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AXIAL PERMEABILITY OF BEECH WOOD TREATED BY MICROWAVE HEATING FOR DISTILLED WATER

Andrea Nasswettrová, Pavel Šmíra
Thermo Sanace S.R.O.
Ostrava – Kunčičky, Czech Republic

Jiří Zejda, Květoslav Nikl, Václav Sebera
Mendel University In Brno
Faculty of Forestry and Wood Technology, Department of Wood Science
Brno, Czech Republic

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ABSTRACT

The paper presents results of measuring axial permeability of beech wood for distilled water after the wood has been treated by microwave energy. Heating was applied to the wood structure in two different versions of energy exposure. Permeability was ascertained in stationary conditions using a device produced in the Department of Wood Science, Mendel University in Brno. Permeability coefficients were calculated by Darcy's law and compared with permeability coefficients of natural beech wood. The results showed an increase in mean values of permeability coefficients in the samples dried by microwave energy.

KEYWORDS: Wood permeability, microwave energy, *Fagus sylvatica* L., wood structure.

INTRODUCTION

Wood permeability for liquids is generally considered a property which substantially affects timber processing and in this way also the quality of final products. This mainly concerns technological processes of drying, steaming, boiling, and surface treatment (Kurjatko et al. 2004). Permeability is of vital importance in the process of impregnation. Wood becomes permeable in conditions determined by its porosity and connection of free spaces in the capillary system (Požgaj et al. 1997). This property is highly variable in dependence on the wood structure, especially the number and size of conducting elements. Beech wood permeability has been explored by many authors (Čop 1974, Babiak et al. 1995, 2001, Hudec 1993, Kurjatko et al. 1998, 2002, Čunderlík and Hudec 2002). A detailed analysis of the issue of wood permeability has been conducted by Hansmann (2002). The author refers to papers which predominantly focus on

selected factors affecting permeability. Besides wood structure, anatomical direction, effect of early- and latewood, he refers to papers dealing with the effect of moisture content and wood treatment performed before measuring of permeability with the aim to increase it. The possible ways of wood treatment aimed at increasing the permeability include the treatment by microwave (MW) energy.

Microwave heating depends on the ability of the microwave's electric field to polarize dipolar molecules (Metaxas a Meredith 1983). The principle is based on the transformation of the energy of alternating electromagnetic (EM) field into heat energy in materials with an uneven distribution of electric charge in molecules. Due to the EM field, dielectric properties of wood are determined by the process of polarization which occurs thanks to an interaction between wood mass molecules and the external field (Torgovnikov 1993). The ability to interact is preconditioned by the presence of dipolar molecules. At a frequency of 2450 MHz the best absorber of irradiated energy is water molecules, which turn into the direction of the affecting field during MW heating. A fast change in field polarity causes rotation of the water molecules and thus intermolecular friction and appearance of water vapour, which is then forced towards spots with lower pressure, i.e. the surface. The surface remains cool as the surrounding air is not heated by MW. The resulting agreement of the gradient of temperature and moisture content makes MW heating a progressive technology for some areas of the processing industry. The studies using MW energy predominantly focus on increasing permeability of species that are not permeable for liquids and gases in normal conditions (Sugiyaento et al. 2008). Increase in permeability by MW energy was examined by Torgovnikov and Vinden within the production of wood-resin composites (Torgovnikov and Vinden 2000, 2004, 2009). Vinden et al. (2010) explored the issue when modifying permeability of pine railway sleepers for better distribution of preservative treatment. There are also other studies into wood permeability increase by means of MW energy (Kang 1998, Liu et al. 2005, Lin and Lu 2004, Jiang et al. 2006, Brodie 2007, Harris et al. 2008).

The aim of the presented study was to experimentally measure the values of axial permeability of MW treated beech wood for distilled water. MW heating was applied to wood in two versions of thermal loading. Permeability was measured using a laboratory device in stationary conditions and the values of coefficients were calculated by Darcy's law. The resulting values of permeability were compared with the permeability of natural beech wood representing the reference group. To verify the methodology for measuring, the conducting paths were identified in microscopic slides obtained from reference samples.

