

VARIATIONS IN BEECH WOOD SURFACE PERFORMANCE ASSOCIATED WITH PROLONGED HEAT TREATMENT AT 200 °C

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ABSTRACT

The research was aimed at analysing the discolouration, morphology and wetting of beech wood thermally modified under influence of a temperature of 200 °C acting during three heating periods (1, 3, and 5 hours). The results show that with progressing heating time, the lightness L^* decreased significantly, while the coordinates a^* and b^* increased as long as for three hours. Subsequently, a moderate decrease followed. Just after one-hour-lasting thermal modification, the total colour difference ΔE value was much higher than 12. It means that a totally new colour resulted from the thermal treatment as short as one-hour. Further treatment prolongation induced further ΔE increase, nevertheless, more moderate. Enhanced roughness was indicated by an inspection of the changes in the beech wood surface morphology. But this fact was not confirmed unambiguously in all three heating periods. The results show that the beech wood thermal treatment resulted in significantly improved resistance of beech wood surface to wetting proven by the wetting contact angle values $\theta > 90^\circ$. Moreover, the time necessary for the complete drop soaking into the substrate increased by one or two orders. The wetting varied mainly due to the treatment temperature. The importance of treatment duration was not confirmed unambiguously. The reduced wood surface wetting significantly affected lowering the wood surface free energy, which was mainly due to a decrease in the polar component of this energy. This fact may negatively affect the surface treatment quality if the coating materials are applied on the wood modified this way.

Keywords: beech wood, thermal modification, colour, roughness, wetting, contact angle, surface free energy.

INTRODUCTION

During the last two decades, considerable interest has been devoted to effects of heat energy on wood performance in the context of wood thermal, hydro-thermal and hydro-thermal-mechanic treatment. The aim of these wood treatment technologies is a purpose-driven modification of specified physical and mechanical properties of the treated wood.

The original purpose of wood thermal treatment was to enhance the wood hydrophobicity and, consequently, its dimensional stability. At the same time, caution was devoted to prevent substantial changes in the mechanic performance of wood treated in this way. The lowered sorption capacity of thermally modified wood is responded by lower values of equilibrium moisture content, FSP included (HILL 2006, BOONSTRA *et al.* 2007, SRINIVAS and PANDEY 2012, VOBOLIS and ALBREKTAS 2014, AYTIN *et al.* 2015, HORVÁTH

et al. 2016). The lowered wood hydrophilicity also impacts the dimensional stability of the thermally modified wood. The results presented in the papers MYES and OKSANEN 2003, AYTIN *et al.* 2015, ESTEVES and PEREIRA 2009, KAČÍKOVÁ and KAČÍK 2011) suggest that the thermally modified wood shows improved dimensional stability, with reduced swelling and shrinkage.

Lower water uptake capacity, swelling and shrinkage in thermally modified wood are supposed resulting largely from the chemical changes in the main wood components. The temperatures associated with wood thermal treatment (150–260 °C) cause first of all degradation of highly hygrophilous hemicelluloses (REINPRECHT and VIDHOLDOVÁ 2011, BOONSTRA and TJEERDSMA 2006, KAČÍK *et al.* 2016). This drop in hemicelluloses content leads to an increase in fragility (NAVI and PIZZI 2015).

The hydrophobicity of thermally modified wood is enhanced also as a result of degradation of amorphous cellulose and the allied increase in the relative proportion of crystalline cellulose. These two facts reduce the accessibility of free hydroxyl groups. The reduction of the number and accessibility of free sorption sites has a decisive influence on dropping the equilibrium moisture content value and improving the associated dimensional stability (BHUIYAN and HIRAI, 2005, ESTEVES *et al.* 2008). Cellulose crystallinity increases as far as 200 °C and exceeding this threshold is followed by a decrease in the crystalline cellulose proportion (ESTEVES and PEREIRA 2009). Thermal treatment also induces a decrease in the cellulose polymerising degree, which causes weakening of bending and tensile strength of the thermally modified material (ESTEVES and PEREIRA 2009, HILL 2006, ZAWADSKI *et al.* 2016).

