, moisture content affected the dielectric properties and thermal conductivity in a similar way, and the properties increased as the moisture content increased.
3. The radial thermal conductivity and dielectric properties were relatively similar to those in the tangential direction.

REFERENCES CITED

ASTM C 1113-99. (2004). *Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique)*, ASTM International; West Conshohocken, USA.

ASTM C 177/C 518. (2004). *Methods of Measuring Thermal Conductivity, Absolute and Reference Method*. ASTM International: West Conshohocken, USA.

Chatterjee, R. (1988). *Advanced Microwave Engineering Special Advanced Topics*. Ellis Horwood, Chichester, England, 493-495.

Gu, H. M. (2001). *Structure Based, Two-dimensional Anisotropic, Transient Heat Conduction Model for Wood*, Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Gu, H. M., and Hunt, J. F. (2007). "Two-dimensional finite element heat transfer model of softwood. Part III. Effect of moisture content on thermal conductivity," *Wood Fiber Sci.* 39, 159-166.

Gu, H. M., and Zink-Sharp, A. (2005). "Geometric model for softwood transverse thermal conductivity. Part 1. *Wood and Fiber Sci.* 37, 699-711.

Jain, V. K., and Dubey, Y. M. (1988). "Dielectric constant of some Indian timbers in axial direction at microwave frequencies," *J. Ind. Acad. Wood Sci.* 19, 25-36.

James, W. L. (1975). "Dielectric properties of wood and hardboard: Variation with temperature, frequency, moisture content, and grain orientation," *USDA Forest Service Research Paper, FPL* 245, 1-32.

James, W. L. (1977). "Dielectric behavior of Douglas-fir at various combinations of temperature, frequency, and moisture content," *Forest Prod J.* 27, 44-48.

James, W. L., and Hamill, D. W. (1965). "Dielectric properties of Douglas-Fir measured at microwave frequencies," *Forest Prod. J.* 15 (2), 51-56.

Kabir, M. F., Daud, W. M., Khalid, K., and Sidek, H. A. A. (1998). "Dielectric and ultrasonic properties of rubber wood. Effect of moisture content, grain direction and frequency," *Holz Roh Werkst* 56, 223-227.

Kabir, M. F., Khalid, K. B., Daud, W. M., and Aziz, S. H. A. (1997). "Dielectric properties of rubber wood at microwave frequencies measured with an open-ended coaxial line," *Wood Fiber Sci* 29, 319-324.

Khalid, K., Sahri, M. H., Keong, N. K., and Fuad, S. A. (1999). "Microwave dielectric properties of wooden cross-arms," *In: Proc. SPIE Conference on Subsurface Sensors* *and Applications*. SPIE Vol. 3752. The Inter. Soc. for Optical Engineering, Bellingham, WA, 146-156.

MacLean, J. D. (1941). "Thermal conductivity of wood," *Heat., Pip. Air Cond*. 13, 380-391.

Martin. P., Collet, R., Barthclemy, P. and.Roussy, G. (1987). "Evaluation of wood characteristics: Internal scanning of the material by microwaves," *Wood Sci. Technol.* 21, 361-371.

Olmi, R., Bini, M., Ignesti, A., and Riminesi, C. (2000). "Dielectric properties of wood from 2 to 3 GHz," *J. of Microwave Power and Electromagnetic Energy* 35(3), 135-143.

Peyskens, E., Pourcq, M., Stevens, M., and Schalck, J. (1984). "Dielectric properties of softwood species at microwave frequencies," *Wood Sci Technol.* 18, 267-280.

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

Rowley, F. B. (1933). "The heat conductivity of wood at climatic temperature differences," *Heat., Pip. Air Cond.* 5, 313-323.

Şahin, H. (2002). *Dielectric Properties of Natural and Impregnated Wood Species at Microwave Frequencies*. Ph D Thesis, Karadeniz Technical University, Trabzon.

Şahin, H., and Ay, N. (2004). "Dielectric properties of hardwood species at microwave frequencies," *J. Wood. Sci*. 50, 375-380.

Sanyal, S. N., Jain, V. K., Dubey, Y. M., and Verma, P. C. (1991). "A Preliminary note on relationship between dielectric properties and thermal conductivity of wood," *J. Ind. Acad. Wood Sci*. 22, 45-49.

Steinhagen, H. P. (1977). "Thermal conductive properties of wood green or dry from -40° to +100° C: A literature review," *General Technical Report FPL*-9, USDA Forest Service, Madison, USA.

Suleiman, B. M., Larfeldt, J., Leckner, B., and Gustavsson, M. (1999). "Thermal conductivity and diffusivity of wood," *Wood Sci. Technol*. 33, 465-473.

Tenwolde, A., McNatt, J. D., and Krahn, L. (1988). "Thermal properties of wood and wood panel products for use in buildings," *INC. DOE/ USDA-21697/1, USDA Forest Service*, Madison, USA.

Tinga, W. R. (1969). "Dielectric properties of Douglas fir at 2.45GHz," *J. Microwave Power* 4, 161-164.

Torgovnikov, G. I. (1993). *Dielectric Properties of Wood and Woodbased Materials*. Springer, Berlin Heidelberg New York, 1-19.

TS 2472. (1976). *Wood - Determination of Density for Physical and Mechanical Tests*, TSE, Ankara, Turkey.

Wangaard, F. F. (1940). "Transverse heat conductivity of wood," *Heat., Pip. Air Cond.* 12, 459-464.

Article submitted: Sept. 4, 2009; Peer review completed: Oct. 22, 2009; Revised version received and accepted: Oct. 23, 2009; Published: Oct. 26, 2009.