MATERIAL AND METHODS

For experimental examination of effects of MW heating on wood permeability in the axial direction we have chosen the wood of beech (*Fagus sylvatica* L.). The samples with dimensions 20 x 20 x 30 mm were made from radial timber, which guaranteed their orthotropic character. The angle of grain deviation from the longitudinal axis was 10° and less. The samples were divided into three groups. The first group was a reference group and was subject to no further modification. The remaining two groups were later used for two versions of MW drying. First, the divided and marked samples were dried to 0 % moisture content at a temperature of 103 ± 2°C. The samples without any bound water were measured in the longitudinal (L), radial (R) and tangential (T) directions with 0.01 mm accuracy. Subsequently, both groups of samples were soaked in water for over 30 days. The final moisture content for each group of samples was

checked gravimetrically. The mean moisture content after soaking was 68.3 % for the first group and 100.8 % for the second group. The difference in moisture contents was caused by the fact that the original timber used for sampling came from different stems.

Subsequently, the samples with an moisture content were placed in the operation space of the laboratory microwave device MIA–4K (Fig. 4) and exposed to MW energy. All measuring was conducted at a total output of magnetron generators of 3.6 kW and a frequency of 2450 MHz. For the first version of drying, the time of exposure to MW energy was 240 s, followed by 60 s relaxation and the whole process was applied periodically with total time of drying of 20 min. In the second version of drying the samples were exposed to MW energy for 120 s followed again by 120 s relaxation. These samples were exposed to thermal loading in this cycle for 50 min. The initial moisture content of both groups of samples was above the fibre saturation point, which corresponds better to real drying conditions. In the relaxation time the samples were left inside the microwave device in order to balance the accumulated heat and moisture in the heated material. During the time of relaxation only the fan creating forced air circulation inside the chamber was working. After the last cycle of drying the samples of both groups were conditioned in a conditioned room to a balanced moisture content corresponding to a relative air humidity of 60 ± 5 % and an air temperature of 20 ± 5°C.

Wood permeability in the longitudinal direction was measured experimentally using a device made at the Department of Wood Science, Mendel University in Brno. Distilled water was used as the testing liquid. The procedure of the test followed from the technical design of the device (Figs. 1 and 2). The samples were fixed between two height-adjustable fixing rings with holes delimiting the flow area (Fig. 3). The flowing distilled water was pressed through the samples into a measuring cylinder, which was placed on the table together with the scales. We measured the time necessary for the amount (volume) of water to flow through the sample. The measuring device started measuring when the first drop reached the measuring cylinder and stopped when 10 ml flew through. To measure the permeability of beech wood we chose a pressure of 0.4 MPa and an affected area of 5 mm. The coefficient of specific permeability was calculated using formula (1), which is based on Darcy's law on stationary permeability:

$$K = \frac{V \cdot \eta \cdot L}{S \cdot \Delta p \cdot t} \qquad (\mathrm{m}^2) \tag{1}$$

where: V – volume of distilled water which flew through the sample (m^3),
η – dynamic viscosity of water (Pa.s),
L – length of sample in the direction of flow (m),
S – surface area of liquid flow (m^2),
Δp – difference in pressures on the opposite sides of the sample (Pa),
t – time of flow (s).

Technical description of the device used for the experiment

The device for wood stationary permeability measuring

The device for measuring the stationary permeability consists of a frame to which all functional and controlling elements of the device are fixed (Fig. 1). The frame also holds a pressure container with 2 l volume, which can be filled with testing liquid at the top. The pressure container is connected to a tank with compressed air with maximum pressure of 1 MPa and the excess pressure is controlled by a control valve at the input of the pressure container. The container is also equipped with a safety valve, air-release valve, inlet of compressed air and an access to testing nozzle. The samples are fixed between fixing rings by means of an eccentric mechanism

which allows samples 0–100 mm long to be fixed. The interchangeable rings have circular holes (nozzles) in the centre with various diameters (inner diameter of 5, 10, 15, 20 mm), which create the area of liquid flow (Fig. 3). The device also includes a time measuring appliance and an appliance to measure the weight increment of liquid (electronic scales). Fig. 2 shows the created device for wood stationary permeability measuring in operation.

