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THE EFFECT OF THE TEMPERATURE OF SATURATED WATER STEAM ON THE COLOUR CHANGE OF WOOD *ACER PSEUDOPLATANUS* L.

Ladislav Dzurenda – Michal Dudiak

ABSTRACT

The colour change of the wood of tree species *Acer pseudoplatanus* L. resulting from the process of thermal treatment with saturated water steam at the temperatures of t_I = 105 ± 2.5 °C, t_{II} = 115 ± 2.5 °C, t_{III} = 125 ± 2.5 °C, t_{IV} = 135 ± 2.5 °C for τ = 7 hours are presented in the paper. The white to pale white-yellow color of native maple wood varies from pale brown to pinkish-yellow to brownish-red, depending on the temperature of the saturated water steam. In the CIE $L^*a^*b^*$ color space, the changes shown are at the L^* - coordinate within the range of L^* = 86.0 - 65.3 and the chromatic coordinates: red a^* = 5.9 – 10.8 and yellow b^* = 16.4 - 19.4. The effect of the temperature of saturated water steam on the variation of the lightness L^*, red a^* and yellow colour b^* of maple wood in the colour space CIE L^* a^* b^* is given in the equation: $L^* = -0.489 \cdot t + 132.86$; $a^* = 0.081 \cdot t + 0.105$; $b^* = 0.059 \cdot t + 11.445$. Significant colour changes of maple wood are observed as a result of technological process at the temperatures above 122 °C. Irreversible changes in colour of the maple wood resulting from one of the modes of colour modification of wood with saturated water steam extend the possibilities of its use in the field of construction-joinery, construction-art and design.

Keywords: maple wood, colour, thermal treatment, saturated water steam.

INTRODUCTION

The colour of wood is one of the macroscopic features to identify wood of individual tree species visually. Chromophores are molecules responsible for the colour of wood, i.e. functional groups of: >C=O, -CH=CH-CH=CH-, -CH=CH-, aromatic compounds absorbing light in the UV/VIS spectra present in the chemical components of wood (lignin and extractive substances such as pigments, tannin, resin, etc.).

Wood placed in the environment of hot water, saturated water steam or saturated humid air is heated and its physical, mechanical as well as chemical properties change. Thermal treatment of wood, besides physical and mechanical changes applied in the process of manufacturing veneers, plywood, bentwood furniture or pressed wood are accompanied with the changes in chemical properties and colour of wood (KOLLMANN and GOTE 1968, NIKOLOV *et al*. 1980, SERGOVSKIJ and RASEV 1987, TREBULA 1986, TOLVAJ *et al*. 2010, DZURENDA and ORLOWSKI 2011, DZURENDA 2013, BARANSKI *et al*. 2017, SIKORA *et al* 2018). In the past, colour changes when wood becoming darker during the steaming process were used to remove the undesirable colour differences between light coloured sapwood and dark coloured heartwood or to eliminate wood stain colours as a result of mould. In recent times, research into thermally modified wood has been focused on the issue of the colour change of specific wood species into more or less bright hues or wood imitation of domestic or exotic tree species (MOLNAR 2002, TOLVAJ *et al*. 2009, DZURENDA 2014, 2018a, b, c, BARCIK *et al*. 2015, BARANSKI *et al*. 2017).

Sycamore is an example of diffuse porous tree species. Maple wood is hard, medium heavy, elastic with good mechanical properties. It is easy to work with, easy to cut, plane, chisel, sand and polish. The colour of dry wood of sycamore is white to yellow-white. Natural aging of maple wood due to UV radiation results in changing the colour, wood is getting darker. Maple wood is used for making furniture, musical instrument, toys, home utilty products and sports equipment, as well as flooring. Joiners and cabinetmakers can imitate wood of other tree species by staining the maple wood.

The aim of the paper is to determine the effect of the temperature of saturated water steam on the colour change of the wood of tree species *Acer pseudoplatanus* L. resulting from the thermal treatment – colour modification with saturated water steam at the temperatures of: t_I = 105 ± 2.5 °C, t_{II} = 115 ± 2.5 °C, t_{III} = 125 ± 2.5 °C, t_{IV} = 135 ± 2.5 °C for τ = 7 hours.

