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Numerical evaluation of beechwood discolouration during drying

Numeričko vrednovanje diskoloracije bukovine tijekom sušenja

Znanstveni rad • Scientific paper
Prispjelo - received: 01. 04. 2000. • Prihvaćeno - accepted: 12. 09. 2000.
*UDK: 634*812.111 i 847*

SAŽETAK • *Obojenja drva, koja se pojavljuju tijekom postupka sušenja, uvelike umanjuju vrijednost drvnih proizvoda i to pogotovo ako želimo istaknuti estetske vrijednosti drva. Uzroci obojenja su vrlo različiti, a na njihovu brzinu i intenzitet utječe više činitelja.*
Na primjeru bukovine, kao problematične vrste drva sa stanovišta stabilnosti boje, smo utvrđivali utjecaj sadržaja vode drva, trajanja i brzine sušenja na opseg i jakost obojenja po presjeku piljenica. Utjecaj temperature, do sada već dosta dobro istražen, smo isključili sušenjem u termostatiranom prostoru (pri konstantnoj temperaturei od 20 °C). Brzinu sušenja smo održavali stalnim strujanjem zraka nad zasićenim otopinama soli tako da je za "brzo sušenje" korišten magnezijev klorid (rel. vlažnost zraka φ_1 = 33%), a za sporo sušenje natrijev nitrit (rel. vlažnost zraka φ_2 = 65%).
Kolorimetrijsko vrednovanje smo radili standardiziranim Judd Hunterovim sustavom mjerenjem svjetlosti (L) a položaja na crveno-zelenoj osi (a*) i plavo-žute koordinate (b*) kolorimetrom Dr Lange MicroColor. Mjerenja smo izvodili susljedno nakon svake promjene sadržaja vode po presjeku za 5 % na 11 slojeva od površine do sredine piljenice. Promjene boje smo određivali razlikama izmjerenih kolorimetrijskih parametara (ΔL*, Δa*, Δb*,), ukupnom promjenom boje (ΔE*), tonom boje (ΔH*) i zasićenošću boje (ΔC*).*
Usprkos sušenju bukovine pri relativno niskoj temperaturi, još uvijek postoji opasnost od nepoželjnog obojenja. Dugotrajnije sušenje (pri relativnoj vlažnosti zraka φ_2 = 65%) predstavlja veću opasnost kako po opsegu, tako i po jakosti obojenja. Svjetloća površine sporo sušećih uzoraka (ΔL je bila između 6 i 7) smanjivala se jednako kao i svjetloća središnjih slojeva pri bržem sušenju (pri φ_1 = 33%), ali je pri tome promjena svjetloće u sredini bila*

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znatno veća ($\Delta L^* \approx 10$). Utjecaj brzine sušenja na obojenje potvrđuju i mjerenja ukupne rezlike u boji i promjene crveno-zelene komponente.

Promjene numeričkih vrijednosti na plavo-žutoj osi (b^*) i promjene tona boje (ΔH^*) nisu bitno ovisne o sadržaju vode ili o trajanju sušenja. Njihove vrijednosti su posljedice varijabilnosti drvne strukture i pokusnih odstupanja i ne pokazuju signifikantne trendove promjene.

Obojenje je kritično samo u određenom području sadržaja vode. Kako vrlo vlažno drvo ($u >$ 50%) i dovoljno suho drvo ($u<20\%$) predstavljaju zadovoljavajuća stanja zaštite od obojenja, može se utvrditi da najosjetljiviji interval obuhvaća šire područje zasićenosti vlakanaca, tj. sadržaj vode između 43 % i 22 %.

Obojenje u kritičnom intervalu se može lako izbjeći dovljno brzom promjenom sadržaja vode, tj. dovoljno brzim sušenjem. Pri sušenju na temperaturi od 20 °C mora promjna sadržaja vode na dan po cijelom presjeku materijala biti veća od 1 %.

Ključne riječi: *diskoloracija, bukovina (Fagus silvatica L.), sušenje, sadržaj vode, CIELab sustav*

ABSTRACT • *The effect of moisture content, time and drying rate on the extent and intensity of discolouration of beechwood was examined. The values of the CIELab colour system (ΔL^*, Δa^*, Δb^*, ΔE^*, ΔH^*, ΔC^*) during drying at a constant temperature and by two different relative humidity ($\varphi_1 = 33\%$ and $\varphi_2 = 65\%$) from surface to core were obtained. During slower drying, discolouration through the entire cross section was observed. L^* and ΔE^* values were much lower at the centre of the board. Only the core was stained during quicker drying. The moisture content from MC = 43 % to MC = 22 % was defined as critical for discolouration.*

Keywords: *discolouration, beechwood (Fagus silvatica L.), drying, moisture content, CIELab system*

1. INTRODUCTION
1. Uvod

During wood processing and woodworking, the activity of various biotic and abiotic factors can lead to numerous forms of discoloration which seriously decrease the value of wood.

In green wood, when this contains a greater quantity of water, slightly higher outdoor temperatures present favourable conditions for the occurrence of biotic discoloration (c.f. Zabel & Morrell 1992). Drying and other hydrothermal treatments, on the other hand, are conducive to abiotic discolouration.

In the case of kiln drying processes, in particular, discolouration is often influenced by a number of factors at the same time, and this makes it difficult to trace the real causes hindering successful protection.

On the surface of wood with high tannin content (birch, cherry tree, chestnut and oak in particular), iron-tannate stains occur when wood has come into contact with iron ions (direct contact of wood with iron items, dripping water from hot water piping etc.) (Charrier, et al. 1992, Wassipaul et al. 1987). As reported in literature, the intensity of discoloration and of chemical reaction depends on temperature, wood moisture content and the quantity of oxygen. Charrier et al. (1992) demonstrate that discolouration can be prevented by dipping wood into sodium carbonate solution, and as this only occurs on the surface, it can be eliminated by planning or by means of oxalic acid.

