

THE EFFECT OF STEAMING ON THE COLOR CHANGE OF FALSE HEARTWOOD BEECH

Ladislav Dzurenda – Michal Dudiak

ABSTRACT

The work presents the results of the color change of false heartwood of beech wood during the steaming process in a pressure autoclave in individual modes in the temperature interval $t = 90$ to 120 °C. The color of the wood of the false heartwood, depending on the steaming conditions, changes in opposite ways, while at temperatures up to $t \approx 105$ °C it becomes pale, and at temperatures above $t \approx 115$ °C it becomes darker.

Based on the results of the research on the color change of the false heartwood wood in the steaming process, 3 steaming modes were proposed to achieve a targeted change in the color of the false heartwood beech. By steaming the wood with saturated moist air $t_I = 90 \pm 2.5$ °C for $\tau = 8$ h, the color of the wood lightens, which is numerically expressed in the color space CIE $L^*a^*b^*$: $L^* = 69.2 \pm 2.9$, $a^* = 12.7 \pm 1.6$ and $b^* = 19.7 \pm 1.4$. Steam mode II with saturated water steam $t_{II} = 115 \pm 2.5$ °C during $\tau = 16$ h, slight darkening of the wood color of the false heartwood reaches the following values: $L^* = 56.0 \pm 2.4$, $a^* = 12.4 \pm 1.4$ and $b^* = 19.2 \pm 1.5$. The dark brown color described in the color space CIE $L^*a^*b^*$ by the values: $L^* = 50.0 \pm 2.1$, $a^* = 12.4 \pm 1.3$ and $b^* = 18.5 \pm 1.4$ is achieved by the vaporization mode III. at the temperature of saturated water steam $t_{III} = 120 \pm 2.5$ °C during $\tau = 24$ h.

Keywords: beech wood; false heartwood; wood color; wood steaming; color difference; color dispersion.

INTRODUCTION

The beech wood belongs to the scattered-porous, coreless woods with the possibility of forming a false heartwood. In some older trees, there is wood of a different color in the middle of the trunk, from brown-yellow to red-brown to brown-red-gray, the so-called false heartwood. A false heartwood is a growth defect in the zone of mature wood, which is caused by the penetration of air into the tree trunk through wounded places of the trunk or branches of the tree and the subsequent oxidation of soluble carbohydrates and starch contained in living or partially dead parenchymal cells with the formation of polyphenolic compounds that penetrate into neighboring mesh and wood are colored by (Nečesaný 1958, Požgaj *et al.* 1997, Bauch and Koch 2001, Račko and Čunderlík 2006, 2010, Baraňski 2020, Vilkovský 2023). In extreme frosts lasting several consecutive days with temperatures below -30 °C, the parenchyma begins to die in the growing tree and conditions are created to form the so-called of brown-yellow to brown-red frosted false heartwood (Gorczyński 1951). According to the shape and position of the false heartwood on the cross-section of the trunk, the false

heartwood is divided into types: Round, Mosaic, Star, Flame (centric, eccentric) (Mahler and Höwecke 1991, Trenčiansky *et al.* 2017).

In contrast to sapwood, the wood of false heartwood is significantly more colorful. In the works of Dzurenda (2023), Dzurenda and Dudiak (2023), visual differences in the darkness and variety of yellow-brown-red shades of wood of individual types of false heartwood are quantified in the color space CIE L*a*b* in the form of the total color difference ΔE_{sx}^* . The color in mosaic wood of false heartwood with values on the lightness coordinate $L^* = 65.2 \pm 6.9$ and on the chromatic coordinates: red color $a^* = 13.2 \pm 2.3$ and yellow color $b^* = 19.2 \pm 1.9$ is the most diverse with a dispersity value of $\Delta E_{sx}^* = 7.5$. The wood of round, flame and star false heartwood is more homogeneous in color with dispersity values in the interval $\Delta E_{xs}^* = 3.9 - 4.3$.

