WOOD RESEARCH
62 (5): 2017
727-736

DIELECTRIC PROPERTIES OF SELECTED WOOD SPECIES IN POLAND

Katarzyna Pentoś, Deta Łuczycka, Tobiasz Wysoczański
Wroclaw University of Environmental and Life Sciences, Faculty of Life Sciences and Technology, Institute of Agricultural Engineering
Wrocław, Poland

(Received January 2017)

ABSTRACT

The dielectric properties of seven wood species from Poland were measured as a function of frequency and grain orientation of wood. Measurements were conducted parallel and perpendicular with respect to the visible grain for specimen cut from sapwood and heartwood, at frequencies ranging from 1 kHz to 1 MHz. Both, relative permittivity and loss coefficient were affected by frequency and anisotropic direction. The most significant influence of wood species on dielectric wood properties was observed below 5 kHz for relative permittivity and below 200 kHz for loss coefficient. The relative permittivity decreases with increasing frequency and loss coefficient increases with increasing frequency (at frequencies above 200 kHz) for all wood species and fiber orientation. Understanding the dependencies between dielectric parameters of wood and other wood parameters at frequency range from 1 kHz to 1 MHz is important when wood is used for electrical insulation or in high-frequency drying.

KEYWORDS: Dielectric wood properties, relative permittivity, loss coefficient, frequency.

INTRODUCTION

Wood is a natural material widely used for its versatility and strength in construction, for furniture manufacturing, as a biomass in combustion process. Electrical and dielectric parameters of wood and wood-based composites can be used in many applications and provide a knowledge regarding the molecular structure of wood and wood-water interactions. Since an end-use wood products must meet certain criteria for market consumers, wood is the subject of processing such as drying, heating or glueing. The knowledge of the fundamental dielectric wood properties such as relative permittivity (often called the dielectric constant) ε', loss factor ε'' and loss coefficient (often called the loss tangent) $tg\delta$ is crucial for a process design, control, optimization and simulation: radio frequency vacuum drying (Koumoutsakos 2001), microwave treatment or heating (Olmi et al. 2000, Salema et al. 2013), microwave pasteurization (Fleming et al. 2003). Microwave techniques are used in the wood industry also for diagnostic purposes such as moisture content or thickness measurement, defects detection, strength characteristics estimation (Sahin and Ay 2004).

Terahertz radiation (below about 1 THz) is used for sensing and imaging of wood by nondestructive electrical measurements. There have been several applications of THz radiation in the wood products industry reported in a prior literature, including moisture content measurement (Inagaki et al. 2014, Teti et al. 2011), defect detection Oyama et al. (2009) and dendrochronology Jackson et al. (2009). Therefore, the wood dielectric parameters analysis have been carried out at frequency range above 1 MHz but at lower frequency range they have been studied insufficiently. Wood can be used also as a dielectric material for electrical insulation or in high-frequency drying. It was proved that complex impedance measured at frequency below 2 kHz can be a useful parameter for wood differentiation (Pentoś et al. 2016). It can be expected that other electrical or dielectric wood parameters may be used for the same purposes because the differences in the dielectric behavior among wood species are related to, among others, a density and a permeability. For these applications, the analysis of dielectric wood parameters at frequencies below 1 MHz is crucial.

There are several factors which can affect the dielectric parameters of wood. The relationships between dielectric wood parameters and material-related properties such as volume porosity, pore size, pore distribution, moisture content and density were the subject of many reports (Bossou et al. 2010, Kabir et al. 1998, Olmi et al. 2000). The influence of measurement conditions such as temperature, frequency and orientation of the electric field with respect to the wood structure was also previously reported (Daian et al. 2006, James, 1975, Koubaa et al. 2008, Sahin and Ay 2004). Avramidis et al. (2006) developed the neural network model of relationship between dielectric loss factor and wood chemical composition.

According to the literature review presented above, there is still a need to analyze dielectric properties of wood at the frequency range 1 kHz – 1 MHz. To the best of our knowledge, dielectric parameters of wood species in Poland measured at frequencies below 1 MHz have not been so far the subject of scientific research. Therefore, this study aimed at the determination of relative permittivity and loss coefficient depending on frequency and anisotropic direction for the seven native soft- and hardwoods from Poland.

