EFFECT OF THERMAL MODIFICATION ON WOOD COLOUR

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Abstract

Colour and colour homogeneity are of special importance for establishing the quality of wood products. In the present study the effect of thermal treatment at 140 °C and 170 °C on colour and its homogeneity was studied for aspen (*Populus tremula* L.), grey alder (*Alnus incana* Moench) and ash (*Fraxinus excelsior*) wood. Wood colour was monitored and evaluated by spectrophotometrical measurements of reflectance spectra and colour parameter calculations using CIELAB colour model with L* as the lightness, and a* and b* as the chromatic parameters. Wood colour changed substantially and all studied types of wood acquired quite similar colour due to the thermal treatment with greater discolouration and almost the same colour detected for treatment at 170 °C. The average colour difference within a board surface as well as among boards of one species was found to be less than 3 DEab units for all thermally treated specimens which can be regarded as hardly perceptible colour difference. However, noticeable differences in colour were detected between the surface and inner layers of thermally treated wood boards. Greater colour heterogeneity throughout the depth of a board was detected for woods treated at 140 °C.

Key words: colour homogeneity, thermal treatment, wood.

Introduction

Thermal wood modification is currently one of the most commercially successful wood treatment methods aimed at production of value-added product (Hill, 2011). There are several thermal modification processes induced in production, differing in modification process parameters (temperature, pressure, duration, oxygen shielding atmosphere) as well as wood material (species, wood moisture content - green, dry). However, all these processes include wood subjection to high temperature in a reduced oxygen atmosphere. Wood properties are permanently changed due to the transformation of wood chemical structure by autocatalytic reactions of the cell-wall constituents during thermal treatment (Tjeerdsma et al., 2005; González-Peña et al., 2009). Chemical changes in wood result in an irreversible improvement of its dimensional stability and enhanced resistance against wood-destroying fungi without using any harmful reacting chemicals, which is an important aspect concerning environmentally friendly management and sustainability (Yildiz et al., 2011). Another consequence of chemical transformations in wood during thermal treatment is the changed wood colour which can be regarded as another benefit of thermally modified wood. Consumers often prefer thermally modified wood just due to its altered colour and sometimes it is even used as an alternative for tropical woods (Ayadi et al., 2003; Esteves et al., 2008; Miklečić et al., 2011; Schnabel et al., 2007).

However, concurrently with above-mentioned benefits, heat treatment commonly results in substantial loss of wood strength. Accordingly, thermally modified wood is mostly recommended for non-structural usage. Therefore, the main use areas of thermally modified wood are garden furniture, flooring, building facades, decking for terraces and similar (Bächle et al., 2010). In all these applications, wood serves as a functional as well as a decorative material. For its decorative function, colour and colour homogeneity are of special significance, since the colour is an important parameter to establish the quality of wood products.

The colour of an object is formed when chemical components named as chromophores absorb certain wavelength of the incident light in a visible range of solar spectrum and the rest part of the light spectrum is reflected which subsequently can be perceived by a human eye. Therefore, the colour characteristics of wood depend on its chemical composition that can interact with light (Hon and Minemura, 2001). A number of chemical reactions, including formation of a range of new chromophoric groups, occur during the thermal modification. Accordingly, wood acquires characteristic lighter or darker brown colour. Colour changes in wood due to thermal treatment have been investigated by several researchers (Menezzi et al., 2009; Mitani and Barboutis, 2013; Chen et al., 2012; Lovrić et al., 2014). It is commonly reported that wood becomes darker when subjected to the heat treatment and the degree of darkening depends on the process conditions. However, these studies have been mainly focused on the average wood colour changes and there is scarce information concerning colour homogeneity of thermally modified wood. Besides, ambiguous results are established regarding colour uniformity in wood due to its thermal treatment. Johansson and Morén (2006) found that colour distribution through the thermally treated boards was not homogeneous. Dubey et al. (2011) established that at lower treatment temperatures there were colour differences between two surfaces of modified boards - decreased when the treatment temperature was raised, and no visible colour difference was found for boards treated at temperature 180 °C and higher, which denote that the homogeneity of wood colour depends on the treatment conditions. Brischke et al. (2007) observed that there was a higher scattering of colour in thermally modified solid wood compared to milled wood, which implies some colour heterogeneity on surface of the thermally treated board.

The objective of the present study was to investigate the effect of thermal treatment of wood in a water vapour medium at two temperatures on the alteration in wood colour and its homogeneity. Three common hardwood species in Latvia – aspen (*Populus tremula* L.), grey alder (*Alnus incana* Moench) and ash (*Fraxinus excelsior*), were used in the present study.

