Microwave Radiation Effect on Axial Fluid Permeability in False Heartwood of Beech (*Fagus sylvatica* L.)

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This study evaluated the effect of microwave radiation on the fluid permeability and compression strength parallel to the grain of beech false heartwood. European beech (*Fagus sylvatica* L.) was selected, and samples of false heartwood with dimensions of 30×20×20 mm^3 were used. The microwave treatment was carried out in a laboratory device at a frequency of 2.45 GHz. The testing samples were divided into three groups (untreated, treated at 20-s intervals, and treated at 30-s intervals). The permeability was measured in the axial direction using distilled water. The coefficient of specific permeability was calculated using Darcy's law. The results showed that the coefficient of specific permeability increased by up to 159% in comparison with untreated samples. The compression strength parallel to the grain decreased by up to to 15%.

Keywords: European beech; False heartwood; High-frequency energy; Microwave treatment; Permeability; Compression strength

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INTRODUCTION

European beech (*Fagus sylvatica* L.) is a species that is heavily used by industry. It provides hard, strong, and resilient wood with good properties for processing, which makes it suitable for a wide range of uses (Pouchanič 2011). *Fagus sylvatica* L. wood density ranges between 620 and 720 kg/m^3 on average, depending on altitude and the specific site (Gryc *et al*. 2008). The density of the false heartwood is usually higher. Many properties of *Fagus sylvatica* surpass the properties of other common European species. Beech wood also has several disadvantages, which limit its possible use as a material. One of the most significant is that it forms false heartwood, which is seen in practice as a flaw, reducing the quality of material entering the production process and thus also reducing its utilization (Pouchanič 2011). The formation of false heartwood in beech is determined by two main factors: the presence of ripe wood (the central part of the trunk has a lower moisture content than that of sap wood), and air entering the wood structure. Both of these factors must be fulfilled for false hardwood to form. A wound in the stem or a branch is the primary cause of air entering the tree stem. Oxygen contained in the air causes oxidation and the production of brown, polyphenolic compounds (Koch *et al*. 2001). At the same time, tyloses grow from parenchyma cells through pits between parenchyma cells and vessels and block them. Such tissue allows very little fluid to permeate beyond the wound, and many investigators thus see the false heartwood of beech as a protective tissue that prevents the origination and development of fungal hyphae (Račko and Čunderlík 2010).

Microwave radiation is used to modify wood to achieve an improvement in its natural drying (Brodie 2004), plasticization (Makovíny and Zemiar 2004; Yu *et al*. 2011), and wood synthesis with other natural materials, *e.g.*, resins (Torgovnikov and Vinden 2004). Structural changes through wood modification can lead to changes in physical wood properties such as permeability, density, strength, flexibility, heat conductivity, shrinkage, and swelling (Torgovnikov and Vinden 2009).

The principle of microwave heating is based on the polar molecules (H_2O, -OH, -CH_2OH, -CHOH, -COOH) contained in the wood (Hansson and Anti 2003). If the wood is exposed to an electromagnetic field of microwaves, molecules that are dipolar in character will begin to move with the same frequency as the electromagnetic field, and the rapid change in field polarity causes vibration and even rotation of molecules, which transforms the energy of microwaves into frictional heat (Nasswettrová and Nikl 2011; Hansson and Anti 2003; Makovíny 2000). Water is the best absorber of microwave radiation with the frequency 2.45 GHz (Nasswettrová and Nikl 2011). By applying microwave radiation to the wood with certain moisture content, the water in the cell cavity absorbs the energy and boils off quickly, forming high steam pressure; the pressure causes cell microstructure change, resulting in the properties change including the permeability. Moreover, Merenda and Holan (2008), Yu *et al*. (2011), and Vinden *et al*. (2011) state that when steam is created, the cell walls become delaminated and wood permeability thus increases. According to Torgovnikov and Vinden (2004), cell walls of ray cells are the easiest to destroy by water steam pressure during microwave heating in which micro-cracks are created in the wood, leading to an increased volume of the wood and a decrease in density. However, the mechanical properties deteriorate. Oloyede and Groombridge (2000) studied the effect of drying Caribbean pine (*Pinus caribaea*) timber using microwaves and concluded that microwave drying could reduce timber's tensile strength by 60%. The authors hypothesized that peculiar mechanisms involved in microwave heating caused this harmful effect on the strength and fracture toughness. Torgovnikov and Vinden (2000 and 2001) treated the wood of *Eucalyptus* by microwave radiation. Steam expansion, caused by microwaves of high intensity, modified selected hardwoods by increasing wood permeability. The MOE was decreased by 12 to 17% and the volume increased by 13.4%. Torgovnikov and Vinden (2009) performed a MW modification of the wood of Paulownia (*Paulownia fortunei*) at an output of 30kW and a frequency of 0.922 GHz. They concluded that the MW modification caused its high heat loading, which led to a decrease in MOE in the tangential direction from 3400 MPa to 1600 MPa and a decrease in MOR in the tangential direction from 39.3 MPa to 16 MPa. Terziev and Daniel (2013) treated samples of Norway spruce (*Picea abies*) for improved wood permeability. Results shows that the water uptake of the treated samples was doubled compared to the untreated controls, but the MOE decreased with 10% after the treatment.

