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# Intensification of beech wood drying process using microwaves

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This paper analyses the influence of the applied microwave power output on the intensification of drying in the context of process kinetics and product quality. The study involved testing samples of beech wood (*Fagus sylvatica* L.). Wood samples were dried in the microwave chamber at: 168 W, 210 W, 273 W, 336 W and 378 W power output level. For comparison, wood was dried convectively at 40 °C and 87% air relative humidity. The analysis of drying process kinetics involved nonlinear regression employing the Gompertz model. Dried samples were subjected to static bending tests in order to specify the influence of the applied microwave power on modulus of elasticity (*MOE*) and modulus of rapture (*MOR*). The obtained correlations of results were verified statistically. Analysis of drying kinetics, strength test results and Tukey's test showed that the applied microwaves of a relatively low level significantly shortened the drying time, but did not cause a reduction in the final quality of dried wood, compared with conventional drying.

**Keywords:** beech wood, microwave drying, strength tests, nonlinear regression

## 1. INTRODUCTION

The search for alternative drying methods – compared with convection has continued for many years. Supporting the conventional drying method with more refined techniques has become a challenge in the era of dynamically developing new technologies. These aimed to reduce energy consumption and intensify drying processes, understood as an improvement in drying kinetics with a particular focus on maintaining final product quality (usable and mechanical properties). One of such methods is drying of moist porous materials in high frequency electromagnetic field. Unlike convective drying – which involves external heat supply through the material surface – in microwave drying microwaves penetrate the structure of the material while heating its entire volume. The volumetric heating method with a properly selected microwave power is much more advantageous in terms of of moisture transport in the material being dried, compared with the conventional method of heating through the surface. Consequently, drying time is reduced, efficiency of energy consumption is improved, and the possibility of obtaining better quality dried products emerges, particularly ones characterised by a high shrinkage rate.

In general, according to data available from literature, the group of materials processed with microwave energy includes: food, plants, textile materials, wood, soils and other biological material (Mujumdar,

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2015). Among publications on the application of microwaves for drying purposes there is a group of works about dielectric heating in industrial processes (Metaxas, 1991; Schiffman and Mujumdar, 1987; Tinga and Nelson, 1973), which discuss both theoretical foundations of microwave drying and ready systemic industrial solutions, examples of process lines, as well as economic considerations. Another group of publications includes strictly experimental papers focusing on both kinetics and material quality (Itaya et al., 2004; Lei et al., 2011). The problems of wood microwave drying in industrial applications were already presented in 1987 by Schiffmann and Mujumdar (Schiffmann, 1987). The authors described a mechanism of moisture transport during dielectric heating, pointing to the need of combining conventional and microwave drying as the most beneficial solution in the context of material quality. Numerous disadvantages and advantages of both wood drying methods were also discussed in the paper.

The comparison of convective and microwave drying methods remains in the area of research interest not only with a view to more in-depth exploration of kinetics, but also in order to optimize the process of moisture removal (Hansson and Antti, 2003; Lei et al., 2011). Some authors tried to assess the impact of drying method on the mechanical properties of dried wood.

According to some researchers (Oloyede and Groombridge, 2000) microwave drying reduces wood strength by as much as 60% compared with the conventional method of drying i.e. convective, carried out at 50 °C to 100 °C. These conclusions are questioned by other authors (Hansson and Antti, 2003) who claim that the drying method has practically no influence on the mechanical properties of wood. The authors of the above-mentioned works (Hansson and Antti, 2003; Oloyede and Groombridge, 2000) used a high power range while analysing the effects of microwave drying process: from 800 W to even 1600 W.

Another group of papers comprises articles that correlate theoretical modelling of the drying process with practical experience. Among those, there are both works whose authors do not account for the mechanical aspect in theoretical considerations, and ones that contain wider references to the issue, including descriptions of drying stress and deformation. In the theoretical sections of most of those works, the authors describe the phenomena of heat and mass transport, relying on Fourier's, Darcy's and Fick's laws (Ratanadecho et al., 2001; 2002; Wei et al., 1985; Zielonka et al., 1997). They also tried to evaluate the function of microwave heat source, which is exponentially conditioned on the microwave attenuation constant in the sample and on the distance from the surface of the material subjected to microwaves. What those works lack, however, is the dependence of absorbed power on current moisture content. The problem is raised in a paper by Ratanadecho (2006) who also analyses the heating-up process and temperature distribution in the material being dried, at various microwave application times and different sample sizes.

