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COLOR OF BIRCH WOOD IN THE PROCESS OF THERMAL TREATMENT WITH SATURATED STEAM AND THE DEPENDENCE OF THE TOTAL COLOR DIFFERENCE ON THE ACIDITY OF WOOD

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ABSTRACT

The paper presents changes in the color of birch wood (Betula pendula Rot.) in the thermal process of wood color modification with saturated water steam in the temperature range t = 105–135 °C during τ = 3–12 hours. The light white-brown color of birch wood acquires color shades from pale brown to brown in the thermal treatment process. Changes in the color of birch wood are expressed in terms of the total color difference in the color space CIE L*a*b*.
In the thermal process of heat on wet wood, conditions are created for the course of chemical reactions, such as the extraction of water-soluble substances, hydrolysis of wood hemicelluloses, depolymerization of polysaccharides, and chemical changes in lignin manifested by modification of the wood chromophore system manifested by wood color change. Due to the hydrolysis of hemicelluloses under given technological conditions, the acidity of birch wood changes with a decrease in the pH value.
The presented dependence of the total color difference ΔE* on the change in the pH of birch wood is a suitable technological tool for the evaluation of the achieved change in the color of birch wood in the technological process.

Key words: wood, white birch, thermal treatment, saturated water steam, color, acidity

1. INTRODUCTION

Wood located in an environment of hot water, saturated water steam, or saturated humid air is heated, and its physical, mechanical, and chemical properties change. Mentioned facts are used in the technology of steam bending and boiling during veneers and plywood, bent furniture, or pressed wood manufacturing processes: *Kollmann and Gote (1968), Nikolov, Rajčev and Deliiski (1980), Sergovskij and Rasev (1987), Lawnniczak (1995), Trebula (1996),* and *Deliiski and Dzurenda (2010).*

Processes of thermal treatment of wood with saturated steam, in addition to targeted physico-mechanical changes, are also accompanied by chemical reactions such as partial hydrolysis of hemicelluloses and extraction. *Fengel and Wegener (1989), Bučko (1995), Kačík (2001), Solár (2005), Samešova et al. (2018), Geffert, Vybohova, Geffertova (2018), Dzurenda et al. (2020).* Depending on the temperature and duration of action of hydrolysis products (acetic acid and formic acid), polysaccharides are degraded by the oxidation of carbohydrates and pectin. Dehydration of pentose to 2-furaldehyde and lignin begins to form free radicals and phenolic hydroxyl groups, resulting in new chromophoric groups and wood discoloration. *Fengel and Wegener (1989), Bučko (1995), Hon (2001), Solar (2004), Sundqvist et al. (2006), Geffert et al. (2018).*

While in the past the color changes of darkening of thermally treated wood were used to remove unwanted color differences between light white and dark core or to remove unwanted color spots caused by steaming, browning, or molding, so recently the research has focused on targeted changes of individual wood colors to more or more pronounced color shades, resp. wood imitations of domestic trees for exotic woods: *Tolvaj et al. (2009), Dzurenda (2014), Barcik, Gašparík, Razumov (2015), Baranski et al. (2017), Hadjiski and Deliiski (2016), Dzurenda (2018).*

The aim of this work is to present the color of birch wood obtained in the process of thermal treatment and the dependence of the change in the total color difference ΔE* on the change in acidity of birch wood achieved by thermal steam treatment in the temperature range t = 105 °C to 135 °C and time τ = 3 to 12 hours.

2. MATERIALS AND WORK METHODS

Material

The wood of *Betula pendula Rot.* in the form of blanks with dimensions of a thickness of 40 mm, a width of 90 mm, and a length of 750 mm in 260 pieces was divided into 13 groups of 20 pieces in one group. The initial moisture content of wet birch wood was in the range of values: *w* = 40 – 55 %. Group 1 blanks were not thermally treated. The other blanks were divided into 12 groups of 20 pieces each and thermally treated with saturated water steam at *t* = 105 °C, *t* = 125 °C, and *t* = 135 °C for 3, 6, 9, and 12 hours. Thermal treatment of birch wood with saturated water steam was carried out in a pressure autoclave APDZ 240 (Himmasch AD, Haskovo, Bulgaria) installed in the company Sundermann s.r.o. Banská Štiavnica (Slovakia).

