Microwave Device for Continuous Modification of Wood

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The aims of this study were to introduce a new laboratory microwave device developed for the modification of wood properties and to examine the effect of microwave radiation on moisture loss, surface temperature, and mechanical properties (the static modulus of elasticity - MOE, and the modulus of rupture - MOR) of Norway spruce (*Picea abies*). The device was developed for a continuous modification process. The microwave (MW) generator works at a frequency of 2450 MHz, and the adjusted output ranges from 0.6 to 6 kW. The experiment was based on four different modes of MW modification, each of them with a varied generator output and conveyor speed. Regarding mechanical properties, the results showed that a feasible output for the MW modification of the samples was up to 3 kW, with a conveyor speed of around 0.4 m/min. The greatest moisture loss, approximately 40%, was found in the group treated at 5 kW and 0.2 m/min. The highest surface temperature, 87 °C, was measured in the group treated at 5 kW and 0.4 m/min after the second passage through the modification chamber.

Keywords: Device; Microwave; Drying; High-frequency energy; Modification; Wood

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INTRODUCTION

Microwave (MW) modification of wood has been used in experiments for drying (Hansson and Antti 2003), pre-drying (Awoyemi 2004; Beikircher *et al.* 2012; Harris *et al.* 2008), better fixation of impregnation agents in the wood structure (Yu *et al.* 2009), better permeability and impregnability (Torgovnikov and Vinden 2009), and to achieve plasticization (Studhalter *et al.* 2009).

A laboratory MW device has been introduced (Brodie 2004; 2007; Dömény *et al.* 2014; Hansson and Antti 2003; 2006; Hansson *et al.* 2005; Harris *et al.* 2011; Sethy *et al.* 2012; Sugiyanto *et al.* 2010; Zhao *et al.* 1998). A device for industrial applications has also been presented (Torgovnikov and Vinden 2004; 2009; Vinden *et al.* 2011). The drawback indicated by Manickavasagan *et al.* (2006), Sebera (2012), and Nasswettrova *et al.* (2013) is the non-homogeneity of the MW field. This negative feature causes an uneven cross-sectional distribution of material drying. The non-homogeneity of the MW field can be eliminated through a continuous modification (Torgovnikov and Vinden 2009), adding a special homogenizing element into the application chamber (Nasswettrová 2013), or increasing the number of waveguides in the application chamber (Sebera *et al.* 2012).

Oloyede and Groombridge (2000) concluded that the tension inside wood decreases by up to 60% when dried by microwave energy as compared to conventional drying. Antti *et al.* (2001) supported this theory. However, they emphasized that all parameters must be set right and the process controlled. Hansson and Antti (2006) investigated the effect of the drying methods (microwave and convectional drying) and temperature (60 to 110 °C) on wood hardness. Provided the drying process is controlled, they concluded that variables such as anatomical direction, anatomical structure, and wood density have more effect on hardness than the drying method or the temperature. Antti (1995) presented the results of microwave dried samples of the pine and the spruce at 8% moisture content. The process was controlled based on the internal temperature (not exceeding 140 °C), internal vapour pressure, and moisture vapourisation velocity. The author concluded that the moisture loss at moisture contents over the fibre saturation point was 0.20 to 0.45% *per* min, and that below the fibre saturation point was 0.10 to 0.20% *per* min. The study showed that spruce samples dried 1.6 times faster than pine samples. No conditioning of the wood was necessary since the wood was free of stresses. Brodie (2008) stated that the dielectric properties of most materials depend on temperature, frequency, and moisture content. According to Torgovnikov (1993), wood has dielectric properties due to the water it contains and the content of hydroxyl (-OH) and methylene (-CH_2OH) groups. These are mostly contained in the cellulose amorphous part. The dielectric properties of wood vary in the three basic directions, *i.e.*, radial, tangential, and longitudinal (R, T, L), and are characterised by two main parameters: the dielectric loss tangent (tgδ) and the relative permittivity (ε'). The dielectric loss tangent (tgδ) represents the radiated energy that turns into heat and is absorbed by the material under the influence of the electric field (Torgovnikov 1993). The relative permittivity is the ratio between the capacity (C) of a capacitor filled with the dielectric and the capacity (C_0) of the same capacitor filled with a vacuum. According to Brodie (2008), the electromagnetic wave transmitted through a dielectric material will manifest a dampening and delay in signal when compared to the same wave passing through a vacuum.

Device Parameters

The research team at the Department of Wood Science, Mendel University in Brno, developed a device with continuous operation (Fig. 1) to further understand the effects of wood microwave modification. The team cooperated with the Romill Company, which has extensive experience regarding research and development due to the high number of microwave applications for various industrial fields in Central Europe they have provided.