Publications accounting for the quality of dried material place the main focus on the negative impact of microwaves on the mechanical properties of the product. The works (Itaya et al., 2004; Schiffmann and Mujumdar, 1987; Zhang and Mujumdar, 1992) are mainly devoted to a theoretical analysis of volumetric drying, intermittent drying (short cycles of microwave heating aiming to reduce energy losses in the drying process), which is expected to result in smaller moisture field gradients, and hence smaller deformation of the products subjected to drying. The theoretical part is devoted to the analysis of stresses generated during drying. On the other hand, another theoretical work (Rajagopal and Tao, 2002) contains a very detailed and advanced model of dielectric drying process. It is a thermomechanical model accounting for thermodynamic aspects and electromagnetic field equations, as well as electro-magnetoelasticity theory based on mixture theory.

Moist material subjected to microwaves is intensively heated up across its entire volume up to the boiling point. Depending on the power output level and time of exposure to microwaves, the resulting pressure inside the material may cause internal structural damage, and in extreme cases complete destruction of the material. The presence of points with a higher level of power density in the chamber may cause local overheating. Rapid temperature increase in these points may enhance the risk of local damage. Internal structure of wooden elements, for example, may by burned at high power at high power output, without exhibiting visible damage on the surface. Therefore evaluating the quality of microwave-dried products exclusively by visual inspection may not be sufficient.

The present paper is devoted to investigating the impact of microwaves on drying kinetics and mechanical properties of beech wood after drying.

Converting microwave energy to heat generated within the drying material occurs very rapidly. In lumen of pores there is a quick steam production and rapid transport of water, even in the liquid form, from the sample surface. The Gompertz model was used to determine whether as a result of such a rapid mass transport individual phase characteristics of the drying process could be observed.

## 2. MATERIAL AND METHODS

Raw material selected for experiments was obtained from Poznań Regional Directorates of the State Forests. The study employed twin samples of green beech (*Fagus sylvatica* L.) wood measuring 20 × 50 × 200 mm in the tangential, radial and longitudinal directions, respectively. These samples were cut from the outer zone of cross-section of log so as to get exactly perpendicular arrangement of annual rings. The initial moisture content (*MC*) of the samples was 90 ± 1%. Prior to drying, all prepared samples were protected against moisture removal. Wood density was 668 ± 28 kg/m$^3$ (*MC* = 10%). Wood samples were dried in PLAZMATRONIKA WS 110 microwave dryer (Fig. 1) until *MC* ca. 10% was obtained. The dryer with a chamber measuring 300 × 400 × 270 mm, in height, width and depth, respectively, ensured that the selected power output level was maintained throughout the process. The sample was placed in the zone with a constant distribution of power density. Measurements were taken for 40%, 50%, 65%, 80% and 90%, respectively, of nominal power output of the magnetron ($P_n$ = 600 W), which – assuming the efficiency of the microwave chamber at the level of 70% – translates into 168, 210, 273, 336 and 378 W, respectively, of estimated microwave power ($P_e$) absorbed by the material during the drying process. For comparison purposes, conventional drying process was conducted at 40 °C and 87% air relative humidity, according to convective drying technology of beech timber drying technology of beech timber (Brunner, 1987). Each option of drying was repeated 3 times. For the tests of mechanical properties, one sample measuring 10 × 10 × 150 mm in tangential, radial and longitudinal direction, respectively, was obtained from each dried sample. During the three-point bending test (ZWICK Z050 testing machine), the following characteristics were determined: modulus of elastic (*MOE*) and modulus of rapture (*MOR*).

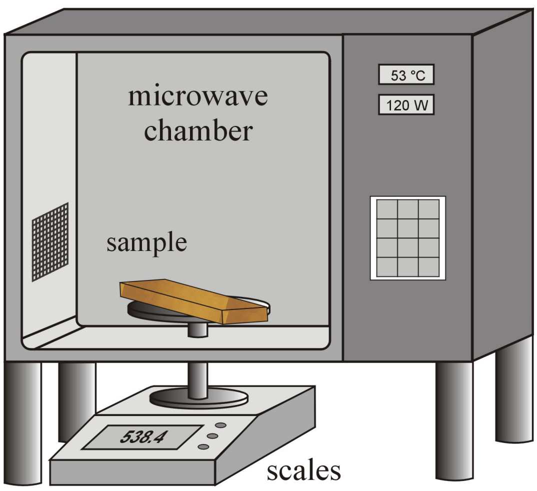


Fig. 1. PLAZMATRONIKA WS 110 Microwave Dryer

The interpretation of the drying process was performed on the basis of drying curves and mass flux curves. The analysis of kinetics of change in wood moisture content employed the Gompertz model (Seber and Wild, 2003):