MATERIALS AND METHODS

As summarized in Tab. 1, the seven native soft- and hardwoods were included in the tests. Since dielectric wood parameters differ according to moisture content, the specimens with similar moisture content were chosen for the measurement. The moisture content was measured by means of Brookhuis Micro-Electronics FME moisture meter and the results are detailed in Tab. 1. According to the results reported by Goreshnev et al. (2016), the differences in moisture content presented in Tab. 1 have insignificant influence on relative permittivity (several %) and loss coefficient (few %).

Tab. 1: Wood species used for determination of dielectric parameters.

Wood species	Botanical name	Moisture content range (%)
Sweet cherry	*Prunus avium* L.	10.0 – 15.5
Roth birch	*Betula pendula* Roth	12.5 – 15.5
Oak	*Quercus robur* L.	13.5 – 18.0
Ash	*Fraxinus excelsior* L.	14.0 – 16.0
European larch	*Larix decidua* Mill.	10.5 – 15.5
Scotch Pine	*Pinus sylvestris* L.	9.5 – 15.0
Norway spruce	*Picea abies* L.	8.5 – 12.0

For each wood species, four rectangular specimens 60 × 60 × 15 mm (width × length × height) were cut - with surfaces which have contact with electrodes during measurement oriented parallel and perpendicular with respect to the visible grain (each from both, sapwood and heartwood). Depends on electrical field orientation with respect to the visible grain and specimen origin, specimens were labeled as 1A, 1B, 2A and 2B what is explained in Fig. 1.

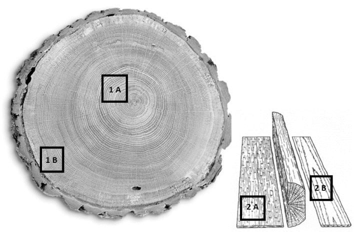

Fig. 1: The method of specimen labeling.

Impedance (Z) is generally defined as the total opposition a material offers to the flow of an alternating current (AC) at a given frequency, and is represented as a complex quantity:

$$Z = Z' + jZ'' \tag{1}$$

where: Z' - real part (resistance),
Z'' - imaginary part (reactance).

The complex impedance measurements were carried out at a room temperature, with parallel plate electrodes shown in Fig. 2, at frequency in a range 1 kHz – 1 MHz and by using ATLAS 0441 HIA apparatus. Two surfaces of the specimen were smoothed with a sand paper (P240) in order to ensure a good contact with electrodes.

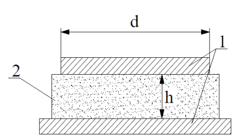

Fig. 2: Parallel plate electrode measuring system: 1 – copper electrodes, 2 – wood specimen, h – specimen height, d – diameter of the electrode.

For each specimen, complex impedance was measured for four types of samples: from sapwood and heartwood and with two anisotropic directions. The impedance is a parameter which characterizes material in certain conditions: frequency and electrode system. Therefore, based on complex impedance values and electrodes' dimensions, two parameters that characterize material depending only on frequency: the relative permittivity (ε') and the loss coefficient (*tanδ*) were determined as follows:

$$\varepsilon' = \frac{C}{\varepsilon_0 \cdot k} \quad (2)$$

$$k = \frac{S}{h} \quad (3)$$

$$tg\delta = \frac{1}{\omega \cdot C \cdot R} \quad (4)$$

where: C - capacitance of capacitor with wood sample (F),
ε_0 - permittivity of vacuum ($F \cdot m^{-1}$),
S - upper electrode surface area (m^2),
h - distance between electrodes (m),
ω - angular frequency of electromagnetic field (Hz),
R - resistance of wood sample (Ω).

The values of C and R were calculated based on real and imaginary part of impedance (Z' and Z").

RESULTS AND DISCUSSION

Since the relative permittivity and the loss coefficient are the parameters that characterize material regardless of electrode system, these two parameters are used for further analysis of wood dielectric features. The relative permittivity represents the ability of the molecule to become polarize under the electric field and loss coefficient determines the ability of the material to convert electromagnetic energy into heat at a specific frequency and temperature.