Steaming of wood is a technological process in which wet wood is heated by the action of heat in the form of saturated moist air or saturated water steam and changes its physical, mechanical and chemical properties. While temporary physical-mechanical changes are used in the production of veneers, plywood, bent furniture, or pressed wood, permanent chemical changes manifested, among other things, by a change in color, serve to purposefully change the color of the wood into more or less distinct color shades (Deliiski 1991, Tolvaj *et al.* 2009, Dzurenda 2014, Milić *et al.* 2015, Geffert *et al.* 2017, Dzurenda and Dudiak 2021, Dzurenda *et al.* 2023, Dudiak 2023).

The aim of the work is based on experimental research aimed at monitoring the color changes of the false heartwood in the color space CIE L*a*b* in the steaming process with saturated atmospheric moist air at a temperature of $t_I = 90 \pm 2.5$ °C, or of saturated water steam at a temperature of $t_{II} = 105 \pm 2.5$ °C, at temperature $t_{III} = 115 \pm 2.5$ °C and temperature $t_{IV} = 120 \pm 2.5$ °C.

MATERIAL AND METHODS

Blanks with dimensions of 40×50×800 mm were made by longitudinal and transverse sawing from the central lumber of thickness $h = 40$ mm from logs with a round and star false heartwood. 375 blanks of false heartwood were randomly selected. The blanks were divided into 25 groups, so there were 15 blanks. The blanks of the 1st group were unsteamed. The other blanks were steamed with saturated atmospheric moist air at a temperature of $t_I = 90 \pm 2.5$ °C, or with saturated water steam modes: mode II with a temperature of saturated water steam $t_{II} = 105 \pm 2.5$ °C, mode III with a temperature of saturated water steam $t_{III} = 115 \pm 2.5$ °C and mode IV with the temperature of saturated water steam $t_{IV} = 120 \pm 2.5$ °C. Individual sets of steamed wood were taken from the steaming autoclave after steaming $\tau = 4$ h, $\tau = 8$ h, $\tau = 12$ h, $\tau = 16$ h, $\tau = 20$ h, and $\tau = 24$ h. Steaming of wood was carried out in a pressure autoclave AZ 240 (Himmasch AD, Haskovo, Bulgaria) installed at Sundermann s.r.o. Banská Štiavnica (Slovakia). The conditions of steaming the false heartwood of beech wood with saturated water steam with marked time intervals of sampling during thermal treatment v are shown in the diagram in Fig. 1.

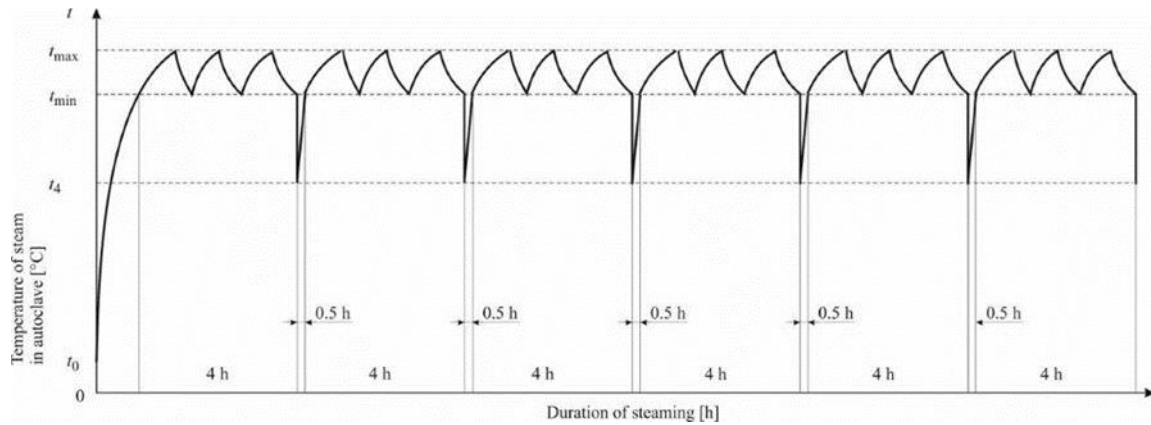


Fig. 1 Diagram of the steaming process of wood in a pressure autoclave.

The temperature of the steam-air mixture (Mode I), or of saturated water steam in steam Modes II to IV is listed in Table 1. Temperatures t_{max} and t_{min} are temperature intervals in which saturated water steam is supplied to the autoclave for the implementation of the technological process. Temperature t_4 is the temperature of the saturated water steam after reducing the pressure to atmospheric pressure, enabling the safe opening of the pressure device and selecting a group of steamed blanks in the specified steaming time.