MATERIAL AND METHODOLOGY

Materials

The wood of *Acer pseudoplatanus* L. in a form of sawn timber with the thickness of h = 40 mm and the moisture content above the fibre saturation point was thermally modified with saturated water steam in the pressure autoclave APDZ 240 (Himmasch AD, Haskovo, Bulgaria) in the company Sundermann s.r.o. Banská Štiavnica.

Methods

Mode of thermal treatment in order to modify the colour of maple wood with saturated water steam is illustrated in Fig. 1. The conditions of thermal treatment of individual modes of colour modification are described in Tab.1.

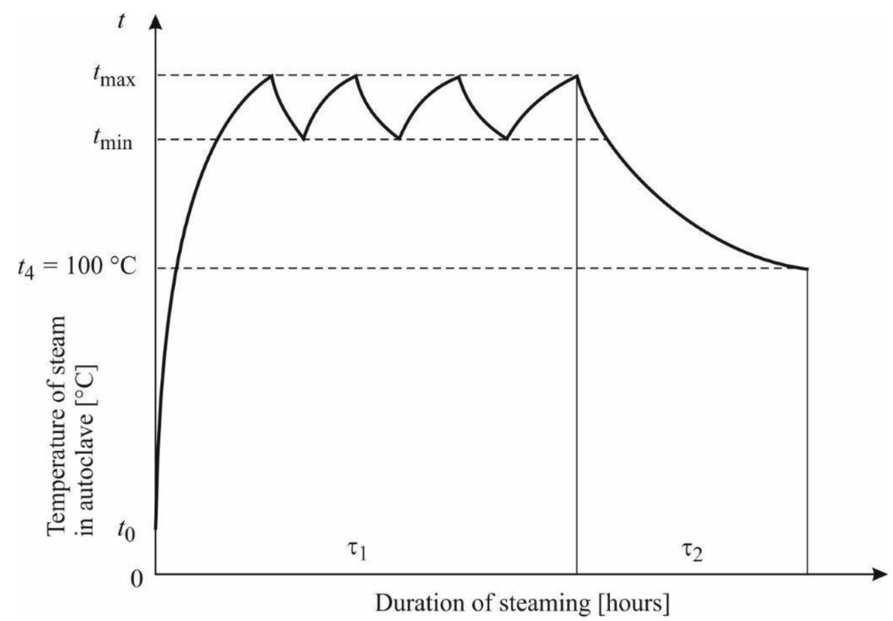

Fig. 1 Mode of colour modification of maple wood with saturated water steam.

Tab. 1 Modes of colour modification of maple wood with saturated water steam.

Modes	Temperature of saturated water steam [°C]			Time of operation [h]		
	t_{min}	t_{max}	t_4	τ_1 -phase I	τ_2-phase II	Total time
Mode I	102.5	107.5	100	6.0	1.0	7.0
Mode II	112.5	117.5	100			
Mode III	122.5	127.5	100			
Mode IV	132.5	137.5	100			

The colour of wood was measured using 35 pieces of sawn timber thermally untreated (green wood) and 35 pieces of sawn timber of maple wood thermally treated with individual modes after being dried to the moisture content of $W_p = 12 \pm 0.5$ % in a conventional wood drying kiln KAD 1 × 6 (KATRES Ltd.). Subsequently, woodturning blanks with the dimensions of 40 × 80 × 800 mm were prepared from sawn timber. Flat surfaces and edges were processed using Swivel spindle milling machine FS 200.

Color Reader CR-10 (Konica Minolta, Japan) was used to assess the colour of maple woodturning blanks in the CIE $L^*a^*b^*$colour space. The light source D65 with lit area of 8mm was used.