Methods

The conditions of thermal treatment of birch wood with saturated water steam and the sampling time intervals during the thermal treatment are shown in Fig. 1.

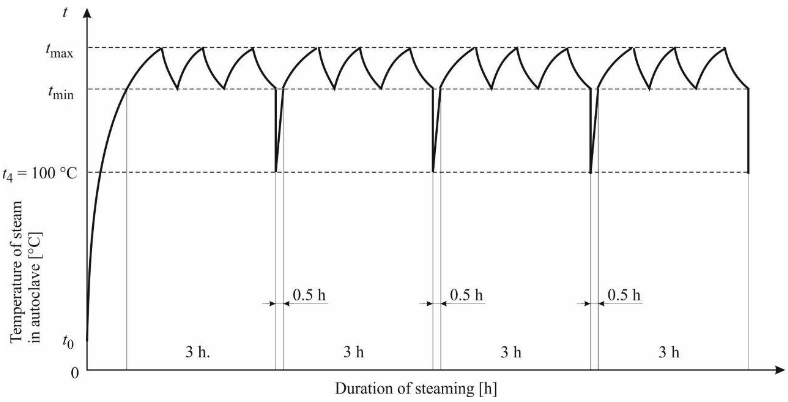

***Figure 1.** Mode of color modification of birch wood with saturated water steam.*

The thermal process of birch wood color modification was performed in an APDZ 240 autoclave at a higher saturated water steam pressure than atmospheric pressure. Saturated water steam temperatures in individual color adjustment modes are given in Table 1. The temperatures t_{max} and t_{min} are the temperature intervals at which saturated water steam is fed into the autoclave to carry out the technological process. Temperature t4 is the temperature of the saturated water steam in the autoclave after the water steam pressure in the autoclave has been reduced to atmospheric pressure to allow safe opening of the pressure equipment and sampling after the thermal treatments of 3, 6, 9, and 12 hours.

***Table 1:** Modes of color modification of birch wood with saturated water steam*

Temperature of saturated water steam	t_{min}	t_{max}	t_4	Time of thermal color modification of wood			
Mode I	102.5	107.5	100	$τ_1$ = 3 h	$τ_2$ = 6 (+0.5[a]) h	$τ_3$ = 9 (+0.5[a]) h	$τ_4$ = 12 (+0.5[a]) h
Mode II	122.5	127.5	100				
Mode III	132.5	137.5	100				

Note: [a] time for taking out the specimens

The pH of wet birch wood was measured using a pH-meter SI 600 with a Lance FET + H puncture probe (Sentron, Roden, Netherlands). A hole with a diameter of 12 mm was created using a cordless drill (DeWalt DCD791NT, Germany). Drilling sawdust was pressed into the hole, and the LanceFET + H sensor head (Geffert *et* al. 2019) was inserted into the wet sawdust. After about 60 seconds of stabilization, the pH value was read on a SI 600 pH meter.

Thermally treated wood of birch woodturning blanks as well as thermally untreated samples were dried to report the moisture content of w = 12 ± 0.5 % in a conventional wood drying kiln KAD 1x6 (KATRES Ltd.). Subsequently, surfaces and edges were processed using the swivel spindle milling machine FS 200.

The color of the thermally treated birch wood in the CIE L*a*b* color space was determined using a Color Reader CR-10 (Konica Minolta, Japan). The light source D65, with a lit area of 8mm, was used.

Lightness coordinates L* and coordinates a* and b* in the CIE-L*a*b* color space on the samples of thermally treated as well as non-thermally treated wood were carried out after drying on the planed surface in the middle of the side and loading surfaces at a distance of 300 mm from the forehead.

The values of the color coordinates of thermally treated as well as untreated birch wood are presented using a formula, i.e., the average measured value and the standard deviation.

The value of the total color difference is described by the equation:

$$\Delta E^* = \sqrt{\left(L_2^* - L_1^*\right)^2 + \left(a_2^* - a_1^*\right)^2 + \left(b_2^* - b_1^*\right)^2} \quad (1)$$

where: L^*_1, a^*_1, b^*_1 are the values of the coordinates in the wood color space of the surface of dried milled thermally untreated birch wood,
L^*_2, a^*_2, b^*_2 are the values of the coordinates in the wood color space of the surface of dried milled thermally treated birch wood.