A number of authors (c.f. Laver et al. 1996, Schmidt 1986, Wassipaul et al. 1992) claim that, in the case of slow drying, staining of lighter coloured hardwoods and of white pine is due to enzymatic activities associated with high moisture content (MC). Discolouration develops in two steps (Kreber 1993): oxidation and enzymatic reactions of wood extractives are followed by their condensation. High temperatures in drying kilns plus sufficient partial pressure of O_2 and presence of enzymes cause further polymerisation and oxidation, which produce stained components (tannins, phlobo-tannins). Discolouration is also more pronounced in the case of sticker stain, which Miller et al.(1990) explain as resulting from a slower process of drying and the accumulation of phenolic extractives which then oxidise and form insoluble phlobaphenes. Theoretical findings have also been confirmed by research concerning the content of water-acetone extract. This has been found to be always lower in stained wood (also under piling sticks) than in natural-coloured wood.

The chemistry of discolouration during the drying process indicates that this may be related to biosynthesis of heartwood substances. In the process of heartwood formation, colourless monomeric and soluble flavonoids turn, under the influence of enzymes (dehydrogenases, peroxydases) and oxygen, into coloured and insoluble products (Dietrichs 1964). Heartwood phenolic substances are supposed to develop already in vacuoles in the vicinity of cambium (Bosshard 1968). As we move away from cambium in centripetal direction, in parenchyma cells the degree of polymerisation of phenolic substances increases simultaneously with a decrease in the content of starch. Heartwood formation, in particular in the species with discoloured heartwood, is also influenced by gas/water ratio (Torelli 1974). Höster (1974), writing on beechwood, reports that the substances stored in vacuoles of parenchyma cells which are still alive are during the drying process transported by water flow to the surface where coloured oxidation products are formed.

Kreber et al. (1998) report that pine sapwood can be discoloured also in the case of MC values high above the saturation point of cell walls, and that drying at higher temperatures only increases discolouration. The predominant chemical classes were water-soluble components including sugars, amino acids and phenols. The reasons for this are ascribed to the reaction of reducing sugars with nitrogenous substances (Maillard-Amadori reaction), where concentration of the latter increases as free water flows towards the surface.

2. AIM OF RESEARCH
2. Cilj istraživanja

As numerical colour evaluation is still unreliable, we wanted to determine the suitability of numerical evaluation of beechwood discolouration during drying and to evaluate which of the colourimetric parameters is the most usable one.

By analysing colourimetric parameters during different drying conditions, we specifically wanted to examine the influence of

a) the drying rate,

b) duration of drying and

c) moisture content

on the intensity and location of discolouration.

3. MATERIAL AND METHODS
3. Material i metode

3.1. MATERIAL, DRYING SCHEDULE AND SAMPLING
3.1. Material, režim sušenja i uzimanje uzorka

Discolouration was studied on beechwood (*Fagus silvatica* L.), which is an extremely sensitive tree species as regards its colour, in particular during the drying process. Boards 50 mm thick were dried at the temperature 20°C and at two relative air humidity values (φ_1 = 33% and φ_2 = 65%), which were regulated by saturated solutions of $MgCl_2$ and $NaNO_2$.

Beechwood was dried from green condition until equilibrium state was reached. With each drop of average MC by 5%, from the dried wood two parallel specimens of 25 mm thick were cut out (Fig. 1). One specimen was dried by intensive and continuous blowing in standard climate until homogenous MC of approx. 12% was reached, and colour was examined in 11 layers from the surface to the core. In the other specimen gravimetric method was used to determine MC, moisture gradient and rate of drying.

3.2. METHOD OF COLOUR EVALUATION
3.2. Metoda određivanja boje

For colour evaluation in the drying process we used Judd Hunter's standardised system CIELab (DIN 5033, DIN 6174), where colour is defined by three dimensions L^*, a^* and b^*. L^* represents lightness, a^* determines the position of the colour on red-green axis and b^* is yellow-blue co-ordinate.

Total colour difference ΔE^* depends on differences or contributions of individual co-ordinates in all of the three directions of colour system. Colour evaluation was also carried out by taking into consideration hue (ΔH^*) and colour saturation (ΔC^*) mathematically expressed as

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$
$$\Delta H^* = \sqrt{(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2} \quad \text{and}$$
$$\Delta C^* = \sqrt{(a_P^*)^2 + (b_P^*)^2} - \sqrt{(a_B^*)^2 + (b_B^*)^2}$$

For measurements we used a spectral photometer Dr. Lange MicroColor with technical characteristics as follows: measuring geometry - d/8, light source – xenon flash lamp, standard illumination – D 65, detector – 3 silicon measuring photo detectors and reference photocells, reproducibility – 0,15 ΔE on white, measuring area - ϕ = 10 mm.

Colour changes from the surface to the core were examined on dried and equilibrated specimens (u_r = 12%) by successively reducing the thickness of specimens by 2.5 mm (11 times e.g. 11 layers). After planning measurements on each layer were carried out on three locations (Fig. 1).

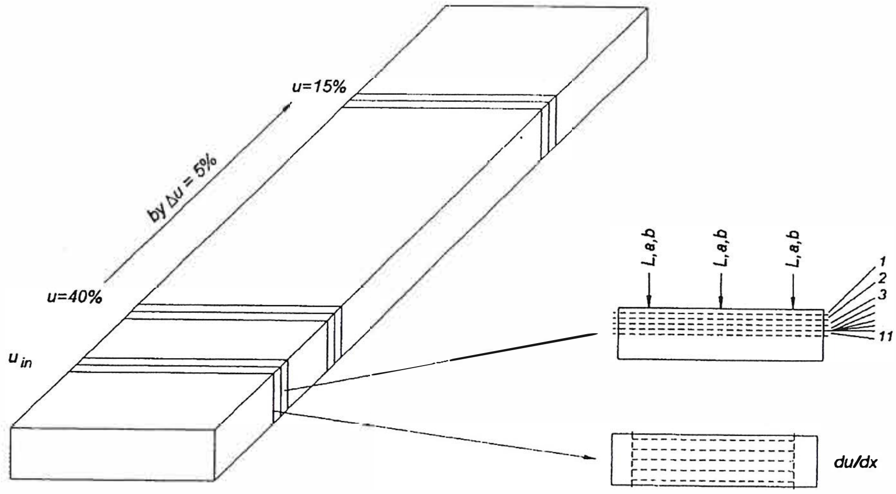

Figure 1
Sampling for colour evaluation of beech wood during drying. • *Uzimanje uzoraka za vrednovanje boje bukovine tijekom sušenja.*