Lightness coordinate L^* and coordinates a^* and b^* of CIE $L^*a^*b^*$ colour space, as well as chroma C^* and total colour difference ΔE^* were measured using a randomly selected samples n = 50 of maple woodturning blanks of thermally untreated wood and using the sample set n = 50 of woodturning blanks of thermally treated sawn timber with individual modes. Measurement of the coordinates L^* , a^* and b^* , chroma C^* and total difference ΔE^* using samples of maple wood was carried out in the centre of the blank width and in the centre of the blank edge, 400 mm far from the face. The values of colour coordinates are mentioned in a form of formula $x = \bar{x} \pm s_x$ i.e. the mean value and standard deviation.

Total colour difference ΔE^* is determined according to the following formula, as a result of the difference in the colour coordinates ΔL^*, Δa^*, Δb^* set following the surface measurements of thermally untreated as well as treated maple woodturning blanks:

$$\Delta E^* = \sqrt{\left(L_1^* - L^*\right)^2 + \left(a_1^* - a^*\right)^2 + \left(b_1^* - b^*\right)^2} \quad (1)$$

where: L^*, a^*, b^* coordinate values in the wood colour space prior to the process of thermal modification of wood.
L^*_1, a^*_1, b^*_1 coordinate values in the wood colour space of thermally modified maple wood.

The change in wood colour, besides changes in the chromatic coordinates in the CIE $L^*a^*b^*$colour space, was assessed also following the changes in the lightness ΔL^*, chroma ΔC^* and hue angle $h°$ in the CIE $L^*C^*h°$ colour space using cylindrical coordinates.
Chroma C^* is an integration of the values of the coordinates of red colour a^* and yellow colour b^* projected onto the chromatic plane of cylindrical colour space:

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

where: b^* the value of the chromatic coordinate of yellow colour,
a^* the value of the chromatic coordinate of red colour.

Hue angle $h°$ is expressed in positive degrees starting at the positive a^* axis and progressing in a counterclockwise direction and is described with the formula:

$$h^{\circ}_{ab} = arctan\left(\frac{b*}{a*}\right) \quad (3)$$

where: b^* the value of the chromatic coordinate of yellow colour,
a^* the value of the chromatic coordinate of red colour.

RESULTS AND DISCUSSION

White and white-yellow colour of maple wood changed during the process of thermal modification with saturated water steam. The wood of tree species of *Acer pseudoplatanus* L. was getting darker and browner. The changes in thermally modified maple wood are illustated in Fig. 2.

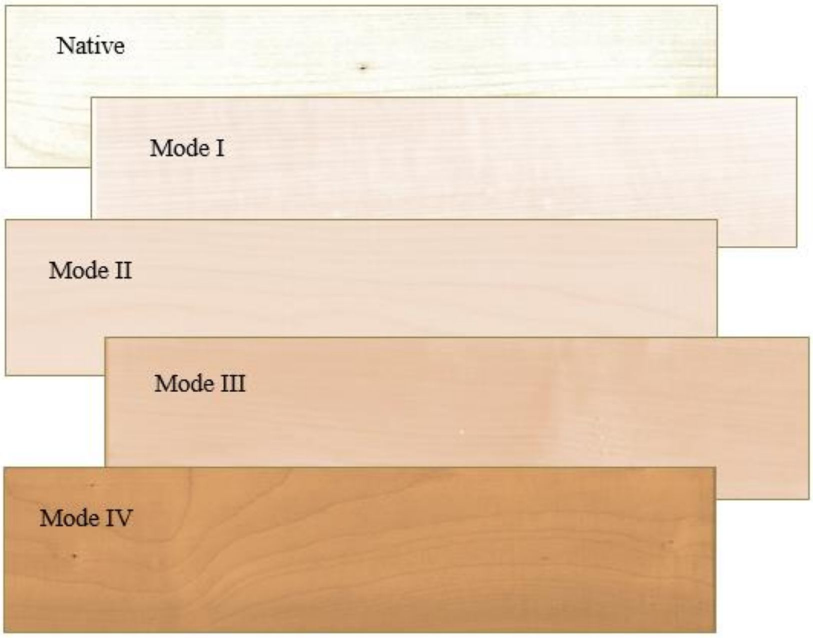

Fig. 2 The colour of maple wood prior to and after thermal treatment by individual modes.