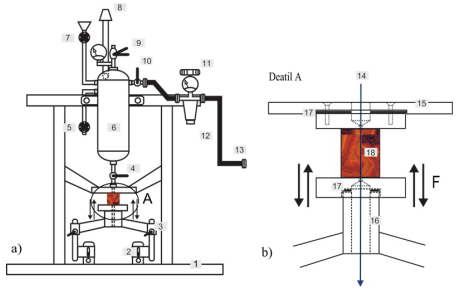

Fig. 1: Diagram of the permeability measuring device: 1 – the frame construction with a base, 2 – a lifting support (fine setting), 3 – a lifting support (rough setting), 4 – a ball valve (distilled water), 5 – an overflow valve, 6 – the pressure container, 7 – a filling valve, 8 – safety pressure valve, 9 – an evacuation valve with a manometer, 10 – a ball valve (compressed air), 11 – pressure controller with a manometer, 12 – a pressure hose, 13 – pressure snap couplings, 14 – testing liquid, 15 – the solid part, 16 – the movable part, 17 – rubber mats, 18 – a sample.

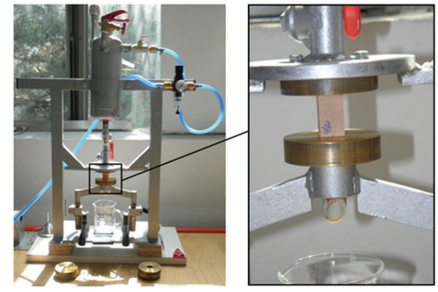

Fig. 2: Created device for wood stationary permeability measuring in operation with a detail of sample fixing.

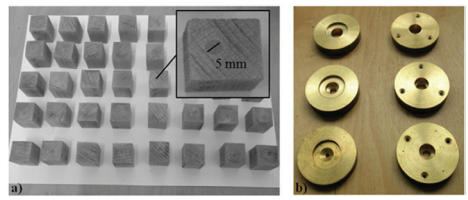

Fig. 3: a) The samples with the defined circular area of liquid flow, b) interchangeable fixing.

Experimental microwave device

All measuring was carried out using the microwave device MIA–4K (Fig. 4); it was primarily designed for the research into the effects of MW energy on wood (Nikl and Nasswettrová 2011). The operational space of MIA-4K is conceived as a multimode resonator with four magnetron generators. They have total output of 3.6 kW (4 x 900 W) and power density of 346 mW.cm^{-3}. Magnetrons work in the CW (continuous wave) mode at 2450 MHz frequency. To reduce the formation of spots with different power density, there are mechanical rotational homogenizers in the chamber. The arising moisture is exhausted from the operational space by an exhaustion fan, which is located at the back of the chamber.

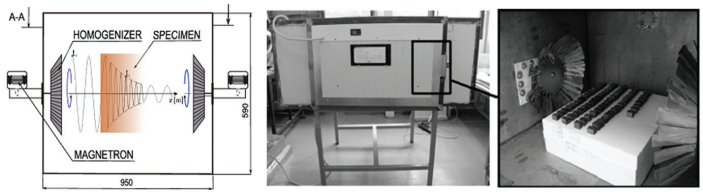

Fig. 4: Device for MW heating – MIA–4K, function and the application space of the chamber.

RESULTS AND DISCUSSION

Selected statistical characteristics of the specific permeability coefficient of beech wood for individual groups are presented in Tab. 1. Permeability values are calculated based on Darcy's law.

Tab. 1: Basic statistical characteristics of permeability coefficients of beech wood for water in the axial direction for all groups.

