Range of Color Changes of Beech Wood in the Steaming Process

Ladislav Dzurenda *

Changes in color were evaluated for beech wood *Fagus sylvatica* L., caused by a steaming process using either a mixture of saturated steam and air or saturated water steam in the temperature range: t = 95 °C to 125 °C for a duration of T = 3 h to 12 h. The initially light white-gray color of beech wood with a yellow tint darkened during the thermal treatment process. It changed to a pale pink-brown and then to dark brown color. According to the visible changes in the color of beech wood obtained by the thermal treatment process with the human eye, , a color scale was proposed as a means to categorize the severity of treatment. The color ranged from a pale pink-brown color to a dark brown-red color depending on the value of the total color difference ΔE^*.

DOI: 10.15376/biores.17.1.1690-1702

*Keywords: Beech wood; Color space CIE L*a*b*; Scale of color changes; Thermal treatment; Saturated water steam*

Contact information: T. G. Masaryka 24, Technical University in Zvolen, 960 01 Zvolen;
** Corresponding author: dzurenda@tuzvo.sk*

INTRODUCTION

Color is one of the basic macroscopic features that distinguish the appearance of wood from individual trees. The color of the wood is caused by chromophores, *i.e.*, chemical functional groups of the type: >C=O, -CH=CH-CH=CH-, -CH=CH, aromatic nuclei, *etc.*, which are found in the chemical constituents of wood (lignin and extractive substances, such as dyes, tannins, resins, and others). These chromophores absorb some components of the electromagnetic radiation of daylight and thus create the color of the wood surface perceived by human vision.

The perception of color by human vision is a psycho-physiological sensation caused by the entry of reflected rays of electromagnetic radiation with wavelengths in the range from 380 to 780 nm from the surface of the object, into the human visual center. Its character depends on the wavelength. Light with shorter wavelengths of 380 to 450 nm evokes a sensation of blue and violet, light of medium wavelengths evokes a sensation of green, yellow, and orange, and longwave light with wavelengths of 630 to 750 nm produces a sensation of red, and wavelengths of 750 to 780 nm with a sensation of dark red.

If the object is red, its surface absorbs all wavelengths of electromagnetic radiation of light except the wavelength of red light that is reflected from the object. The white color is an object that does not significantly absorb any wavelength and at the same time reflects most of the light. A black object, in turn, absorbs most of the electromagnetic radiation of daylight. From the aspect of the physiology of human vision, as stated by the authors

(Wilson and Keil 1999), the color of objects is evaluated through three features: tone, chroma, and lightness of color.

The wood of the *Fagus sylvatica* L. tree belongs to the deciduous scattered-porous tree category. It has a light white-gray color with a yellow or reddish tinge. Around the center of some old trees there is an irregularly demarcated reddish-brown color called false core. In the color space *CIE L*a*b** system (Babiak *et al.* 2004), the color of beech wood on the luminance coordinates is described with the value $L^* = 75.96$ and in the chromatic coordinates with the values: $a^* = 6.62$ and $b^* = 17.63$. In the study by Meints *et al.* (2017), for the color of beech wood the values are $L^* = 75.4$, $a^* = 10.1$, and $b^* = 23.7$.

In the thermal treatment of wet beech wood, when using a steaming process, changes in the physical, mechanical, and chemical properties of beech wood occur. These changes are divided into reversible and irreversible changes in wood (Kollman and Cote 1968; Trebula 1996; Dzurenda and Deliiski 2010). Irreversible changes in the properties of wood arise from thermal treatment of wood that exhibits new chemical properties after cooling. The irreversible chemical changes occur even under mild conditions of heat on wet wood. Increasing the temperature and prolonging the heating time create conditions for the course of chemical reactions, such as extraction of water-soluble compounds, hydrolysis of wood hemicelluloses, depolymerization of polysaccharides, and chemical changes in lignin from modification of the chromophoric system of wood, and color change of wood (Fengel and Wegener 1989; Bučko 1995; Hon and Shiraishi 2001; Solar 2005; Geffert *et al.* 2019; Dzurenda *et al.* 2020).

In the technology of thermal treatment (steaming of wood), the phenomena described above are used to modify the color of wood into non-traditional color shades and darkness of wood of individual wood species. An example is the change of light white-gray color with a yellow tinge of beech wood in the process of steaming wood with saturated moist air at atmospheric pressure, or saturated with steam, to pink-red, or red-brown color shade (Tolvaj *et al.* 2009; Dzurenda 2014; Milić *et al.* 2015; Geffert *et al.* 2017; Dzurenda and Dudiak 2021). Another example is the change in the color of the core of agate wood, which changes from greenish-yellow to dark brown-gray color shades depending on the steaming conditions (Tolvaj *et al.* 2010; Dzurenda 2018d). By steaming the wood with saturated steam in pressure autoclaves, the maple wood acquires brownish-red color shades (Dzurenda 2018a) and the light white-gray color of alder wood changes from light reddish brown to dark brown-brown color by steaming (Dudiak and Dzurenda 2021).

This study evaluated the changes in the color of beech wood in the color space *CIE L*a*b** during the thermal treatment in the temperature range of the saturated steam-air mixture or saturated water steam $t = 95$ °C to 125 °C during the technological process $\tau =$ 3 to 12 h. The design of a color scale is presented for the evaluation of the change of beech wood fragrance from pale pink to dark brown-red color depending on the value of the total color difference ΔE^*.

EXPERIMENTAL

Material

Approximately 425 pieces of *Fagus sylvatica* L. wood blanks with dimensions: thickness of 38 mm, width of 100 mm, and length 800 mm were divided into 17 groups.