The device consists of the bearing construction, conveyor, modification chamber, waveguide, and source. The dimensions are 3400 x 500 x 1425 mm^3 (length × width × height). The conveyor velocity is controlled by the frequency changer. The dimensions of the modification chamber are 600 x 600 x 600 mm^3. The maximum possible dimensions of the treated material are 3000 x 450 x 50 mm^3. The center of the device is the microwave generator, containing a magnetron with an output adjustable from 0.6 to 6 kW. To achieve the maximum possible absorption of the output radiation by the material, the waveguide is equipped with two electric motors that modify the geometry of the electromagnetic wave entering the chamber. The device is equipped with two inserts from attenuation ceramics to prevent leaks of the unabsorbed output from the chamber.

The entire construction of the device and the modification chamber were developed as a unique prototype. Therefore, one of the aims of the study is to examine the effect of MW radiation on moisture loss, surface temperature, and mechanical properties of the wood of Norway spruce (*Picea abies*) using this device.

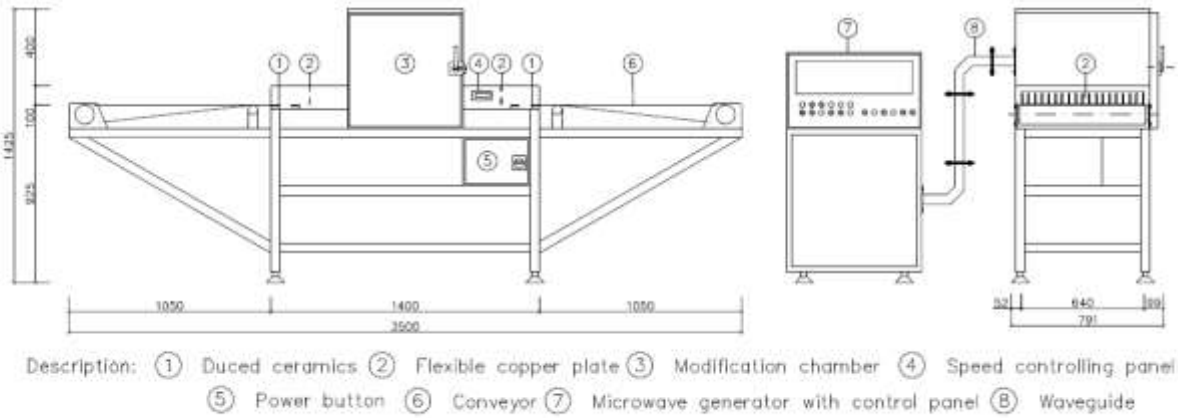

Fig. 1. Continuous microwave device

EXPERIMENTAL

Sample Preparation

Samples with dimensions of 40 × 110 × 500 mm^3 (radial × tangential × longitudinal) were made from Norway spruce (*Picea abies*) wood. The materials used were free of defects such as cracks, pith, fibre deflection, reaction wood, fungi, and insects. Before microwave drying, the samples were soaked in distilled water for five weeks. The material entering the modification process had on average 77% moisture content (Table 1).

Microwave Modification

The samples tested were divided into four groups, based on the mode of MW modification. The groups differed by the different radiation outputs and the speed of movement through the modification chamber, *i.e.*, conveyor speed. The first group was treated with an output of 3 kW at a conveyor speed of 0.4 m/min in two cycles (2 passages through the modification chamber). The second group was exposed to an output of 5 kW with the same speed in two cycles. The third and fourth groups were only treated by one cycle, at outputs of 3 kW and 5 kW, respectively, and a conveyor speed of 0.2 m/min (Fig. 2). The laboratory was conditioned at 20 °C and 40% relative humidity.

Moisture Content

The samples were weighed before entering the device and after coming out at each cycle. Then, the samples were dried to 0% moisture content in a conventional laboratory drying chamber. The moisture content was calculated by the oven-dry (OD) method in compliance with EN-13183 (European standard 2002).

Temperature

The temperature of the samples was measured using a contactless infrared thermometer (IR -380) at three points (front, centre, and rear) before and after the modification (Fig. 3). These values were used to calculate the arithmetic mean.