The lignin structure consists of covalent bonds that stabilize thermal oxidation and reactions during thermal treatment. Lignin degrades in lower intensity than polysaccharides. Carboxyl and free phenolic hydroxyl groups are created during the thermal treatment. These groups allow networking of lignin, which also contributes to hydrophobicity after the treatment (ESTEVES and PEREIRA 2009, HILL, 2006, KAČÍKOVÁ and KAČÍK 2011). Moreover, lignin incrusts fibrils in the secondary cell walls and its hydrophobicity hampers access of water to free hydroxyl groups (BOONSTRA and TJEERDSMA 2006).

Dealing with wood thermal modification, it is also needed to identify the changes in wood surface properties. Characteristic wood surface property is its colour. The colour is important for differentiating between the species and it also serves as a wood quality indicator (BABIÁK *et al.* 2004, HRČKA 2010). Wood colour can be considerably modified under heat during thermal, hydro-thermal and thermo-hydro-mechanic treatment (ČERMÁK and DEJMAL 2013, DZURENDA 2014, BEKHTA *et al.* 2014, KÚDELA *et al.* 2018, KÚDELA and ANDOR 2018, KUČEROVÁ *et al.* 2019 and others).

Up to present, the variation in the wood colour space has been dealt on empiric background only, without possibility to attain a pre-defined required discolouration. This is especially true in the case of thermal treatment (thermo-wood), hydro-thermal treatment (steaming, boiling) and thermos-hydro-mechanic treatment (pressing). Unveiling the mechanism backing up the discolouration of wood subjected to these processes should facilitate the development of methods for attaining pre-defined wood colour modifications and, at the same time, ensuring better colour stabilisation. The colour obtained through thermal treatment is not stable and varies significantly under the influence of environmental factors in outdoor conditions (ANDOR 2018). KUČEROVÁ *et al.* (2019) even propose that the discolouration, as a relatively easy to measure parameter, could serve as a predictor for the surface quality of thermally treated wood.

The results obtained by TODARO *et al.* (2015), BEKHTA *et al.* 2018, KÚDELA *et al.* (2018) also point at the fact that the thermally treated wood exhibits restricted wetting with

water and other liquids. The enhanced resistance against liquid water is the result of chemical changes and the surface morphology that is modified by the thermal treatment too. On one hand, the enhanced resistance of thermally treated wood against wetting with liquids seems like a profit; on the other hand, there may be negative impacts on the glued joint strength and on the adhesion of coating films to the wood substrate.

It is indisputable that this subject area has been exploited rather poorly and that there are numerous questions to answer and problems to solve. This is obvious not only based on the very variable quality of thermally treated wood, but also based on the up-to-present used methods and approaches for calculation of thermodynamic characteristics, differing in the mathematical tools applied and also in the number of liquids necessary to carry out the experiments (GINDL and TSCHEGG 2002, BLANCHARD *et al.* 2009, PIAO *et al.* 2010, HUBBE *et al.* 2015, PETRIĆ *et al.* 2015). As liquid standards, there are used liquids with limited wood surface wetting: non-polar and non-polar-polar ones, with an additive characteristic of the surface free energy. The differences in the chemical composition of liquids initiate the formation and the nature of the interface between liquids and wood, which is reflected in different values of surface free energy and its components (KÚDELA 2014).

The referred works allow us to conclude that all the discussed changes in the performance of thermally modified wood are affected by the technique of the thermal treatment, temperature, heating period, wood species and others.

The aim of this work was to evaluate the influence of duration of thermal treatment on changes in selected surface properties in beech wood. Under specific setup conditions, there were studied changes in beech wood surface colour and morphology. There were also performed experimental studies focused on wetting with standard polar and non-polar liquids, from which surface free energy values were determined.

MATERIAL AND METHODS

The study was performed on beech (*Fagus sylvatica* L) wood material. For experiments, there were prepared four series of test specimens, each with the following dimensions: radial face $50 \times 100 \text{ mm}^2$ and thickness – 15 mm (Fig. 1). Before the experiment, the specimen surface was sanded with a sandpaper grit P180. The first series consisted of control specimens. The other three series were firstly dried down to the zero moisture content, and then there were treated thermally in a laboratory hot-air drying kiln without moisturizing climate, with an open system, at a temperature of 200 °C. These series differed in their treatment periods: one, three and five hours. The measurement of roughness, colour and contact angles at the wetting process followed the methods proposed by KÚDELA *et al.* (2019).