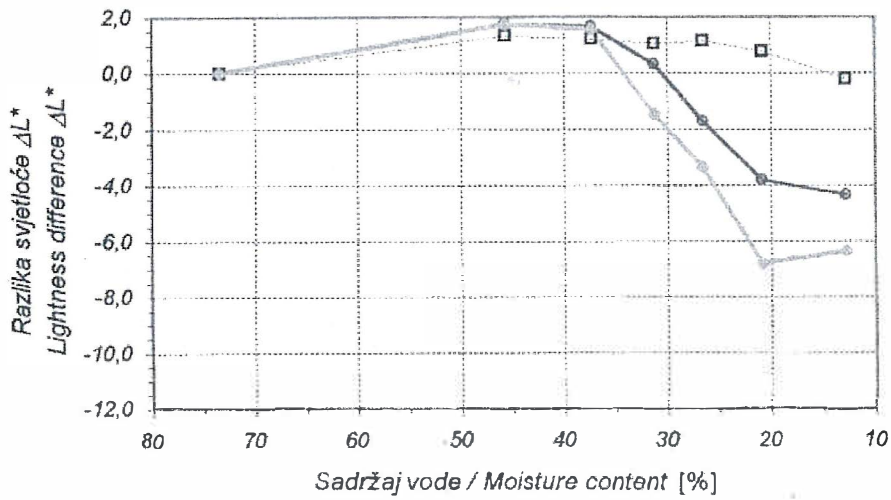

Figure 2
Lightness difference (ΔL^*) of different layers (just below suface – layer 2; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature (T = 20^{o} C) and relative humidity (φ_1 = 33 %) (za legendu vidi sl. 3). • *Razlike svjetloće (ΔL^*) različitih slojeva (podpovršinski sloj = sloj 2; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi (T = 20^{o} C) i relativnoj vlažnosti zraka (φ_1 = 33%) (leg. see fig.3).*

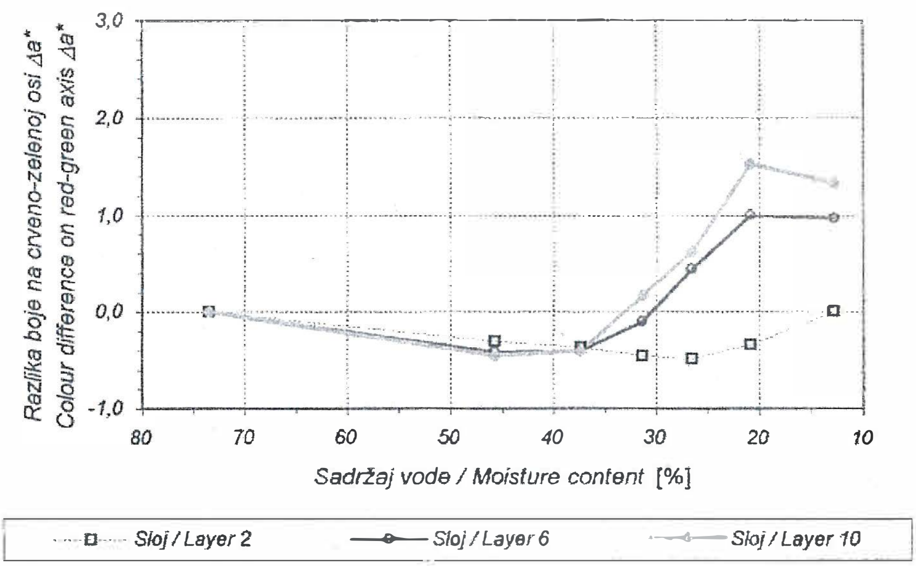

Figure 3
Colour difference on red-green coordinate (Δa^*) of different layers (just below suface – layer 2; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature (T = 20^{o} C) and relative humidity (φ_1 = 33 %) (leg. see fig. 3). • *Razlike boje na crveno-zelenoj koordinati (Δa^*) različitih slojeva (podpovršinski sloj = sloj 2; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi (T = 20 ^{o}C) i relativnoj vlažnosti zraka (φ_1 = 33%) (za legendu vidi sl. 3).*

4. RESULTS
4. Rezultati

4.1. DISCOLOURATION OF BEECHWOOD DRYED AT A TEMPERATURE OF 20°C AND RELATIVE HUMIDITY OF 33%
4.1. Diskoloracije bukovine pri sušenju na temperaturi 20°C i relativnoj vlažnosti zraka 33%

Naturally, the drying at lower relative humidity (φ_1 = 33%) was faster than at higher relative humidity. On the surface of quickly dried specimens (relative air humidity φ_1 = 33%), at around fiber saturation (MC ≈ 30 %), lightness (L^*) increased by approx. 2.83 (Table 1 and Fig. 2). Just below the surface (layer 2), lightness remained constant and independent of MC. In the core section of the board (layers 8 to 11), at the beginning of the drying up to MC 40%, no difference in lightness was observed, but the change was marked and was quick in the MC range between 38 and 22%. With respect to the initial condition, lightness dropped by 6.35 during the entire drying process.

At the beginning of drying of green wood, the co-ordinate of red-green axis (a^*) moved into the green area and then in the surface layers (layers 1 to 3) remained at the same level until the end of the drying process (Tab. 1 and Fig. 3). In the core section of the board (layers 8 to 11), the red component started to become more prominent at MC 38%,and reached a maximum deviation when approaching MC 22%. By further drying, the values did not change any more. The greatest and quickest changes of the values on red-green axis were observed in the same MC interval as in the case of changes in lightness.