$$f(x) = \alpha \exp\left\{-e^{-\kappa(x-\gamma)}\right\} \tag{1}$$

where: $\alpha$, $\kappa$, $\gamma$ are shape parameters. One advantage of the Gompertz model is the possibility of interpreting model parameters in the context of drying kinetics (Straže et al., 2010). The $\alpha$ parameter, which constitutes the horizontal asymptote of function $f(x)$, is identified as maximum of mass flux in the first phase of the drying process. The $\gamma$ parameter is the inflexion point of the Gompertz function. The derivative of function $f(x) = 0$ for $x = \gamma$, constitutes maximum drying rate, while the $\kappa$ parameter denotes the rate of moisture removal in the second phase of drying.

The solution of linear equations:

$$\begin{cases} y = \alpha \\ y = ax + b \end{cases} \tag{2}$$

where: $\alpha$ – estimated parameter of the Gompertz model, and $a$ – derivative of $f(x)$ function at $\gamma$ point:

$$a = \left(\frac{df}{dx}\right)_{x=\gamma} \tag{3}$$

allows to determine the wood moisture content ($MCT$), corresponding to a theoretical boundary between characteristic phases of the drying process, i.e. that of constant and decreasing drying rate, respectively.

## 3. RESULTS AND DISCUSSION

Experimental drying curves are shown in Figs. 2 and 3. The application of microwaves resulted in extreme reduction of drying time compared with the convective method (3.5 days). Depending on the applied microwave power output, the drying time varied from ca. 30 min for 40% power, through 20 min for 50%, to ca. 10 min for 65%, 80% and 90% of maximum magnetron power, respectively. Increase of the power output level over 65% did not lead to further reduction in the drying time (Fig. 2). This fact may indicate

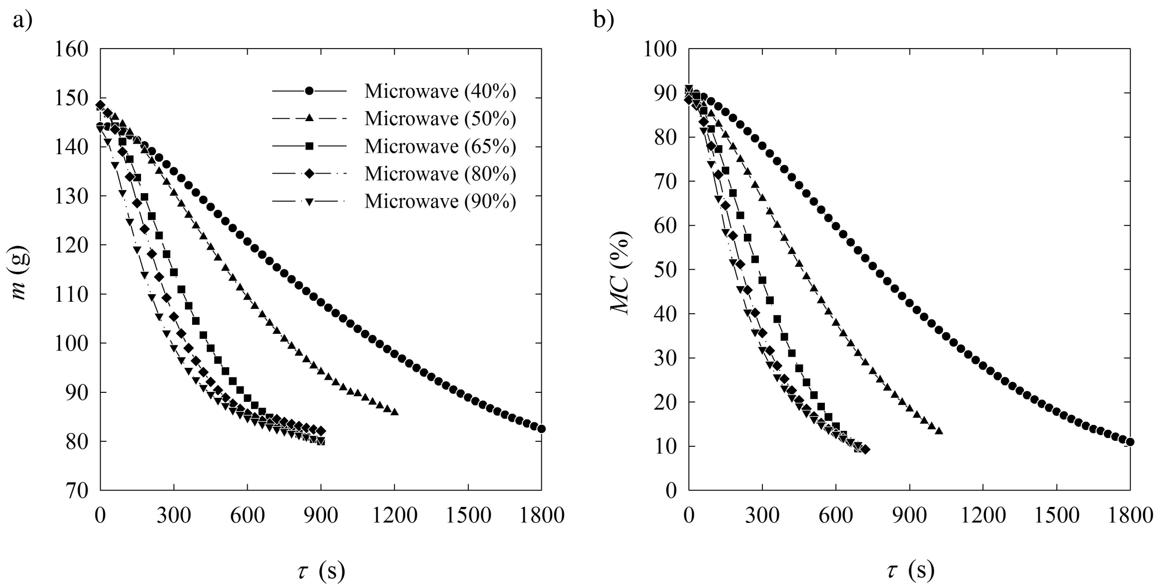


Fig. 2. Comparison of a) mass change curve and b) moisture content in microwave-dried beech wood at varied magnetron power output