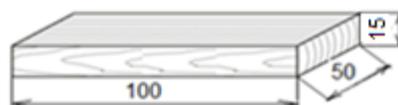


Fig. 1 Specimen for a thermal treatment, dimensions and shape.

Colour measurement

The colour coordination values in the colorimetric space CIE $L^*a^*b^*$ before and after thermal treatment and the differences in the colour coordinates ΔL^* , Δa^* , Δb^* related to the control specimens were measured with a spectre-photometer Spectro-guide 45/0 gloss

(BYK- GARDNER GmbH, Germany). The discolouration extent was determined through the total colour difference ΔE calculated according to the equation:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}, \quad (1)$$

$$\Delta L^* = L_T - L_R \quad (2)$$

$$\Delta a^* = a_T - a_R \quad (3)$$

$$\Delta b^* = b_T - b_R \quad (4)$$

Note: the index „T“ is used for the colour value after wood surface treatment, „R“ means so-called referential (control) value obtained for the surface of original, untreated wood.

Roughness measurement

The morphological changes in the thermally treated wood surface were assessed through roughness parameters. The roughness was measured with a profilometer Surfcom 130A (Carl Zeiss, Germany). The measurements were carried out on thermally treated radial faces of beech specimens, parallel and perpendicular to the grain. There were measured the following roughness parameters: Ra – arithmetic mean deviation, Rq – root-mean-square deviation, Rz – maximum height of the assessed profile within a sampling length, Rt – maximum height of the assessed profile within the total length, Rsm – mean distance between the valleys. The sampling length, representing 2.5 mm, was determined based on the preliminary measured values of roughness parameters Ra and Rz . The total measured length consisted of five sampling lengths.

Wood wetting with liquids and assessment of its surface free energy

During the wetting process, contact angles were measured up to the complete soaking of the testing-liquid drop into the substrate. The used measuring equipment was a goniometer Krüss DSA30 Standard (Krüss, Germany). There were two applied testing liquids, differing in their polarity – redistilled water and diiodomethane. The reasons for using namely these liquids can be found in KÚDELA (2014). Diiodomethane is a non-polar liquid with its non-polar component of surface free energy higher than the disperse component of this energy in the wood. Redistilled water represents polar-non-polar liquid with its polar component of surface free energy higher than the polar component of wood. The parameters of these two liquids are in Table 1.

Tab. 1 Surface free energy and its components for the testing liquids.

Testing liquid	Liquid character	γ	γ^d	γ^p	γ^+	γ^-
		[mJ·m ⁻²]				
water	polar	72.8	21.8	51.0	25.5	25.5
diiodomethane	non-polar	50.8	50.8	0.0	0.0	0.0

From the moment of the contact of the testing drop (volume 0.0018 ml) with the wood surface, the wood wettability and drop spreading along the fibre direction were inspected. The history of the drop shape, from the first contact up to the complete soaking, was recorded with a camera. The scanning frequency (number of scans per second) was adjusted according to the wetting duration.

The drop shape was analysed, and the contact angle was determined based on two methods: drop perimeter (*circle*) method and drop height and diameter (*height-width*) method.

The contact angle value θ_0 was measured at the beginning of the wetting process, immediately after the drop applying onto the wood surface. The moment of reversing the advancing angle to receding one was determined based on the parameter d (drop width) values. The contact angle measured at this moment was considered as „equilibrium“ contact angle – θ_e . The contact angle values θ_0 and θ_e were then used for calculating the contact angle θ_w for an ideally smooth surface, following the method proposed by LIPTÁKOVÁ and KÚDELA (1994). This angle was subsequently applied for calculation of surface free energy and its components. The contact angle measurements were carried out on each specimen, at six points.

As the wood was wetted with two different liquids, the wood surface free energy was determined separately for wetting with water and with diiodomethane, according to the adjusted equation originally proposed by NEUMANN *et al.* (1974).

with the disperse and polar components γ_s^d and γ_s^p calculated in the following way, as suggested by KLOUBEK (1974).

The resulting surface free energy of thermally treated beech specimens was determined as the sum of the polar component of this energy quantified with water and the disperse component obtained with diiodomethane.