Variations in colour values on yellow-blue axis (b^*) - both in cross section and depending on MC and drying time - result from the variability of wood structure and experimental deviations (Tab. 1 and Fig. 4) and do not show any characteristic trend.

When evaluating colour changes during the drying process, total colour differ-

τ[dana/ days]	0		10		14		20		28		41		62	
u [%]	73,4		45,7		37,3		31,3		26,5		20,9		12,8	
Layer no./Sloj	L*	s	L*	s	L*	s	L*	s	L*	s	L*	s	L*	s
1	75,4	3,40	76,2	2,15	78,4	1,06	79,0	1,10	78,9	1,25	78,6	0,86	77,0	4,24
2	77,0	1,82	78,3	1,13	78,2	0,55	78,1	0,63	78,2	0,42	77,8	0,67	76,8	3,14
3	76,4	1,78	78,0	0,99	77,6	0,97	76,2	0,81	75,9	0,61	75,5	0,81	74,3	2,54
4	76,2	1,92	78,0	0,98	77,8	0,83	76,4	0,67	75,3	0,68	74,4	0,96	72,5	2,20
5	76,0	1,69	77,8	1,00	78,0	0,76	76,3	0,85	74,8	0,90	73,3	0,76	72,2	2,38
6	76,0	1,66	77,8	0,90	77,7	0,60	76,3	0,77	74,3	1,01	72,2	0,99	71,7	2,31
7	76,0	1,77	77,7	0,65	77,4	0,61	75,4	1,05	73,8	1,62	71,0	1,48	70,9	2,42
7	75,8	1,74	77,7	0,31	77,3	0,62	74,8	1,33	72,8	2,04	70,1	1,80	70,2	2,24
8	75,6	1,82	77,7	0,27	77,1	0,96	74,5	2,16	72,4	2,81	69,5	2,06	69,6	2,15
10	75,8	1,74	77,5	0,44	77,3	0,99	74,3	2,44	72,4	3,12	69,0	2,51	69,4	1,92
11	75,4	1,80	77,5	0,58	77,4	1,15	74,48	2,31	73,0	3,06	69,8	2,50	69,8	1,67
Layer no./Sloj	a*	s	a*	s	a*	s	a*	s	a*	s	a*	s	a*	s
1	6,60	0,994	6,48	0,578	5,85	0,432	5,58	0,523	5,70	0,566	5,75	0,362	6,27	1,003
2	6,38	0,605	6,08	0,331	6,02	0,223	5,93	0,288	5,90	0,190	6,05	0,243	6,38	0,826
3	6,57	0,579	6,17	0,280	6,35	0,367	6,65	0,345	6,67	0,280	6,75	0,373	7,07	0,619
4	6,67	0,572	6,23	0,339	6,25	0,339	6,62	0,271	6,88	0,331	7,10	0,400	7,58	0,488
5	6,68	0,512	6,22	0,331	6,17	0,314	6,62	0,264	7,03	0,403	7,40	0,335	7,63	0,532
6	6,72	0,567	6,30	0,261	6,32	0,264	6,62	0,319	7,15	0,362	7,72	0,354	7,68	0,492
7	6,80	0,544	6,37	0,186	6,47	0,294	6,90	0,374	7,25	0,489	8,15	0,524	7,95	0,493
7	6,88	0,512	6,37	0,151	6,47	0,207	7,02	0,354	7,42	0,479	8,30	0,447	8,18	0,382
8	6,97	0,557	6,30	0,126	6,45	0,339	7,05	0,554	7,42	0,595	8,32	0,488	8,17	0,427
10	6,95	0.606	6,50	0,179	6,55	0.327	7,12	0,618	7,57	0,659	8,47	0,524	8,28	0,445
11	7,13	0,674	6,57	0,258	6,45	0,423	7,05	0,572	7,42	0,665	8,32	0,471	8,22	0,407
Layer no. / Sloj	b*	s	b*	s	b*	s	b*	s	b*	s	b*	s	b*	s
1	14,07	0,308	14,77	0,280	14,42	0,343	14,57	0,356	14,35	0,327	14,30	0.310	14,22	0,519
2	14,05	0,207	14,63	0,463	14,67	0,468	14,68	0,560	14,42	0,504	14,50	0,374	14,38	0,483
3	14,05	0,217	14,73	0,501	14,88	0,445	14,95	0,718	14,67	0,557	14,83	0,432	14,52	0,471
4	14,02	0,306	14,70	0.374	14,88	0,392	14,97	0,528	14,73	0,418	14,90	0,245	14,63	0,547
5	13,97	0,418	14,67	0,393	14,92	0,479	14,72	0,659	14,77	0,403	14,93	0,372	14,58	0,479
6	14,10	0,506	14,68	0,397	14,97	0,472	14,97	0,554	14,77	0,427	15,03	0,403	14,63	0,403
7	14,15	0,554	14,73	0,378	15,02	0,436	14,97	0,585	14,70	0,456	15,07	0,565	14,62	0,412
7	14,18	0,585	14,67	0,450	15,03	0,446	14,95	0,476	14,62	0,621	14,95	0,521	14,60	0,540
8	14,22	0,665	14,57	0,378	14,97	0,520	14,82	0,646	14,45	0,616	14,72	0,578	14,45	0,575
10	14,13	0,427	14,70	0,460	14,92	0,449	14,88	0,652	14,50	0,610	14,63	0,585	14,43	0,635
11	14,18	0,382	14,68	0,560	14,87	0,437	14,82	0,668	14,67	0,489	14,70	0,629	14,45	0,650

Table 1

Average colourimetric values (lightness L^*, red-green a^* and yellow-blue coordinate b^*) and st. deviations (s) of layers from surface (layer 1) to core (layer 11) at average moisture content (u) of beech wood dried at constant temperature (T = 20° C) and relative humidity (φ_1 = 33 %). • Prosječne kolorimetrijske vrijednosti (svjetloća L^*, crveno-zelena a^* i žuto-plava koordinata b^*) i standardne devijacije (s) slojeva od površine (sloj 1) do sredine uzorka (sloj 11) pri prosječnom sadržaju vode (u) bukovine sušene pri stalnoj temperaturi (T = 20 °C) i relativnoj vlažnosti zraka (φ_1 = 33%).

ence (ΔE^*) was found to be the most suitable parameter comparable also to visual assessment (Fig. 5). With high MC values, total colour difference was lower and uniformly spread over the entire cross section of the board. In the case of drying below cell wall saturation point, colour values of the surface layers remained unchanged, while exactly during the same period the greatest colour changes occurred in the core. When the MC dropped below 20%, colour values did not change any more.