Tab. 1 Technological conditions for the homogenization of the color of beech wood in a pressure autoclave.

Temperature of saturated water steam	t_{min} [°C]	t_{max} [°C]	t_4 [°C]	Wood color homogenization time					
				τ_1	τ_2	τ_3	τ_4	τ_5	τ_6
Mode I	87.5	92.5	87.5						
Mode II	102.5	107.5	100	4 h*	8 h*	12 h*	16 h*	20 h*	24 h
Mode III	112.5	117.5	100						
Mode IV	117.5	122.5	100						

Note: * taking a group of steamed blanks from the autoclave at planned intervals took 0.5 h. The actual steaming time compared to the planned steaming time was extended by the time of technological breaks.

Unsteamed and steamed beech wood blanks of the false heartwood were dried in a hot air oven according to Dzurenda (2022) mode in order to preserve the original color of the wood achieved by the technological process of steaming. The bedding surfaces of the dried lumber were machined on a FS 200 horizontal plane milling machine.

Color measurement was performed with a Color reader CR-10 Plus colorimeter (Konica Minolta, Japan) with a 400-700 nm reflection spectrum. A D65 light source was used and the diameter of the optical sensing aperture was 8 mm. The color measurement was performed on the milled surfaces of each blank at three points.

The results of the measured values: lightness L^* , red color a^* , yellow color b^* on the coordinates of the color space CIE $L^*a^*b^*$, are presented in the form of writing the average measured value \bar{x} and the standard deviation s_x .

$$x = \bar{x} \pm s_x \quad (1)$$

Where: \bar{x} – average value,
 s_x – standard deviation.

The color dispersion of unsteamed and steamed wood beech wood of the false heartwood is determined through the standard deviations from the measured values at individual coordinates in the color space CIE $L^*a^*b^*$ and quantified by a modified equation of the total color difference Dzurenda (2023), Dzurenda and Dudiak (2024) in the form:

$$\Delta E_{sx}^* = \sqrt{(s_L)^2 + (s_a)^2 + (s_b)^2} \quad (2)$$

Where: s_L – value of standard deviation of lightness,
 s_a – value of the standard deviation on the red color coordinate,
 s_b – value of standard deviation on the yellow color coordinate.

The differences between the color of the sapwood and the color of the heartwood before steaming and after steaming are evaluated by the total color difference ΔE^* :

$$\Delta E^* = \sqrt{(\bar{L}_1 - \bar{L}_2)^2 + (\bar{a}_1 - \bar{a}_2)^2 + (\bar{b}_1 - \bar{b}_2)^2} \quad (3)$$

Where: $\bar{L}_1, \bar{a}_1, \bar{b}_1$ – average values on the coordinates of lightness, red and yellow color of unsteamed beech wood,
 $\bar{L}_2, \bar{a}_2, \bar{b}_2$ – average values on the coordinates of lightness, red and yellow color of steamed beech wood.

RESULTS AND DISCUSSION

The course of changes in the color of the false heartwood on the individual coordinates of the color space CIE $L^*a^*b^*$ during $\tau = 24$ h vaporization with saturated moist air at temperature $t_I = 90 \pm 2.5$ °C and saturated water steam at temperature $t_{II} = 105 \pm 2.5$ °C, temperature $t_{III} = 115 \pm 2.5$ °C and temperature $t_{IV} = 120 \pm 2.5$ °C are shown in Fig. 2 to 4.