RESULTS AND DISCUSSION

Colour change

The first change detectable visually on beech wood surface subject to thermal treatment was discolouration. With prolonged treatment time, the colour coordinates L^* , a^* and b^* exhibited significant changes, which is also in accord with the results of the two-way variance analysis performed. The basic statistic characteristics for these coordinates are in Table 2. The colour spaces of thermo-wood varieties obtained with particular thermal treatment modes can be considered clearly separated.

Tab. 2 Basic statistic characteristics of colour coordinates L^* , a^* , b^* related to different heating periods at 200 °C.

Duration of thermal treatment [hours]	Basic statistic characteristics	Colour coordinates		
		L^*	a^*	b^*
0	\bar{x}	81.13	4.91	16.09
	SD	0.76	0.21	0.38
1	\bar{x}	55.16	6.39	16.58
	SD	1.84	0.56	0.44
3	\bar{x}	44.71	8.21	16.69
	SD	1.30	0.30	0.69
5	\bar{x}	40.34	7.79	14.61
	SD	0.97	0.31	0.81

\bar{x} – average, SD – standard deviation, the number of measurements performed for each series was 60

The colour coordinates of the original, non-treated beech specimens were from the interval reported for beech wood by BABIAK *et al.* (2004), HRČKA (2010), KÚDELA *et al.* (2017). The variability was relatively low, which means that the beech wood specimen surface was homogeneous in colouration. With prolonged thermal treatment, the lightness values L^* decreased distinctly.

The steepest descent in this coordinate, in comparison with referential specimens, was observed after one-hour heating at 200 °C. Later, at the same temperature, the significant decrease in lightness was continuing, nevertheless, the rate was getting lower

with the progressing time. The values of coordinates a^* and b^* were moderately increasing with progressing treatment time, up to three hours. This change was not as conspicuous as in the case of lightness, however, the statistical differences were significant.

The drop in lightness and shift of coordinates a^* and b^* towards red and yellow caused that the wood was getting more and more dark-brown saturated. After five treatment hours, the values of coordinates a^* and b^* began to decrease moderately. The impact on the beech specimen discolouration is documented in Fig. 2.

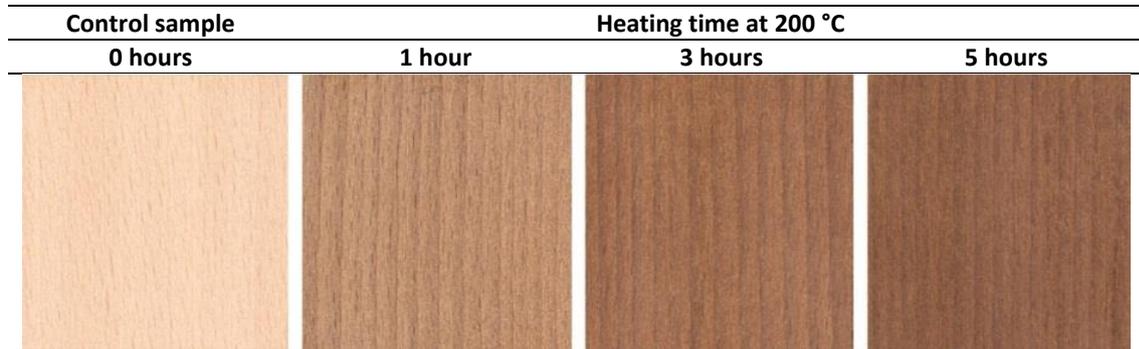


Fig. 2 Tint of the beech specimen surface after thermal treatment at 200 °C, treatment duration 1, 3 and 5 hours.

The differences in the colour coordinates ΔL^* , Δa^* , Δb^* and the total colour difference ΔE^* are represented in Fig. 3. The total colour difference ΔE was much over the value of 12 as early as after one-hour-treatment. According to the assessment scale reported by ALLEGRETTI *et al.* (2009), the value of 12 means, a completely new colour compared to the original. Qualitatively similar colour variation in beech wood was also observed by other authors (GONZALES *et al.* 2009, DZURENDA 2014, KÚDELA and ANDOR 2018 and others). The observed quantitative differences were the result of different methods used for thermal treatment.