4.2. DISCOLOURATION OF BEECHWOOD DRYED AT A TEMPERATURE OF 20°C AND RELATIVE HUMIDITY OF 65%

4.2. Diskoloracije bukovine pri sušenju na temperaturi 20°C i relativnoj vlažnosti zraka 65%

During the drying process carried out at higher relative air humidity (φ_2 = 65%), lightness (L^*) decreased right at the beginning of the drying both on the surface and in the core (Tab. 2 and Fig. 6). By the time the average MC reached 43.3%, more rapid darkening of surface layers was already observed (L^* = 77 of green wood condition dropped to L^* = 68). On the other hand, lightness in this MC range decreased in core layers to a slightly lesser degree (from L^* = 77 to L^* = 73). The colour of sufficiently dried surface subsequently did not change any more. But lightness changes in the core of the board in the MC range between 43% and 26% was of greatest intensity and rapidity.

Pronounced red component (a^*) on red-green axis was characteristic for surface layers in the initial stage of drying; in the case of relatively high MC (43%) it increased by the factor 2 (Fig. 7). During that time colour difference on yellow-blue axis in the core of the board was not yet characteristic, but one could observe rapid accentuation of the red axis associated with slightly lower MC values. The greatest and most rapid changes in a^* component were observed in MC range between 43,3 and 28%.

As drying with the relative air humidity of 33%, the drying at relative air humidity of 65% showed variations in values on yellow-blue axis (b^*), both in cross section and in so far dependent on MC and drying time,

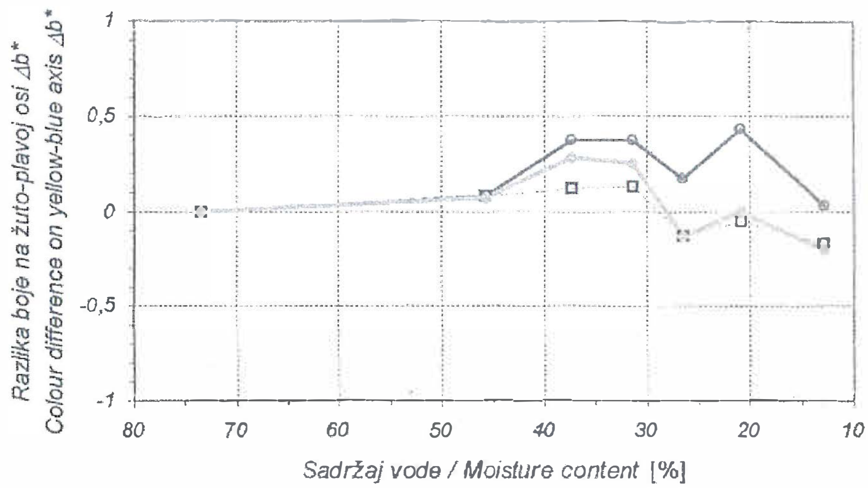

Figure 4
Colour difference on yellow-blue coordinate (Δb^*) of different layers (just below suface – layer 1; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature (T = 20° C) and relative humidity (φ_1 = 33 %) (leg. see fig. 3). ● *Razlike boje na žuto-plavoj koordinati (Δb^*) različitih slojeva (podpovršinski sloj = sloj 1; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi (T = 20 °C) i relativnoj vlažnosti zraka (φ_1 = 33%) (za legendu vidi sl. 3).*

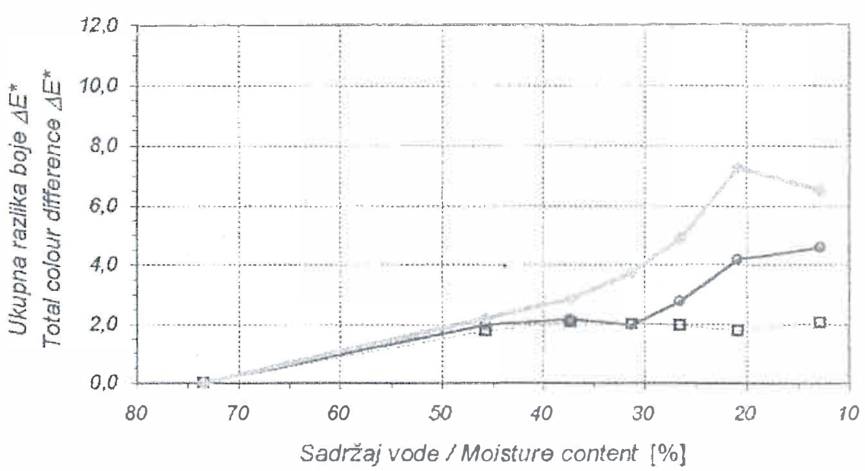

Figure 5
Total colour difference (ΔE^*) of different layers (just below suface – layer 1; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature (T = 20° C) and relative humidity (φ_1 = 33 %) (leg. see fig. 3). ● *Ukupne razlike boje (ΔE^*) različitih slojeva (podpovršinski sloj = sloj 1; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi (T = 20 °C) i relativnoj vlažnosti zraka (φ_1 = 33%) (za legendu vidi sl. 3).*

which were primarily due to the influence of the variability of wood structure and did not show any characteristic deviations (Fig. 8).

Total colour difference (ΔE^*) of the surface was already detected at the beginning of the drying process. At that time, total colour difference of moisture saturated core was not yet critical, but it increased very much in the range of cell wall saturation up to MC 28%, where the greatest deviations were observed (Fig. 9).