The moisture content of wet beech wood was in the range of 55.8% to 58.6%. Group 1 blanks were not thermally treated and were used as the control group. The other sections were divided into 16 groups of 25 pieces and thermally treated with a saturated steam-air mixture at a temperature of t^* = 95 °C and saturated water steam at temperatures: t = 105 °C, t = 115 °C, and t = 125 °C for τ^* = 3, 6, 9, and 12 h. Thermal treatment of beech wood blanks was performed in a pressure autoclave APDZ 240 (Himmasch AD, Haskovo, Bulgaria) installed by Sundermann sro Banská Štiavnica Company (Banská Štiavnica, Slovakia).

Thermal Treatment

To modify the color of beech wood by thermal treatment using saturated steam-air mixture or saturated water steam, various time intervals of sampling were employed during the thermal treatment. The temperature-time profile is shown in Fig. 1.

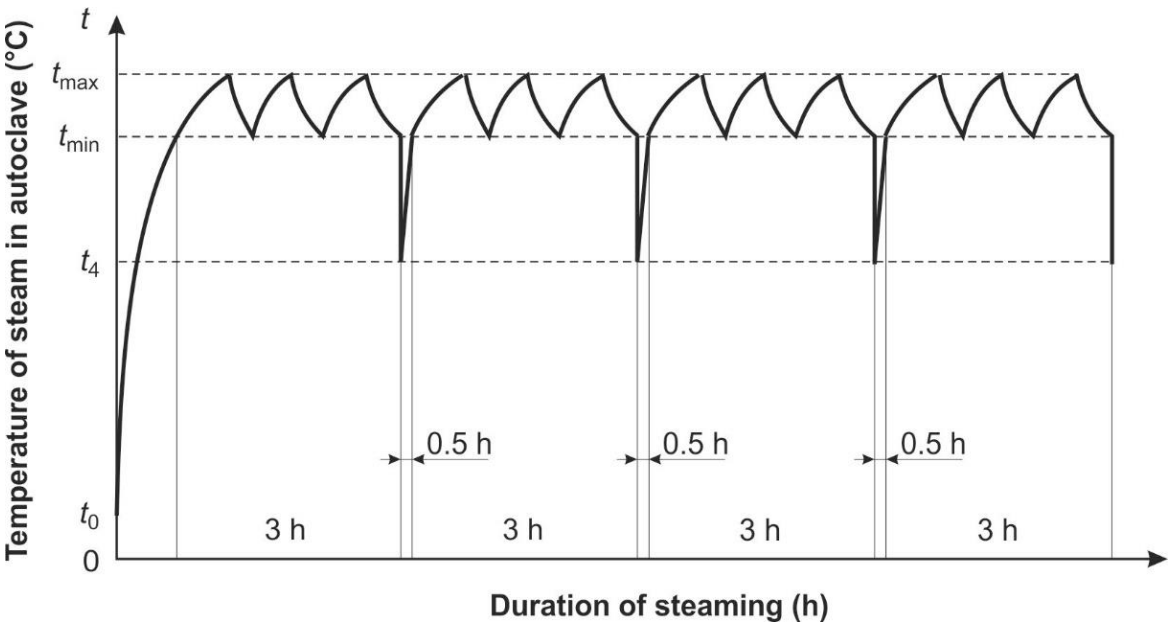


Fig. 1. Thermal treatment of beech wood color modification using saturated steam-air mixture or saturated water steam

The temperatures of the saturated steam-air mixture and saturated water steam in the individual treatment modes are given in Table 1.

Table 1. Breakdown of Temperatures of Saturated Steam Air Mixture or Saturated Water Steam and Time of Thermal Treatment of Beech Wood

Temperature Modes	t_{min}	t_{max}	t_4	Times of Thermal Treatment of Beech Wood			
Mode I	92.5	97.5	-	τ_1 = 3 h	τ_2 = 6 (+0.5[a]) h	τ_3 = 9 (+1.0[a]) h	τ_4 = 12 (+1.5[a]) h
Mode II	102.5	107.5	100				
Mode III	112.5	117.5	100				
Mode IV	122.5	127.5	100				
* Note: [a] time (h) for removing the specimens							

The values of temperatures, t_{max} and t_{min}, are the temperatures for controlling the supply of saturated water steam to the pressure autoclave for performing the treatment process. The temperature t_4 is a parameter of the saturated water steam pressure in the autoclave, to which the steam pressure in the autoclave must be reduced before the pressure device can be opened safely and samples taken at the time of thermal treatments at 3, 6, 9, and 12 h.

Thermally treated as well as thermally untreated beech wood blanks were dried using a mild drying mode (Dzurenda and Deliiski 2012a,b) to a final moisture content of w = 12 ± 0.5%. The loading and side surfaces of the dry blanks were machined on a FS 200 horizontal face milling machine (BENET Trading, Kvasiny, Slovakia).

Measurement of Wood Color

The color of treated beech wood in the color space *CIE L*a*b** was evaluated using a Color Reader CR-10 colorimeter (Konica Minolta, Japan). A standard light source D65 was used. The sensor head of the colorimeter has a diameter of the scanning hole at 8 mm.

Measurements of luminance values *L**, color coordinates *a**, and *b** on samples thermally treated as well as thermally untreated wood were performed after drying on a planed surface in the middle of the side and loading surfaces at a distance of 300 mm from the front. The values of the light sheets *L** of the color coordinates *a**, *b** of beech wood are given in the form of a notations, $x = \bar{x} \pm s_x$ *i.e.*, average measured value, and standard deviation.