The rate of change in the wood color and hues during the processes of thermal treatment following the total color difference ΔE* is classified according to the chart mentioned by the authors *Cividini et al. (2007)* shown in Tab. 2.

Table 2: *Classification of the total color diference ΔE**

0.2 < ΔE*	There is no visible difference
0.2 < ΔE* < 2	Small difference
2 < ΔE* < 3	The color difference is visible on a low-quality screen
3 < ΔE* < 6	The color difference is visible on a medium-quality screen
6 < ΔE* < 12	High color difference
ΔE* > 12	Different colors

3. RESULTS

According to the authors *Perelygin (1965), Makoviny (2010), Klement, Réh, and Detvaj (2010),* the wood color of the wood species *Betula pendula Rot*. is light white-brown. The color of birch in the CIE $L^*a^*b^*$ color space is described by the authors *Babiak, Kubovský and Mamoňova (2004),* with the coordinates: L^* = 78.07; a^* = 5.92; b^* = 20.02. In our research, L* = 83.7 ± 1.3; a* = 6.8 ± 0.6; and b* = 19.8 ± 0.9 were the values of coordinates in CIE L*a*b* color space measured on the planed surface of birch wood when the moisture content was w ≈ 12 %. The acidity of wet, thermally untreated birch wood at a moisture content of w = 53.9% was pH = 5.3 ± 0.2.

The degree of coloring of birch wood by thermal treatment with saturated water steam is dependent on the temperature and duration of the technological process, as evidenced by Fig. 2. Information on changes in the color of birch wood during thermal treatment on the coordinates of lightness L*, red color a*, and yellow color b* is given in Table 3.

Mode I. t = 105 ± 2.5 °C

Figure 2: *Changes in the color of birch wood during thermal modification*

Table 3*: Values of the moisture content, acidity, and coordinates L*, a*, and b* of birch wood in the process of thermal treatment.*

Temperature of saturated water steam	Time of thermal color modification of birch wood			
	3 hours	6 hours	9 hours	12 hours
t_I = 105 ± 2.5 °C	pH = 4.9 ± 0.1	pH = 4.7 ± 0.1	pH = 4.6 ± 0.2	pH = 4.4 ± 0.3
	L* = 80.7 ± 1.2	L* = 75.8 ± 1.2	L* = 74.7 ± 0.8	L* = 71.3 ± 1.2
	a* = 8.5 ± 0.8	a* = 10.7 ± 0.7	a* = 10.5 ± 0.7	a* = 10.5 ± 0.8
	b* = 19.2 ± 0.6	b* = 21.1 ± 0.5	b* = 21.4 ± 0.6	b* = 19.8 ± 0.4
t_{II} = 125 ± 2.5 °C	pH = 3.9 ± 0.1	pH = 3.8 ± 0.2	pH = 3.7 ± 0.3	pH = 3.6 ± 0.2
	L* = 73.9 ± 1.1	L* = 66.6 ± 1.2	L* = 64.3 ± 1.2	L* = 63.8 ± 1.2
	a* = 10.3 ± 0.8	a* = 11.9 ± 0.7	a* = 12.5 ± 0.7	a* = 12.2 ± 0.8
	b* = 19.8 ± 0.9	b* = 18.9 ± 0.5	b* = 18.5 ± 0.5	b* = 19.8 ± 0.4
t_{III} = 135 ± 2.5 °C	pH = 3.6 ± 0.1	pH = 3.4 ± 0.2	pH = 3.2 ± 0.1	pH = 3.2 ± 0.1
	L* = 65.1 ± 1.9	L* = 59.9 ± 1.5	L* = 55.6 ± 0.9	L* = 53.5 ± 0.7
	a* = 11.6 ± 0.6	a* = 12.5 ± 0.4	a* = 12.5 ± 0.3	a* = 12.1 ± 0.4
	b* = 18.7 ± 0.6	b* = 19.4 ± 0.5	b* = 19.5 ± 0.6	b* = 18.8 ± 0.4

The values of the total color difference ΔE* of birch wood in the process of thermal modification with saturated steam at temperatures t_I = 105 ± 2.5 °C, t_{II} = 125 ± 2.5 °C, and t_{III} = 135 ± 2.5 °C at times τ = 3, 6, 9, and 12 hours are shown in Fig. 3.