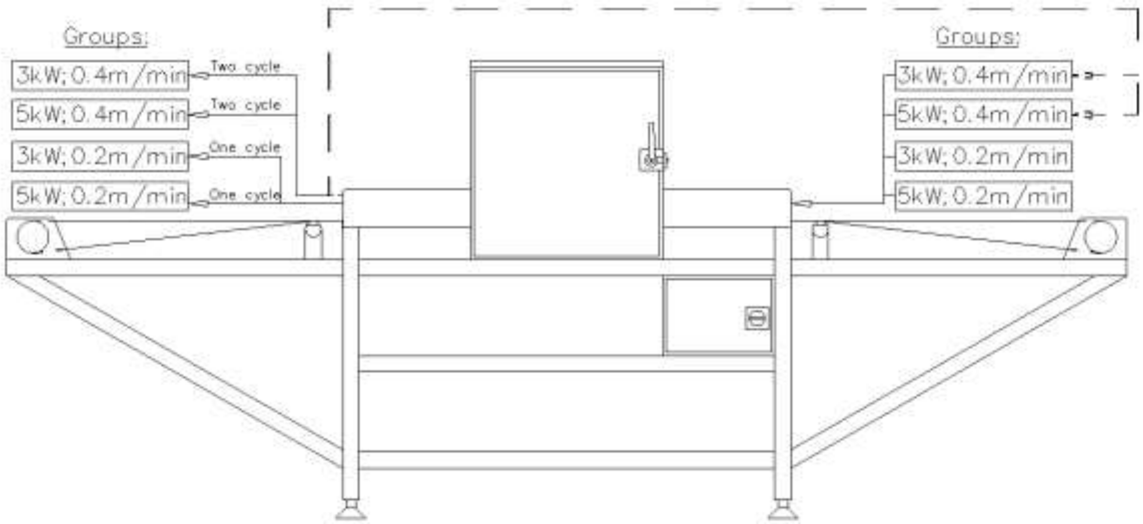

Fig. 2. Scheme of tested procedures (groups and cycles)

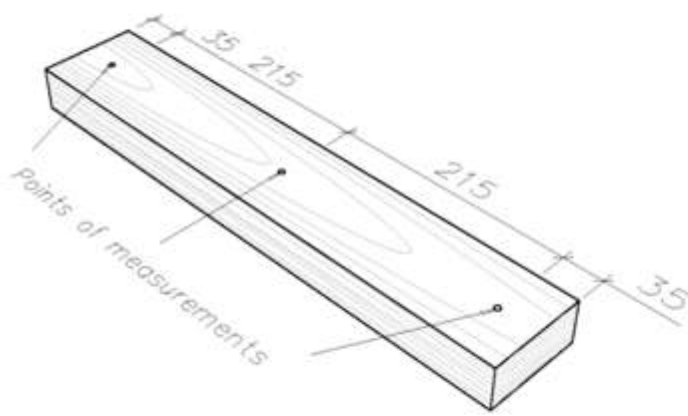

Fig. 3. Temperature measurement points

Mechanical Properties

After the microwave modification and the measuring of temperature and moisture content, the samples were cut (Fig. 4) into bending samples with dimensions of 20 × 20 × 300 mm^3 (R × T × L). The modulus of elasticity (MOE) and the modulus of rupture (MOR) in static bending perpendicular to the grain in the radial direction (Fig. 5) were measured in at 12% moisture content.

The span of supports was 240 mm, the radius of supports and the forcing head was 15 mm (Fig. 5). The value of MOR was calculated from the maximum loading force, as given in Eq. 1:

$$MOR = 3 F_{max} l / (2 b h^2) \tag{1}$$

where *Fmax* is the maximum loading force, *l* is the span of supports, *b* is the width of a cross-section of the sample, and *h* is the thickness of the sample (height of a cross-section).

The calculation of MOE was based on forces measured at 10% and 40% of the maximum loading force (force of destruction) and the corresponding deflections of a bended beam measured by an extensometer. The MOE was calculated from Eq. 2,

$$MOE = l^3 (F_{40\%} - F_{10\%}) / [4\ b\ h^3 (u_{40\%} - u_{10\%})] \quad (2)$$

where l is the span of supports, $F_{40\%}$ and $F_{10\%}$ are forces at 40% and 10% level of the maximum force *Fmax*, respectively, b is the width of the sample cross-section, h is the thickness of the sample (height of a cross-section), and $u_{40\%}$ and $u_{10\%}$ are deflections at forces $F_{40\%}$ and $F_{10\%}$, respectively.