The values of the coordinates in the CIE $L^*a^*b^*$colour space, chroma C^* and total colour difference ΔE^* describing the colour of maple wood prior to and after the thermal treatment by individual modes are mentioned in Tab. 2

Tab. 2 The values of the coordinates in the CIE-$L^*a^*b^*$ colour space describing the maple wood prior to and after thermal treatment with saturated water steam by individual modes.

Temperature of saturated water steam	Coordinates of the CIE L*a*b*colour space			Chroma	Total colour difference
	L^*	a^*	b^*	C^*	ΔE^*
Not thermally treated wood	86.0 ± 2.6	5.9 ± 1.3	16.4 ± 1.7	17.4	- - -
t_I = 105 ± 2.5 °C	80.3 ± 1.8	8.4 ± 1.5	17.7 ± 1.6	19.6	6.5
t_{II} = 115 ± 2.5 °C	77.5 ± 1.8	9.6 ± 1.7	18.1 ± 1.5	20.5	9.2
t_{III} = 125 ± 2.5 °C	73.6 ± 1.6	10.5 ± 1.5	18.9 ± 1.5	21.6	13.4
t_{IV} = 135 ± 2.5 °C	65.3 ± 1.4	10.8 ± 1.3	19.4 ± 1.3	22.2	25.1

The thermal treatment of maple wood with saturated water steam of a temperature of t_I = 105±2.5°C for τ = 7 resulted in the light white-brown-pink hue, in the CIE $L^*a^*b^*$colour space defined by the coordinates: L_I^* = 80.3 ± 1.8; a_I^* = 8.4 ± 1.5; b_I^* = 17.7 ± 1.6. According to the colorimetric classification of the change in the colour of wood during thermal treatment (CIVIDINI *et al*. 2007), the total colour difference ΔE_I^* = 6.5 is not considered the high colour difference but only the colour difference visible with light quality screen. The mode of thermal treatment of maple wood at a temperature of t_{II} = 115±2.5°C resulted in light brown-pink hue with the coordinates: L_{II}^* = 77.5 ± 1.8; a_{II}^* = 9.6 ± 1.7; b_{II}^* = 18.1 ± 1.5. More significant changes in wood colour, i.e. getting more darker, more browner, resulted from the thermal treatment by the modes II and III with a temperature of saturated water steam of t_{III} = 125±2.5 °C, or a temperature of t_{IV} = 135±2.5 °C. Rate of change in the wood colour and hues during the processes of thermal treatment of maple wood by the mode III is defined by the values of coordinates: L_{III}* = 73.6 ± 1.6; a_{III}* = 10.5 ± 1.5; b_{III}* = 18.9 ± 1.5. Unique brown-red colour of maple wood with the values of coordinates: L_{IV}* = 65.3 ± 1.4; a_{IV}* = 10.8 ± 1.3; b_{IV}* = 19.4 ± 1.3 resulted from the thermal treatment with the saturated water steam at a temperature of t_{IV} = 135±2.5°C. According to the colorimetric classification of the change in the colour of wood during thermal treatment (CIVIDINI *et al*. 2007), the total colour difference ΔE_{IV}* = 25.1 is considered high colour difference.

Following the visual control of the wood colour on edges of woodturning blanks as well as the measurement of the colour on mentioned faces, the fact that the colour of maple wood cross section is uniform could be seen. The same changes in the colour through the volume of wood is due to fast heating of wood to the required temperature with saturated water steam in the cross section of woodturning blanks (DZURENDA 2018d). This way, good conditions for the processes of hydrolysis and extraction of water soluble substances modifying the chromophoric system of wood were created.

Mentioned findings is beneficial for practice allowing the thermally treated woodturning blanks to be used for making lamellae for flooring or for other 3D processing of solid timber without risk of the change in the wood colour between the surface and the centre.

The effect of the temperature of saturated water steam in the range between t = 105 – 135 °C on the change in the values of individual coordinates in the CIE *L*a*b** colour space are illustrated in Fig. 3.