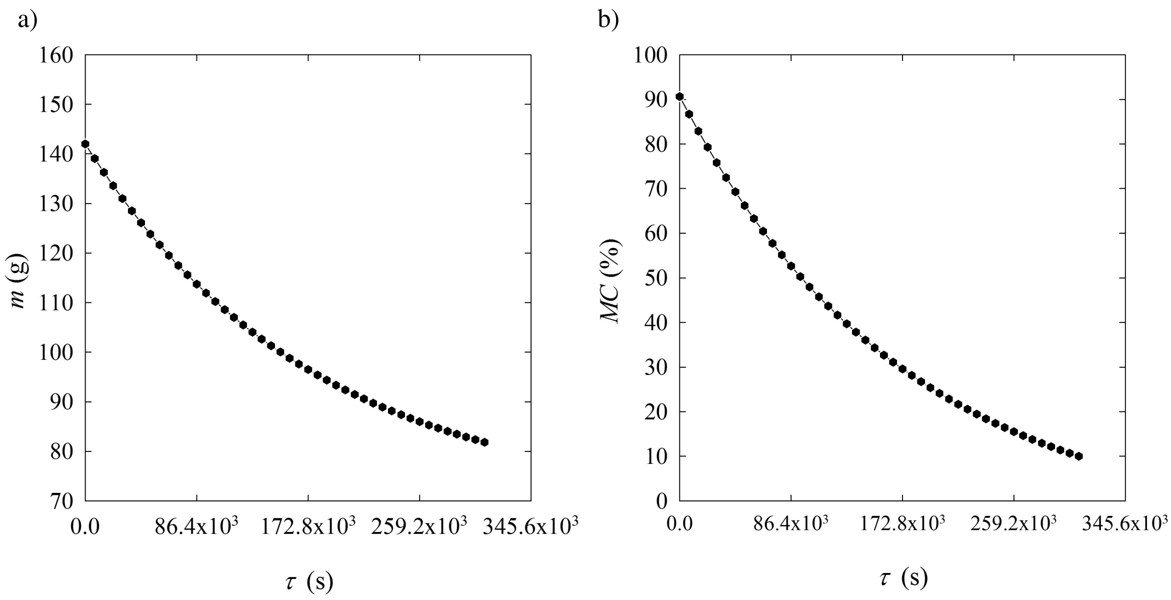


Fig. 3. Mass change curve a) and beech wood sample moisture content curve b) for conventional drying (pitch = 1 day)

certain limitations in the material's capacity to remove moisture, in connection with the anatomic structure of wood.

Parameters of the Gompertz function are presented in Table 1.

Table 1. Estimated values of the Gompertz model parameters (Eq. (1)) and wood moisture content (MCT) corresponding to the theoretical boundary between the constant and decreasing drying rate

| Drying option | $\alpha$ [g/m$^2$s] | $\kappa$ | $\gamma$ $MCC$ [%] | $f'(x)_\gamma$ [g/m$^2$s] | $F'(x)_\gamma$ | $MCT$ [%] | $R^2$ |
|---|---|---|---|---|---|---|---|
| Conventional | 0.034 | 0.015 | 64.1 | 0.013 | 0.0002 | 177.8 | 0.991 |
| 40% | 1.98 | 0.064 | 13.8 | 0.77 | 0.047 | 39.8 | 0.961 |
| 50% | 3.11 | 0.067 | 13.3 | 1.15 | 0.077 | 39.0 | 0.945 |
| 65% | 5.61 | 0.062 | 13.2 | 1.93 | 0.128 | 41.9 | 0.995 |
| 80% | 7.37 | 0.066 | 17.9 | 2.71 | 0.180 | 43.8 | 0.924 |
| 90% | 9.95 | 0.048 | 29.9 | 3.60 | 0.176 | 65.9 | 0.980 |

Significant differences were observed between the mass flux of evaporated water in microwave drying and that in conventional drying (3 orders of magnitude higher compared with the lowest level of the used magnetron power, and 4 orders of magnitude higher compared with the highest level of the used magnetron power) (Fig. 4a).

Duration of microwave drying was independent on the power output over 65%. For the all applied microwave power output levels, the mass flux of evaporated moisture was characterised by a progressive linear relationship with the power output (Fig. 5a).