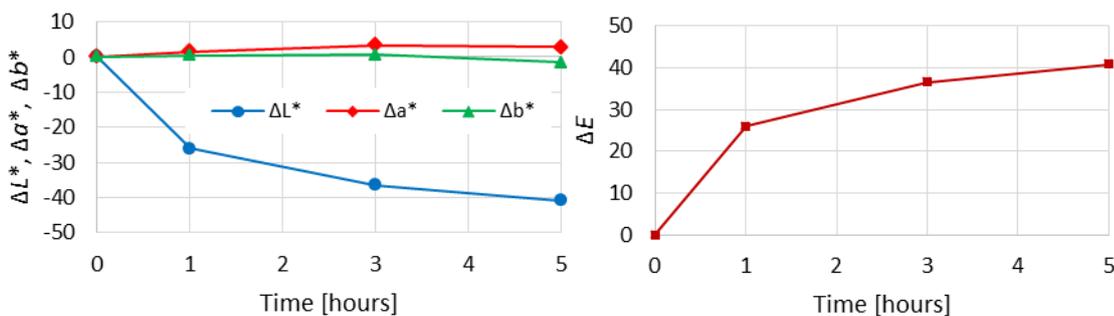


Fig. 3 Colour coordinates ΔL^* , Δa^* , Δb^* and the total colour difference ΔE^* after thermal treatment at 200 °C, treatment duration 1, 3 and 5 hours.

GONZALES *et al.* (2009) report that the beech wood discolouration during thermal treatment is participated by all wood components, with the highest correlation between discolouration and modification of hemicelluloses. There have also been identified links between colour modification and modification in the lignin structure. The colour coordinate b^* after 5 hours of treatment dropped back under the reference sample colour. According to KUČEROVÁ *et al.* (2019), this alteration of colour coordination b^* is related to the rapid decrease of saccharide content and relative increase of lignin content.

Surface morphology

Beech wood thermal treatment had also effects on this wood surface morphology assessed through specified roughness parameters. The impacts of the treatment duration and the anatomic direction was evaluated with the aid of two-way variance analysis. The results of this analysis confirmed that the two tested parameters had significant effects on the roughness parameters values. The values of roughness parameters Ra , Rq , Rz , and RSm obtained parallel to grain and perpendicular to the grain, for all the treatment modes are presented in Fig.4.

The results suggest that in all cases, the Ra , Rq and Rz values were lower parallel to the grain than perpendicular to the grain. In the case of RSm , the opposite was true. The roughness parameters values logically result from the interaction between the internal wood structure and mechanic treatment of wood surface (in our case, sandpaper with a grit size P180). Due to the high heterogeneity of beech wood structure, the roughness of this wood displayed a rather high variability. During thermal treatment, the two interacting factors were supplemented with a third one – heat.

The heating temperature of 200 °C and treatment duration of one hour caused enhanced roughness in both anatomic directions. With prolonged treatment time under the same temperature, there followed a moderate smoothing, and after five treatments hours, the roughness of the treated specimens was again almost the same as the roughness of the untreated control. This roughness variation is in good correspondence with the changes to the chemical structure, explicitly the relative increase in lignin content (KUČEROVÁ *et al.* 2019). It could be assumed that incrustation of lignin into fibrils throughout the cell wall smoothed out the surface, namely in the case of longer heating.