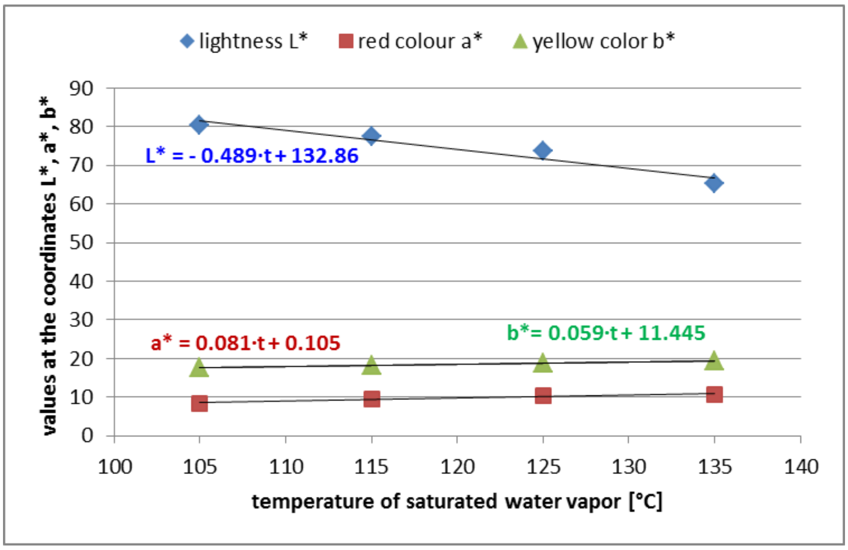

Fig. 3 Correlation between a decrease in lightness, an increase in the values of red and yellow colours of thermally treated maple wood in the CIE *L*a*b colour space and the temperature of saturated water steam.**

Following the assessment of the change in the colour of thermally treated maple wood according to the parameters of the CIE *L*C*h°* colour space, the fact that an increase in the temperature of wood in the technological process caused a significant decrease in changes in lightness Δ*L** and slight increase in chroma Δ*C** can be stated. Mentioned changes are shown in Fig. 4.

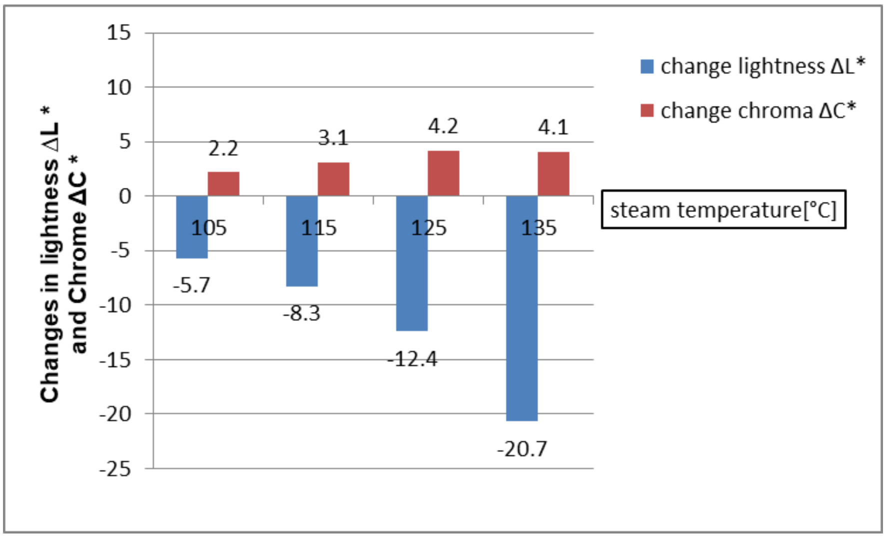

Fig. 4 Correlation between the changes in lightness Δ*L, chroma Δ*C** and the temperature of saurated water steam in the technological process.**

Changes in chroma *C** in the chropmatic plane *a**, *b** and the hue angle *h*° of wood of *Acer pseudoplatanus* L. due an increase in a temperature of saturated water steam ranging between *t* = 105 – 135 °C is given in Fig. 5.