It is interesting – from the point of view of drying kinetics – how moisture content in the material changed, exhibiting characteristic critical points of the process, depending on the applied microwave

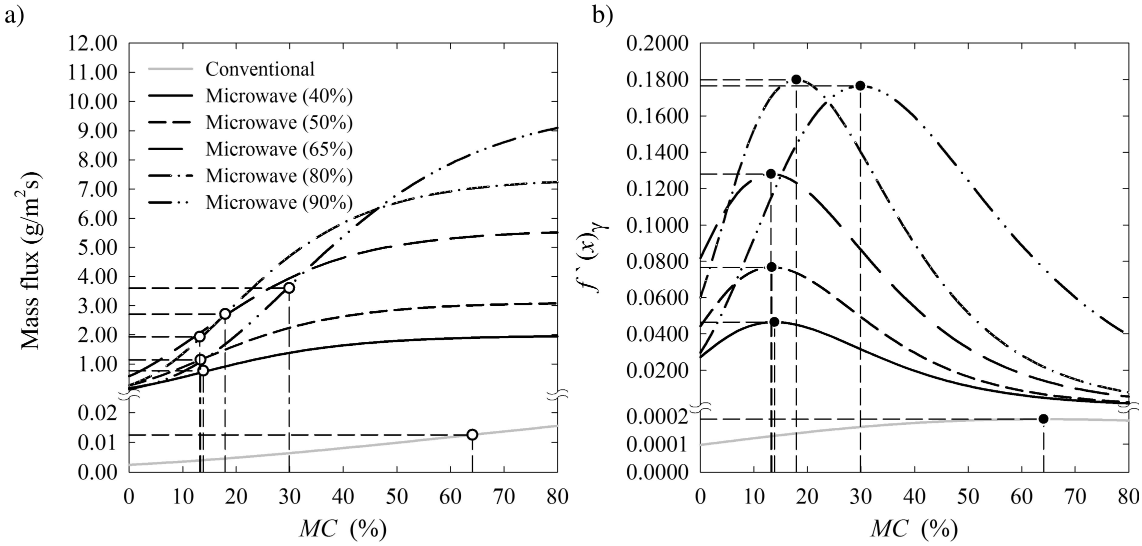


Fig. 4. Estimated values a) of the mass flux of evaporated water and b) drying rate, depending on wood moisture content and drying method (white dots – wood moisture content *MCC* corresponding to the change in moisture transport mechanism, black dots – maximum drying rate)