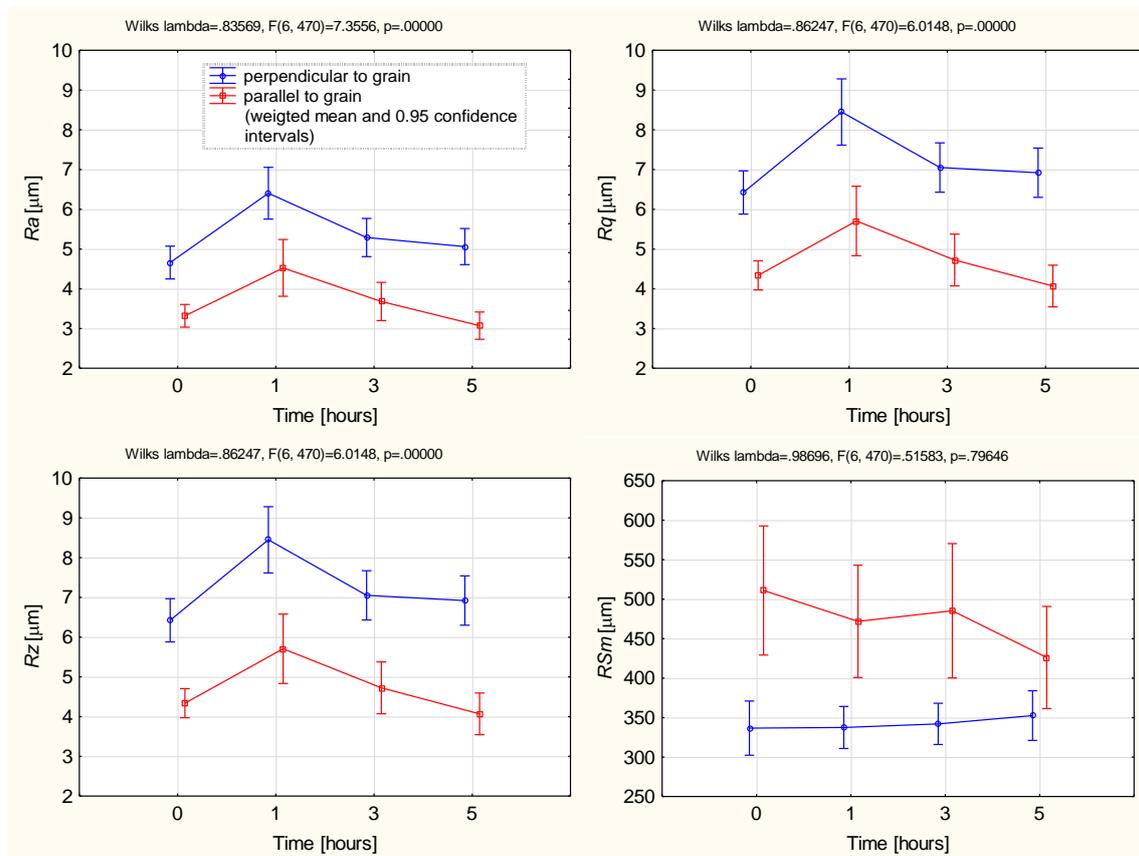


Fig. 4 Changes in beech wood roughness parameters after thermal treatment performed at 200 °C for one, three and five hours.

Wood surface wetting with water and diiodomethane

The thermal-treatment-induced chemical changes signalled through beech wood surface discolouration as well as the morphological changes on the beech wood surface affected significantly the wood surface's wetting with standard liquids, primarily water. In all cases, water drop applied on the wood surface was spreading continually over the surface, and, at the same time, soaking into the substrate. The differences in wood wetting performance before and after thermal treatment were mostly detected in the values of contact angles θ_0 , θ_e , θ_w , as well as in the duration of the wetting process up to the complete soaking of the drop into the wood substrate.

The best water-wetting performance was observed in beech wood surface before thermal treatment. Sanding prior the treatment enhances the proportion of polar hydroxyl groups, and, consequently, the wood surface becomes more hydrophilous, in comparison, for example, with a milled surface (LIPTÁKOVÁ *et al.* 1995, KÚDELA *et al.* 2016). This fact was reflected in notable drops in contact angle values θ_0 , θ_e and θ_w and in faster spreading over and soaking of the drop into the wood. The average contact angle θ_0 value at the moment of the application was 21° , the value of the equilibrium contact angle θ_e was somewhat lower (13°). The angle for an ideally smooth surface θ_w had an average value of 15° (Fig. 5). The values of these angles confirm the appropriate wetting of the wood surface before the thermal treatment. The time necessary for the drop to soak completely into the substrate was several seconds.

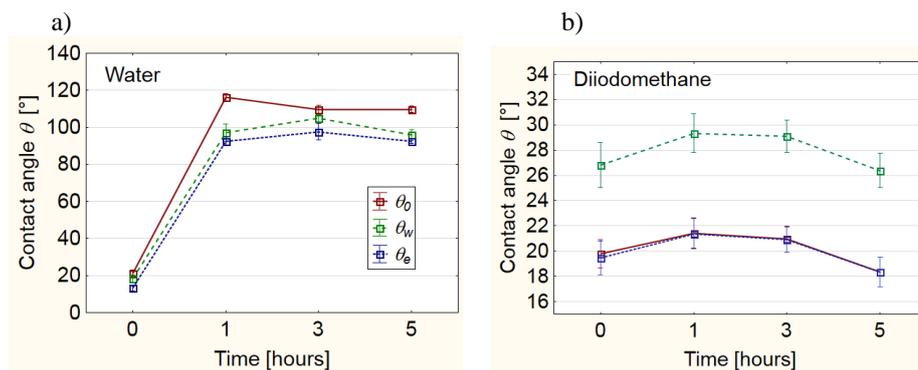


Fig. 5 Duration of beech wood thermal treatment performed at 200 °C, and the resulting contact angle values.