Beech wood has a relatively low resistance to biodegradation factors, which is usually compensated for by chemical treatments (impregnation by natural oils, waxes, *etc.*). The determining factor deciding the uptake of the chemical treatment is wood permeability. The measure of permeability is not only wood porosity but also the interconnection of free spaces in the capillary system. Concerning wood, this means the connection of cell lumina by perforated screens – cell wall pits or cross-fields of rays (Požgaj *et al*. 1997). The actual permeability depends on many factors: from the wood element distribution and the size of pits in the cell walls to the anatomical direction, density, moisture, *etc*.

The goal of this work was to find out if microwave radiation will increase the axial permeability of beech false heartwood. Should this hypothesis be confirmed, impregnation and durability of false heartwood in beech would increase. Healthy false heartwood would not have to be excluded and after impregnation; rather it would become an adequate material for the construction and furniture industries.

EXPERIMENTAL

Materials

The testing samples were selected with dimensions of 30×20×20 mm^3 (Length × Width × Height) from a section of European beech (*Fagus sylvatica* L.) containing false heartwood. The size of the testing samples was used with respect for measuring the axial permeability and strength in compression parallel to the grain. The section was chosen without fungi or insect damage. The samples did not contain defects, such as cracks, knots, pits, fiber deflection, or reaction wood. Before microwave treatment, the samples were soaked in distilled water for 3 weeks. Before beginning the modification process, the material contained 85% moisture content on average (standard deviation, σ=8.2%). The testing samples were divided into three groups. Each group (untreated, first treated group, second treated group) contained 70 samples.

Microwave Treatment

The samples were treated in a small laboratory microwave device with chamber dimensions 515 × 415 × 290 mm^3 (Width × Depth × Height). The device works with a frequency of 2.45 GHz and an output of 900 W. Testing samples were rotated during the treatment process, and microwaves came from a linear direction. The treatment process consisted of two intervals with a 30-s pause in between for material relaxation (balancing tension and decreasing wood temperature). The experiment included two treatment groups. The first group of samples was exposed to microwaves at 20-s intervals (20 s of treatment, 30 s of relaxation, and 20 s of treatment); the second group of samples was treated at 30-s intervals (30 s of treatment, 30 s of relaxation, and 30 s of treatment). To ensure homogeneity, the samples were treated separately. After microwave treatment, the testing samples were soaked to 85% moisture content (standard deviation, σ=12.4%) and then the permeability was measured.

Measuring of Permeability

Permeability was measured experimentally with distilled water using a measuring device designed for testing the axial permeability of fluids through porous materials (Fig. 1). The test was conducted with water and also a sample temperature of 20 °C and a fluid pressure of 0.5 MPa; the diameters of the openings for distilled water flow were 10 mm. The moisture content of samples in the permeability test was above the saturation point, and the following coefficient of specific permeability was calculated using a formula based on Darcy's law,

$$K = \frac{V\, L\, \eta}{t\, S\, \Delta\rho} \qquad (1)$$

where K is the coefficient of specific permeability in $m^3 \cdot m^{-1}$, η is the dynamic viscosity of water by Čmelík *et al.* (2001) in Pa·s, V is the volume of fluid flowed through in m^3, S is the area of the flow in m^2, t is the time of flow duration in s, Δp is the difference in pressures at the ends of samples in Pa, and L is the length of a sample in m.