Materials and Methods

Wood boards of aspen (*Populus tremula* L.), grey alder (*Alnus incana* Moench) and ash (*Fracsinus excelsior*) without any visible defects measuring 1000 × 100 × 25 mm were supplied by sawmill. The thermal mofification of boards were performed in a laboratory experimental wood modification device produced by Wood Treatment Technology (WTT). The modification was carried out in a water vapour medium at super atmospheric pressure (0.6 MPa). Treatments were performed at two operative treatment temperatures – 140 °C and 170 °C, duration of the treatment at the efficient temperature was one hour for both regimes. After modification, the boards were conditioned at 20 °C and 65% relative humidity.

For evaluation of wood surface colour homogeneity, both sides of the conditioned boards wereplaned. In the same way, specimens of untreated boards of the same species were prepared. Whereas, boards intentioned for evaluation of wood colour homogeneity along (throughout) the thickness of the board, were planed prior to the thermal treatment.

A portable spectrophotometer Minolta CM-2500d (standard illuminant D65, d/8^o measuring geometry, 10° standard observer, measuring area Ø 8 mm) was used for wood reflectance spectra and colour measurements. Reflectance spectra were recorded against a white optical standard in the wavelength range from 360 to 740 nm with a scanning interval of 10 nm. Colour was expressed in accordance with the CIELAB colour model (introduced by the International Commission on Illumination (Commission Internationale de l'Eclairage), 1976) which is mostly used for objective quantification of colour and colour differences in wood. According to this model, each colour is a point in the three-dimensional colour space with the colour parameters L*, a*, b*, where parameter L* describes the lightness (from zero – black to 100 – white) and parameters a* and b* describe the chromaticity coordinates on the green-red and yellow-blue axis, respectively. From the L*, a*, b* parameter values obtained at two points, the differences of the colour parameters ΔL*, Δa*, Δb* and the total colour difference ΔEab between these two points were calculated according to DIN 6174 2007:

$$\Delta \mathrm{E}_{ab} = \left(\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2 \right)^{\frac{1}{2}} \qquad (1)$$

The ΔEab value corresponds to the shortest distance in the CIELAB colour space between the two points. Chromaticity change, which characterises change in colour intensity, was calculated according to the equation:

$$\Delta C^* = \left(\left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2 \right)^{\frac{1}{2}} \qquad (2)$$

The effect of thermal treatment on colour uniformity of wood was evaluated in three levels:

- *Surface colour homogeneity in a board*. Colour parameters (L*, a*, b*) were measured at 15 points on each board two surfaces and colour differences ΔEab between all possible pairs of measured points (105 combinations) were computed according to the equation (1). The average colour difference, which represented the colour homogeneity of the particular board, was calculated from the colour differences of these pairs. Six boards were used for the evaluation of surface colour homogeneity for each treatment regime.

- *Inter-board homogeneity*. For each surface of six boards, average values of colour parameters (L*, a*, b*) were calculated from measurements at 15 points on the surface. These average values represented the colour parameters of the board in the further calculations. Colour differences ΔEab between all possible pairs of board surfaces were calculated (66 combinations) according to the equation (1). The average inter-board colour difference, which represented colour homogeneity characteristic to the treatment regime, was calculated from the colour differences of these pairs.

- *Homogeneity of colour throughout the board thickness*. Wood layers were planed down from both surfaces of the boards with a step of 2 mm. Colour parameters (L*, a*, b*) were measured at five points on each planed surface and the average values calculated. Colour differences ΔEab between the surface and each of the planed surface were calculated.

In the case of ash wood, boards containing both sapwood and heartwood were used and measurements were performed individually on the sapwood and heartwood parts.

Table 1

Changes in colour parameters and total colour changes (ΔEab) of woods due to thermal treatment