Table 2
Average colourimetric values (lightness L^*, red-green a^* and yellow-blue coordinate b^*) and st. deviations (s) of layers from surface (layer 1) to core (layer 11) at average moisture content (u) of beech wood dried at constant temperature ($T = 20^oC$) and relative humidity ($\varphi_2 = 65$ %). • *Prosječne kolorimetrijske vrijednosti (svjetloća L^*, crveno-zelena a^* i žuto-plava koordinata b^*) i standardne devijacije (s) slojeva od površine (sloj 1) do sredine uzorka (sloj 11) pri prosječnom sadržaju vode (u) bukovine sušene pri stalnoj temperaturi ($T = 20\ ^oC$) i relativnoj vlažnosti zraka ($\varphi_2 = 65$%).*

t[dana/ days]	0		14		20		28		48		76	
u [%]	77,9		43,3		37,5		32,1		26,5		19,1	
Layer no. / Sloj	L*	s	L*	s	L*	s	L*	s	L*	s	L*	s
1	77,0	1,78	67,8	1,14	68,6	1,21	69,1	2,24	69,7	2,27	69,4	2,31
2	77,6	1,47	69,5	0,98	70,0	2,06	70,6	2,53	71,8	2,59	71,1	1,77
3	77,4	1,36	71,2	1,36	71,0	2,32	72,0	1,31	71,8	2,70	70,5	1,73
4	77,4	1,56	71,7	1,13	71,0	2,30	72,3	1,23	71,4	2,79	69,8	2,45
5	77,6	1,45	72,0	1,53	71,5	2,22	72,4	1,60	71,0	2,86	69,5	3,21
6	77,7	1,42	72,4	1,58	71,9	1,93	72,0	1,72	70,3	2,86	69,7	3,64
7	77,7	1,39	72,9	1,37	72,1	1,62	71,5	2,16	69,6	2,66	68,9	3,66
7	77,6	1,37	73,5	1,25	72,1	2,32	71,4	2,45	68,7	2,07	68,2	3,14
8	77,6	1,60	73,6	1,18	72,2	1,94	70,8	2,36	68,0	1,69	67,7	2,81
10	77,7	1,53	73,7	1,32	72,3	1,84	70,6	2,22	67,2	0,96	67,7	2,50
11	77,7	1,57	73,6	1,47	72,2	2,16	70,07	2,11	67,2	1,07	67,9	2,54

Layer no. / Sloj	a*	s	a*	s	a*	s	a*	s	a*	s	a*	s
1	6,20	0,729	8,47	0,493	8,30	0,329	8,25	0,797	7,93	0,437	7,90	0,443
2	6,28	0,679	7,85	0,399	7,82	0,725	7,87	1,102	7,35	0,437	7,60	0,469
3	6,28	0,615	7,33	0,294	7,48	0,655	7,33	0,543	7,23	0,543	7,68	0,483
4	6,38	0,796	7,38	0,223	7,65	0,644	7,30	0,316	7,52	0,621	7,92	0,564
5	6,30	0,651	7,33	0,361	7,60	0,769	7,28	0,349	7,62	0,601	7,95	0,734
6	6,28	0,574	7,33	0,393	7,63	0,671	7,50	0,335	7,88	0,527	7,97	0,848
7	6,33	0,665	7,18	0,331	7,57	0,599	7,52	0,512	8,03	0,398	8,17	0,819
7	6,32	0,643	6,95	0,259	7,43	0,650	7,45	0,442	8,05	0,442	8,13	0,606
8	6,32	0,665	6,97	0,294	7,43	0,388	7,63	0,476	8,37	0,361	8,38	0,449
10	6,30	0,607	6,95	0,226	7,45	0,339	7,65	0,446	8,50	0,452	8,37	0,427
11	6,37	0,695	7,03	0,308	7,43	0,234	7,73	0,472	8,55	0,550	8,35	0,539

Layer no. / Sloj	b*	s	b*	s	b*	s	b*	s	b*	s	b*	s
1	14,15	0,356	14,52	0,655	14,57	0,372	14,53	0,468	14,28	0,640	14,27	0,137
2	14,45	0,295	14,33	0,403	14,42	0,534	14,82	0,842	14,37	0,356	14,52	0,306
3	14,57	0,393	13,98	0,331	14,27	0,450	14,38	0,360	14,28	0,264	14,58	0,271
4	14,50	0,525	14,10	0,438	14,58	0,397	14,40	0,358	14,48	0,462	14,70	0,290
5	14,43	0,568	14,10	0,335	14,62	0,649	14,37	0,327	14,48	0,412	14,65	0,432
6	14,43	0,582	14,32	0,354	14,70	0,675	14,62	0,483	14,62	0,578	14,68	0,512
7	14,47	0,547	14,33	0,314	14,68	0,605	14,53	0,596	14,62	0,646	14,70	0,518
7	14,38	0,496	14,12	0,256	14,52	0,714	14,45	0,692	14,52	0,747	14,45	0,635
8	14,45	0,547	14,00	0,237	14,52	0,564	14,42	0,662	14,60	0,792	14,63	0,550
10	14,37	0,602	13,97	0,137	14,43	0,568	14,30	0,713	14,62	0,906	14,53	0,513
11	14,45	0,683	14,07	0,186	14,33	0,641	14,45	0,779	14,53	0,747	14,57	0,388