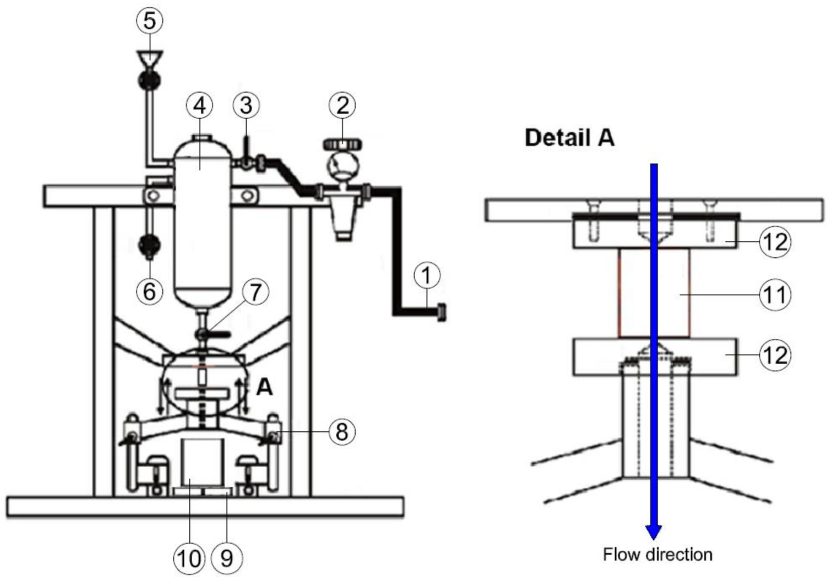

Fig. 1. Permeability measuring device

Label key: 1) Supply of pressured air, 2) Pressure regulator with manometer, 3) Ball valve (air), 4) Pressure tank, 5) Fill valve, 6) Safety valve, 7) Ball valve (distillate water), 8) Eccentric support for clamping the sample, 9) Scale, 10) Beaker, 11) Testing sample, 12) Washers with a hole (diameter 10 mm)

Measurement of Mechanical Properties

After microwave treatment and permeability tests, the samples were kiln dried to 0% moisture content following the European standard EN 13183-1:2002. Subsequently, the wood strength in compression parallel to the grain was measured using a universal testing device.

RESULTS AND DISCUSSION

Permeability

The samples treated by microwaves showed higher permeability than the untreated samples. Figure 2 depicts the calculated coefficients of specific permeability. The mean permeability of untreated beech false heartwood was $4.72 \cdot 10^{-13}$ $m^3 \cdot m^{-1}$ (standard deviation, $\sigma = 8.8 \cdot 10^{-13}$ $m^3 \cdot m^{-1}$). The samples exposed at 20-s intervals showed an increase in the mean permeability value of 28% (to $6.04 \cdot 10^{-13}$ $m^3 \cdot m^{-1}$, $\sigma = 6.81 \cdot 10^{-13}$ $m^3 \cdot m^{-1}$) compared to the untreated samples. The samples exposed at 30-s intervals with a mean coefficient of $12.2 \cdot 10^{-13}$ $m^3 \cdot m^{-1}$ ($\sigma = 19.1 \cdot 10^{-13}$ $m^3 \cdot m^{-1}$) exhibited a higher increase in permeability, representing a 159% increase in mean permeability. This phenomenon explains the findings of Torgovnikov and Vinden (2009): the longer the wood is exposed in microwave radiation, the more the structure of wood micro-cracks are developed, which increases the permeability.

Although the standard deviations showed high variability, statistically significant differences could be found between untreated samples and treated samples at 30-s intervals, as well as between both treated groups (Tukey's test). The differences can be explained by the different treatment time and thus a different mode of heat stress.

