Todd F Shupe
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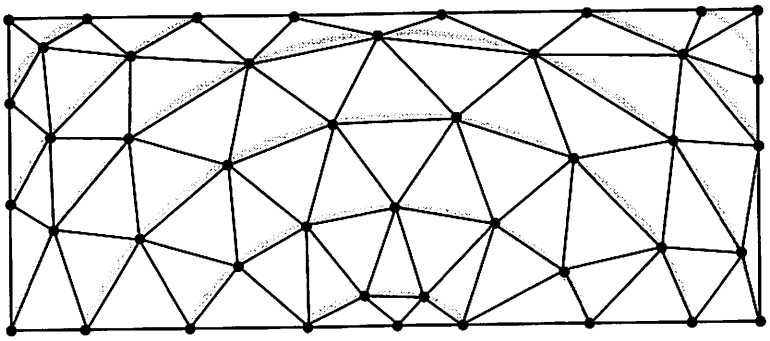
5th INTERNATIONAL IUFRO WOOD DRYING CONFERENCE

Quality Wood Drying Through Process Modelling and Novel Technologies



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Proceedings of the

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Effect of Steaming and Hot-water Soaking on the Movement of Moisture in Hardwoods During Drying

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ABSTRACT

Samples of six hardwood species were steamed in the green condition or near the fiber saturation point at 100° C or soaked in hot-water at 70° C. In phase 1, the samples were dried at 45° C and 97 % relative humidity from a near saturated condition to near the fiber saturation point. In phase 2, samples were dried at 45° C and 30 % relative humidity to the final equilibrium moisture content. Steaming and hot-water soaking treatments improved the movement of moisture in the free-water range as well as in the hygroscopic range. Hot-water soaking for 10 hours was as effective to increase drying rate as steaming in the green condition for 5 hours. The improvement in moisture movement during drying was due to the redistribution of the water-soluble extractives in wood, which increases the accessibility of water in the cell walls.

INTRODUCTION

A common goal of research in hardwood drying is to reduce the drying times with minimal degradation. The attempt to advance drying technology by optimizing process variables such as temperature, relative humidity, and air velocity has not been as effective for refractory hardwoods. To help attain this goal, the blockage of the moisture passageways, within wood must be minimized through treatment.

Steaming is one of several predrying treatment techniques that has been used to open the moisture passageways and increase the drying rate of wood. Steaming has been reported by Mackay (1971) to increase the diffusivity of two Australian hardwoods by 10 to 12 % in the green condition, and by 30 to 40 % at 22 % moisture content (MC). Steaming also has been reported by several researchers to decrease the drying time (Ellwood and Erickson 1962, Kininmonth 1971) and increase drying rate (Sharma and Bali 1969, Simpson 1975, Alexiou et al. 1990) in wood. However, the effect of steaming on the drying rate depends on the species. Simpson (1975) reported that among four species investigated, oaks (*Quercus* sp.) responded the most favorable.

Removal or redistribution of water-soluble extractives has been considered among the likely reasons for the increases in drying rate. Kininmonth (1971) showed that steaming changed the continuous layer of extractives lining the cell lumina and pit membrane in a New Zealand hardwood (*Nothofagus fusca*) into a generally discontinuous layer, which appeared cracked and blistered. Alexious et al. (1990) described a similar effect of steaming on regrown *Eucalyptus*. Chen and Workman (1980) reported that steaming black walnut (*Juglans nigra* L.) heartwood partially reduced its extractive content, since the condensed water always showed a black color. Simpson (1975) reported that steaming sweetgum (*Liuqidambar styraciflua* L.) heartwood resulted in an increase in the drying rate by about 20 to 30 %, while steaming sweetgum sapwood had no beneficial effect. Sweetgum heartwood, which has a considerable amount of polymeric phenolic glycosides, is relatively impermeable (Rowe and Conner 1979), and steaming may remove some polymers.

Simpson (1975) urged caution when interpreting the effects of steaming since the temperature of the steamed samples is usually higher than that of the unsteamed samples, and the moisture contents of steamed and unsteamed samples may be different before drying. Therefore, for comparative purposes, the experiment

should be designed to minimize variation due to temperature and MC.

Hot-water soaking is a direct method of removing the water-soluble extractives from wood. Like steaming, hot-water soaking also partially hydrolyzes some of the cell wall substances, such as hemicelluloses (Rowe and Conner 1979). Hot-water extraction increases not only the permeability of southern pine (*Pinus* sp.) (Fogg 1968) but also the shrinkage and equilibrium moisture content of most domestic and tropical woods (Nearn 1955, Choong and Achmadi 1991). However, Shupe et al. (1996) found no significant difference between the shrinkage of extracted and nonextracted sweetgum.