Group	Number of measuring	Arithmetic mean	Standard deviation	Variation coefficient
	n	$K.10^{12}$ (m^2)	$S_x.10^{12}$ (m^2)	V_x (%)
Reference	50	4.487	2.610	58.161
Version 1	74	10.164	6.553	64.470
Version 2	74	12.413	10.503	84.611

The mean values of permeability coefficients for individual versions with their standard deviations provide us with a basic idea about the selected datasets (Tab. 1). The results show that the mean values of permeability coefficient for distilled water in the axial direction are higher for MW treated samples (versions 1 and 2) than for samples from natural beech wood, which confirms our hypothesis. The mean value of permeability of beech wood unloaded by MW heating (the reference group) is $4.487x10^{-12}$ m^2 with 58.161 % variability. The arithmetic mean of permeability coefficient of MW treated samples in version 1 is $10.164x10^{-12}$ m^2 with 64.47 % variability. The mean permeability coefficient for version 2 is $12.413x10^{-12}$ m^2 with variability of 84.611 %. Tab. 1 highlights the difference between the values of permeability of the samples from the reference group and the samples treated by MW energy represented by versions 1 and 2. The achieved mean value of permeability coefficients of MW treated samples in the first and second version was 2.3 times and 2.8 times higher respectively than the permeability of the reference samples. The permeability coefficient of version 1 is 1.2 times lower than in the case of version 2. The differences in the values can be explained by the selected mode of thermal loading and the total time of MW heating.

The mean value of permeability coefficient for beech wood from the reference group most approaches the value presented by Babiak and Kúdela (1993) K = $4.90x10^{-12}$ m^2. Hudec and Danihelová (1992) present the value of beech axial permeability for water K = $7.56x10^{-12}$ m^2, Požgaj et al. (1997) K = $8.51x10^{-12}$ m^2 and Kúdela (1999) K = $10.00x10^{-12}$ m^2. Studies by other authors present even higher values of permeability coefficients, usually without any further specifications. When comparing the values of permeability coefficient, we can see a substantial difference between the values we obtained for natural and MW treated beech wood and also

from the values the other authors reached. However, the studies dealing with wood permeability usually do not provide the conditions in which samples were measured. Moreover, the variability of results and thus also the final values of permeability are significantly different, which makes mutual comparison very hard. For these reasons, we further compare the values of permeability coefficients of both MW heating versions with our reference group. For a better idea about the comparison of permeability among the three groups, Fig. 5 shows its statistical evaluation graphically.

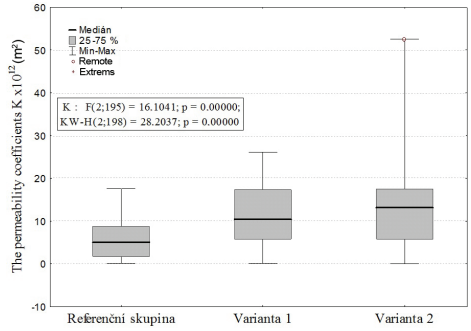

Fig. 5: Mean values of coefficients of axial permeability for individual versions of MW drying.

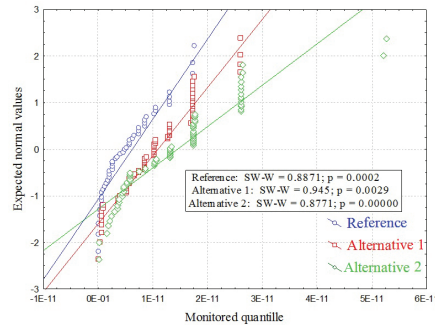

Fig. 6: Probability chart (P-P chart) for the results from the Shapiro–Wilk test of normal distribution of the sets.

Experimentally measured data of permeability coefficients for all groups were subject to exploratory data analysis. The said statistics revealed anomalies and deviations in the distribution of the selection from the typical normal (Gauss) distribution. The normality of data sets for individual groups was tested by means of the Shapiro–Wilk test. Fig. 6 graphically shows the normality test on the measured data of permeability coefficients. The graphical display in the form of a probability chart (P-P chart) compares distribution functions of the selection expressed through the order probability with the standardised distribution function of the selected theoretical distribution (Meloun and Militký 2002). In the case of agreement of the selection distribution with the selected theoretical distribution, the P-P chart would be linear with the unit slope of line and a zero section. Fig. 6 shows the empiric curves of all the tested sets did not correspond to any curve of the symmetric (normal) distribution. The distribution thus was asymmetric and the real behaviour of the measured values prevailingly showed the flat distribution.