Chroma *C** is an integrated value of the coordinates of red *a** and yellow *b**, as given by Eq. 1,

$$C^* = \sqrt[2]{a^{*2} + b^{*2}} \quad (1)$$

where *a** value denotes the chromatic coordinate of red color, and *b** value is the chromatic coordinate of yellow color.

From the difference of values on the coordinates in the color space *CIE L*a*b** determined on the basis of measurements of the color of the thermally treated and untreated beech wood, the total color difference Δ*E** was determined according to Eq. 2 according to the EN ISO 11 664-4 (2019) standard,

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

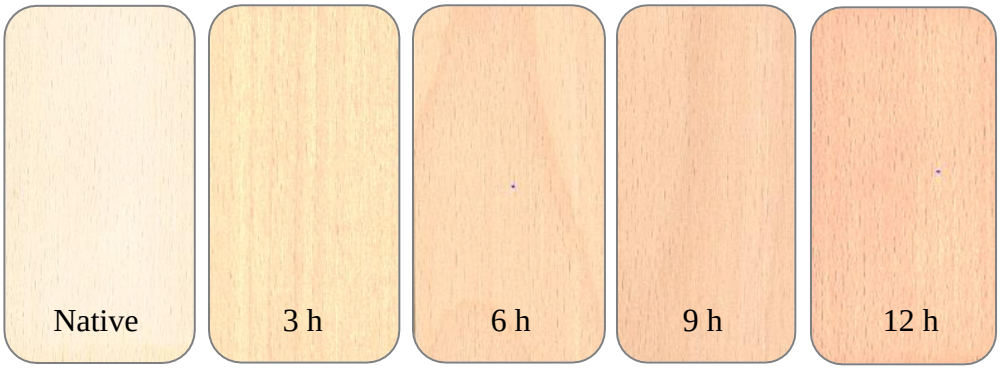
where L_1*, a_1*, and b_1* values represent the coordinates of the color space of the surface of the thermally untreated beech wood, and L_2*, a_2*, and b_2* values are the coordinates of the thermally treated beech wood.

Using the program Statistica 12 (Statsoft, V12.0 SP2, Tulsa, OK, USA), mathematical dependences of the coordinate values of lightness *L**, chroma *C**, and total color difference Δ*E** on saturated water steam temperature and the duration of the thermal process τ were determined from the measured data for the ranges: temperatures t = 95 to 105 °C and time $\tau \leq 12$ h.

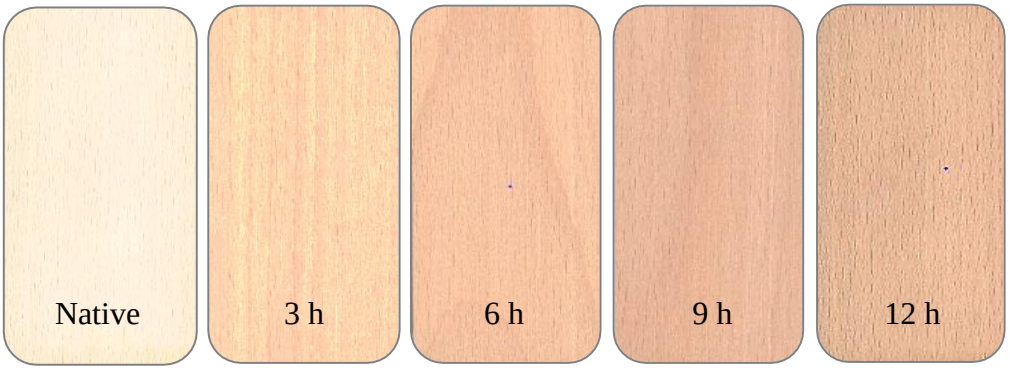
RESULTS AND DISCUSSION

The light white-gray color with a yellow tinge of dry beech wood is identified in the color space *CIE L*a* b** by the coordinates values: L_0* = 76.8 ± 2.5; a_0* = 6.9 ± 1.9; and b_0* = 19.8 ± 1.6. The obtained values of beech color were comparable with the literature values of color coordinates (Babiak *et al.* 2004; Meints *et al.* 2017).

Mode *I*: Temperature of saturated water steam-air mixture t_I = 95 ± 2.5 °C



Mode *II:* Saturated water steam temperature t_{II} = 105 ± 2.5 °C



Mode *III:* Saturated water steam temperature t_{III} = 115 ± 2.5 °C

Mode *IV:* Saturated water steam temperature t_{IV} = 125 ± 2.5 °C

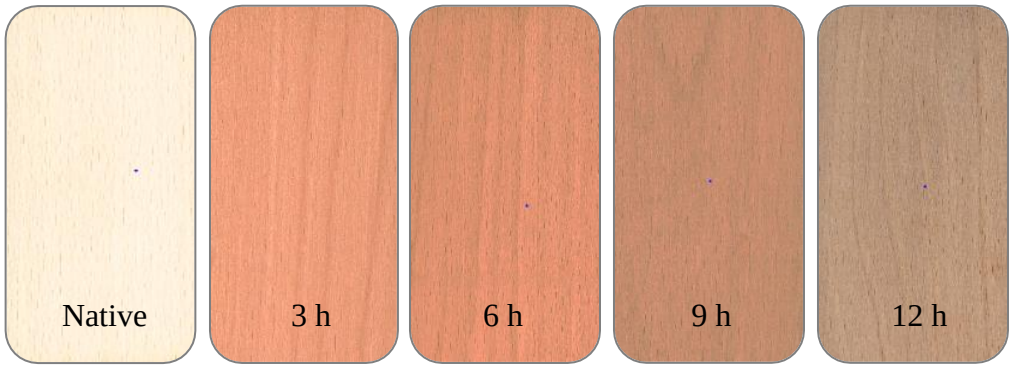


Fig. 2. Color of beech wood samples in the process of thermal treatment

The color of beech wood in the process of thermal treatment changes noticeably, the wood darkens and acquires a pale pink-brown, brown-pale red, brown to dark brown color. The color of thermally treated wood at individual heating temperatures in the technological process is shown in Fig. 2. The values on the coordinates of the color space *CIE L*a* b** are given in Table 2.