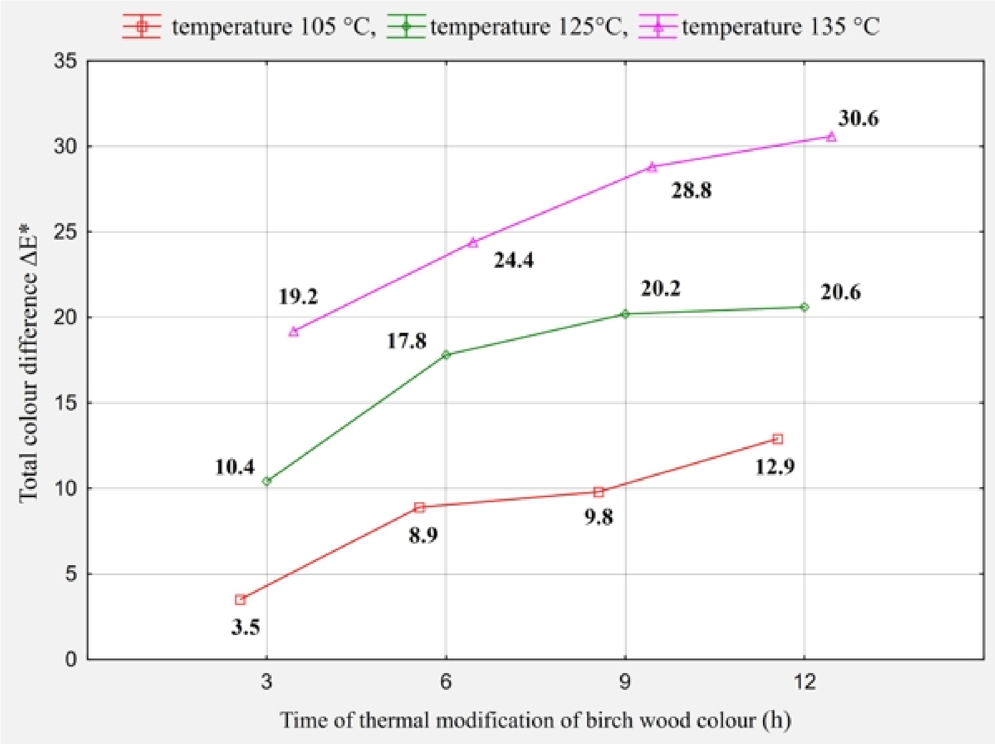

Figure 3: *Dependence of the total color difference (ΔE*) on the time of thermal treatment of birch wood*

Changes in acidity values of wet thermally modified birch wood in the process of thermal modification with saturated steam with temperatures $t_I = 105 \pm 2.5$ °C, $t_{II} = 125 \pm 2.5$ °C, and $t_{III} = 135 \pm 2.5$ °C at time τ = 3, 6, 9, 12 hours are shown in Fig. 4.