Based on the results of normality, the zero hypothesis that the analyzed selections come from basic sets with normal distribution had to be refused. Due to these reasons the Box–Cox transformation was performed at these sets. The data transformation was purposely used for stabilizing the spread, for making the distribution more symmetric and particularly for achieving the normality of distribution. It was necessary to find an x' function of the original x values which would ensure the minimum inclination or the maximum credibility of the transformed data with regard to the normal distribution. To approximate the selection to the normal distribution with regard to the inclination and pointedness characteristics, it was suitable to use the Box–Cox transformation in the following form (2):

$$\Psi(x) = \begin{cases} \dfrac{x^{\lambda} - 1}{\lambda} & \lambda \neq 0 \\ \ln x & \lambda = 0 \end{cases} \quad (2)$$

where: λ – the searched for optimum power of transformation.

The optimum estimate of the λ exponent was sought after with regard to optimizing asymmetry (inclination) and pointedness characteristics. To estimate the λ parameter in the Box–Cox transformation, the selection chart according to the Hineses´ was used, Fig. 7. According to the location of experimental point around the nomographic chart of theoretical curves of the selection chart it was possible to visually estimate the λ exponent and to assess the quality of transformation in various distances from the median.

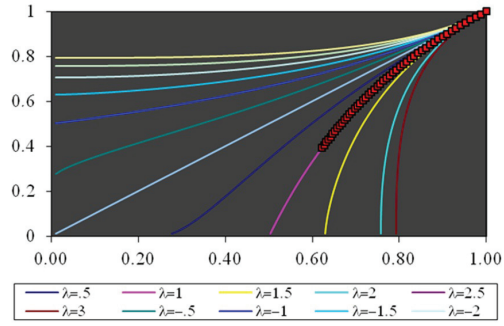

Fig. 7: Graphical display of the selection chart according to the Hineses´ used in the estimate of an optimum λ exponent.

Retransformed parameters of the position (arithmetic average) and spread (standard deviation) of the original data were estimated from the transformed data by means of the software created for retransformation using Taylor´s development. The software enables to retransform the mean value of the basic set with non-normal distribution from the transformed values by means of the Box–Cox transformation. Lambda coefficients from the transformation matrix of every set obtained from the Box–Cox transformation were entered to the software, Tab. 2. The obtained values of position characteristics are stated as resulting representative values of the statistical analysis in Tab. 1 and Fig. 5. By using the aforementioned procedure, we achieved better estimates of positions and spread and an overall higher level of symmetry. The software was created on purpose for the permeability issues specified by Petr Koňas.

Tab. 2: Parameters of the Box–Cox transformation for the analyzed sets.

Wood	**Box–Cox transformation**	
BEECH	**Lambda**	**Matrix for transformation**
Reference	0.325	((v1^(0.325890))-1) / (0.325890)
Alternative 1	0.681	((v2^(0.681829))-1) / (0.681829)
Alternative 2	0.461	((v3^(0.461259))-1) / (0.461259)

Figs. 8, 9 and 10 state the graphic display of histograms and quantille-quantille charts (Q-Q charts) showing the distribution of selections before and after the performed Box–Cox transformation.

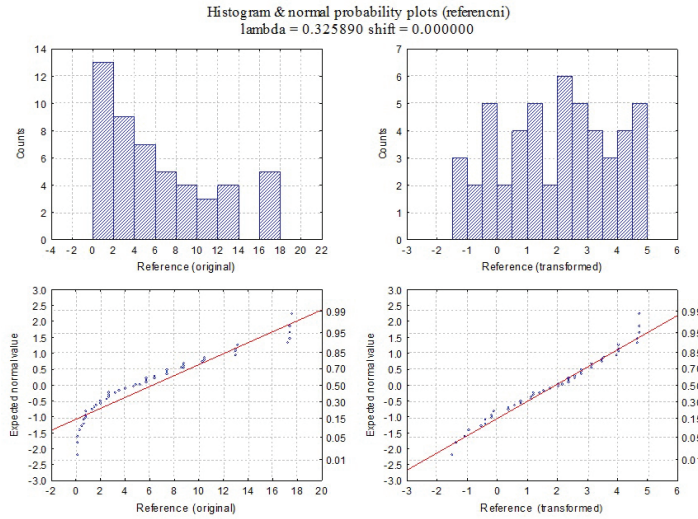

Fig. 8: Histograms and Q-Q charts showing the distribution of mean values before and after the data transformation – the reference group.