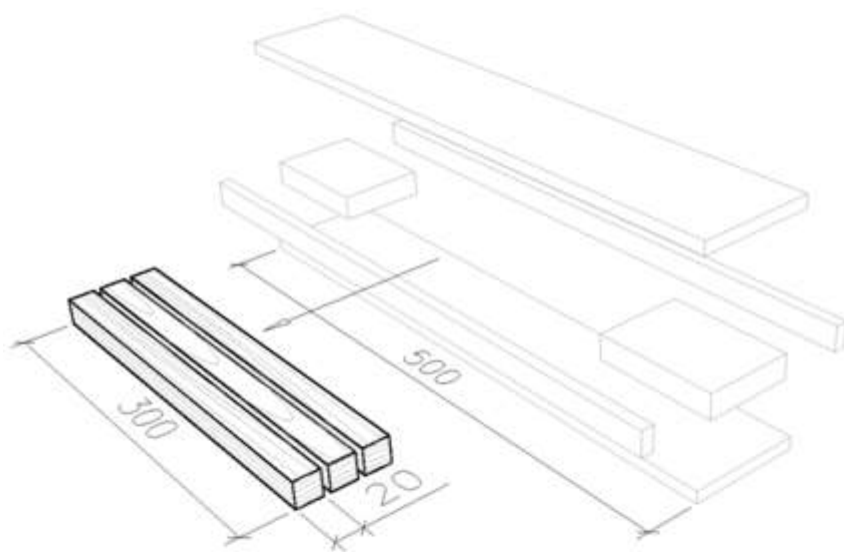

Fig. 4. Cutting of a sample for the bending measurement

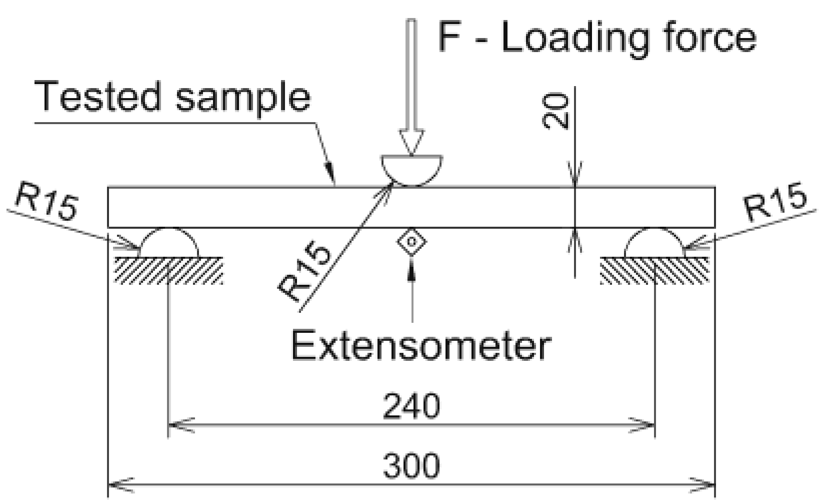

Fig. 5. Measuring modulus of elasticity and modulus of rupture

Processing of Results

The results were processed in STATISTICA. They were evaluated using one-factor analysis of variance (ANOVA), complemented with Tukey's HSD test.

RESULTS AND DISCUSSION

Moisture Content

Table 1 shows the statistical analysis of the moisture content data for all MW modification modes.

Table 1. Moisture Content

Moisture Content						
Cycle	Number of samples	Average (%)	Median (%)	Minimum (%)	Maximum (%)	Variability (%)
Untreated (3 kW; 0.4 m/min)	6	77	77	74	82	4
1st 3 kW; 0.4 m/min	6	73	73	71	77	3
2nd 3 kW; 0.4 m/min	6	64	64	58	69	6
Untreated (5 kW; 0.4 m/min)	6	79	78	69	90	9
1st 5 kW; 0.4 m/min	6	68	68	59	78	9
2nd 5 kW; 0.4 m/min	6	45	46	38	53	12
Untreated (3 kW; 0.2 m/min)	5	76	75	72	82	5
1st 3 kW; 0.2 m/min	5	57	56	51	62	8
Untreated (5 kW; 0.2 m/min)	5	77	80	69	82	7
1st 5 kW; 0.2 m/min	5	37	36	33	43	10

Figure 6 shows the moisture loss of the samples (wood). The MW modification mode with an output of 3 kW and a conveyor speed of 0.4 m/min reduced the wood moisture content by 4% after the first passage through the modification chamber, which is 10 times more than that published by Antti (1995). She concluded that the loss of moisture over the fibre saturation point was 0.20 to 0.45% *per* min. After the second passage, the wood moisture content was up to 13% lower than the initial moisture content. The doubled moisture loss after the second passage was caused by the increased material temperature (Table 2 and Fig. 8). The MW modification mode with an output of 5 kW and a conveyor speed of 0.4 m/min caused an 11% moisture content decrease at the first passage through the chamber and a 34% moisture content decrease at the second passage, when compared with the initial wood moisture content. The MW modification modes with a conveyor speed of 0.2 m/min consisted of only one passage through the modification chamber. The output of 3 kW resulted in a 19% moisture content decrease; the output of 5 kW decreased the moisture content by up to 40%. Figure 7 displays the dependence of moisture content on the speed of the conveyor and MW power, and Eq. 3 describes this relationship,

$$MC = 76.9899-(4.0197*POW)-(5.2876*CS)+(12.6141*POW^{2})+(7.9003*POW*CS)-(0.8603*CS^{2}) \quad (3)$$

where MC is moisture content, POW is MW power, and CS is conveyor speed.