Table 2. Measured Values on the Coordinates *L**, *a**, *b** in the Color Space *CIE L*a*b**, Values of the Total Color Diffusion Δ*E** of Beech Wood during Thermal Modification

Temperature in Modes	Times Thermal Treatment Beech Wood			
	3 h	6 h	9 h	12 h
t_I = 95 ± 2.5 °C	*L** = 73.4 ± 1.9	*L** = 69.8 ± 1.6	*L** = 66.7 ± 2.0	*L** = 64.9 ± 2.2
	*a** = 8.3 ± 1.2	*a** = 9.8 ± 1.1	*a** = 10.1 ± 1.0	*a** = 10,3 ± 1.8
	*b** = 20.4 ± 1.0	*b** = 20.5 ± 1.2	*b** = 20.6 ± 1.1	*b** = 20.7 ± 1.2
	Δ*E** = 2.1	Δ*E** = 6.3	Δ*E** = 8.9	Δ*E** = 10.7
t_{II} = 105 ± 2.5 °C	*L** = 70.0 ± 2.2	*L** = 66.3 ± 2.1	*L** = 61.6 ± 2.3	*L** = 59.2 ± 2.0
	*a** = 9.5 ± 1.1	*a** = 10.8 ± 0.8	*a** = 11.0 ± 1.0	*a** = 11.6 ± 0.9
	*b** = 20.1 ± 1.2	*b** = 20.3 ± 1.0	*b** = 20,6 ± 1.2	*b** = 20.9 ± 1.2
	Δ*E** = 5.7	Δ*E** = 9.8	Δ*E** = 14.1	Δ*E** = 16.6
t_{III} = 115 ± 2.5 °C	*L** = 66.3 ± 1.9	*L** = 60,5 ± 2.0	*L** = 57.0 ± 2.1	*L** = 54.5 ± 1.7
	*a** = 10.3 ± 0.9	*a** = 11.9 ± 1.2	*a** = 12.3 ± 0.9	*a** = 12.4 ± 1.0
	*b** = 20.7 ± 1.1	*b** = 20.3 ± 0.9	*b** = 20.9 ± 1.1	*b** = 21.0 ± 0.9
	Δ*E** = 9.4	Δ*E** = 14.8	Δ*E** = 18.9	Δ*E** = 21.4
t_{IV} = 125 ± 2.5 °C	*L** = 61,5 ± 2.1	*L** = 56,3 ± 1.9	*L** = 52.5 ± 1.8	*L** = 49.1± 1.7
	*a** = 11.0 ± 1.2	*a** = 12,3 ± 1.1	*a** = 12,7 ± 1.1	*a** = 13.3 ± 1.0
	*b** = 20.6 ± 1.3	*b** = 20.5± 1.1	*b** = 20.3 ± 1.1	*b** = 21.3 ± 0.9
	Δ*E** = 14.2	Δ*E** = 19.5	Δ*E** = 23.4	Δ*E** = 26.8

Visual control of the color of the wood on the side surfaces of the sawn blanks, as well as color measurements using CR-10 colorimeter on these surfaces showed that the wood was evenly colored throughout its cross-section. Full-volume coloring of wood is

realized because of the rapid heating of wood to the required technological temperature with saturated water steam along the entire cross-section (Deliiski 2003; Dzurenda 2018b) and creation of conditions for processes of extraction of water-soluble substances and hydrolysis of beech wood hemicelluloses.

The course of changes in the brightness L^* and chromium C^* in the color space of beech wood during thermal treatment with saturated water steam at temperature T_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C , t_{III} = 115 ± 2.5 °C, and t_{IV} = 125 ± 2.5 °C during τ = ≤ 12 h is shown in Figs. 3 and 4.

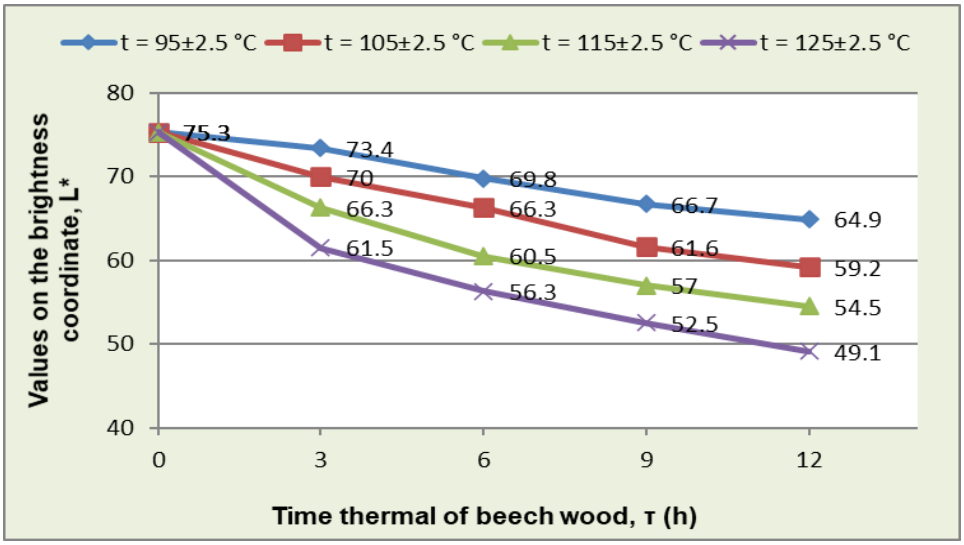


Fig. 3. Values on the light coordinate L^* in the process of thermal modification of beech wood with saturated steam-air mixture and saturated water steam with temperature t_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C t_{III} = 115 ± 2.5 °C, t_{IV} = 125 ± 2.5 °C during τ = 12 h