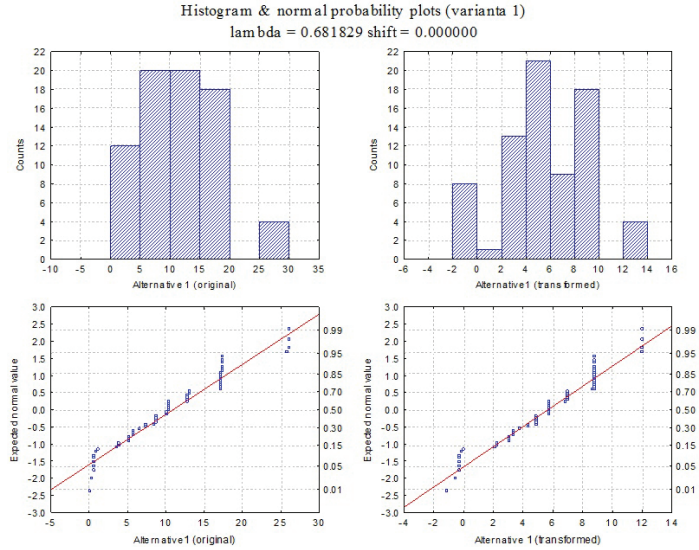

Fig. 9: Histograms and Q-Q charts showing the distribution of mean values before and after the data transformation – Alternative 1.

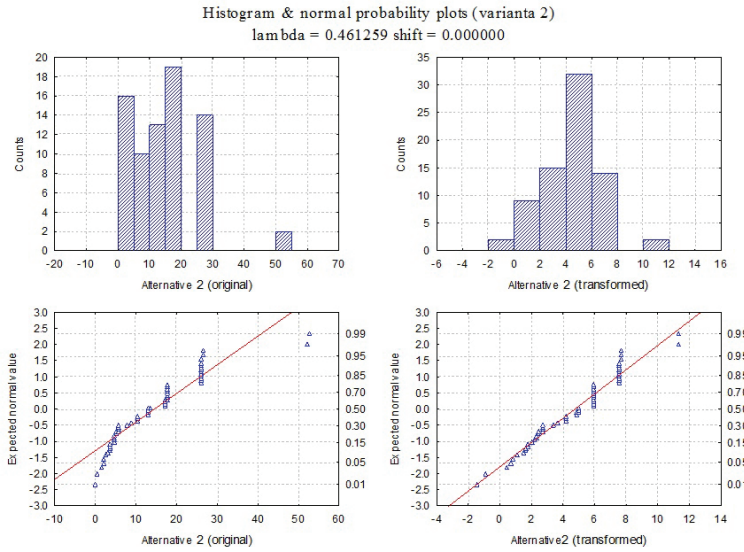

Fig. 10: Histograms and Q-Q charts showing the distribution of mean values before and after the data transformation – Alternative 2.