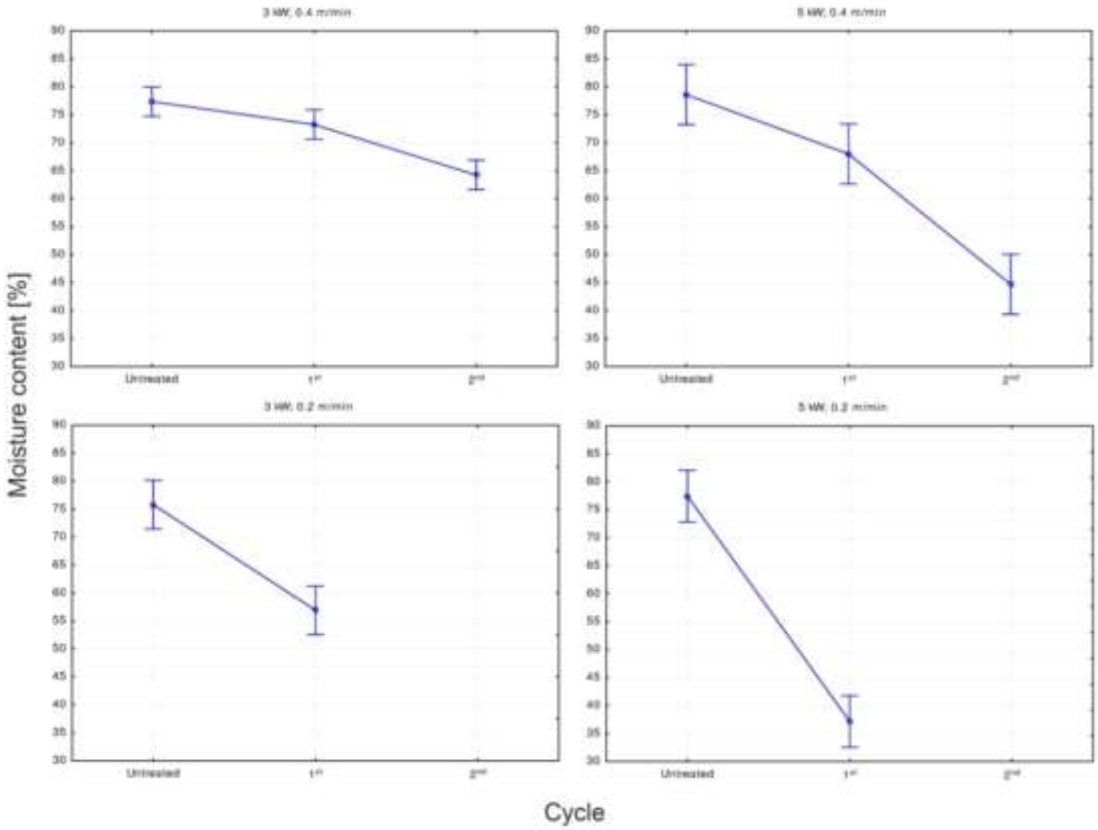

Fig. 6. Moisture content with different modification cycles

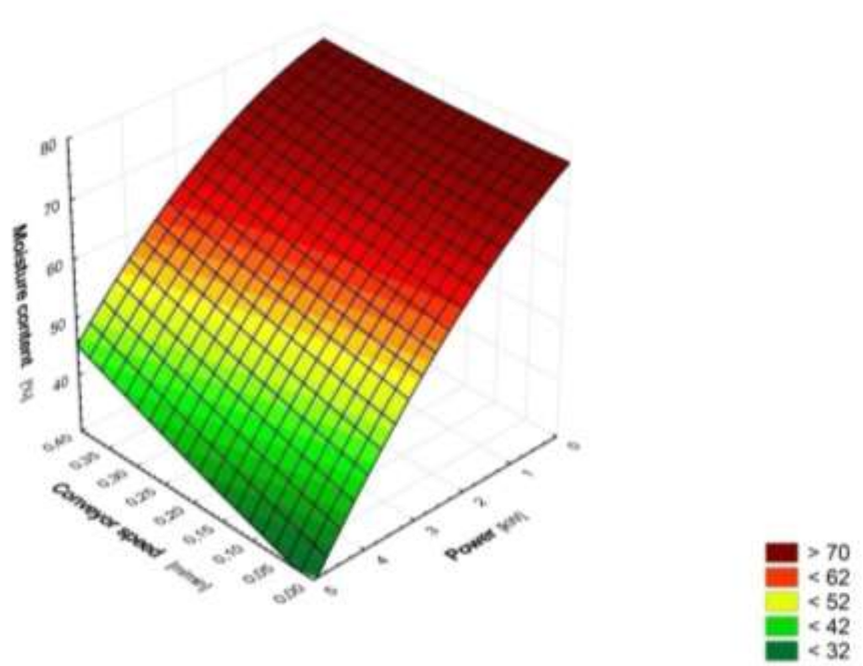

Fig. 7. Influence of MW power and conveyor speed on moisture content

The only statistically insignificant moisture content reduction, according to Tukey's HSD test, was found for the first passage through the modification chamber at an output of 3 kW and a speed of 0.4 m/min. The decrease in the moisture content of the samples was statistically significant in the case of all the other modes (2nd 3 kW, 0.4 m/min; 5 kW, 0.4 m/min; 3 kW, 0.2 m/min; 5 kW, 0.2 m/min).