In Figs. 3 and 4 the dependence of relative permittivity and loss coefficient on frequency is presented for samples 1A of all wood species. The measurements were performed at frequency range 1 kHz – 1 MHz, however in plots concerning ε', the frequency range was reduced for greater readability of figures. For higher frequencies, the parameters presented in plots are constant.

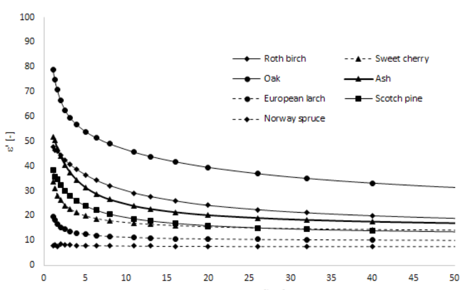

Fig. 3: Effect of frequency on relative permittivity values for samples 1A of all wood species.

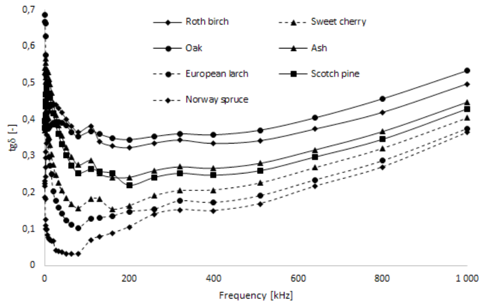

Fig. 4: Effect of frequency on loss coefficient values for samples 1A of all wood species.

The changes in relative permittivity and loss coefficient as a function of frequency are of a similar nature for all wood species. The differences in relative permittivity and loss coefficient between wood species are observed over the entire frequency range. However, the most significant differences appear for lower frequencies (below 5 kHz for ε' and below 200 kHz for $tg\delta$). The lowest values of relative permittivity and loss coefficient are observed for Norway spruce and the highest ones for oak. For the frequency 4 kHz, the difference between the relative permittivity of Norway spruce and oak is about 600%. In the case of loss coefficient calculated for the frequency 110 kHz, the difference between Norway spruce and oak is 425 %. In Figs. 5 and 6 the dependence of relative permittivity and loss coefficient on frequency is presented for samples 2A of all wood species. The data presented in plots show that there is significant difference in both, ε' and $tg\delta$, between oak and other species. The differences between other species are significantly lower than in the case of samples 1A – between Norway spruce and ash: 61% for ε' measured at frequency 4 kHz and 100% for $tg\delta$ measured at frequency 110 kHz. The differences in relative permittivity between wood species are caused by a different volume porosity. However, woods with the same volume porosity may have slightly different ε' value because of the differences in the actual pore size distribution as suggested by Hilfer (1991). Higher porosity results with a lower relative permittivity, therefore the hardwoods, which have generally lower porosities, have higher ε' than the softwoods. Since volume porosity is correlated with density, at constant moisture content, species with higher density have higher ε' (Ay and Sahin 2004). The results presented in Figs. 3 - 6 generally comply with this rule, with the exception of Sweet cherry which have lower relative permittivity than other hardwoods. It can be explained by the fact that density of Sweet cherry is similar to density of European larch (610-700 $kg \cdot m^{-3}$).

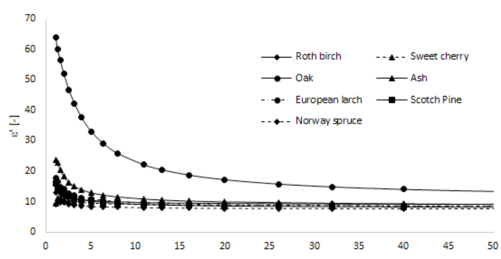

Fig. 5: Effect of frequency on relative permittivity values for samples 2A of all wood species.