There is no literature describing the effect of hot-water soaking on drying of of North American hardwoods. Therefore, the objective of this study was to determine the effect of steaming and hot-water soaking treatments on moisture movement above and below the fiber saturation point (FSP) in six hardwood species.

EXPERIMENTAL PROCEDURE

The heartwood of white oak (*Quercus alba* L.), Southern red oak (*Quercus falcata* Michx.), American elm (*Ulmus almericana* L.), sweetgum (*Liquidambar styraciflua* L.), black willow (*Salix nigra* Marsh.), and Eastern cottonwood (*Populus deltoides* Bartr. ex Marsh) was selected for this study based on anatomical structure, commercial importance, and their relatively slow drying rate. Movement of moisture during drying was restricted to one of the three structural dimensions of wood, i.e., longitudinal, tangential, or radial. The five treatments were:

A) Control,
B) Steaming in the green condition for 1 hour at 100° C,
C) Steaming in the green condition for 5 hours at 100° C,
D) Hot-water soaking for 10 hours at 70° C, and
E) Steaming near the FSP for 1 hour at 100° C.

The samples were dried in two phases: phase 1 -- drying in the free water range, from a near saturated condition to near the FSP; and phase 2 -- drying in the hygroscopic range, from near the FSP to the final equilibrium moisture content (EMC). Samples undergoing treatment E were dried only in the hygroscopic range, since their MCs were already near the FSP. A completely randomized design with two replications each was applied in this study.

All sample boards were obtained in the green condition from a local sawmill. For each treatment assigned to a particular species, two flat-sawn boards about 5 cm thick and 20 cm wide were selected. They were cut into 2-meter long sections, wrapped with Visqueen plastic sheet, and then stored in a cold room at 4.44 °C.

From each board, a randomly selected sample with nominal dimensions of 2.5 cm x 2.5 cm x 2.0 cm was obtained. To ensure that moisture movement followed the true structural dimensions (i.e., radial, tangential, and longitudinal), an adjusting miter gauge was used to determine the cutting direction.

After cutting, the samples were submerged in water to maintain their green condition. For the steaming treatments, samples were randomly chosen from each corresponding group and placed inside a small pressure retort. High pressure steam generated in an electric steam boiler was continuously released into the retort. Hot-water soaking was done in a thermostatically-controlled water container equipped with a stirrer.

After treatment, all samples, except those receiving treatment E, were subjected to a periodic vacuum at 56-cm Hg for 1 hour while submerged in water before released to atmospheric pressure. This process was carried out three times per day, and the interval from the end of pressure recovery to the beginning of the next vacuum was never less than 2 hours. After 10 days, only a few bubbles could be observed on the samples under the vacuum; therefore, the samples were considered to be saturated. The samples were then coated with a waterproof polymer resin (Dow's Saran F-120) on the four 2.5 cm x 2.0 cm faces to provide a uni-directional movement of moisture. After coating, the samples were again submerged inside desiccators in water to keep them saturated.

In Phase 1 (drying above the FSP), an Aminco environmental chamber was adjusted to 45° C and 97 % relative humidity (RH), corresponding to a nominal 25 % EMC. The air velocity in the drying chamber was maintained at approximately 2 m/s. The samples were divided into two subgroups because the Aminco chamber was not large enough to accommodate all the samples at

one time. After the samples in the first subgroup had been dried to near the FSP, they were taken from the Aminco chamber to a Blue-M chamber set to the same conditions, so that the samples in the second subgroup could be placed in the Aminco chamber. Thus, the Blue-M was used to keep the samples in a "holding" condition of about 25 % EMC until they were ready for Phase 2. After the samples in the second subgroup had been dried to near the FSP, the samples for treatment E were steamed in the pressure retort before they were coated with Dow's Saran F-120 resin.

In Phase 2 (drying below the FSP), the drying conditions in the Aminco chamber were adjusted to 45 °C and 30 % RH, corresponding to a nominal 6 % EMC. After the samples had been dried to the final EMC, they were oven-dried in a Supermate oven at 103 °C for 3 days before determining their MCs.