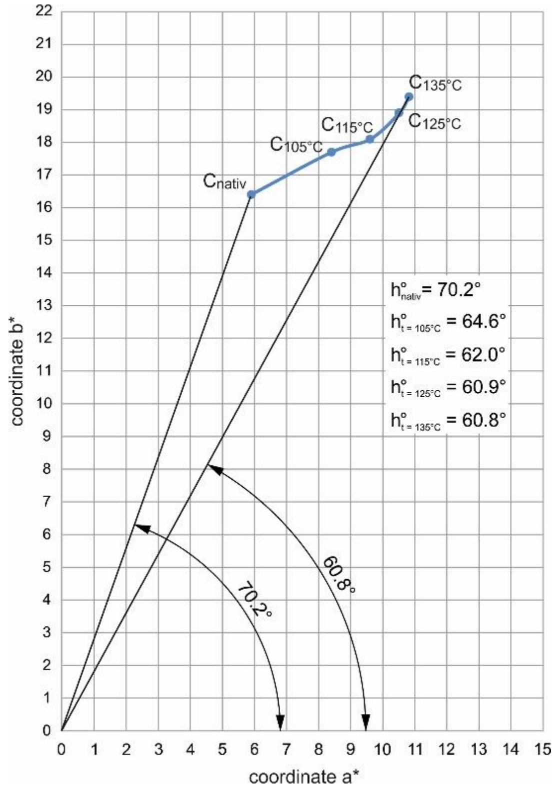

Fig. 5 Changes in chroma *C and the hue angle *h*° in the chromatic plane *a**,*b**.**

Correlation between the change in the total colour difference Δ*E** of maple wood and the temperature of saturated water steam in the technological process is given in Fig. 6.

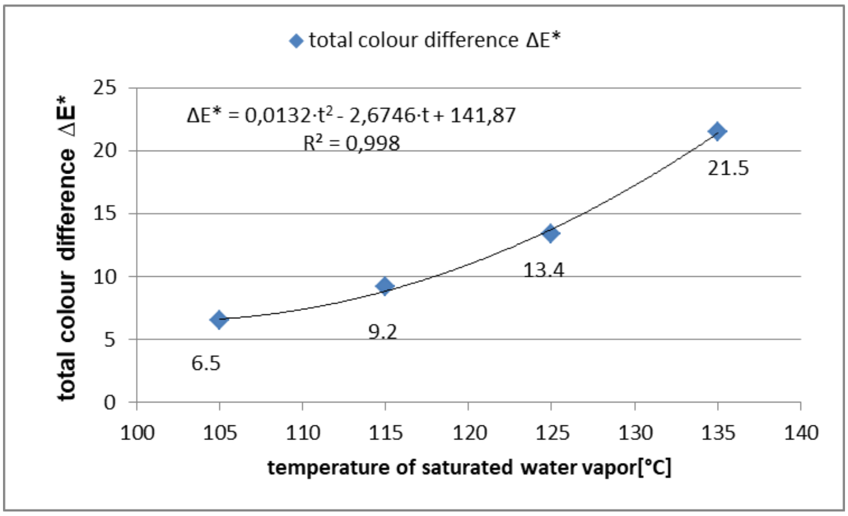

Fig. 6 Correlation between the change in total colour difference Δ*E of maple wood and the temperature of saturated water steam in the technological process.**

A decrease in lightness of thermally modified wet wood is in compliance with the knowledge about changing the colour of wood, its darkening, during technological processes like steaming the wood mentioned in works: (TOLVAJ *et al*. 2009, 2010, DZURENDA 2018 b,c), drying in the environment of hot humid air, or overheated water steam (KLEMENT and MARKO 2009, DZURENDA and DELIISKI 2012a, b, BARANSKI *et al*. 2017), or during thermowood production processes (BARCIK *et al*. 2015, PINCHEVSKAJA *et al*. 2019).

The hydrolysis of wood, and following the works (FENGEL and WENEGER 1989, SOLÁR 2004, LAUROVA *et al*. 2004, BUČKO 2005) subsequent polysaccharide degradation, as well as oxidation of saccharides and pectin, dehydration of pentoses to 2-furaldehyde and condensation of polysaccharide cleavage products, chemical changes in lignin (free radicals, increase in the phenolic hydroxyl groups) and also forming the phenolic extracts are the main causes of mentioned changes resulting from the higher temperature of wet wood. Mentioned reaction result in forming new chromophoric groups causing the changes in wood colour. It is confirmed (Fig. 4.) by a decrease in the lightness ΔL^* from –5.7 to –20.7 and an increase in chroma ΔC^* from 2.2 to 4.1, as well as by the visual changes in the colour of maple wood in Fig. 2.