Surface Temperature

The surface temperature of all the wood samples entering the MW modification was 16 °C. Table 2 presents the surface temperatures of the samples after they came out of the modification chamber. Figure 9 displays the dependence of surface temperature on the conveyor speed and MW power, and Eq. 4 describes this relationship,

$$TEMP = 16.052 + (22.4409 * POW) + (20.7302 * CS) - (1.7989 * POW^2) - (7.1643 * POW * CS) - (65.529 * CS^2) \quad (4)$$

where *TEMP* is surface temperature, *POW* is MW power, and *CS* is conveyor speed.

The temperature of the wood surface after the first passage through the chamber at an output of 3 kW and a speed of 0.4 m/min increased by 36 °C when compared with the initial temperature. The second passage increased the temperature by another 23 °C, which was an increase of 59 °C when compared to the initial temperature. The MW modification with an output of 3 kW and speed of 0.2 m/min increased the temperature by 53 °C. The MW modification with an output of 5 kW and a speed of 0.2 m/min increased the temperature by 59 °C when compared with the initial temperature. In the case of a speed of 0.4 m/min and an output of 5 kW, the temperature increased by 54 °C after the first passage and another 9 °C after the second passage of the samples through the modification chamber, a difference of 63 °C from the initial temperature. The smaller increase in temperature after the second passage is caused by the lower content of water in the wood (Table 1, Fig. 6) and thus also a lower absorption of MW radiation. The absorption of MW radiation decreases when the temperature of the material increases because water molecules oscillate by themselves due to their high enthalpy. Moreover, individual molecules are further from each other with an increased temperature and thus their collisions, influencing the friction of molecules and heating up of the material, do not occur often. Based on Tukey's HSD test, all modes and cycles of the MW modification were statistically significant from the perspective of the temperature increase.

Table 2. Sample Surface Temperatures

Surface Temperatures						
Cycle	Number of samples	Average (°C)	Median (°C)	Minimum (°C)	Maximum (°C)	Variability (%)
1st 3 kW; 0.4 m/min	6	52	50	50	56	5
2nd 3 kW; 0.4 m/min	6	75	77	69	80	7
1st 5 kW; 0.4 m/min	6	70	70	65	75	5
2nd 5 kW; 0.4 m/min	6	79	77	75	87	7
1st 3 kW; 0.2 m/min	5	69	70	65	71	4
1st 5 kW; 0.2 m/min	5	75	75	70	80	6