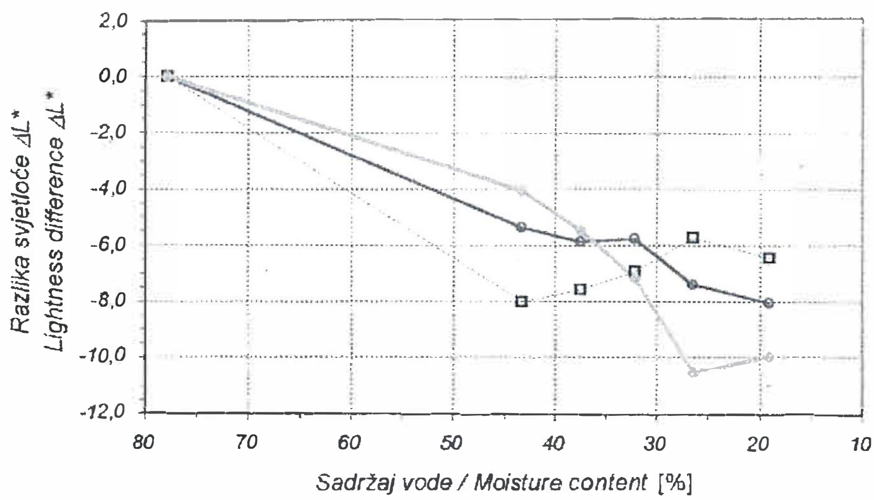

Figure 6
Lightness difference (ΔL^*) of different layers (just below suface – layer 2; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature ($T = 20^o$ C) and relative humidity ($\varphi_2 = 65$ %) (leg. see fig. 3). • *Razlike svjetloće (ΔL^*) različitih slojeva (podpovršinski sloj = sloj 2; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi ($T = 20\ ^oC$) i relativnoj vlažnosti zraka ($\varphi_2 = 65$%) (za legendu vidi sl. 3).*

5. DISCUSSION
5. Diskusija

The results of the numerical analysis of discolouration during the drying process confirmed the assumption that the duration and intensity of discolouration are influenced by several factors at the same time. In spite of the relatively low temperature at which the experiment was carried out, our experiment also confirmed the existence of a considerable influence of the duration and rate of drying as well as of wood MC on colour changes in wood.

The changes in lightness (ΔL^*), red-green component (a^*) and total colour difference (ΔE^*) were found to be suitable colourimetric parameters for the evaluating of discolourations during the drying process. On the other hand deviations on blue-yellow axis (b^*) and those regarding colour hue (ΔH^*), were found to be insignificant.

Slower and longer drying at higher relative air humidity (65%) led to greater and more intense discolouration. Darkening, or change in lightness (ΔL^*), of the surface of specimens which dried more slowly was comparable to the darkening of the core of the specimens which dried more rapidly (change in lightness in both cases dropped by approx. 6). The process can be ascribed to identical drying rate. Over an identical period of time, the core of boards of the former group was subject to more intense staining ($\Delta L^* \approx 10$). A similar effect of the rate of drying on discolouration is also confirmed by total colour difference ($\Delta E^*>10$), where similar trends are observed as in the case of lightness. Total colour difference on the surface of specimens which dried quicker was three times lower than that observed on the surface of specimens which dried over a longer period of time. Twice greater total colour difference was observed in the core of the said specimens. Lightness differences (ΔL^*) and total colour differences (ΔE^*) increased with the duration of drying.

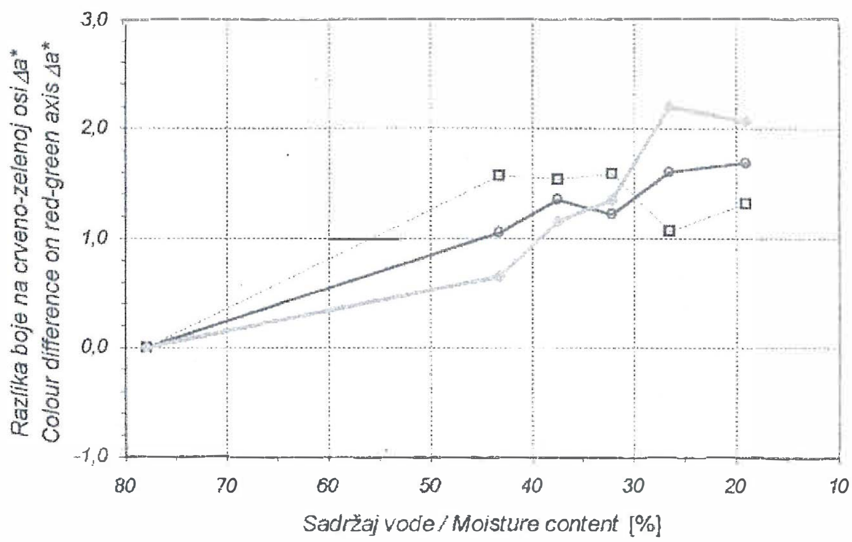

Figure 7 *Colour difference on red-green coordinate (Δa^*) of different layers (just below suface – layer 2; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature ($T = 20^{\circ}C$) and relative humidity ($\varphi_2 = 65$ %) (leg. see fig. 3). • Razlike boje na crveno-zelenoj koordinati (Δa^*) različitih slojeva (podpovršinski sloj = sloj 2; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi ($T = 20\ ^{\circ}C$) i relativnoj vlažnosti zraka ($\varphi_2 = 65\%$) (za legendu vidi sl. 3).*

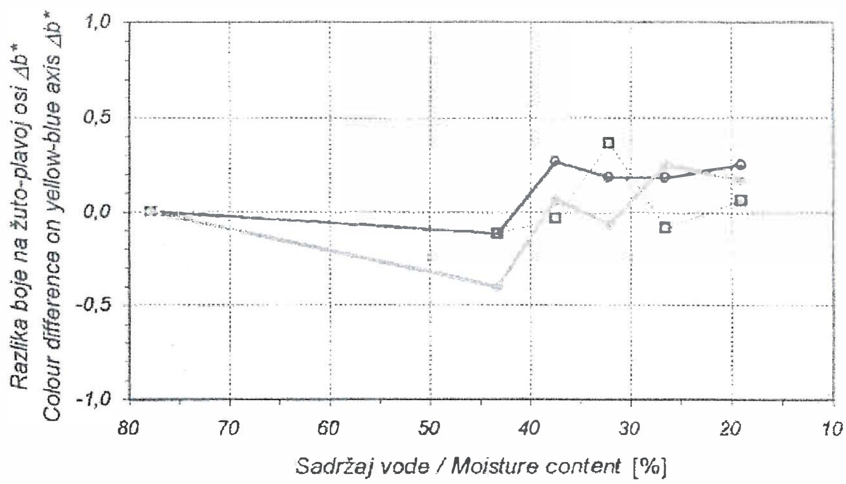

Figure 8 *Colour difference on yellow-blue coordinate (Δb^*) of different layers (just below suface – layer 2; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature ($T = 20^{\circ}C$) and relative humidity ($\varphi_2 = 65$ %) (leg. see fig. 3). • Razlike boje na žuto-plavoj koordinati (Δb^*) različitih slojeva (podpovršinski sloj = sloj 2; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi ($T = 20\ ^{\circ}C$) i relativnoj vlažnosti zraka ($\varphi_2 = 65\%$) (za legendu vidi sl. 3).*