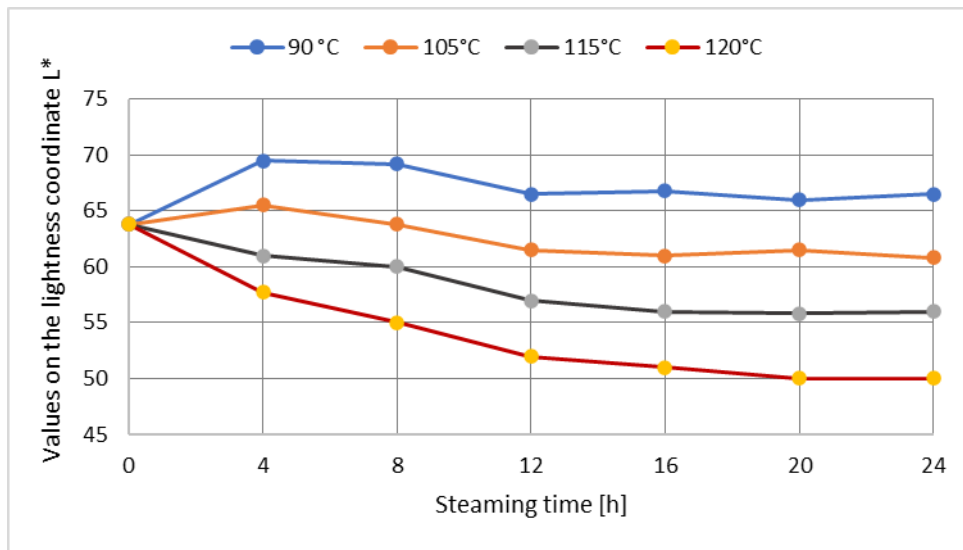


Fig. 2 Color changes on the lightness coordinate L^* within 24 h steaming of wood of the false heartwood at individual temperatures.

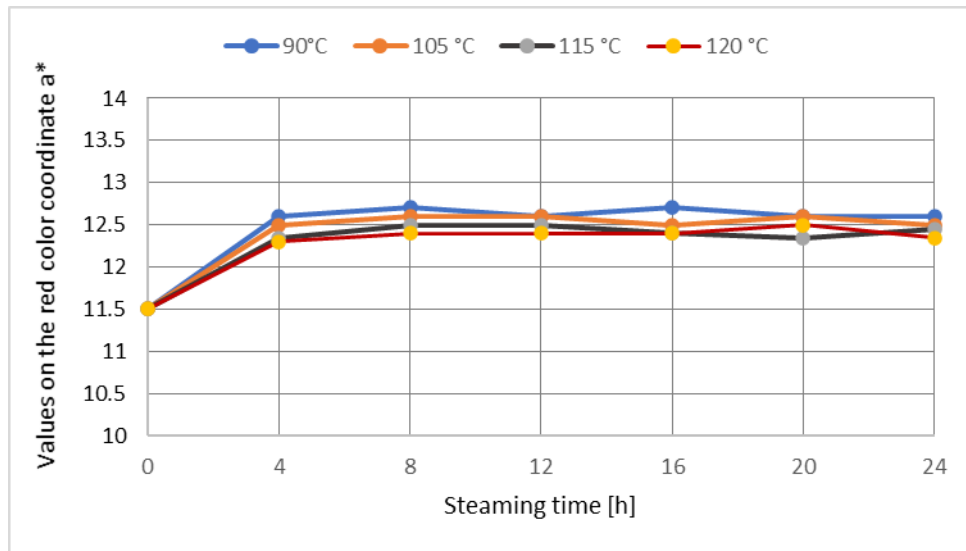


Fig. 3 Color changes on the chromatic coordinate of red a^* within 24 h steaming of wood of the false heartwood at individual temperatures.