From the difference between the values on the light coordinate L^* of untreated beech wood L_0^* = 76.8 and the values L_4^* of thermally treated beech wood after 12 h at individual temperatures of thermal treatment, it follows that while at thermal treatment temperature of t_I = 95 ± 2.5 °C the luminosity decreased by ΔL_4^* = 11.9, with t_{II} = 105 ± 2.5 °C it decreased by ΔL_4^* = 17.6, at t_{III} = 115 ± 2.5 °C it was ΔL_4^* = 23.3, and at t_{IV} = 125 ± 2.5 °C the luminosity decreased by ΔL_4^* = 27.7. The decrease in the brightness of beech wood with increasing temperature is not directly proportional. At higher temperatures of the heat treatment process, the decrease in brightness is prominent and the darkening of beech wood is more pronounced.

The decrease of the values on the luminosity coordinate L^* is in accordance with the knowledge about wood darkening in thermal and hydrothermal technological processes, such as wood steaming reported by others (Varga and Van der Zee 2008; Tolvaj *et al*. 2009, 2010; Dzurenda 2018a, 2018c; Deliiski *et al*. 2018; Banski and Dudiak 2019), high temperature drying (Klement and Marko 2009); Baranski *et al*. 2017), or thermal treatment of wood at temperatures above 150 °C (González-Peña and Hale 2009; Esteves and Pereira 2009; Nasir *et al*. 2019).

Dependence of the brightness L^* of beech wood on the temperature of saturated water steam t = 95 °C to 125 °C and the duration of the technological process τ = 0 to 12 h can be mathematically described as shown in Eq. 3,

$$L^* = 96.4199 - 0.0951t + 0.0020\tau - 0.0011t^2 - 0.0159t \cdot \tau + 0.0370 \cdot \tau^2 \quad (3)$$

where t denotes the temperature of the saturated water steam in °C, and τ is the time of thermal treatment of beech wood in h.

Course of changes of chromium C^* in the color space *CIE* $L^*a^*b^*$ of beech wood during thermal treatment with saturated water steam at temperature t_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C, t_{III} = 115 ± 2.5 °C, and t_{IV} = 125 ± 2.5 °C during $\tau = \leq 12$ h is shown in Fig. 4.

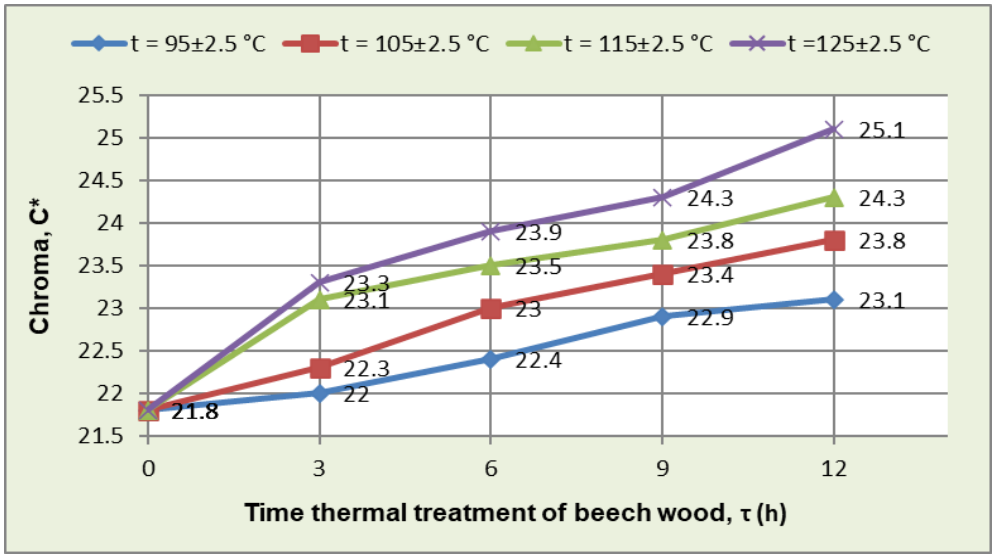


Fig. 4. Changes of chromium C^* in the process of thermal modification of beech wood by saturated steam-air mixture and saturated water steam with temperature t_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C t_{III} = 115 ± 2.5 °C, t_{IV} = 125 ± 2.5 °C during τ = 12 h

The chroma C^* values, in contrast to the luminance difference L^*, increased slightly during the beech wood thermal treatment process. The magnitudes of changes in chromium C^* were noticeably smaller compared to changes in the luminance coordinate L^* values.

Changes in chroma are decisively influenced by changes in the values on the chromatic coordinate of the color red a^*, which indicated an increasing tendency. The value on the red color coordinate of native wood a_0^* = 6.9 increases over a period of 12 h in a thermal process with a saturated water steam temperature at t_I = 95 ± 2.5 °C to a_4^* = 10.3 and at a water steam temperature of t_{III} = 125 ± 2.5 °C to value a_4^* = 13.3.