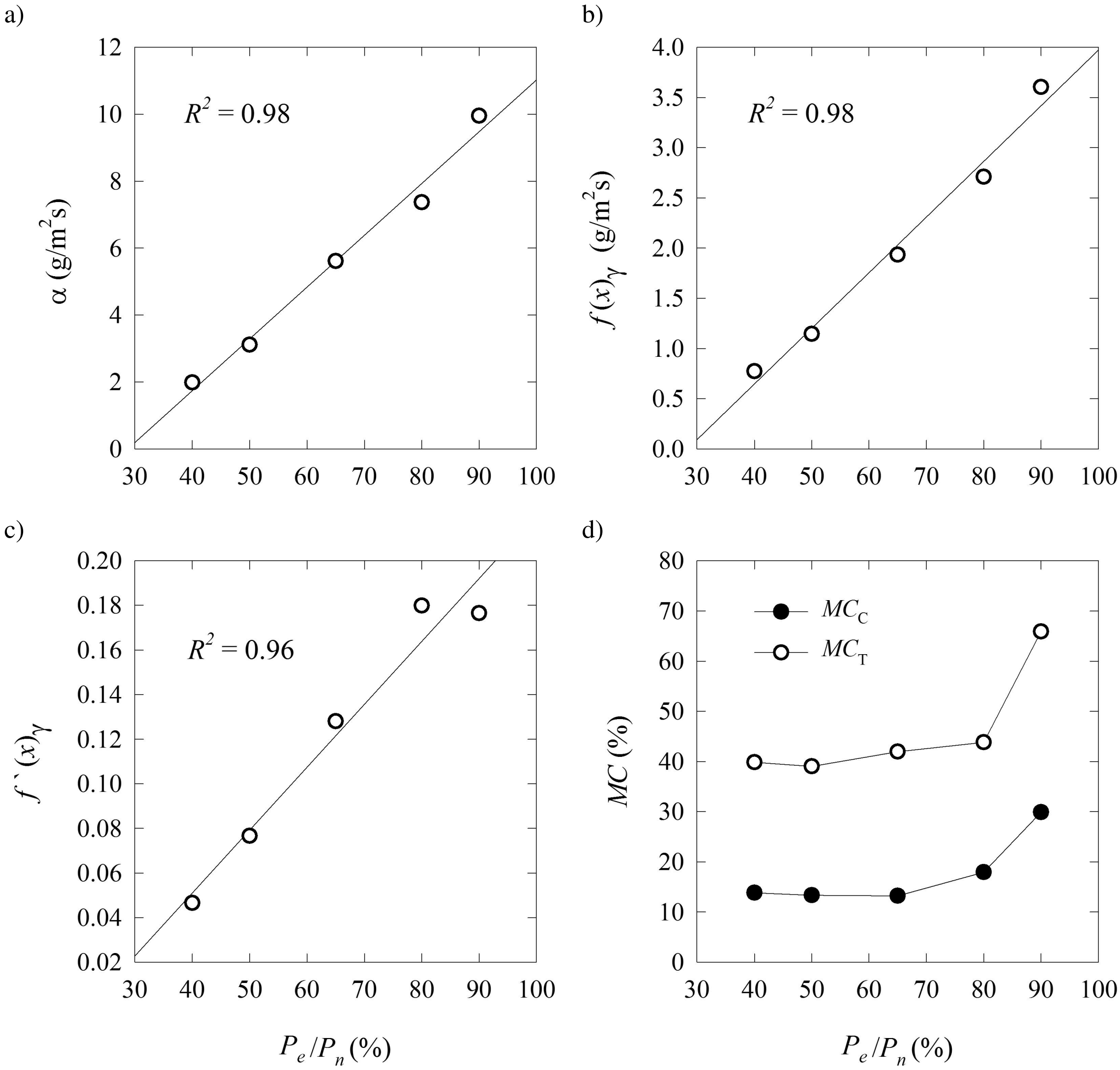


Fig. 5. a) Maximum of mass flux in the first phase of the drying process, b) mass flux at $x = \gamma$, c) maximum drying rate and d) moisture content between characteristic phases of microwave drying of beech wood, assuming different option of magnetron output power

power output. The first critical point from the start of the process i.e. *MCT* is the transition from the phase of a constant drying rate (saturated surface evaporation) to the phase of falling drying rate. This takes place over the fibre saturation point, and for the power output levels of 40%, 50%, 65% and 80%, respectively it happened at the water content of approximately 40%. For the highest applied power output (90%) the transition from the phase of constant drying rate to the phase of decreasing drying rate took place at considerably higher material *MC*, namely ca. 65%. Another critical process point i.e. *MCC* is the achievement of material moisture content, in the second phase of drying, at which a change in the moisture transport mechanism occurs. In the case of wood, this happened below the fibre saturation point, when it exhibited hygroscopic properties. It is believed that moisture transfer is caused by the Stefan diffusion resulting from the moisture gradient in the material, or capillary conductivity (Kneule, 1975). Also in this case, for the applied maximum microwave output power of 40%, 50%, 65% and 80%, respectively, the change in the moisture transport mechanism took place at the *MC* of ca. 15%, while for the highest microwave power output applied it took place at the point corresponding to the fibre saturation point (Fig. 5d).

Dried samples were subjected to static bending tests in order to specify the influence of the applied microwave power on the modulus of rapture (*MOR*) and the modulus of elasticity (*MOE*) of the dried samples. The results of experiments are given in Table 2. The standard deviation was calculated from for the mean value of three replications.

Table 2. Results of mechanical property designation in the three point bending test