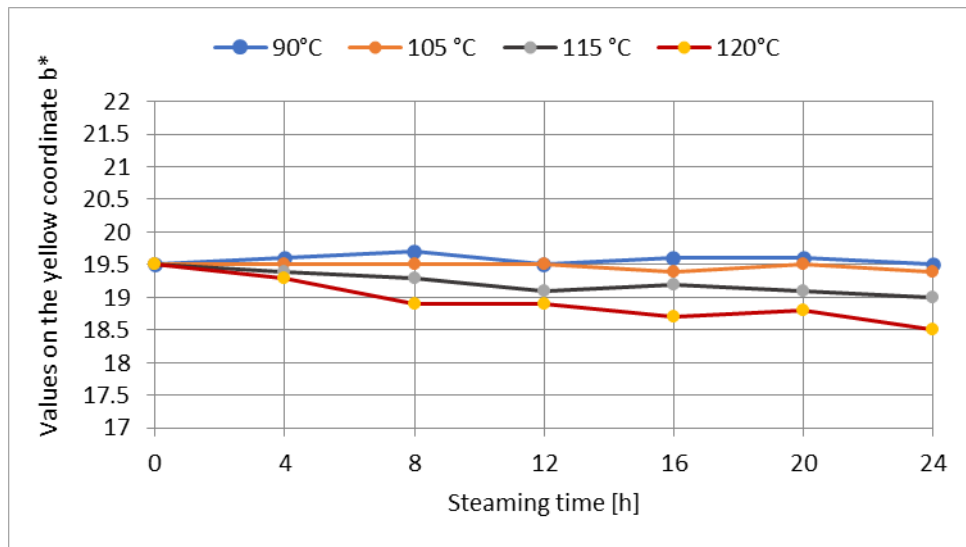


Fig. 4 Color changes on the chromatic coordinate of yellow b^* within 24 h steaming of wood of the false heartwood at individual temperatures.

Changes in the lightness coordinate L^* and the chromatic coordinates of red color a^* and yellow color b^* indicate changes in the color and color diversity of the wood of the false heartwood, which the wood acquires at individual temperatures during the steaming process. The most significant changes are on the lightness coordinate, minor changes on the chromatic coordinate of the red color a^* and the chromatic coordinates of the yellow color b^* .

The wood color of the false heartwood by steaming at $t_1 = 90 \pm 2.5$ °C during the first 8 h of steaming, as documented in Fig. 2. fades out. The fading of the color of the wood declares an increase in the lightness of the wood from the value $L_0^* = 63.7$ to the value $L_{I-4}^* = L_{I-8}^* = 69.3$. Due to the further application of heat in the steaming process, the fading of the wood not only stopped but gradually darkened, which documents the decrease in lightness values to $L_{I-24}^* = 65.5$.

At the steaming temperature $t_{II} = 105 \pm 2.5 \text{ }^\circ\text{C}$, the wood of the false heartwood also lightens at the beginning of steaming. Within 4 h of evaporation, the value on the lightness coordinate increased from $L_0^* = 63.7$ to $L_{II-4}^* = 65.5$. Due to the subsequent heat action, the wood darkens similarly to the steaming temperature $t_I = 90 \pm 2.5 \text{ }^\circ\text{C}$, which is reflected in the lightness coordinate by a decrease to $L_{II-24}^* = 60.8$.

The lightness of the wood of the false heartwood at the steaming temperatures $t_{III} = 115 \pm 2.5 \text{ }^\circ\text{C}$ and $t_{IV} = 120 \pm 2.5 \text{ }^\circ\text{C}$ during the entire steaming time decreased from the lightness value $L_0^* = 63.8$ to the value $L_{III-24}^* = 56.0$ and at temperature $t_{IV} = 120 \pm 2.5 \text{ }^\circ\text{C}$ to the value $L_{IV-24}^* = 50.0$. The steamed wood darkened, and the rate of darkening increased as the temperature of the steaming process increased.

Fig. 5 shows the magnitude of changes in the lightness coordinate ΔL^* at individual temperatures of the steaming process in bar diagram form at time intervals of 4 h.