The fact that chroma C^* moves away on the colour plane a^*, b^* (Fig. 5) from the centre of the coordinates of red colour a^* and yellow colour b^* proclaims the saturation of the colour of thermally treated wood. This findings is important for the wood workers and for the users of products from thermally treated wood as well, as intense colours in interior are more acceptable by a human than range of colours from greys. Moreover, the mode of thermal treatment of maple wood at a temperature of saturated water steam t_{IV} =135 ± 2.5 °C resulted in highlighting the texture of maple wood with the darker hue of brown colour in annual ring of earlywood in comparison to the latewood in the tangential and radial section and the structure of maple wood is highlighted this way.

The values of total colour difference of the colour of maple wood ΔE^* caused by the processes of thermal treatment with saturated water steam at the temperature ranging from 105 °C to 135 °C were ΔE^* = 6.5 ÷ 21.5. The correlation describing the change in the colour of maple wood in Fig. 6 is caused, to a large extent, by changes in the coordinates of lightness L^* and to a lesser extent, by the changes in coordinates of red colour red a^* and yellow colour b^*. Following the colorimetric classification of the change in the colour of wood during thermal treatment mentioned by CIVIDINI *et al.* (2007), according to a mentioned correlation, significant changes in the hues – brown-red of maple wood occurred at the temperature of saturated water steam above $t \geq 122$ °C.

According to the description of physical and mechanical properties resulting from the thermal treatment of wood mentioned by the authors: KOLLMANN – GOTE 1968, Trebula 1986, the changes in the colour of maple wood resulting from the thermal treatment by presented modes are in the group of irreversible changes in wood. Irreversibility of the changes in the colour of maple wood is confirmed by the differences in the analyses of ATR-FTIR spectroscopy in lignin-carbohydrate complex of thermally treated wood as well as untreated wood (VYBOHOVÁ *et al*. 2018), and by the presence of monosaccharides, organic acids and basic structural elements of guaiacyl-syringyl lignin in the condensate mentioned in the works: (BUČKO 1995, DZURENDA and DELIISKI 2000, KAČÍK 2001, LAUROVA *et al*. 2004, KAČÍKOVÁ and KAČÍK 2011, SAMEŠOVA *et al*. 2018).

Irreversible changes in colour of the maple wood resulting from one of the modes of colour modification of wood with saturated water steam extend the possibilities of its use in the field of construction-joinery, construction-art and design.

CONCLUSION

1. The results of experiments focused on observing the changes in the colour of tree species *Acer pseudoplatanus* L. during the process of thermal treatment with saturated water steam at the temperatures ranging between: t = 105–135 °C for τ = 7 hours are presented in the paper.
2. The colour of maple wood thermally treated with saturated water steam changes, gets darker and becomes from white-brown-pink to brown-red.
3. The effect of the temperature of saturated water steam on the change of lightness L^*, red colour a^* and yellow colour b^* of maple wood in the CIE $L^*a^*b^*$ colour space are given in following formulae:
$$L^* = -0.489 \cdot t + 132.86,$$
$$a^* = 0.081 \cdot t + 0.105,$$
$$b^* = 0.059 \cdot t + 11.445.$$
4. The dependence of the total colour difference ΔE*on the temperature of wood in the technological process of colour modification of maple wood with saturated water steam is described with the formula: $\Delta E^* = 0.0132 \cdot t^2 - 2.6746 \cdot t + 141.87$.
5. Significant changes in the colour of maple wood occurs at a temperature above 122 °C.

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AUTHORS' ADDRESSES

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

Michal Dudiak
Technical University in Zvolen
T. G. Masaryka 24
960 01 Zvolen
Slovakia
xdudiak@is.tuzvo.sk