For all three treatment periods, thermal treatment at 200 °C yielded significantly better beech wood resistance against surface wetting with water. This was also evident from the evidently higher values of all three contact angles θ_0 , θ_u and θ_w (Fig. 5). The average values of contact angle θ_0 ranged between 110° – 116° , the average values of contact angles θ_e and θ_w were in all cases above 90° . There was also observed more time necessary to reach the equilibrium state at the interface wood – water (t_e), and the time of duration of the entire wetting process until the complete soaking of the drop into the substrate was multiplied by two orders (Fig. 6). These facts give evidence for the hydrophobic nature of the beech wood surface after thermal treatment. The different wetting capacities were mainly to the heating. In this case, the heating duration was not confirmed as an important factor unequivocally. The thermal treatment also eliminated differences in wetting caused by different mechanic pre-treatments of the wood surface before thermal treatment (milling, grinding).

The beech wood wetting with diiodomethane was different from water. In the first case, the contact angle values of the liquid with thermally modified wood were

significantly lower, and there were also significantly shorter times necessary for the complete drop soaking into the substrate (Fig. 5b and 6). On the other hand, the treatment-mode-dependent differences in the contact angle values were small.

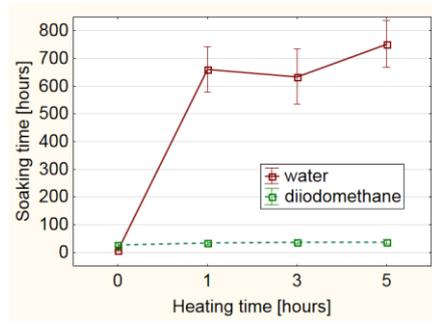


Fig. 6 Heating time and complete soaking of the drop into the wood substrate

Degraded wetting of thermally modified beech wood has also been reported by other authors (TODARO *et al.* (2015), MIKLEČIĆ *et al.* 2016, BEKHTA *et al.* 2018). These authors, however, observed smaller changes in the contact angle values in the thermally modified wood compared to our results. The reasons may be several, such as a method used for wood wetting with liquid, a method for contact angle value evaluation, and quality of the experimental material used. MIKLEČIĆ *et al.* (2016) point at the importance of the fact whether or not the thermally treated wood was subsequently mechanically treated. The work referred as well as our observations suggest that the additional wood surface sanding after thermal treatment may, to some extent, restore the surface hydrophilicity. We can see that there are manifold factors possibly masking the influence of the thermal treatment as such on the wetting process.

According to LIPTÁKOVÁ and Kúdela (1994), the values of contact angles θ_o and θ_u are the results of both wood surface morphology and wood chemical composition, while the θ_w values depend only on the chemical structure of the wood surface. Consequently, the different θ_w values confirm the chemical modifications induced by the thermal treatment.

Surface free energy in thermally modified beech wood

For the particular thermal modification modes, the values of beech wood surface free energy γ_s with its disperse and polar components γ_d^s and γ_p^s were firstly determined, according to the methods discussed above, separately based on the wetting with water and the wetting with diiodomethane. For the surface free energy calculation, the contact angle θ_w was used. The obtained results are in Fig. 7.

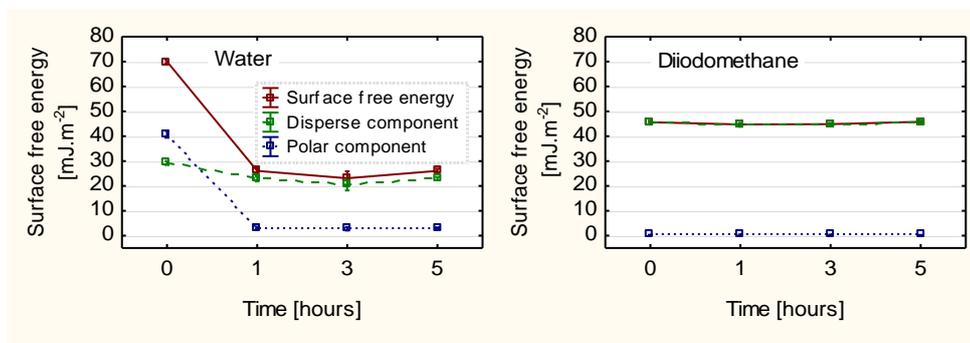


Fig. 7 Duration of thermal treatment at 200 °C and the related values of the surface free energy and its components determined based on wetting with water and diiodomethane.