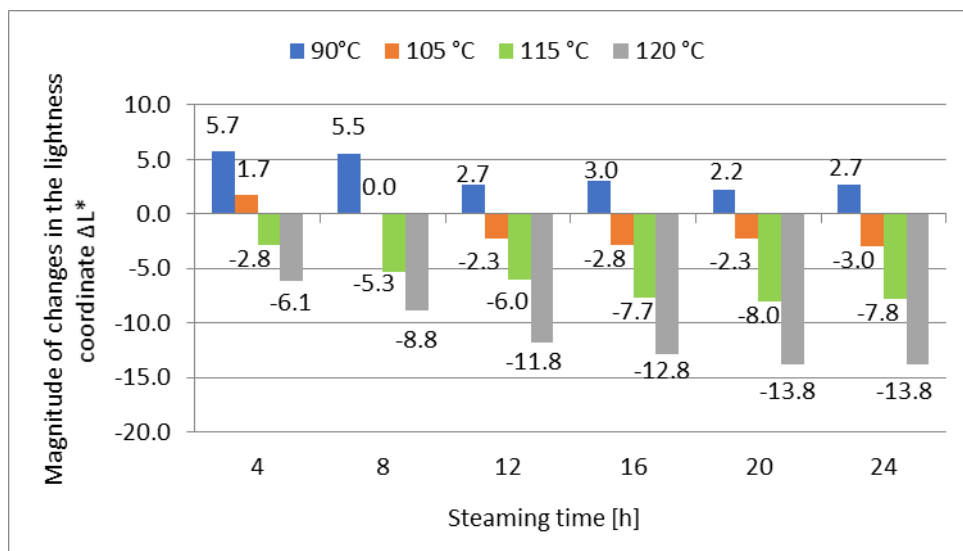


Fig. 5 The magnitude of changes in the lightness coordinate ΔL^* over time at individual temperatures of the wood steaming process.

The lightening of the steamed wood of the false heartwood at the steaming temperature $t_I = 90 \pm 2.5 \text{ }^\circ\text{C}$ and at the steaming temperature $t_{II} = 105 \pm 2.5 \text{ }^\circ\text{C}$ in the first 4 h point to the instability of the chromophoric system of the wood of the false heartwood formed by the enzymatic processes of peroxidase and polyphenoloxidase, which are responsible for the oxidation of phenolic compounds and the characteristic coloration of the wood of the false heartwood (Hofmann *et al.* 2004, Albert *et al.* 2003, Tolvaj *et al.* 2009).

Wood darkening after 4 h steaming at temperature $t = 105 \pm 2.5 \text{ }^\circ\text{C}$, or at higher steaming temperatures $t \geq 115 \text{ }^\circ\text{C}$ is consistent with the opinions of Bekhta and Niemz (2003), Geffert *et al.* (2017), Laskowska *et al.* (2020), Dzurenda and Dudiak (2021), who darken they attribute the decrease of hemicelluloses caused by hydrolysis processes and thus the increase of the lignin content in the steamed wood.

The values on the chromatic coordinate of the red color a^* of beech wood of the false heartwood showed a slight increase during the first hours of steaming, independent of the steaming temperature, from the value $a_0^* = 11.6$ to the value $a^* \approx 13.5$. However, these values remained stable and did not change further during the steaming process, providing a clear picture of the color changes during the process.

The values on the chromatic coordinate of the yellow color b^* of the wood of the false heartwood did not change at the steaming temperature $t_I = 90 \pm 2.5 \text{ }^\circ\text{C}$ and the steaming temperature $t_{II} = 105 \pm 2.5 \text{ }^\circ\text{C}$. The measured values of the yellow color b^* during the

steaming show the values oscillating around $b^* \approx 19.5$. The stated finding is similar to the works of Tolvaj *et al.* (2009), and Dzurenda and Dudiak (2024). At the steaming temperature $t_{III} = 115 \pm 2.5$ °C and the temperature $t_{IV} = 120 \pm 2.5$ °C, a slight decrease is recorded during $\tau = 24$ h in the interval $\Delta b^* = 0.5 - 1.0$.

The influence of the steaming conditions on the chemical changes of beech wood in the steaming process is comprehensively expressed by the overall change in the color of the steamed wood. In Fig. 6 shows the change in the color of the wood of false heartwood during $\tau = 24$ h of the steaming process, shown as the total color difference ΔE^* .