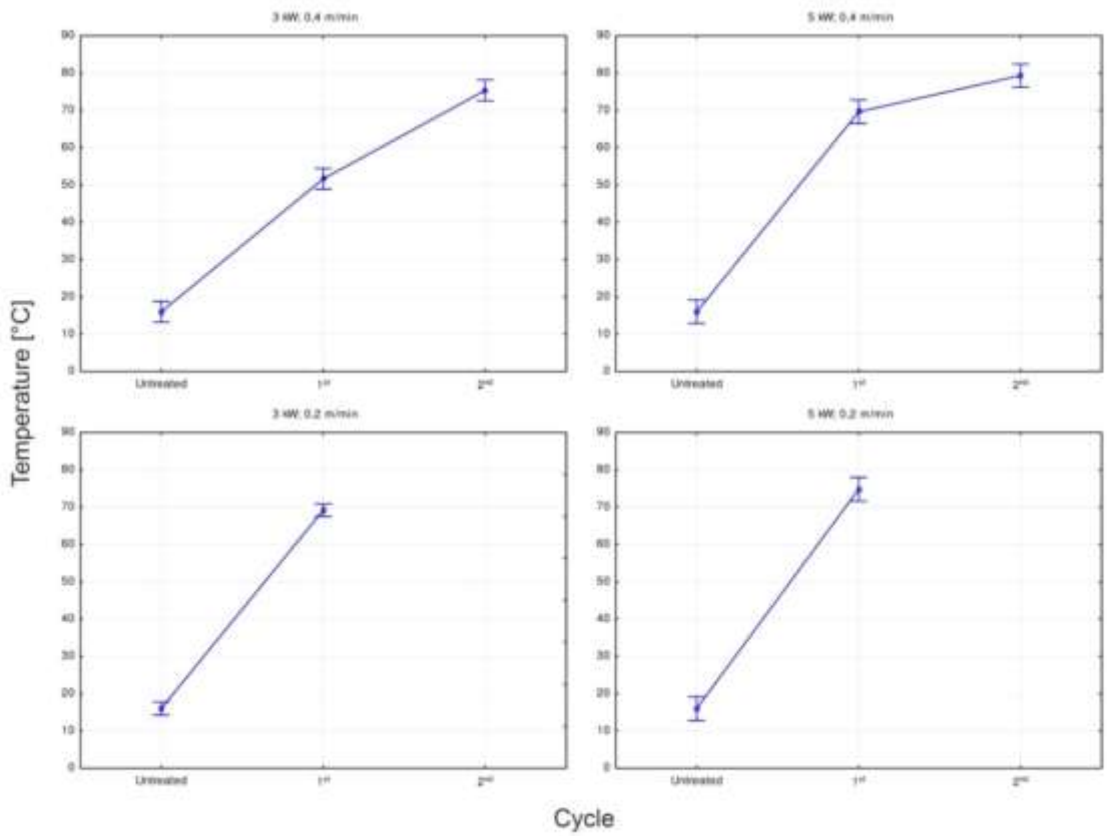

Fig. 8. Temperature with different modification cycles

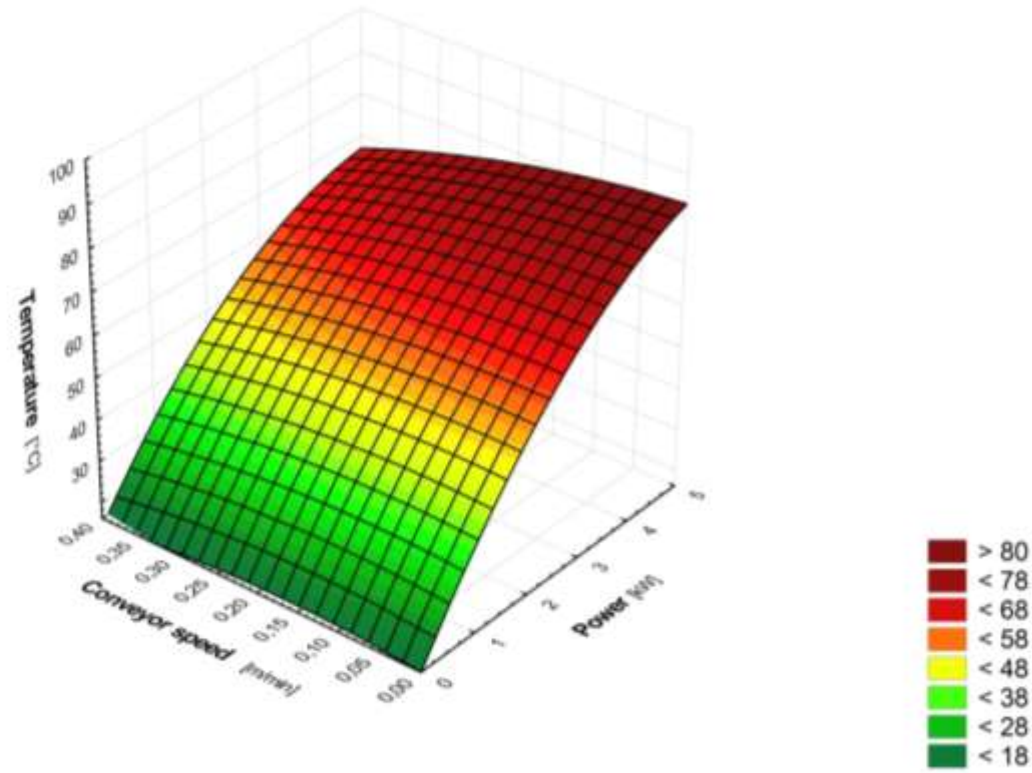

Fig. 9. Influence of microwave power and conveyor speed on the sample surface temperature

Mechanical Properties

The mechanical properties of the microwave-treated wood were assessed with static bending perpendicular to the grain. The mechanical properties of the samples exposed to (5 kW, 0.4 m/min), (3 kW, 0.2 m/min), and (5 kW, 0.2 m/min) could not be measured. Their structures were totally damaged, indicating an improper setting of MW modification parameters. Table 3 shows that the MW modification parameters (generator output and conveyor speed) were set correctly only in the case of the group treated at 3 kW and 0.4 m/min. The values of MOE (8289 N/mm^2) and MOR (74 N/mm^2) in this group are comparable to the reference group and data published in the literature (Požgaj *et al.* 1997).