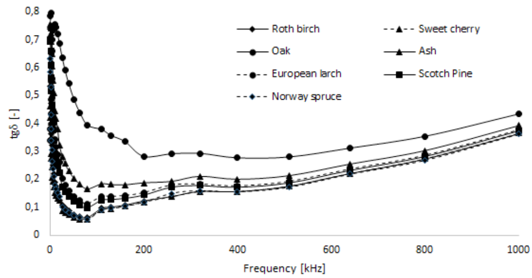

Fig. 6: Effect of frequency on loss coefficient values for samples 2A of all wood species.

The relative permittivity decreases with increasing frequency for all wood species regardless of electrical field orientation with respect to the visible grain. This is the result of the relaxation of the polar radicals with respect to the macromolecules forming the microfibrils (Brown et al. 1952). The relative permittivity is more influenced by porosity, while loss coefficient is more sensitive to the adsorbed water (Duchow and Gerhardt 1996). Therefore, loss coefficient measured at frequencies above 200 kHz, increases with increasing frequency. It can be explained by the fact that water is a polar molecule (Torgovnikov, 1993). The similar results were reported by Duchow and Gerhardt (1996) according to dependence of *ε'* and *tgδ* on frequency. However, the values of dielectric parameters were different from presented in this paper, what can be caused by differences in wood species and samples moisture. Similar values of *ε'* and *tgδ* were reported by Goreshnev et al. (2016) for birch wood and by Kabir et al. (1998) for rubber wood.

The method of sample collection (1A, 1B, 2A and 2B) affects relative permittivity and loss coefficient differently depending on wood species. In Figs. 7 and 8 the influence of sample type on *ε'* and *tgδ* is presented for two softwoods and two hardwoods.

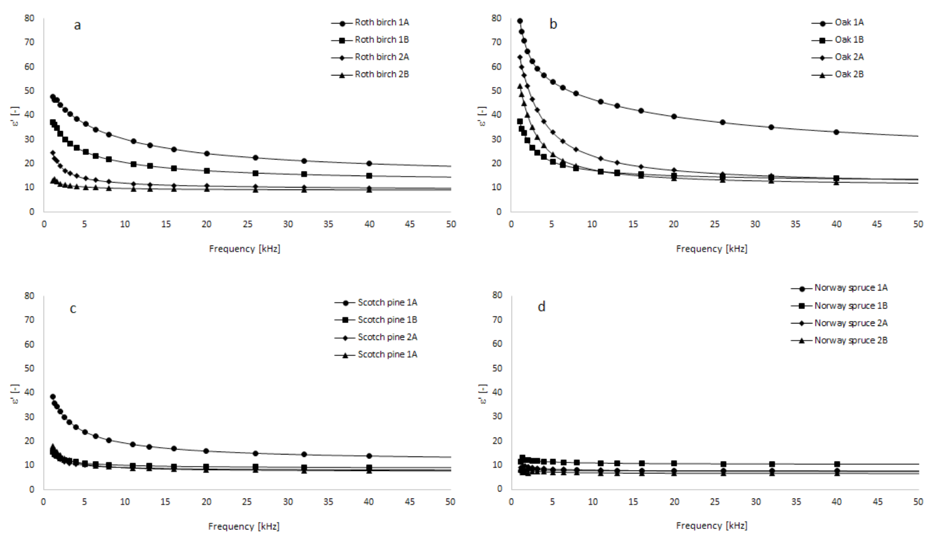

Fig. 7: Dependence of relative permittivity on frequency and sample type for different wood species (a – Roth birch, b – oak, c – Scotch pine, d – Norway spruce).