Treatment temperature (°C)	Wood	ΔL*	Δa*	Δb*	ΔC*	ΔEab
140	Aspen	-24.7 (1.8)	7.6 (0.1)	3.6 (0.9)	5.2 (0.9)	26.1 (1.6)
	Grey alder	-10.3 (1.6)	-2.6 (0.2)	-1.9 (0.8)	-2.8 (0.9)	10.8 (1.6)
	Ash-sapwood	-24.5 (0.8)	6.9 (0.5)	5.0 (1.5)	6.9 (1.5)	25.9 (0.5)
	Ash-heartwood	-10.9 (1.6)	2.8 (0.5)	4.1 (0.8)	4.8 (0.8)	12.0 (1.5)
170	Aspen	-64.5 (1.7)	8.3 (0.6)	-0.6 (0.6)	1.6 (1.7)	47.2 (1.6)
	Grey alder	-29.4 (1.6)	-2.2 (0.2)	-6.0 (1.1)	-6.4 (1.0)	30.1 (1.8)
	Ash-sapwood	-49.2 (1.7)	4.1 (0.9)	-8.0 (1.9)	-6.0 (2.1)	50.0 (1.8)
	Ash-heartwood	-35.1 (1.7)	0.5 (0.9)	-8.4 (1.9)	-7.3 (2.1)	36.1 (1.9)

Values in parenthesis are standard deviations
ΔL* - changes in lightness, Δa*- changes in parameter a*, Δb* - changes in parameter b*, ΔEab – total colour changes

Results and Discussion

Spectrophotometrical colour measurements showed that thermal treatment had caused changes in all colour parameters for all woods which resulted in substantial total colour changes ΔEab (table 1) and the magnitude of changes differed on the species. The treatment at a higher temperature (170 °C) facilitated greater colour changes ΔEab.

Woods darkened (negative ΔL* values) at both studied treatment conditions and a greater reduction in lightness was detected for wood treated at the higher temperature which agrees with earlier findings (Esteves et al., 2008; Srinivas and Pandey, 2012). Decrease in lightness indicates that components absorbing visible light were formed during thermal treatment (Yao et al., 2012). Reduction in lightness due to thermal treatment is a well established effect (Brischke et al., 2007; Tuong and Li, 2010; Chen et al., 2012), while different trends have been observed concerning changes in chromaticity parameters, which can be explained by different treatment conditions and durations as well as different wood species used for the experiments. Yao et al. (2012) observed increase in both chromaticity parameters (a* and b*) of wood due to thermal treatment, while Chen et al. (2012) found that the yellowness parameter b* decreased during wood thermal modification in both oxygen and nitrogen atmosphere. In the present study, the changes in the colour parameters a* and b* and consequently in chromaticity C*, evolved differently depending on the treatment temperature. Different effects of treatment conditions on changes in chromaticity were stated also by other researchers (Schnabel et al., 2007; Menezzi et al., 2009; Lovrić et al., 2014). These results indicate that different chromophores are formed during wood thermal treatment at different conditions. Besides, the trends of changes in chromaticity differed for the studied wood species. Chromaticity of grey alder decreased at both treatment conditions and greater reduction was detected at 170 °C. Aspen and ash woods showed increase in chromaticity at 140 °C whereas elevated treatment temperature (170 °C) caused a substantial reduction in chromaticity. Different behaviour of wood during thermal treatment regarding the patterns of changes in chromaticity, implies the formation of diverse chromophoric systems, which may be attributed to variations in the chemical composition of different species.

According to the data recorded in Table 1, the colour of aspen and ash-sapwood was changed more considerably. Analysis of impact of each colour parameter on the total colour change ΔEab, showed that decrease in the lightness (ΔL*) was the dominant contributor to the colour changes of all studied specimens, but for aspen and ash-sapwood the dominance of changes in lightness was more pronounced. These two types of wood, when not thermally treated, are significantly lighter than grey alder and ash-heartwood. Consequently, the greater decrease in lightness of these two types of wood due to thermal treatment resulted in quite similar colour parameters (not shown) of treated wood. It means that during the thermal modification all wood acquired more alike appearance regarding their colour. This is also well illustrated by the reflectance spectra presented in Figure 1. The reflectance spectra of unmodified wood (Fig. 1-a) differ noticeably. Substantial loss in reflectance with concurrent reduction of difference in reflectance among wood was observed after thermal treatment at 140 °C (Fig. 1-b). Moreover, there is only a slight difference among reflectance spectra of all studied wood after modification at 170 °C (Fig. 1-c), which implies that studied wood became quite uniform in colour during the thermal treatment.