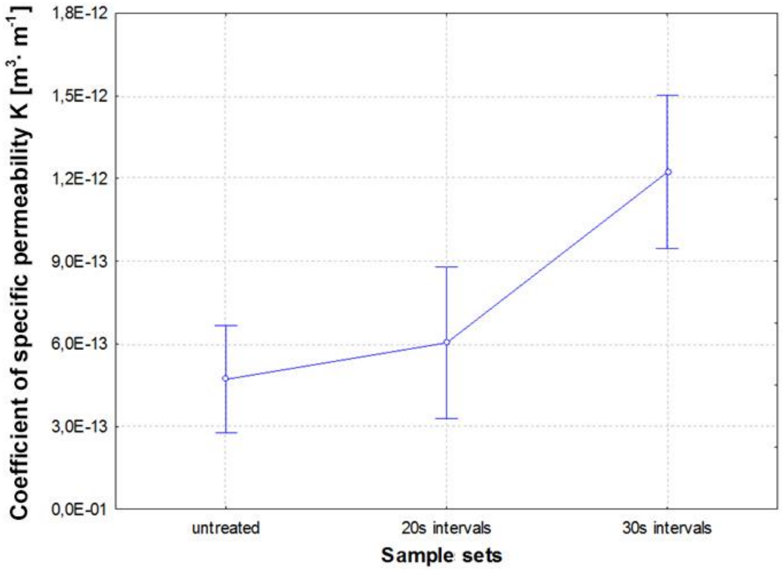

Fig. 2. Permeability of the different sample sets

The observed data cannot be compared with literature because no scientific papers were found dealing with the issue of permeability of beech false heartwood. However, the presented data can be compared with studies that discuss the permeability of *Fagus sylvatica* L. wood without false heartwood. The conclusion seems to be feasible if common values of permeability can be reached by microwave. Several authors have observed the permeability of beech wood, as listed in Table 1. It is apparent that permeability is highly variable. High variability in the beech wood may be related to differences in the number of vessel per mm^2 (80 to 130) and their different radius (15 to 50 m·10^{-6}) Požgaj *et al.* (1997). Different permeability of sapwood and heartwood may be attributed to differences in chemical composition and anatomical structure. Microscopic studies by Gholamiyan and Tarmian (2010) revealed that the presence of tyloses in the vessels as a result of false heart wood formation is the main factor for the decreased axial permeability.

Table 1. Permeability of Beech According to Various Authors

Author	Permeability [$m^3 \cdot m^{-1}$]
Hudec (2002)	$2.91 \cdot 10^{-11}$
Kurjatko *et al.* (2002)	$1.39 \cdot 10^{-11}$
Čunderlík and Hudec (2002)	$1.3 \cdot 10^{-11}$
Babiak and Kúdela (1993)	$4.9 \cdot 10^{-12}$
Požgaj *et al.* (1997)	$8.51 \cdot 10^{-12}$
Kúdela (1999)	$10 \cdot 10^{-12}$
Hudec and Danihelová (1992)	$7.56 \cdot 10^{-12}$

Similarities can be found between the permeability of samples treated at 30-s intervals and the results of permeability in normal beech without the false heart wood presented by Babiak and Kúdela (1993).

Mechanical Properties

Figure 3 shows the mean values of strength in compression parallel to the grain in the false heartwood of beech. The mean value of strength of the untreated samples was 102.95 MPa (σ=9.83 MPa). The samples treated at 20-s intervals reached a mean value of 94.41 MPa (σ=8.97 MPa), and those treated at 30-s intervals had a mean value of 89.22 MPa (σ=10.48 MPa). The wood strength decreased by 9% in the first group; there was a 15% reduction of wood strength in the second group, compared with the untreated samples. Samples treated in 30-s intervals achieved much better permeability with an insignificant decrease in strength compared with samples treated in 20-s intervals.

Statistically significant differences were found between untreated samples and both treated groups (Tukey's test). Measurements of mechanical properties showed that the treatment did not cause a large decrease in strength. The values suggested that the treated material would be acceptable for further use in practice. Moreover, there was better impregnation capacity, which could substantially improve the mechanical properties in some cases.

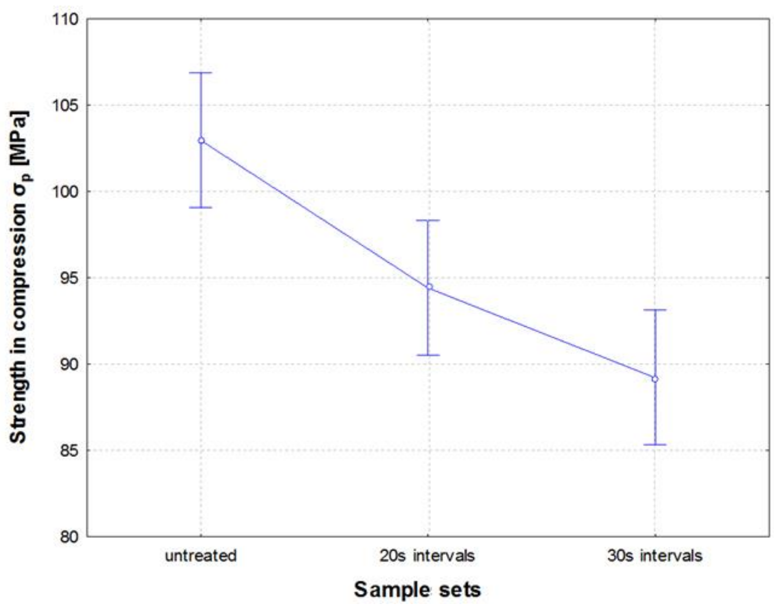

Fig. 3. Compression strength parallel to the grain

Figure 4 illustrates the correlation between permeability and strength in compression parallel to the grain. The correlation coefficient was very low (r=-0.53). It seems that with increasing permeability due to microwave treatment, the strength in compression parallel to the grain decreased. Micro-cracks, which tend to increase the wood permeability, occurred during the microwave treatment. With longer treatment, there were increases in the number and size of the micro-cracks. Therefore the mechanical properties such as strength in compression were decreased. This influence on micro-cracks was demonstrated by Torgovnikov and Vinden (2009).