The substantial difference in the permeability of MW treated beech wood can be explained by the changes in wood structure caused by the differing cycles of MW heating, the total time of MW energy exposure, and the initial high moisture content of the wood. These factors significantly affected the movement of mass and energy during the removal of water from the capillary system of the wood. In our case, the moisture content of samples before exposure to MW energy was higher than the fibre saturation point (w > FSP): on average, 68.3 % for version 1 and over 100 % for version 2. A high content of moisture increases the ability of MW energy absorption and thus also the temperature in the cross section. The free water, which is inside the cell cavities, is kept there mechanically and by the forces of mutual capillary interaction. If the moisture content exceeds the fibre saturation point, a free water molecule reacts with EM field independent of wood, therefore, an increase in free water amount in a unit of volume means a change in the value of the dielectric constant (ε´) and the loss tangent (tgδ) (Torgovnikov 1993). The stated dielectric parameters are of an anisotropic character and they express the size of energy dissipation in wood and its subsequent transformation into heat (Makovíny 1999). At a frequency of 2450 MHz the loss angle has a positive temperature coefficient and thus evaporation of water molecules and their shifting over the complex inhomogeneous structure occurs. The produced water vapour is kept near the surface layers by heavier cold liquid, which can be together with the small diameter of conducting paths and large volume of vapour the cause of damaged wood elements. In the establishment of the specific coefficient of wood axial permeability, also the moisture content at which permeability is found out is important. In our case, the moisture content after MW heating was below the fibre saturation point (w < FSP) for both versions. At this moisture content, also other wood polymers, cellulose, hemicellulose and lignin which create the cell wall substance, are affected by the EM field (Torgovnikov 1993). The process of polarization is brought about by the EM field. It is associated with a displacement and rotation of hydroxyl (-OH) and methylol (-CH_2OH) polar groups, or even entire cellulose molecules, relative

to the immovable parts of the macromolecules (Torgovnikov 1993). The process of polarization (dipole) causes a dissipation of electric energy and its transformation into heat energy. We can assume that the MW energy affecting these polymers and water in wood could cause a thermal tension in cells and between them, which could afterwards become the cause of the change in conducting paths and thus also the increase in the permeability coefficient. Nevertheless, the changes (deformations) in the structure may not appear in the entire volume of the sample at the same number and extent, due to the uneven distribution of moisture in the cross section and the MW heating itself. Zielonka and Gierlik (1999) say that the interaction of the MW energy with wood polymers only little contributes to MW heating of moist wood and that the main actor reacting with MW energy is a water molecule. Based on this and with respect to the large variance of measured values, the effect of factors such as high moisture content and the time of exposure to MW energy may not be the only causes of the increase in permeability coefficient in versions 1 and 2. Wood permeability is a highly variable quantity dependent besides moisture content on density and structure of wood.

CONCLUSIONS

The aim of the study was to establish the values of permeability of MW treated beech wood for distilled water in the axial direction. MW energy was applied to samples in two versions of measurement. The device for MW heating worked at an output of 3.6 kW and a frequency of 2450 MHz. For the first version of MW heating, the exposure time was 240 s and the relaxation time was 60 s; the entire process was applied for 20 min. In the second version, both the exposure and the relaxation time was 120 s, the total time of MW heating exposure was 50 min. The initial moisture content of samples for both versions was above the fibre saturation point. Longitudinal wood permeability was measured by means of a device fabricated at the Department of Wood Science, Mendel University in Brno. The values of permeability coefficients were calculated by Darcy's law and compared with permeability of reference samples. Based on the results, we can state that mean permeability coefficient for distilled water reaches higher values for samples treated by MW energy (versions 1 and 2) in comparison with the reference samples. The mean permeability of samples not treated by MW heating is 4.487×10^{-12} m^2 – this value approaches the values presented by other authors. The permeability values of versions 1 and 2 were 2.3 times ($k = 10.164 \times 10^{-12}$ m^2) and nearly 2.8 times ($k = 12.413 \times 10^{-12}$ m^2) higher, respectively. The value of permeability in version 1 was 1.2 times lower than the mean permeability of version 2. The difference between these values can be contributed to the changes in the structure of conducting paths caused by the selected mode of thermal loading, the total time of MW exposure and the high content of initial moisture in the structure of samples. With respect to the great variance of measured data and the high variability of the wood permeability, it is recommendable to perform further research into the mentioned property of material exposed to MW heating.

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Andrea Nasswettrová, Pavel Šmíra
Thermo Sanace S.R.O.,
Chamrádova 475/23
718 00 Ostrava – Kunčičky,
Czech Republic
Corresponding author: andrea.nasswettrova@gmail.com

Jiří Zejda, Květoslav Nikl, Václav Sebera
Mendel University in Brno
Faculty of Forestry and Wood Technology
Department of Wood Science
Zemědělská 1
613 00 Brno
Czech Republic