On the coordinate yellow color b^*, the changes observed were slight and contradictory, oscillating around the value b^* = 20.6. They point to the formation of less stable compounds with absorption of the electromagnetic radiation spectrum with a yellow wavelength of 560 nm. These compounds react with water steam or extraction products to form further thermal decomposition products with lower or zero absorption of the yellow wavelength in the electromagnetic radiation spectrum.

The analysis of the influence of the parameters: Temperature and duration of the treatment process shows that the development of changes in chroma C^* shows that with increasing temperature of the unsaturated steam-air mixture or saturated water steam, the

values of chroma C^* increased more intensely than that due to prolongation of the process time.

Dependence of chroma C^* values of beech wood on saturated water steam temperature of t = 95 °C to 125 °C and duration of treatment for $\tau \leq 12$ h is described by Eq. 3,

$$C^* = 13.9476 + 0.0973t + 0.1755\tau - 0.0002t^2 + 0.0008t \cdot \tau - 0.0072\tau^2 \quad (3)$$

where t denotes the temperature of the saturated water steam in °C, and τ is time of thermal treatment of beech wood in h.

The course of changes in the values of the total color difference ΔE^* of beech wood in the color space *CIE L*a*b** during the technological process is shown in Fig. 5.

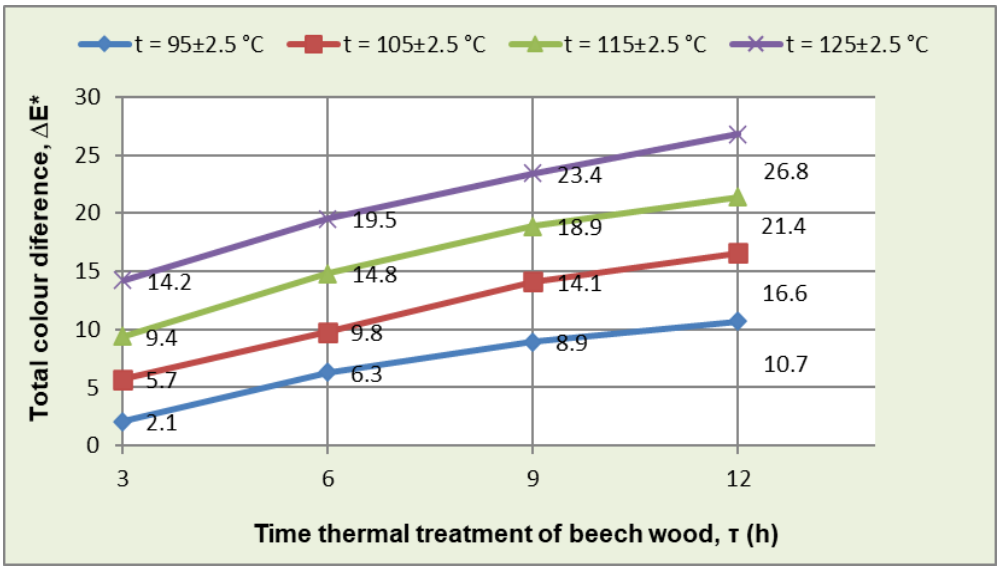


Fig. 5. Values of the total color difference ΔE^* in the process of thermal modification of beech wood with saturated steam-air mixture and saturated steam with temperature temperature t_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C t_{III} = 115 ± 2.5 °C, t_{IV} = 125 ± 2.5 °C during τ = 3 h to 12 h

Dependence of the total color difference ΔE^* of beech wood on the temperature of the saturated steam-air mixture, or saturated water steam t = 95 °C to 125 °C and the duration of the technological process τ = 3 to 12 h is described by Eq. 4,

$$\Delta E^* = -28.3812 + 0.1925t + 0.5667\tau + 0.0008t^2 + 0.0143t\,\tau - 0.0611\tau^2 \quad (4)$$

where t is the temperature of the saturated water steam in °C, and τ denotes the time of thermal treatment of beech wood in h.

Based on the achieved changes in the color of beech wood by the thermal treatment process using saturated steam-air mixture or steam at temperatures: t_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C, t_{III} = 115 ± 2.5 °C, t_{IV} = 125 ± 2.5 °C during 3, 6, 9, and 12 h (Fig. 2). An opinion survey was conducted to assess the achieved changes in the color shades of beech wood in individual modes and time intervals of the thermal process. Based on visual similarity, the samples of modified wood were included in the color scale. The statistical survey was conducted on respondents aged 20 to 35 years, where the total number of respondents was 300 women and 250 men. According to the respondents of the survey, a color scale was created, supplemented by the parameter of the total color difference ΔE^*.

The proposed color range of modified beech wood and the parameters of ΔE^* are given in Table 3.

Table 3. Classification ΔE^*

$0 < \Delta E^* < 2$	Original - Light white-gray color of beech wood with a yellow tint
$2 < \Delta E^* < 8$	Light pink-brown color
$8 < \Delta E^* < 16$	Brown-pale red color
$16 < \Delta E^* < 24$	Brown color
$\Delta E^* > 24$	Dark brown color

The application of the proposed classification of color shades based on ΔE^* is illustrated in Fig. 6.