| Drying option | *MC* [%] | *MOR* [MPa] | *MOE* [MPa] | $MOE^{*}_{15}$ [MPa] |
|---|---|---|---|---|
| Conventional | $12.0^{b} \pm 1.9$ | $103.3^{a} \pm 8.4$ | $9386^{a} \pm 729$ | $8812^{a} \pm 731$ |
| Microwave (40%) | $10.8^{ab} \pm 1.2$ | $119.8^{abc} \pm 15.7$ | $10178^{ab} \pm 993$ | $9303^{ab} \pm 701$ |
| Microwave (50%) | $11.4^{ab} \pm 0.1$ | $112.5^{abc} \pm 7.7$ | $9651^{ab} \pm 824$ | $8951^{ab} \pm 740$ |
| Microwave (65%) | $12.1^{b} \pm 0.4$ | $104.3^{ab} \pm 2.0$ | $9150^{a} \pm 245$ | $8613^{a} \pm 170$ |
| Microwave (80%) | $8.4^{a} \pm 0.7$ | $132.9^{c} \pm 13.6$ | $11943^{c} \pm 763$ | $10354^{b} \pm 604$ |
| Microwave (90%) | $8.7^{a} \pm 0.4$ | $123.7^{bc} \pm 7.5$ | $11015^{bc} \pm 337$ | $9627^{ab} \pm 264$ |

± standard deviation ($n = 3$), identical superscripts (a, b, c) denote no significant ($p < 0.05$) difference between mean values in columns (according Tukey's HSD test (ANOVA), *corresponding to the 15% moisture content of wood (recalculated by Bauschinger's equation)

*MOE* of the wood samples used in the study was characterised by relatively high variability, therefore a decision was made to verify the statistic hypothesis that microwave drying does not result in increased *MOR* and *MOE* of wood. A Tukey's HSD test (ANOVA) for investigated option of drying was applied. Identical superscripts (a, b, c) denote no significant ($p < 0.05$) difference between mean values in the columns.

Statistically this means that microwave drying (without power output variation) led to increased wood strength $MOE_{15}$ compared with convective drying. However, the average increase was ca. 10% compared with that after convective drying, which is a range falling within the limits of interspecies variation for this characteristics (Wood Handbook, 2010). It can therefore be concluded that microwave drying did not exert a negative effect on mechanical properties of wood during the tests conducted under the present study.

## 4. CONCLUSION

Microwave drying improves process efficiency, adding dynamism to moisture removal from the interior of the material to the surface. It might be expected that such a rapid drying process would result in considerable deterioration of mechanical properties of wood. The conditions of microwave drying analyzed in this work were adjusted in such a manner (with a relatively low power output level) that the final quality of dried wood evaluated on the basis of mechanical properties did not deteriorate, compared with conventional drying. The application of microwaves helped to significantly reduce the drying time without impairing the quality of the wood subjected to drying. Drying stresses did not reach a critical level due to the compatibility of diffusion and thermodiffusion mass flux. Moreover, it was not observed by the visual quality assessment, as any cracking would provide an advanced stage of damage of the wood. Increasing the applied microwave power output beyond a certain critical threshold did not lead to further reduction of the drying time. This fact may indicate certain limitations in the material's capacity to release moisture due to its internal structure rather than to set microwave power output. The present paper indicates the possibility of applying the Gompertz model in the analysis of microwave drying kinetics of beech wood. The meaning of individual parameters is explained, and function diagrams are compared in relation to the conventional and microwave drying processes. The applied model facilitated an interpretation of the obtained results. The model enables to better understand ongoing changes and to specify the direction of further experiments aimed at drying process optimization. The Gompertz model facilitated the identification of three characteristic phases of the drying process: the phase of constant drying rate in which free water is removed, the phase of decreasing drying rate in which both free water and bound water are removed, and the phase of decreasing drying rate in which only bound water is removed.

The use of microwave energy intensified mass transfer exchange during drying by the thermal effect (the absorbed energy was transformed into heat). Microwave energy significantly accelerated the water removing process, without substantial changing of the process characteristics.

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## SYMBOLS

| | |
|---|---|
| $a$, $f'(x)_\gamma$ | derivative of Gompertz function at $\gamma$ point |
| $m$ | mass of sample, g |
| $MC$ | moisture content, % |
| $MCC$ | critical moisture content (change in moisture transport mechanism), % |
| $MCT$ | critical moisture content (between constant and decreasing drying rate), % |
| $MOE$ | modulus of elasticity, MPa |
| $MOE^*_{15}$ | modulus of elasticity corresponding to the 15% $MC$, MPa |
| $MOR$ | modulus of rapture, MPa |
| $P_e$ | estimated microwave power, W |
| $P_n$ | nominal power of magnetron, W |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | shape parameter of Gompertz function, g/(m$^2$s) |
| $\gamma$ | shape parameter of Gompertz function, % |
| $\kappa$ | shape parameter of Gompertz function |
| $\tau$ | time, s |

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