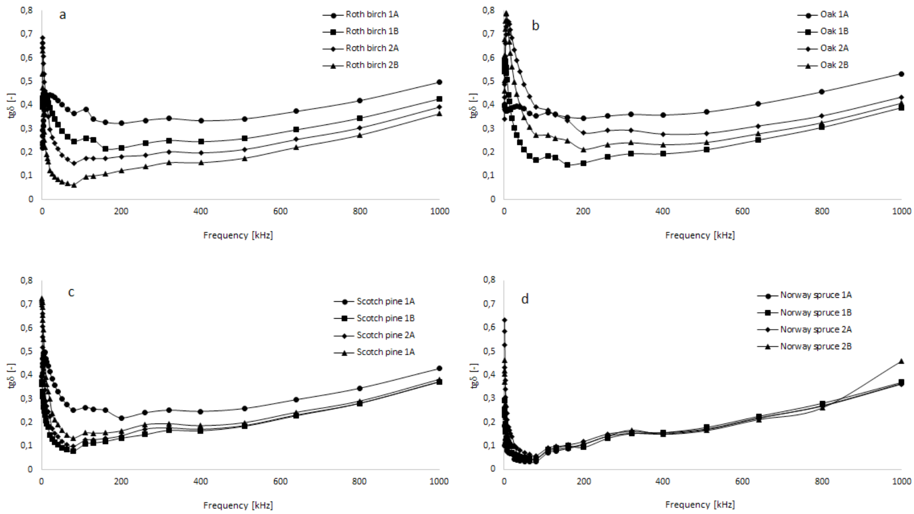

Fig. 8: Dependence of loss coefficient on frequency and sample type for different wood species (a – Roth birch, b – oak, c – Scotch pine, d – Norway spruce).)

The influence of orientation of the electric field with respect to the wood structure on dielectric wood properties was reported also by other researchers (Duchow and Gerhardt 1996, Gerhardt 1994, Goreshnev et al. 2016). Across fibers, relative permittivity is expected to be lower than along fibers what is explained by a water penetrability of capillary and porous structure of wood. This phenomenon was also the subject of analysis reported by Norimoto and Yamada (1972), who concluded that dielectric properties of wood are strongly influenced by cellulose (higher dielectric properties) and mannan in the longitudinal direction, and by lignin (lower dielectric properties) in the transverse direction. The data presented in Fig. 7 and 8 show that the influence of fiber orientation is stronger in the case of hardwoods and is negligible for Norway spruce. Generally, when sample was cut from heartwood, the relative permittivity is lower across the fibers.

CONCLUSIONS

Dielectric parameters of seven Polish native soft- and hardwoods were the subject of this research. Dielectric wood parameters are usually investigated at microwave or terahertz frequency range. However, parameters such as relative permittivity *ε'* and loss coefficient *tgδ* at the high-frequency range (1 kHz – 1 MHz) are crucial for many wood applications. Based on the results presented in this paper it can be concluded that *ε'* and *tgδ* were affected by frequency and anisotropic direction. The influence of wood species on *ε'* and *tgδ* was observed over the entire frequency range but the most significant differences between wood species appeared below 5 kHz for *ε'* and below 200 kHz for *tgδ*. Generally, higher relative permittivity and loss coefficient values were observed for the hardwoods than for the softwoods. The *ε'* decreases with increasing frequency and *tgδ* measured at frequencies above 200 kHz increases with increasing frequency for all wood species regardless of fiber orientation. Dielectric wood parameters can be potentially used for wood species differentiation, however proper frequency and anisotropic direction should be chosen.