Hansson and Antti (2006) stated that variables such as moisture content of the initial material, anatomical structure, and density affect the hardness of wood more than the selected mode of drying (MW x convectional). According to our results, the parameters that significantly affected the mechanical properties of MW-treated wood are the MW output and the conveyor speed used. The variables mentioned by Hansson and Antti (2006) are difficult to control. On the contrary, parameters such as the output power and the conveyor speed can be adjusted precisely. However, if they are set wrong, it has fatal consequences for the treated material (Table 3). Torgovnikov and Vinden (2009) performed a MW modification of Paulownia (*Paulownia fortunei*) wood at an output of 30 kW and frequency of 0.922 GHz. They concluded that the MW modification caused high heat loading. Moreover, water vapour developed a high pressure in its structure and delaminated cell wall tracheids and pith rays. This led to a decrease in the tangential direction MOE from 3400 to 1600 N/mm^2 and a decrease in the tangential direction MOR from 39.3 to 16 N/mm^2. Torgovnikov and Vinden (2000; 2001) treated eucalyptus wood with MW power. The MOE decreased by 12 to 17% and the volume increased by 13.4%. Liu *et al.* (2005) treated the wood of larch (*Larix olgensis*) with MW power and then measured the permeability, MOE, and MOR of the samples in bending and compared the acquired values with data from reference samples. They stated that the correct selection of MW modification parameters improved the permeability of the treated samples, without any considerable decrease in the MOE and the MOR. The permeability increased due to the delamination of the pit membranes in the radial parenchyma and the occurrence of small cracks in cell walls. Zhou *et al.* (2007) exposed the larch wood to intensive MW heating and then examined the changes in bending properties and toughness. The results showed that a correct setting of the MW modification parameters decreased the MOE and impact toughness by only about 10%.

Table 3. Sample Bending Test Results (MOE and MOR)

Bending	Reference	3 kW, 0.4 m/min	5 kW, 0.4 m/min	3 kW, 0.2 m/min	5 kW, 0.2 m/min	Literature (Požgaj *et al.* 1997)
MOE [N/mm^2]	*8463*	*8289*	*unmeasurable*	*unmeasurable*	*unmeasurable*	*8210*
MOR [N/mm^2]	*75*	*74*	*unmeasurable*	*unmeasurable*	*unmeasurable*	*73*

CONCLUSIONS

1. Because of the unique construction of the microwave device, the results of our experiments differ from the results of similar studies (Brodie 2004; 2007; Hansson and Antti 2003; 2006; Hansson *et al.* 2005).
2. The average surface temperature was 75 °C, and the average moisture loss was 13% after two cycles of modification in the group treated at 3 kW and 0.4 m/min. The static bending perpendicular to the grain manifested values of MOE and MOR of 8289 N/mm^2 and 74 N/mm^2, respectively. The average surface temperature of the group treated at 5 kW and 0.4 m/min was 79 °C, and its average moisture loss was 34%. The MOE and MOR could not be measured. The average surface temperature of the group treated at 3 kW and 0.2 m/min was 69 °C, and its average moisture loss was 19%. The MOE and MOR could not be measured. The average surface temperature of the group treated at 5 kW and 0.2 m/min was 75 °C, and its average moisture loss was 40%. The MOE and the MOR could not be measured.
3. The acquired data show that the primary parameters affecting the properties of microwave-treated spruce (*Picea abies*) wood are the generator output and conveyor speed. A high power output (5 kW) and a slow conveyor speed (0.2 m/min) had a negative impact on the changes in the wood structure and the mechanical properties of the wood. Wood treated in this way can be used for pressure impregnation by synthetic resins with a following material densification or for pulping during the production of fibreboards, cellulose, and paper (Torgovnikov and Vinden 2009). Another possible application could be the drying of firewood and wood chips.
4. The results of this study indicate that it is necessary to conduct further experiments to optimize the process of wood microwave modification. Based on the data obtained during the first experiment, a lower output and a faster movement through the modification chamber will be used for the modification to maintain the mechanical properties of the material. The authors are planning to conduct experiments in which the internal temperature of the material would also be measured (optical sensors), microscopic analysis of the wood structure will be performed, and the changes in the density of the modified material will be examined.

ACKNOWLEDGEMENTS

This work is supported by the European Social Fund and the state budget of the Czech Republic, project "The Establishment of an International Research Team for the Development of New Wood-based Materials" (reg. no. CZ.1.07/2.3.00/20.0269), and by the Internal Grant Agency (IGA) of the Faculty of Forestry and Wood Technology, Mendel University in Brno (IGA I 32/2013, IGA V 79/2013).

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Article submitted: February 3, 2014; Peer review completed: March 27, 2014; Revised version received: April 2, 2014; Accepted: April 6, 2014; Published: April 9, 2014.