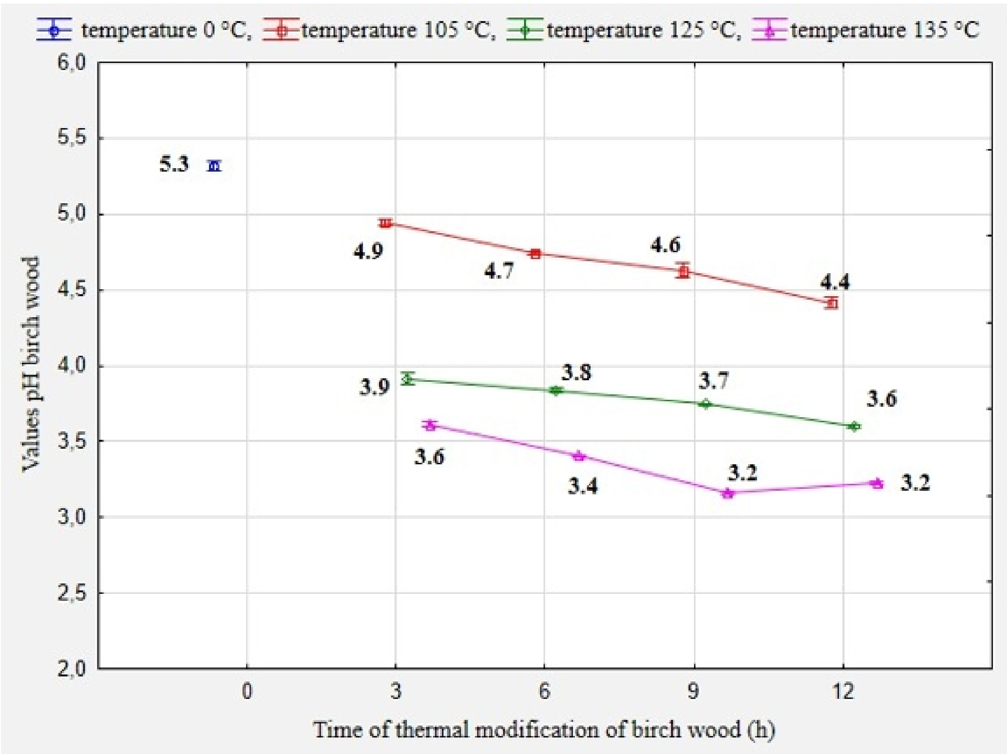

Figure 4: *Dependence of birch wood acidity on thermal treatment time*

The dependence of the total color difference ΔE* on the acidity of wet birch wood in the process of thermal treatment in the temperature range t = 105 - 135 °C and the time of the technological process τ = 3 - 12 hours is shown in Fig. 5.

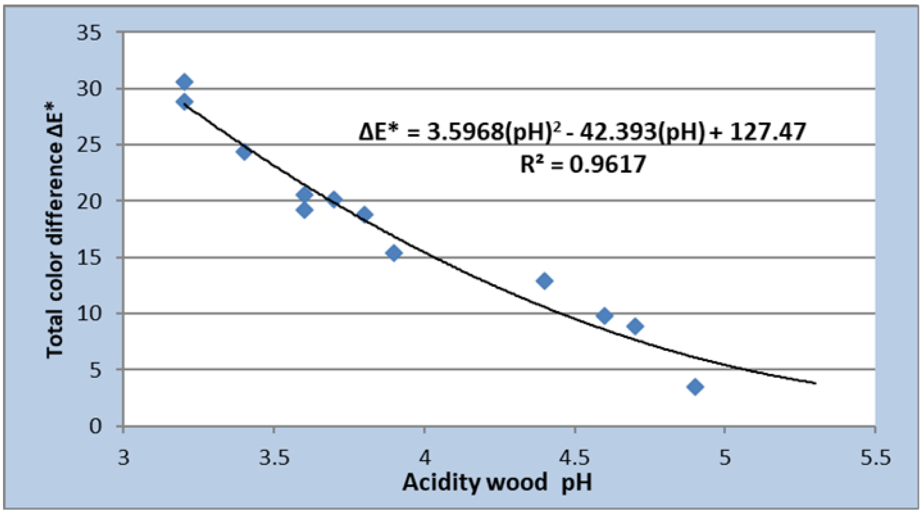

Figure 5: *The dependence of the total color difference of birch wood (ΔE*) on the acidity value (pH) of wet birch wood in the thermal treatment process*

4. DISCUSSION

The color of birch in the process of thermal treatment with saturated water steam changes from light white-brown to light brown at the temperature of saturated water steam of t_I = 105 ± 2.5 °C and the time of thermal treatment of τ = 6 - 12 hours through brown hues resulting from the application of saturated water steam with the temperature of t_{II} = 125 ± 2.5 °C for 6 to 12 hours up to the brown color of birch wood at the temperature of t_{III} = 135 ± 2.5 °C for τ = 9 - 12 hours of thermal treatment.