The average diffusion coefficient, D, was calculated from Equation 1, the theoretical solution of Fick's second law, under equilibrium boundary condition, using the optimization method described by Chen et al. (1994):

$$E = \left(8/\pi^2\right)\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}e^{-\left(\frac{2n-1}{2L}\right)^2\pi^2 Dt} \qquad (1)$$

where E is the fraction of evaporable moisture present in wood, L is the half-thickness of the sample, and t is the drying time. This equation assumes that the diffusion coefficient is a constant, and the value E at the surface immediately drops to zero when drying begins. In this method, the best values of D could be searched to derive a theoretical drying curve that best fits the experimental data based on the least squares principle. A statistical analysis was performed separately for both drying phases.

RESULTS AND DISCUSSION

Phase 1 (drying above the FSP)

The average diffusion coefficient in each direction-treatment-species combination is given in Table 1. An analysis of variance for the diffusion coefficients (Table 2) shows that the treatment effect was significant, but that it was not as large as the effect of direction or species. Since the F value of the treatments is one order higher than that of treatment*species interaction, the treatment effect was generally the same for all directions and species. The result of pair-wise t-tests (LSD) for treatments (Table 3) indicates that all the predrying treatments increased the diffusion coefficients. Treatments C and D did not show any difference, but they were more effective than treatment B.

Steaming before drying should open the passageways for capillary movement in wood. Since the samples were soaked in water after steaming, the differences in initial temperature and MC between the untreated control and the steamed samples were minimized. The effect of steaming is mainly due to the redistribution of blocking substances from wood and to the distortion of materials lining the cell lumina and pit areas (Kininmonth 1971, Kubinsky 1971, Alexiou et al. 1990). The process of rearranging the blocking substances can be time consuming. Steaming for 1 hour for the size of the samples in this study may not be long enough to fully open all passageways.

Partially removing the hot-water soluble extractives and effectively rearranging them in the wood during the relatively long treating period are two possible explanations for the better performance of treatment D than treatment B. Since the samples came in direct contact with hot-water, the water-soluble extractives could diffuse into the surrounding water under a concentration gradient. However, not all the hot-water soluble extractives could be removed from the samples by soaking in circulating hot-water for 10 hours; therefore, redistribution of the extractives also contributed to the increase in the diffusion coefficients. Some species showed a better response to hot-water soaking than steaming. As shown in Table 1, the average diffusion coefficient of hot-water soaking for Southern red oak was higher than that for steaming. This also accounts for the significant effect of treatment*species interaction (Table 2).

Phase 2 (drying below the FSP)

The average diffusion coefficients in each direction, treatment, and species combination are given in Table 4. An AOV for the diffusion coefficients (Table 5) shows that the treatment effect was significant, although it was not as large as the effect of direction or species. Since its F value is at least one order higher than those of treatment*direction and treatment*species interactions, the treatment effect also tends to be the same for all directions and species. There is a significant treatment*direction

interaction ($P < 0.05$), which arises, as indicated in Table 4, from the fact that the increase of the average diffusion coefficients by various predrying treatments in the longitudinal direction is larger than that in either the radial or tangential direction.

The results of the pair-wise t-tests (LSD) for treatments are given in Table 3. Except for Treatment B, all other predrying treatments resulted in a significant increase in the diffusion coefficients. The t-tests do not show any difference of effects among treatments C,D, and E. It also does not show a difference between treatments A and B. In 15 tropical woods from Indonesia, Choong et al. (1996) reported that more species responded to steaming than to hot-water soaking.

The increase in the diffusion coefficients by hot-water soaking and steaming in the green condition is not only due to the opening up of capillary passageways but also to the reduction in resistance of moisture moving through the cell walls. Moisture movement below the FSP is a diffusion phenomenon. Choong (1965), through model calculations, showed that the pit openings are important for moisture diffusion only at low MCs, and Siau (1984) indicated that the contribution of the pit openings to diffusion at high MC may be neglected. Therefore, the main resistance to the movement of moisture comes from the cell walls. Soaking and steaming treatments redistributed the water-soluble substances in wood; consequenly, the cell walls became more accessible to water, which facilitated moisture movement.

CONCLUSIONS

Steaming and hot-water soaking treatments improved the movement of moisture during drying above as well as below the FSP. The effectiveness of steaming depended on the length of treatment time. Steaming in the green condition for 5 hours was more effective in increasing the diffusivity than steaming for 1 hour. Steaming in the green condition or near the FSP resulted in similar diffusivitites as for samples dried below the FSP. Hot-water soaking for 10 hours was as effective as steaming in the green condition for 5 hours.