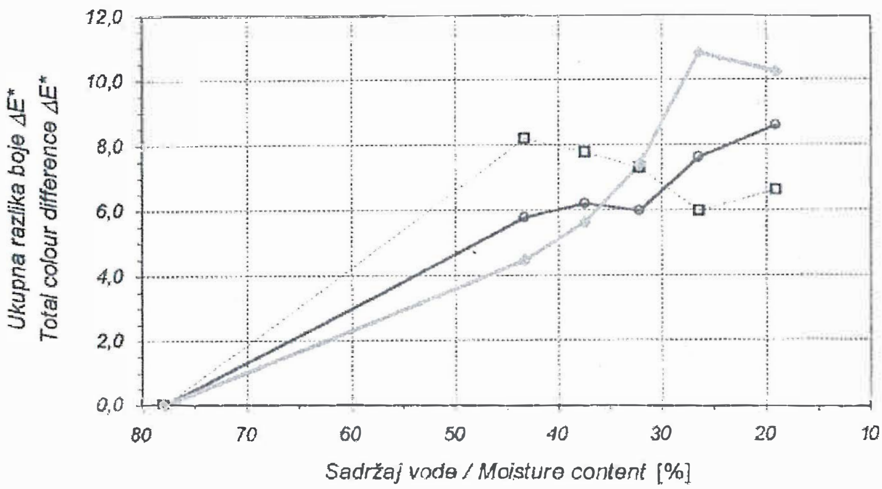

Figure 9
Total colour difference (ΔE^*) of different layers (just below suface – layer 1; at 1/3 depth – layer 6; at the core – layer 10) of beech wood dried at constant temperature (T = 20° C) and relative humidity (φ_2 = 65 %) (leg. see fig. 2). • *Ukupne razlike boje (ΔE^*) različitih slojeva (podpovršinski sloj = sloj 1; na 1/3 dubine = sloj 6; središnjica = sloj 10) bukovine sušene pri stalnoj temperaturi (T = 20 °C) i relativnoj vlažnosti zraka (φ_2 = 65%) (za legendu vidi sl. 2).*

Maintaining of high MC of green beechwood prevents discolouration (Charrier, et al. 1992), and this can be seen in the case of the slower drying process (relative air humidity φ_2 = 65%), where such a condition was ensured at the beginning of the drying process in the core of the boards. During that time, the surface of those boards was already stained due to a slow decrease in MC below the fiber saturation point. After slow drying in the so called second period, in the somewhat larger range of fiber saturation, most rapid and greatest changes in colourimetric values were observed. If we compare the discolouration in the drying process with the formation of red heartwood in a tree (Torelli 1974, 1984, Bauch 1984, Bauch et al. 1991), it is precisely in this MC range that the ratio between gases and water in lumens enables a sufficient partial pressure of O_2 required for oxidation processes creating discoloration.

In the case of quicker drying (relative air humidity φ_1= 33%), the layers just below the surface were not subject to staining because the drying time in the critical interval (between MC 43 and MC 22%) was sufficiently short, and discolouration could not take place. A somewhat greater deviation on the surface itself (layer 1) was due to the surface levelling, which was not ideal for initial measurements, and was also due to the effect of light on the surface during the carrying out of the experiment. A more detailed analysis of deviations of the first layer was not effected because the outermost layer is not important in practical terms, for it was removed already by the first levelling. In the case of slower drying of the core, instances of discolouration occurred when MC in the core section of the board started to fall below 43%. When MC was 22%, maximum differences between colourimetric parameters were obtained, and with further decrease in MC this did not change any more.

The red component parameter also changed within the same time and MC intervals within which lightness and total colour difference changed. This indicates a probability of formation of substances colouring the wood red. Changes on the blue-green axis are not correlated with wood MC, the duration and the rate of drying.

Due to mathematical relations between colourimetric parameters, change in colour hue (ΔH^*) is in agreement with the change on the blue-yellow axis, and the change of colour saturation (ΔC^*) with that on the red-green axis.

6. CONCLUSIONS
6. Zaključci

The study showed that numerical colour evaluation can be used to assess, in an objective and accurate manner, the discolouration of wood during the drying process. The discolouration on beechwood occured although when the drying temperature was low (T = 20 °C). Among the colourimetric parameters, the most marked changes concern lightness (ΔL^*), red-green component (a^*) and total colour difference (ΔE^*). Deviations on the blue-yellow axis (b^*) and those regarding colour hue (ΔH^*) are insignificant.

In the case of accelerated drying in a climate with lower relative air humidity (φ_1 = 33%), changes in colourimetric parameters are smaller than in the case of slower drying (φ_2= 65%). The magnitude of colour change increases with the duration of drying This explains why colour differences increase in the direction from the quicker drying surface towards the core section of the board.

In the wider range of cell wall saturation (MC 43 to 22%), changes in lightness (ΔL^*), total colour difference (ΔE^*) and components on the red-green axis(a^*) are significant, because this range is considered to be the critical interval within the drying process, and coincides with critical MC at which diffusion resistance occurs, with the highest possibility of occurrence of mechanical defects (cracks) (Gorišek, 1992).

At lower temperatures, discolouration can be prevented or at least rendered less pronounced by maintaining wood at a high MC level (above 50%), or by drying it as quickly as possible to the MC level which ensures that discolouration would not take place.

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