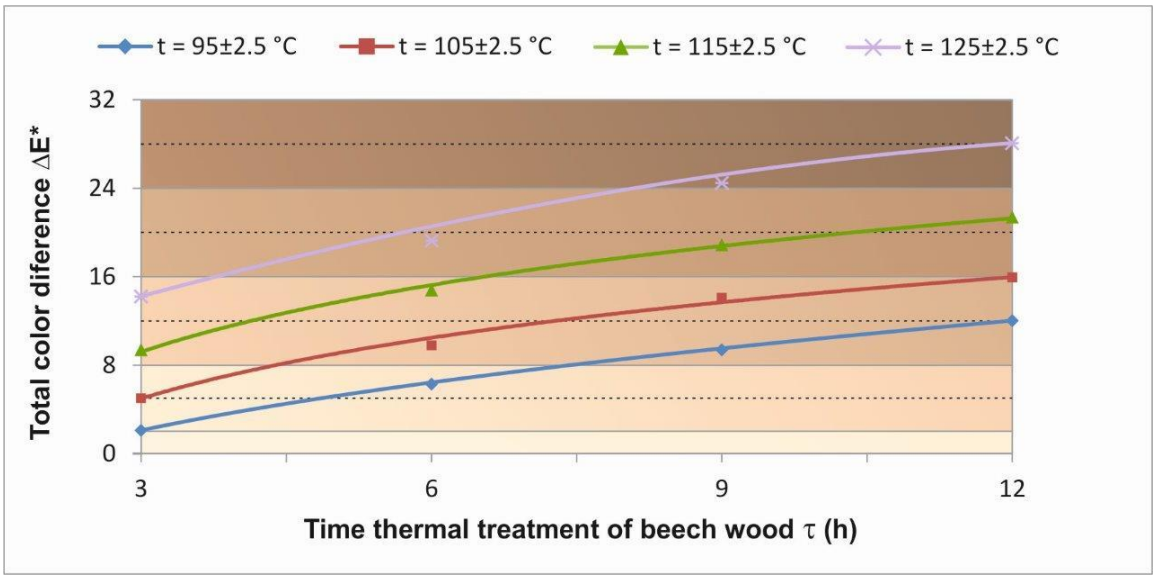


Fig. 6. The course of changes in the total color difference ΔE^* of beech wood during the technological process at the temperatures of the saturated steam-air mixture or saturated water steam with temperature t_I = 95 ± 2.5 °C, t_{II} = 105 ± 2.5 °C t_{III} = 115 ± 2.5 °C, t_{IV} = 125 ± 2.5 °C during τ = 3 to 12 h

From the course of changes in the color of beech wood in the technological process and the overall color difference ΔE^*, it follows that it is possible to determine the length of thermal treatment through the intersection of the mean value of ΔE^* color grade and the temperature of saturated water steam:

a) Small changes in the color of beech wood in the range of values ΔE^* = 2.1 - 8 expressed by the acquisition of a pale pink-brown color shade occur under the conditions of thermal treatment: Temperature of saturated steam air mixture t = 95 °C and duration of technological process τ = 4.5 h or saturated steam temperature t = 105 °C during τ = 3 h.
b) Slight darkening and acquisition of a brown-pale red color shade of beech wood in the range of values ΔE^* = 8 - 16 occurs under thermal treatment conditions in the temperature range: Saturated steam-air mixture t = 95 °C and duration of thermal

treatment above τ = 12 h, temperature saturated water steam t = 105 °C at time τ = 6.5 h or temperature t = 115 °C in time τ = 4 h.

c) Noticeable darkening of beech wood to brown color in the range of ΔE^* = 16 - 24 beech wood acquires under conditions of thermal treatment: Temperature of saturated water steam t = 115 °C and duration of technological process over τ = 9.5 h or saturated steam temperature t = 125 °C and time τ = 5.5 h.

d) In the conditions of thermal treatment of beech wood: Temperature t = 125 °C and time above τ = 12 h, beech wood acquires a dark brown color. The total color difference has a value of $\Delta E^* > 24$.

CONCLUSIONS

1. The color was affected when beech wood was thermally treated with a saturated steam-air mixture, or with steam from t = 95 °C to t = 125 °C, and varied times from 3 to 12 h. The wood darkened and took on a pale pink-brown color to a dark-brown color.
2. The color and color shades of beech wood obtained by the thermal treatment process were identified by the values on the coordinates in the color space *CIE L* a* b**.
3. A color scale was created for the color of beech wood obtained by the thermal treatment process, enabling the color thermall treated beech wood to be classified into individual color classes by steaming on the basis of the value of the total color difference ΔE^*.
4. The color scale is a suitable tool for technologists in designing optimal conditions for thermal treatment of wood, taking into account the temperature of saturated steam produced by the heat source.

ACKNOWLEDGMENTS

This study was supported by the grant project APVV 17-0456, as the result of work of author and the considerable assistance of the APVV agency.

REFERENCES CITED

Babiak, M., Kubovský, I., and Mamoňová, M. (2004). "Farebný priestor vybraných domácich drevín [Color space of selected domestic trees]," *Interaction of Wood with Various Forms of Energy* 3(1), 113–117.

Banski, A., and Dudiak, M. (2019). "Dependence of color on the time and temperature of saturated water steam in the process of thermal modification of beech wood," *AIP Conference Proceedings* 2118(1), article ID 030003. DOI: 10.1063/1.5114731

Barański, J., Klement, I., Vilkovská, T., and Konopka, A. (2017). "High temperature drying process of beech wood (*Fagus sylvatica L.*) with different zones of sapwood and red false heartwood," *BioResources* 12(1), 1861-1870. DOI: 10.15376/biores.12.1.1761-1870

Bučko, J. (1995). *Hydrolýzne Procesy [Hydrolysis Processes]*, Technical University in Zvolen, Zvolen, Slovakia.