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Table 1. Mean diffusion coefficients of six hardwoods for phase 1 (drying above the fiber saturation point)[1].

Direction	Treatment	S. red oak	White oak	Elm	Sweetgum	Willow	Cottonwood
			---------- x10^{-6} cm^2/s ----------				
Longitudinal	A	0.522	0.445	0.407	0.438	0.332	0.437
	B	0.528	0.454	0.409	0.448	0.341	0.455
	C	0.556	0.477	0.439	0.482	0.356	0.505
	D	0.598	0.480	0.417	0.477	0.362	0.499
Radial	A	0.388	0.324	0.346	0.401	0.273	0.423
	B	0.466	0.346	0.353	0.417	0.281	0.431
	C	0.510	0.371	0.363	0.425	0.319	0.463
	D	0.502	0.377	0.366	0.436	0.299	0.468
Tangential	A	0.378	0.340	0.314	0.391	0.293	0.411
	B	0.442	0.367	0.340	0.418	0.312	0.418
	C	0.458	0.379	0.351	0.433	0.330	0.470
	D	0.490	0.377	0.364	0.439	0.334	0.463

[1]Each value represents the mean of two replications.

Table 2. Analysis of variance of average diffusion coefficients for phase 1 (drying above the fiber saturation point).

Source	DF	MS	F	P
Direction	2	6.507×10^{-2}	224.07	0.001
Treatment	3	1.939×10^{-2}	66.78	0.001
Species	5	8.729×10^{-2}	300.58	0.001
Time[1]	1	6.385×10^{-4}	2.20	0.143
Direction*treatment	6	2.797×10^{-4}	0.96	0.456
Direction*species	10	3.073×10^{-3}	10.58	0.001
Treatment*species	15	8.627×10^{-4}	2.97	0.001
Direction*treatment*species	30	2.258×10^{-4}	0.78	0.775
Error	71	2.904×10^{-4}	--	--

[1]Batch effect of drying samples at different times in the Aminco chamber.

Table 3. Comparison of the effect of treatment on average diffusion coefficients by pairwise t-tests (LSD) at $\alpha = 0.05$.

Drying above the fiber saturation point		
Treatment	Diffusivity (x106 cm^2/s	LSD grouping
A	0.381	C
B	0.401	B
C	0.427	A
D	0.430	A
Drying below the fiber saturation point		
A	8.01	C
B	9.72	BC
C	11.99	A
D	11.57	AB
E	10.10	AB

Table 4. Mean diffusion coefficients of six hardwoods for phase 2 (drying below the fiber saturation point.[1])

Direction	Treatment	Red oak	White oak	Elm	Sweetgum	Willow	Cottonwood
			---------- x10^{-6} cm^2/s ----------				
Longitudinal	A	9.05	8.03	18.97	14.45	15.66	20.35
	B	10.67	10.22	21.59	21.25	20.71	25.30
	C	14.24	11.73	24.11	22.62	26.91	32.94
	D	13.29	10.74	27.58	24.27	24.94	28.25
	E	11.35	9.48	19.25	18.92	17.65	29.98
Radial	A	1.44	2.41	9.11	4.80	9.96	5.46
	B	1.72	2.99	10.38	5.44	11.37	6.38
	C	2.22	3.12	14.80	9.73	10.61	6.99
	D	1.72	2.89	10.77	5.07	15.40	8.33
	E	2.10	2.39	12.13	7.84	11.62	7.99
Tangential	A	1.26	1.36	6.47	4.80	5.91	4.62
	B	1.50	1.55	6.70	4.85	6.86	5.52
	C	1.56	2.63	10.81	5.22	7.23	8.38
	D	2.11	3.75	12.78	4.87	6.35	5.19
	E	1.30	2.75	9.08	4.78	7.41	5.86

[1]Each value represents the mean of two replications.

Table 5. Analysis of variance of average diffusion coefficients for phase 2 (drying below the fiber saturation point).

Source	DF	MS	F	P
Direction	2	3.185×10^3	480.83	0.001
Treatment	4	8.840×10^1	13.35	0.001
Species	5	5.278×10^2	79.68	0.001
Time[1]	1	3.172×10^{-1}	0.05	0.827
Direction*treatment	8	2.170×10^1	3.28	0.003
Direction*species	10	7.862×10^1	11.87	0.001
Treatment*species	20	4.731	0.71	0.802
Direction*treatment*species	40	5.192	0.78	0.803
Error	89	6.624	--	--

[1]Batch effect of drying samples at different times in the Aminco chamber.