It may be an advantage for decorative applications, that pronounced colour difference between ash sapwood and heart wood was substantially reduced during the thermal treatment. Ash colour homogenisation is corroborated by the results of evaluation of colour differences ΔEab between ash-sapwood and ash-heartwood: for unmodified wood

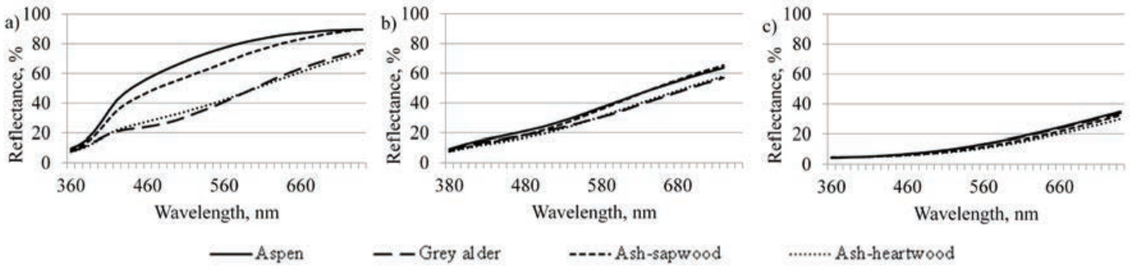

Figure 1. Reflectance spectra of unmodified and thermally modified aspen, grey alder, ash-sapwood and ash-heartwood: a) unmodified; b) modified at 140 °C; c) modified at 170 °C.

-14.7 units, for wood treated at 140 °C – 6.6 units and for wood treated at 170 °C – 1.4 units, respectively. It proves that the treatment at 170 °C ensured uniform colour of ash sapwood and heartwood, as ΔEab = 2-3 units is approximately the limit for human eye to recognize a colour difference (Sundqvist and Morén, 2002). This finding agrees with the observation of Lovrić et al. (2014) who investigated colour changes during thermal treatment of veneers manufactured from poplar species with a pronounced colour difference between sapwood and heartwood. They established that the thermal treatment reduced the colour difference and at a certain temperature it dropped into the category of no perceptible colour difference (ΔEab < 2).

More or less variation in colour is a common feature of all types of wood and the nature and magnitude of characteristic colour difference depends on wood species (Buchelt and Wagenführ, 2012). Extractives are known to be mainly responsible for specific colour of unmodified wood while coloured products formed from extractives and hemicelluloses degradation as well as quinones like products stemmed from lignin have been considered as a reason for wood colour change due to thermal treatment (Yao et al., 2012).

In general, from all analysed homogeneity levels, smaller average differences were detected for colour within the board surface. Unmodified ash-heartwood was the most heterogeneous wood regarding the board surface colour but even in this case the average colour difference was only 3.1 ΔEab units (Fig. 2a).

The average colour differences were between 2 and 3 ΔEab units for all other specimens which allowed to regard their colour as quite homogenous. Besides, these differences were statistically insignificant ($p>0.05$). Thermal modification resulted in an even more uniform colour within the board surface for grey alder and ash wood while aspen wood became less homogenous regarding its colour. However, the colour difference of thermally treated aspen wood still was hardly perceptible (ΔEab = 2.4). Thus, boards with a uniform surface colour were produced during thermal treatment at both studied temperatures.

Among all studied specimens, the highest inter-board heterogeneities were found for unmodified grey alder and ash-heartwood (Fig. 2b) for which the average colour difference reached 3.9 and 3.4 units, respectively. Average colour differences of the other specimens were less than 3 ΔEab units. Similarly as in the case of a board surface, the average colour difference among boards of all studied types of wood decreased during the thermal treatment and the decrease in colour difference was even more pronounced. Similar results were established by Dubey et al. (2011) who examined thermally treated *Pinus radiata* and found that the colour difference between the two board surfaces was smaller for thermally treated than unmodified wood.

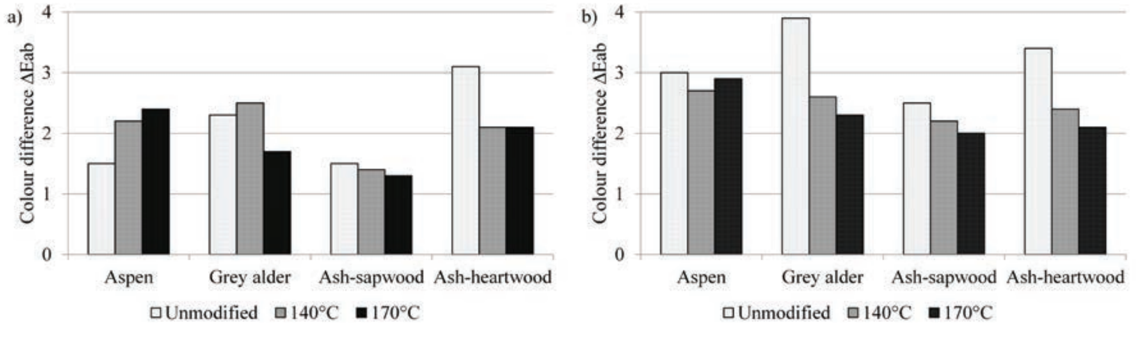

Figure 2. Colour difference ΔEab of thermally modified aspen, grey alder, ash wood and ash-heartwood: a) within a surface of the board; b) among boards.