The beech wood surface free energy determined using the parameter values obtained with wetting with water was the highest before the thermal treatment. Thermal treatment lasting one hour at a temperature of 200 °C considerably reduced these energy values, primarily due to the reduction of its polar component. With advancing treatment time, no significant changes occurred any more. For all the treatment modes, the dispersive component was dominant (Fig. 7). The surface free energy values determined before the thermal treatment with the aid of diiodomethane were lower than the corresponding values obtained using water; in case of diiodomethane, the free energy values were practically equal to the values of a disperse component of this energy. The thermal treatment did not cause any significant changes.

The obtained results show that the liquid standards used for assessment of wood surface properties at the interface between wood and liquid differed, as for the values of surface free energy and its disperse and polar components. KÚDELA (2014) demonstrates that the polar component of surface free energy in wood is best fitted with water the polar component of which is higher than the polar component of wood. For obtaining the disperse component values, diiodomethane was identified as the most suitable liquid, as the disperse component of surface free energy of diiodomethane is higher than the disperse component of wood. Then the surface free energy is the sum of the polar and disperse components determined as described just above. The surface free energy results obtained in this way are in Tab. 3. Such determined surface free energy values for beech wood are somewhat higher, with dominant disperse component. Similar results for surface free energy have been reported in MIKLEČIĆ *et al.* (2016). However, for all the thermal treatment modes, the surface free energy values obtained in this way were relatively low, which may have negative impacts on the adhesion of the film-forming materials applied on thermally modified wood.

Tab. 3 Surface free energy (γ_s) of thermally modified beech wood determines as the sum of the polar component (γ_s^p) based on wetting with water and the disperse component (γ_s^d) based on wetting with diiodomethane.

Surface free energy and its components	Control	Heating period at 200 °C		
	0 h	1 hour	3 hours	5 hours
γ_s [mJ.m ⁻²]	84.99	47.66	47.34	48,65
γ_s^d [mJ.m ⁻²]	44.24	44.39	44.51	45.55
γ_s^p [mJ.m ⁻²]	40.75	3.275	2.826	3.095

CONCLUSIONS

The results and their analysis indicate that the beech wood thermal treatment running at a temperature of 200 °C during three different treatment periods (1, 3, and 5 hours) was noticeably responded through changes in the studied surface properties.

With prolonged treatment time, the lightness L^* was decreasing significantly. After five-hour-lasting treatment, the lightness was reduced to one half of the initial value. The coordinates a^* and b^* were increasing during the first three hours, then, there was a moderate decrease. The drop in lightness and shift of colour coordinates a^* and b^* towards red and yellow caused that the wood was gradually coloured saturated deep brown. As early as after one-hour thermal treatment, the value of the total colour difference ΔE markedly exceeded the value of 12, which means a completely new wood tint compared to the referential specimens.

The thermal treatment also induced changes to the beech wood surface morphology. These changes were observable as enhanced roughness. In all cases, the roughness parameters Ra , Rq and Rz values were lower parallel to the grain than perpendicular to the grain. However, in the case of RSm , the reverse was true.

The results disclosed that the thermal treatment of beech wood improved significantly this wood surface resistance against wetting with water. This was evident from the contact angle values $\theta > 90^\circ$. The time necessary for the complete soaking of the drop into the substrate was one order of magnitude longer than in untreated wood. In the case of thermo-wood wetting with non-polar diiodomethane, the influence of thermal treatment was not found important. The resistance to liquid water can be considered to be a profit. However, it is necessary to address the expected durability of the resistance.

Reduced wood surface wetting had a significant influence on lowering the wood surface free energy, primarily due to the substantial decrease in the polar component of this energy. This may imply negative consequences for the quality of a surface coating process of thermally modified wood.

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