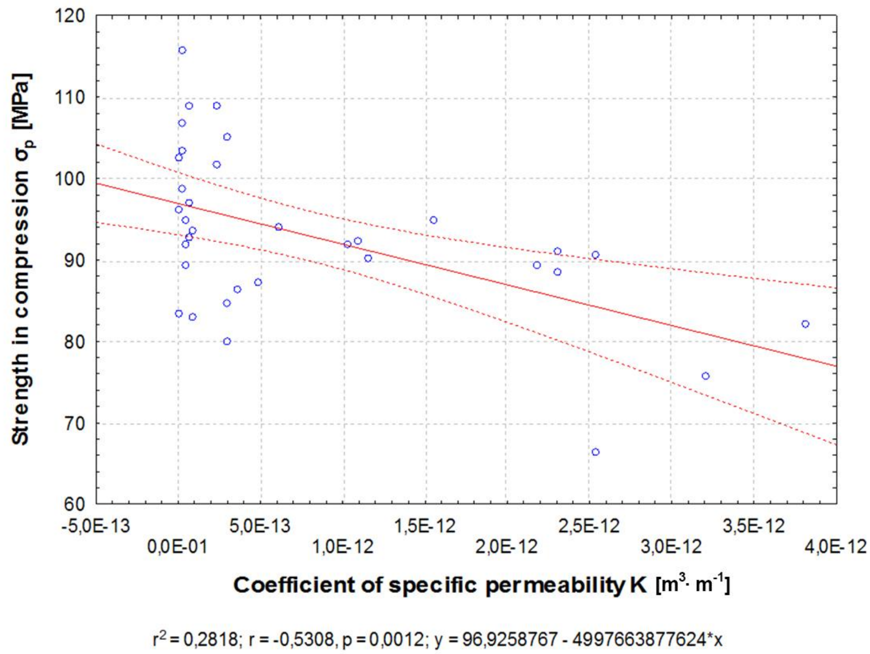

Fig. 4. Compression strength in dependence of wood permeability

CONCLUSIONS

1. The aim of this paper was to determine if microwave radiation influences the axial permeability by distilled water and the compression strength parallel to the grain of beech false heartwood. Microwave radiation increased the mean specific permeability at group 20-s intervals of treatment by 28% (statistically insignificant) and at group 30-s intervals of treatment by 159% (statistically significant) compared to the untreated samples. The difference between the two treated groups (20-s intervals of treatment and 30-s interval of treatment) was statistically significant.
2. The mean compression strength parallel to the grain decreased at group 20-s intervals treated up to 9% (statistically significant) and at group 30-s intervals up to 15% (statistically significant) compared to the untreated samples. There were no statistically significant differences between the two treated groups (20-s intervals of treatment and 30-s interval of treatment).

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REFERENCES CITED

Babiak, M., and Kúdela, J. (1993). "Transport of free water in wood," in: *Interaction of Wood with Various Forms of Energy*, Technical University in Zvolen, pp.53-56.

Brodie, G. (2004). "Microwave preconditioning to accelerate solar drying of timber," Conference Paper, AIChE Annual Meeting, Austin, TX.

Čunderlík, I., and Hudec, J. (2002). "Axial permeability of normal and tension beech wood," Wood structure and properties '02 : [proceedings of the 4th IUFRO Symposium]. Zvolen, Arbora Publishers, 2002, ISBN 80-967088-9-9.pp. 63-67.

Čmelík, M., Machonský, L., and Šíma, Z. (2001). *Mathematical, Physical and Chemical Tables for Secondary Schools*, SPN, Prague

Gryc, V., Vavrcik, H., and Gomola, Š. (2008)."Selected properties of European beech (*Fagus sylvatica* L.)," *Journal of Forest Science* 54(9), 418-425.