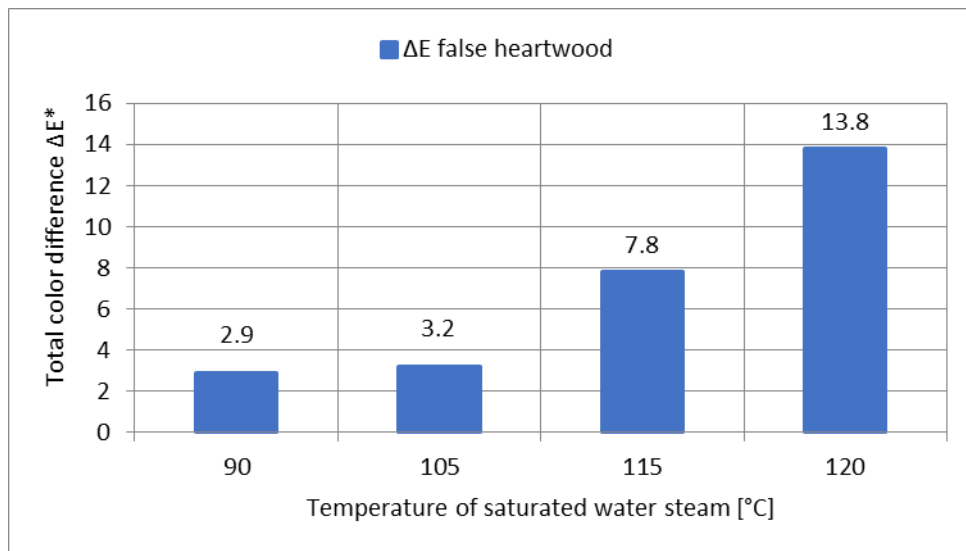


Fig. 6 Sizes of changes in the color of the false heartwood achieved by the steaming process during $\tau = 24$ h for individual temperatures.

The lower values of the total color difference $\Delta E^* = 2.9 - 3.2$ at steaming temperatures $t = 90$ °C – 105 °C point to the partial resistance of wood of the false heartwood to the influence of heat on the color change manifested by opposite changes in the lightening and darkening of the color of the wood. The effect of heat on the steaming process with temperatures above $t \geq 115$ °C is more favorable for continuous changes in the color of the wood manifested by the darkening of the wood. Numerically, this is evidenced by a 2.5 to 4.5 fold increase in the values of the total color difference ΔE^* compared to the value of the total color difference at temperature $t = 90$ °C.

Based on the presented results of the lightening of the wood color of the fake heartwood during the steaming process, fig. 7b, respectively darkening fig. 7c and fig. 7d the technological conditions of steaming were proposed. Technological conditions of steaming to achieve the targeted color of steamed wood, such as steaming temperature, the minimum steaming time required to achieve the targeted wood color, the steamed wood color identified by values on the coordinates of the color space CIE $L^* a^* b^*$, the dispersion of the steamed wood color ΔE_{sx}^* is given in Tab. 2.

Tab. 2 Technological conditions of steaming to achieve the targeted color of steamed wood.

Beech wood of false heartwood	Steaming time	Values on the color space CIE L*a*b*			Color dispersion
	h	L*	a*	b*	ΔE_{sx}^*
Unsteamed	0	63.7 ± 3.7	11.5 ± 1.8	19.5 ± 1.5	4.4
Steamed with mode I $t_I = 90 \pm 2.5 \text{ }^\circ\text{C}$	8	69.2 ± 2.9	12.7 ± 1.6	19.7 ± 1.4	3.6
Steamed with mode II $t_{II} = 115 \pm 2.5 \text{ }^\circ\text{C}$	16	56.0 ± 2.4	12.4 ± 1.4	19.2 ± 1.5	3.1
Steamed with mode III $t_{III} = 120 \pm 2.5 \text{ }^\circ\text{C}$	24	50.0 ± 2.1	12.4 ± 1.3	18.5 ± 1.4	2.8

The color of the wood of the false heartwood before cooking and after steaming according to the proposed technological conditions is shown in Fig. 7b to 7d.



Fig. 7 Color of unsteamed and steamed wood of false heartwood.

Changes in the color of steamed wood of false heartwood achieved by the proposed steaming modes are characterized by the following facts:

- Steaming mode I enables lightening of the wood color of the false heartwood of saturated atmospheric moist air at a temperature $t_I = 90 \pm 2.5 \text{ }^\circ\text{C}$ during $\tau = 8 \text{ h}$. On the coordinates color space CIE L*a*b* values: $L^* = 69.2 \pm 2.9$, $a^* = 12.7 \pm 1.6$ and $b^* = 19.7 \pm 1.4$. The given coloring of steamed wood reaches the value on the lightness coordinate by $\Delta L^* = +5.5$ and the values on the chromatic coordinates of red color by $\Delta a^* = +1.2$ and yellow color by $\Delta b^* = +0.2$. A decrease in the color dispersion value from $\Delta E_{sx}^* = 4.4$ before steaming to $\Delta E_{sx}^* = 3.6$ points to the homogenization of the wood color of the false heartwood by the steaming process.