Deliiski, N., Dzurenda, L., Angelski, D., and Tumbarkova, N. (2018). "An approach to computing regimes of autoclave steaming the prisms for veneer production with a limited power of the heat generator," *Acta Facultatis Xylologiae Zvolen* 60(1), 101-112. DOI: 10.17423/afx.2018.60.1.11

Dudiak, M., and Dzurenda, L. (2021). "Changes in the physical and chemical properties of alder wood in the process of thermal treatment with saturated water steam," *Coatings* 11, 898. DOI: 10.3390/coatings11080898

Dzurenda, L. (2014). "Sfarbenie bukového dreva v procese termickej úpravy sýtou vodnou parou *[Coloring of beech wood in the process of thermal treatment with saturated steam]*," *Acta Facultatis Xylologiae Zvolen* 56 (1), 13-22.

Dzurenda, L. (2018a). "Hues of *Acer platanoides* L. resulting from processes of thermal treatment with saturated steam," *Drewno* 61(202), 165-176. DOI: 10.12841/wood.1644-3985.241.11

Dzurenda, L. (2018b). "The effect of moisture content of black locust wood on the heating in the saturated water steam during the process of colour modification," *MATEC Web of Conferences* 168, article ID 06004. DOI: 10.1051/matecconf/202032804004

Dzurenda, L. (2018c). "The shades of color of *Quercus robur* L. wood obtained through the processes of thermal treatment with saturated water vapor," *BioResouces* 13(1), 1525-1533. DOI: 10.1063/biores 13.1.1525-1533

Dzurenda, L. (2018d). "Colour modification of *Robinia pseudoacacia* L. during the processes of heat treatment with saturated water steam," *Acta Facultatis Xylologiae Zvolen* 60(1), 61-70. DOI: 10.17423/afx.2018.60.1.07

Dzurenda, L., and Deliiski, N. (2012). "Convective drying of beech lumber without color changes of wood," *Drvna Industrija* 63(2), 95-103. DOI: 10.5552/drind.2012.1135

Dzurenda, L., and Dudiak, M. (2021). "Cross-correlation of color and acidity of wet beech wood in the process of thermal treatment with saturated steam," *Wood Research* 66 (1), 105-116. DOI: 10.37763/wr.1336-4561/66.1.105116

Dzurenda, L., Geffert, A., Geffertová, J., and Dudiak, M. (2020). "Evaluation of the process thermal treatment of maple wood saturated water steam in terms of change of pH and color of wood," *BioResources* 15(2), 2550-2559. DOI: 10.15376/biores.15.2.2500-2559

Esteves, B., and Pereira, H. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404.

Hon, N. S. D., and Shiraishi, N. (2001). *Wood and Cellulosic Chemistry*, CRC Press, New York, NY, USA.

ISO 11 664-4 (2008). "Colorimetry – Part 4: CIE 1976 L*a*b* colour space," International Organization for Standardization, Geneva, Switzerland.

Fengel, D., and Wegener, G. (1989). *Wood: Chemistry, Ultrastructure, Reaction*, Walter de Gruyter, Berlin, Germany.

Geffert, A., Výbohová, E., and Geffertová, J. (2017). "Characterization of the changes of colour and some wood components on the surface of steamed beech wood," *Acta Facultatis Xylologiae Zvolen* 59(1), 49–57. DOI: 10.17423/afx.2017.59.1.05

Geffert, A., Geffertová, J., and Dudiak, M. (2019). "Direct method of measuring the pH value of wood," *Forests* 10(10), article no. 852. DOI: 10.3390/f10100852

González-Peña, M. M., and Hale, M. D. (2009). "Colour in thermally modified wood of beech, Norway spruce and Scots pine. Part 2: Property predictions from colour changes," *Holzforschung* 63(4), 394-401. DOI: 10.1515/HF.2009.077

Klement, I., and Marko, P. (2009). "Colour changes of beech wood (*Fagus sylvatica* L.) during high temperature drying process," *Wood Research* 54(3), 45-54.

Kollmann, F., and Cote, W. A. (1968). *Principles of Wood Sciences and Technology, Vol. 1- Solid Wood*, Springer Verlag, Berlin, Germany.

Meints, T., Teischinger, A., Stingl, R., and Hassmann, C. (2017). "Wood colour of central European wood species: CIELAB characterisation and colour intensification," *European Journal of Wood and Wood Products* 75(4), 499-509. DOI: 10.1007/s00107-016-1108-0

Milić, G., Todorović, N., and Popadić, R. (2015). "Influence of steaming on drying quality and colour of beech timber," *Glasnik Šumarskog Fakulteta* 83-96.

Nasir, V., Nourian, S., Avramidis, S., and Cool, J. (2019). "Prediction of physical and mechanical properties of thermally modified wood based on color change evaluated by means of "group method of data handling" (GMDH) neural network," *Holzforschung* 73(4), 381-392.

Solár, R. (2004). *Chémia Dreva [Wood Chemistry]*, Technical University in Zvolen, Zvolen, Slovakia.

Tolvaj, L., Nemeth, R., Varga, D., and Molnar, S. (2009). "Colour homogenisation of beech wood by steam treatment," *Drewno* 52(181), 5-17.

Tolvaj, L., Molnar, S., Nemeth, R., and Varga, D. (2010). "Color modification of black locust depending on the steaming parameters," *Wood Research* 55(2), 81-88.

Varga, D., and Van der Zee, M. E. (2008). "Influence of steaming on selected wood properties of four hardwood species," *Holz als Roh-und Werkstoff* 66, 11-18. DOI: 10.1007/s00107-007-0205-5

Wilson, R. A., and Keil, F. C. (1999). *MIT Encyclopedia of Cognitive Sciences*, MIT Press, Cambridge, MA, USA.

Article submitted: June 24, 2021; Peer review completed: September 5, 2021;
Revised version received: September 14, 2021; Revised version accepted:
January 13, 2022; Published: January 20, 2022.
DOI: 10.15376/biores.17.1.1690-1702