Gholamiyan, H., and Tarmian, A. (2010). "Radial variation in longitudinal permeability of beech wood containing red heart wood," *Journal of Forest and Wood Products* 63(1), 37-46.

Hudec, J., (2002). "Mutual comparison of axial permeability of beech stems for water amongst selected localities from surroundings of Zvolen," Wood Structure and Properties '02 : [proceedings of the 4th IUFRO Symposium]. – Zvolen, Arbora Publishers, 2002, ISBN 80-967088-9-9.pp. 69-72.

Hudec, J., and Danihelová, A. (1992). "Permeability of natural and hydrothermal treated wood," in: *Interaction of Wood with Various Forms of Energy*, Technical University in Zvolen, pp. 53-56.

Koch, G., Bauch, J., Puls, J., and Welling, J. (2001). "Ursachen und wirtschaftliche Bedeutung von Holzverfärbungen," Interdisziplinäre Forschung am Beispiel der Rotbuche, Forschungsreport, pp. 30-33.

Kúdela, J. (1999). "Selected physical properties of pension beech wood," in: *Interaction of Wood with Various Forms of Energy*, Mišíková *et al.* (eds.), Technical University in Zvolen, pp.53-56.

Kurjatko, S., Solár, R., Mamo Ňová, M., and Hudec, J. (2002). "Selected properties of beech wood biodegraded by white-rot fungi," in: *Wood Structure and Properties*, Arbora Publishers, Zvolen, pp.57-62.

Makovíny, I. (2000). "Dielectric and electromagnetic characteristics of beech wood," *Wood Research* 45(3), pp. 23-34.

Makovíny, I., and Zemiar, J. (2004). "Heating of wood surface layers by infrared and microwave radiation," *Wood Research* 49(4), 33-39.

Merenda, L., and Holan, J. (2008). "The permeability of microwave treated wood for distilled water," *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* 56(1), 137-142.

Nasswettrová, A., and Nikl, K. (2011) "Microscopic identification of ganges in beech (*Fagus sylvatica* L.) and pine (*Pinus sylvestris* L.) cell structure after drying using high-frequency energy of the microwave band," *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* 59(1), 173-182.

Oloyede, A., and Groombridge, P. (2000). "The influence of microwave rating on the mechanical properties of wood," *Journal of Material Processing Technology* 100(1), 67-73.

Pouchanič, J. (2011). "Comparison of selected properties of normal wood and false core wood of beech," BS Thesis, Mendel University in Brno.

Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). "Structure and properties of wood," *Bratislava, Príroda* 485.

Račko, V., and Čunderlík, I. (2010). "The ripewood as a limiting factor of the false heartwood formation of beech (*Fagus sylvatica* L.)," Wood Structure and Properties '02: [proceedings of the 4th IUFRO Symposium], Zvolen, Arbora Publishers, 2002, ISBN 80-967088-9-9, pp. 39-41.

Terziev and Daniel (2013). "Application of high frequency treatments for improved permeability of Norway spruce (*Picea abies* Karst.) wood," In: *Wood the Best Material for Mankind*, Zvolen: Arbora Publishers, pp.15-19.

Torgovnikov, G. I., and Vinden, P. (2000). "New wood based materials TORGVIN and VINTORG," 5th Pacific Rim Bio-based Composite Symposium, Canberra, Australia, pp. 756-757.

Torgovnikov, G. I., and Vinden, P. (2001). "Microwave method for increasing the permeability of wood and its applications," The 8th International Conference on Microwave and High Frequency Heating Symposium, Bayreuth, Germany, pp. 3-7.

Torgovnikov, G. I., and Vinden, P. (2004). "New MW technology and equipment for wood modification," Austin, Fourth World Congress on Microwave and Radio Frequency Applications, pp. 91-98.

Torgovnikov, G. I., and Vinden, P. (2008). "Main aspects of microwave wood modification applicable for the timber industry," Japan, Global Congress on Microwave Energy Applications, pp. 407-410.

Torgovnikov, G. I., and Vinden, P. (2009). "High intensity microwave wood modification for increasing permeability," *Forest Products Journal* 59(4), 84-92

Vinden, P., Torgovnikov, G., and Hann, J. (2011) "Microwave modification of radiata pine railway sleepers for preservative treatment," *European Journal of Wood and Wood Products* 69(2), 271-279.

Yu, J., Li, H., Sun, B., and Duo, H. (2011)."Effects of the conditions on the temperature changes inside the wood during microwave heating," International Conference on Materials Science and Computing Science, Wuhan, pp. 100-104.

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