- The steaming mode II carried out by saturated steam with a temperature of $t_{II} = 115 \pm 2.5$ °C during $\tau = 16$ h causes the wood to slight darkening and acquire a brown color with values on the coordinates of the color space $L^* = 56.0 \pm 2.4$, $a^* = 12.4 \pm 1.4$ and $b^* = 19.2 \pm 1.5$. The change in the color of the wood of the false heartwood is accompanied by a decrease in the value on the lightness coordinate by $\Delta L^* = -7.7$ and an increase in the value on the red color coordinate by $\Delta a^* = +0.9$ and a decrease in the value on the yellow color coordinate by $\Delta b^* = -0.3$.
- Steam mode III with saturated steam with temperature $t_{IV} = 120 \pm 2.5$ °C during $\tau = 24$ h changes the original color of the wood to a dark brown color. In the color space CIE $L^* a^* b^*$ it is identified by the values at the coordinates $L^* = 50.0 \pm 2.1$, $a^* = 12.4 \pm 1.3$ and $b^* = 18.5 \pm 1.4$. The stated steaming conditions not only contribute to the most significant darkening of the wood of the false heartwood, but also contribute to reducing the color dispersion of the steamed wood characterized by the color dispersion value $\Delta E_{sx}^* = 2.8$.

CONCLUSION

Results of analysis of the effect of temperature on the steaming process of beech false heartwood within 24 h point to a relatively wide range of color changes from pale brown to dark brown color.

False heartwood steamed with saturated atmospheric moist air at a temperature of $t_I = 90 \pm 2.5$ °C in the first 8 h, or with saturated water steam at a temperature of $t = 105 \pm 2.5$ °C in the first 4 h, fades from the original brown-red color to a pale brown color and then gradually darkens to a brown color. The mentioned facts point to a certain instability of the chromophoric system of false heartwood formed during the growth of the tree against the action of heat.

Steaming false heartwood core with saturated water steam with a temperature of $t = 115 \pm 2.5$ °C and with a temperature of $t = 120 \pm 2.5$ °C, the wood gradually darkens to brown to dark brown. The rate of wood darkening increases with increasing steaming temperature. Qualitative differences in wood color in the wood steaming process of false heartwood at temperatures above $t \geq 115$ °C declare the values of the total color difference ΔE^* , which are 2.5 to 4.5 times higher than the color changes at the steaming temperature $t = 90$ °C.

On the basis of the presented results of the color changes of the false heartwood in the steaming process, the technological steaming conditions for 3 color changes of the false heartwood by the steaming process were proposed for the targeted color changes of the false heartwood.

Steaming mode I allows the color of the wood to lighten. By steaming wood with a saturated atmospheric moist air at a temperature of $t_I = 90 \pm 2.5$ °C for $\tau = 8$ h, the original color of the wood changes to a pale brown color with coordinates in the color space CIE $L^* a^* b^*$: $L^* = 69.2 \pm 2.9$, $a^* = 12.7 \pm 1.6$ and $b^* = 19.7 \pm 1.4$.

Steaming mode II a slight darkening of the wood color is achieved. Steaming of wood of the false heartwood is carried out with saturated water steam with a temperature of $t_{II} = 115 \pm 2.5$ °C during $\tau = 16$ h. The acquired wood color in the color space CIE $L^* a^* b^*$ is identified by the following values: $L^* = 56.0 \pm 2.4$, $a^* = 12.4 \pm 1.4$ and $b^* = 19.2 \pm 1.5$.

Steaming mode III it changes the color of the wood of the false heartwood to a dark brown. It is realized with saturated water steam with temperature $t_{III} = 120 \pm 2.5$ °C during $\tau = 24$ h. The dark brown color is in the color space CIE $L^* a^* b^*$ described by the values: $L^* = 50.0 \pm 2.1$, $a^* = 12.4 \pm 1.3$ and $b^* = 18.5 \pm 1.4$.

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AUTHOR ADDRESS

Ladislav Dzurenda
Michal Dudiak
Technical University in Zvolen
T. G. Masaryka 24
960 01 Zvolen, Slovakia
dzurenda@tuzvo.sk
xdudiak@tuzvo.sk