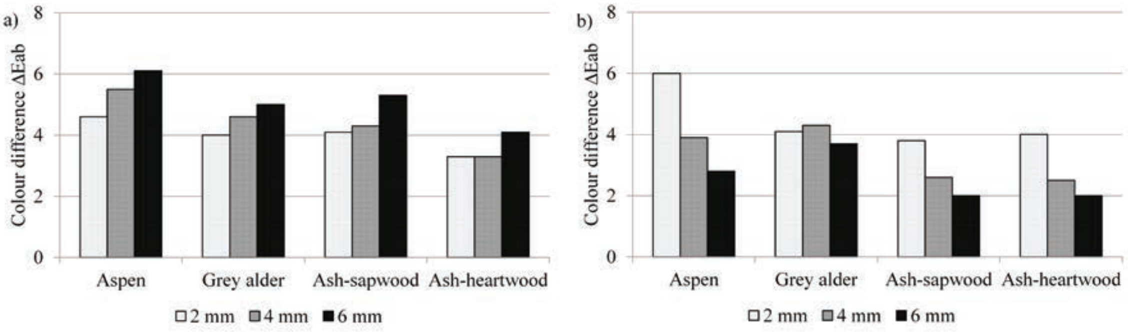

Figure 3. Colour difference ΔEab between the surface and the inner layers of boards of thermally modified aspen, grey alder, ash: a) modified at 140 °C; b) modified at 170 °C.

However, noticeable differences in colour were detected between the surface and inner layers of thermally treated wood boards (Fig. 3). Greater reduction in lightness and increase in chromaticity parameters a* and b* were found for all studied specimens at the board surfaces compared to deeper layers. The statistical analysis showed that the differences between the board surfaces and deeper layers were significant ($p<0.05$). The reason of these colour differences could be an uneven temperature distribution throughout the board thickness during thermal treatment and was lower at the core of the board which subsequently resulted in fewer chemical transformations and fewer colour changes. Besides, the surfaces of boards were exposed to more wet conditions during treatment as the modification was carried out in a water vapour atmosphere. It can significantly contribute to a more intense discolouration as water facilitates chemical decomposition of wood at high temperatures.

For the boards treated at 140 °C (Fig. 3a), a common trend was observed that the colour difference between the surface and the layers underneath the surface became lighter with an increase of the distance between the two planes. The colour differences ΔEab between the surface and all other examined planes throughout the boards exceeded the ΔEab value of 3 units for all types of wood. The greatest colour heterogeneity of wood in various depth from the board surface was observed for aspen wood. During treatment at 170 °C (Fig. 3b), more uniform wood throughout the board was produced. Nevertheless, the colour difference between the surface and the plane of 2 mm underneath the surface, which was the greatest colour difference detected in boards subjected to this treatment conditions, was greater than 3 ΔEab units. Colour of aspen wood was the most heterogeneous among the studied wood also for treatment temperature of 170 °C. Johansson and Moren (2006) and Dubey et al. (2001) have reported a similar trend that during the thermal treatment wood acquired quite a homogeneous surface while colour difference between surface and core was found to be noticeable, though decreased when the treatment temperature was raised.

By contrast, the difference between colour of deeper layers were found to be smaller than 2 ΔEab units (not shown) for all types of wood for both treatment conditions and these differences were statistically insignificant ($p>0.05$). It suggests that the colour of thermally treated wood is homogeneous under the upper layer. As boards, intended for the evaluation of colour uniformity throughout the board thickness, were planed before thermal treatment, the substantial colour difference between the upper and deeper layers might be avoided if rough boards were thermally treated and subsequently the outer layer was planed after the modification.

Conclusions

1. The colour of aspen, grey alder and ash wood changed substantially during the thermal treatment with greater discolouration detected for the treatment at 170 °C. All studied types of wood acquired quite similar colour due to the thermal treatment.
2. The average colour difference within the board surface as well as among boards was found to be less than 3 ΔEab units for all thermally treated specimens which can be regarded as a hardly perceptible colour difference.
3. Noticeable differences in colour were detected between the surface and inner layers of thermally treated wood boards for all studied wood. A greater colour heterogeneity throughout the board was found for wood treated at 140 °C.

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