Dependences of changes in values on the luminance coordinate L* and chromatic coordinates: red a* and yellow b* in the CIE L*a*b* color space on birch wood thermal treatment parameters: thermal saturated water steam at the time of thermal treatment τ are given by the work of *Dzurenda, Dudiak* (2019).

Color changes in birch wood ΔE* resulting from the thermal treatment with saturated water steam at a temperature of t_I = 105 ± 2.5 °C at the time of thermal modification for up to 3 hours are considered not significant changes in color and not visible with the naked eye. Following the conditions of thermal treatment of birch at the temperature of saturated water steam of t_{II} = 125 ± 2.5 °C with the color difference: ΔE* = 17.8 ÷ 20.6 birch wood is classified as wood, changing the color to brown hues visible with the naked eye. The color of birch resulting from the thermal treatment with saturated water steam at a temperature of t_{III} = 135 ± 2.5 °C for more than 6 hours is a unique, rich brown.

A decrease in the lightness of birch wood thermally treated with saturated water steam and an increase in the values of total color differences ΔE* in the CIE $L^*a^*b^*$ color space are in compliance with the knowledge about color changes of wood in the thermal treatment processes by steaming presented in the following works: *Molnar and Tolvaj (2002)*, and *Dzurenda (2014, 2018)*, as well as by high temperature drying in the environment of overheated water steam *Klement and Marko (2009)*, or by thermal treatment processes during thermowood manufacturing *Barcik, Gašparík and Razumov (2015).*

Measured pH values of birch in the process of thermal treatment confirm our knowledge about the hydrolysis of polysaccharides in wet wood during the application of heat. Products of hydrolysis and extraction after wood boiling or other thermal treatment processes mentioned in the following works: *Melcer et al. (1989), Kačík (2001), Laurova et al. (2004)*, and *Samešova, Dzurenda, and Jurkovič (2018)* were quantified using the hydromodulus or created condensate. Measuring the pH value of wet wood using the potentiometer SENTRON SI 600 with the sensor head LenceFET+H 22704-010 can be considered unique. This way, wood hydrolysis and its effect on the wood color change can be monitored. Following the measured values of acidity of wet wood resulting from the given modes of thermal treatment of birch wood, the fact is that temperature affects the hydrolysis of hemicelluloses, and it can be stated that the change in the chromophore system of wood is more significant than the time of the thermal treatment process.

The derived dependence of the total color difference ΔE* on the change in acidity of birch wood in the thermal process of wood color modification of birch blanks $\Delta E^* = 3.5968\,(pH)^2 - 42.393\,(pH) + 127.47$ is a suitable tool for evaluating the achieved color change by the value pH of birch wood.

5. CONCLUSION

The paper presents the results of experimentation monitoring the acidity and color change of birch wood in the process of thermal treatment of wood by saturated water steam in the temperature range t = 105-135 °C for τ 3-12 hours.

Birch wood, in the process of thermal treatment, loses its whiteness (darkens) and acquires color shades from pale brown to brown. In the CIE color space L*a*b*, the values on the luminance coordinate decrease in the range of L* = 83.7 - 53.5, on the red chromaticity coordinate, they increase to a* = 6.8 – 12.5; and on the chromaticity coordinate, yellow oscillates around the values b* = 18.5 - 21.4. The color change of birch wood expressed by the value of the total color difference is ΔE* = 3.5 - 30.6.

Wet birch wood changes pH in the range of pH = 5.3 ÷ 3.2 due to the partial hydrolysis of hemicelluloses. Wood acidity measurement was performed with a SENTRON SI 600 potentiometer with LenceFET + H probe 22704-010.

In order to determine the color change of birch wood in the technological process of wood color modification with saturated steam using the pH value of birch wood, the dependence of the total color difference ΔE* on the change in acidity of birch wood in the form: $\Delta E^* = 3.5968\,(pH)^2 - 42.393\,(pH) + 127.47$. This dependence is a suitable tool for evaluating the achieved color change of birch wood in the technological process.

The aforementioned changes in the color of birch wood achieved by the thermal process of saturated water steam extend the possibilities of using color scales of birch wood in the construction-firearm area for the production of flooring and cladding, as well as structural-artistic design in the manufacture of solid wood furniture, toys, or other utility and decorative objects.

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