REFERENCES

1. Avramidis, S., Iliadis, L., Mansfield, S.D., 2006: Wood dielectric loss factor prediction with artificial neural networks, Wood Science and Technology 40: 563-574.
2. Ay, N., Sahin, H., 2004: Dielectric constant of Turkish timbers in the longitudinal direction at a 9.8-GHz frequency, Forest Products Journal 54: 65-68.
3. Bossou, O.V., Mosig, J.R., Zurcher, J.F., 2010: Dielectric measurements of tropical wood, Measurement 43: 400-405.
4. Brown, H.P., Panshin, A.J., Forsaith, C.C., 1952: Textbook of Wood Technology, Vol. II. McGraw-Hill, New York.
5. Daian, G., Taube, A., Birnboim, A., Daian, M., Shramkov, Y., 2006: Modeling the dielectric properties of wood, Wood Science and Technology 40: 237-246.
6. Duchow, K.J., Gerhardt, R.A., 1996: Dielectric characterization of wood and wood infiltrated with ceramic precursors, Materials Science & Engineering C-Biomimetic Materials Sensors and Systems 4: 125-131.
7. Fleming, M.R., Hoover, K., Janowiak, J.J., Fang, Y., Wang, X., Liu, W.M., Wang, Y.J., Hang, X.X., Agrawal, D., Mastro, V.C., Lance, D.R., Shield, J.E., Roy, R., 2003: Microwave irradiation of wood packing material to destroy the Asian longhorned beetle, Forest Products Journal 53: 46-52.
8. Gerhardt R., 1994: Microstructural characterization of composites via electrical measurements, proceedings of: the 18th annual conference on composites and advanced ceramic materials - B: Ceramic Engineering and Science Proceedings, Volume 15, Issue 5, p. 1174–1181.
9. Goreshnev, M.A., Litvishko, E.S., Lopatin, V.V., 2016: Dielectric properties of birch wood in the high-frequency range, Russian Physics Journal 58: 1297-1300.
10. Hilfer, R., 1991: Geometric and dielectric characterization of porous media, Physical Review B 44(1): 60-75.
11. Inagaki, T., Ahmed, B., Hartley, I.D., Tsuchikawa, S., Reid, M., 2014: Simultaneous prediction of density and moisture content of wood by terahertz time domain spectroscopy, Journal of Infrared Millimeter and Terahertz Waves 35: 949-961.
12. Jackson, J.B., Mourou, M., Labaune, J., Whitaker, J.F., Duling III, I.N., Williamson, S.L., Lavier, C., Menu, M., Mourou, G.A., 2009: Terahertz pulse imaging for tree-ring analysis: a preliminary study for dendrochronology applications, Measurement Science & Technology 20(7): 075502 (10pp).
13. 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.
14. Kabir, M.F., Daud, W.M., Khalid, K., Sidek, H.A., 1998: Dielectric and ultrasonic properties of rubber wood. Effect of moisture content, grain direction and frequency, Holz Als Roh-Und Werkstoff 56: 223-227.
15. Koubaa, A., Perre, P., Hutcheon, R.M., Lessard, J., 2008: Complex dielectric properties of the sapwood of aspen, white birch, yellow birch, and sugar maple, Drying Technology 26: 568-578.

16. Koumoutsakos, A., Avramidis, S., Hatzikiriakos, S., 2001: Radio frequency vacuum drying. Part I. Theoretical model, Drying Technology 19(1):65–84.
17. Norimoto, M., Yamada, T., 1972: The dielectric properties of wood VI, on the dielectric properties of chemical constituents of wood and the dielectric anisotropy of wood Wood Research 52: 30–43.
18. Olmi, R., Bini, M., Ignesti, A., Riminesi, C., 2000: Dielectric properties of wood from 2 to 3 GHz, Journal of Microwave Power and Electromagnetic Energy 35: 135-143.
19. Oyama, Y., Zhen, L., Tanabe, T., Kagaya, M., 2009: Sub-terahertz imaging of defects in building blocks, Ndt & E International 42: 28-33.
20. Pentoś, K., Łuczycka, D., Wysoczański, T., 2016: The use of complex impedance as a parameter for wood differentiation Wood Research 61: 13-24.
21. Sahin, H., Ay, N., 2004: Dielectric properties of hardwood species at microwave frequencies, Journal of Wood Science 50: 375-380.
22. Salema, A.A., Yeow, Y.K., Ishaque, K., Ani, F.N., Afzal, M.T., Hassan, A., 2013: Dielectric properties and microwave heating of oil palm biomass and biochar, Industrial Crops and Products 50: 366-374.
23. Teti, A.J., Rodriguez, D.E., Federici, J.F., Brisson, C., 2011: Non-destructive measurement of water diffusion in natural cork enclosures using terahertz spectroscopy and imaging, Journal of Infrared Millimeter and Terahertz Waves 32: 513-527.
24. Torgovnikov, G.I., 1993: Dielectric properties of wood and wood-based materials, Springer, Berlin.

Katarzyna Pentoś*, Deta Łuczycka, Tobiasz Wysoczański
Wroclaw University of Environmental and Life Sciences
Faculty of Life Sciences and Technology
Institute of Agricultural Engineering
J. Chełmońskiego 37/41
51-630 Wrocław
Poland
Phone: +48713205970
Corresponding author: katarzyna.pentos@upwr.edu.pl