Potential sources of variation that influence the final moisture content of kiln-dried hardwood lumber

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Abstract

Excessive variability in the final moisture content (MC) of hardwood lumber may have a significant impact on secondary wood processing and final product performance. Sources of final MC variation during kiln-drying have been studied in prior research. A test examining the final MC of red oak (*Quercus* spp.) and yellow-poplar (*Liriodendron tulipifera*) lumber after kiln-drying was conducted to obtain empirical knowledge of the effects from anatomical structures and lumber thickness. A 2^3 fixed-effects linear statistical model was used to examine MC changes and the effects that growth rate, thickness, and wood type have on MC variability of red oak and yellow-poplar 4/4 lumber during the kiln-drying process. Growth rate was comprised of "fast" and "slow" levels. Lumber thickness had "thin" and "thick" levels, and wood type had heartwood and sapwood levels. The entire experiment was duplicated to improve the inference of experimental results. Variability in the MC of red oak lumber steadily increased during kiln-drying before the equalizing treatment, and was significantly reduced after equalization. This empirical study may suggest that the equalization treatment is an important step in the kiln-drying of red oak lumber. Variability in the MC of yellow-poplar declined during the entire kiln-drying process. There was statistical evidence in the duplicate experiments that suggested that the wood type (heartwood or sapwood) had a significant effect on red oak final MC. There was no statistical evidence to suggest that the three factors studied had an effect on the final MC of yellow-poplar lumber.

The goal of quality control during lumber drying is to reduce final moisture content (MC) variability and prevent drying defects. Wood scientists have studied factors that affect MC variation in lumber during kiln-drying for many years (Smith and Dittman 1960, Culpepper and Wengert 1982, James et al. 1984, Trofatter et al. 1986, Garrahan and Cane 1988, Steele et al. 1990, Boone et al. 1993, Milota et al. 1993, and Armstong 1995). Factors that affect the final moisture of kiln-dried softwood lumber species have been studied extensively (Culpepper and Wengert 1982, James et al. 1984, Milota et al. 1993, and Rice and Shepard 1993). Steele et al. (1990) did a study in hardwood species and presented empirical evidence from the industrial sector on factors that may affect the final moisture of kiln-dried oak lumber. Final MC variability in kiln-dried hardwood lumber outside 6 to 8 percent MC is likely to produce end products that have poor reliability. Capturing sources of variation that affect process outcomes is critical in directing process study and improvement (Leitnaker et al. 1995). The sources of variation in any

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Table 1. — The average thickness for thin and thick boards in each test.

Thickness classification	Red oak		Yellow-poplar	
	Load 01	Load 02	Load 01	Load 02
	- - - - - - - - - - - -	- - - - - (in.) - - - - -	- - - - - - - - - - - -	
Thin board	1.122 (0.0132)[a]	1.119 (0.0106)	1.105 (0.0151)	1.118 (0.0173)
Thick board	1.184 (0.0261)	1.171 (0.0384)	1.154 (0.0164)	1.169 (0.0206)

[a]Values in parentheses are standard deviations.

process can be categorized into raw material variation, equipment variation, measurement variation, method variation, and personal variation. This study focused on material variation and data were gathered on the effects that natural variation in wood anatomical structure and sawing thickness variation have on the final MC of kiln-dried red oak (*Quercus* spp.) and yellow-poplar (*Liriodendron tulipifera*) lumber.[1]

Methods

Two loads (256 board feet [BF] each) of red oak (*Quercus* spp.) and two loads (256 BF each) of yellow-poplar (*Liriodendron tulipifera*) were tested in a 500-BF capacity lab kiln. Freshly sawn 4/4 lumber was procured from two hardwood sawmills in eastern Tennessee that were approximately 40 miles apart. One load was selected for drying during the spring months and the other load was selected for drying during the summer months.

To reduce potential nuisance factors in the experiment, all lumber was cut to uniform widths and lengths (6 in. wide by 8 ft. long) before drying. Drying schedules followed the traditional kiln schedules developed by Boone et al. (1993).[2] All four test loads were equalized at the end of the drying process. The equalizing treatment was designed to reduce the MC variation between boards. Both red oak and yellow-poplar were equalized at 180°F/137°F (dry bulb/ wet bulb temperature) for targeting 7 percent final MC. The EMC at 180°F/ 137°F condition was 5 percent, which was the MC of the driest sample board when the equalizing started. Equalizing stopped when the wettest sample reached the 7 percent target MC. Conditioning was performed if necessary based on Boone et al. (1993).

Experimental design

A three-factor, two-level classical fixed effects linear statistical model was assumed in the experiment (Hinklemann and Kempthorne 1993, Montgomery 2001):

$$y_{ijkm} = \mu + \tau_i + \beta_j + \gamma_k \left(\tau\beta\right)_{ij} + \left(\tau\gamma\right)_{ik} + \left(\beta\gamma\right)_{jk} + \left(\tau\beta\gamma\right)_{ijk} + \varepsilon_{ijkm} \qquad \textbf{[1]}$$

where μ is the overall mean effect; τ_i is the effect of the ith level of the thickness factor A; β_j is the effect of the jth level of type of wood factor B; γ_k is the effect of the kth level of the growth rate factor C; $(\tau\beta)_{ij}$ is the effect of the interaction between τ_i and β_j; $(\tau\gamma)_{ik}$ is the effect of the interaction between τ_i and γ_k; $(\beta\gamma)_{jk}$ is the effect of the interaction between β_j and γ_k; $(\tau\beta\gamma)_{ijk}$ is the effect of the interaction between τ_i, β_j, and γ_k; ε_{ijkm} is a random error component; $i = 1$ or 2 (4/4 lumber thickness < 1.135 in. or ≥ 1.135 in.); $j = 1$ or 2 (heartwood or sapwood lumber); $k = 1$ or 2 (slow: < 5 rings per in.; fast: ≥ 5 rings per in.); $m = 1, 2, 3, \ldots, 7$, (sample size). The entire experiment was duplicated for all factors and levels to strengthen the inference of the results.

Board categorization

The lumber was manually selected from the sawmill green chain and was loaded in the kiln no later than 3 days after selection in order to minimize any air pre-drying nuisance effect. The growth rate was determined by counting the number of rings on the end of each green board. Boards with less than five rings were characterized as "fast" growth and boards with five or more rings were defined as "slow" growth boards. Sapwood/heartwood boards were categorized after visual examination of the color and the ring curvature on the end of every board. Boards with pure heartwood were not easy to obtain. Therefore, boards with more than 60 percent of total volume of the board as heartwood were categorized as heartwood boards for the tests. Sapwood boards were either pure sapwood or more than 80 percent as sapwood. Ten thickness measurements were taken for each board (five measurements per edge) in the longitudinal direction after the boards were edged and trimmed into dimensions of 6 inches wide and 8 feet long. Thin boards were categorized as less than or equal to 1.135 inches in board average thickness (averaged from the 10 measurements on each board) and thick boards were greater than 1.135 inches in average thickness (**Table 1**). The experiment had a balanced design of 8 boards for each category (64 total boards), in which 1 board from each category was used as the sample board in drying process control.

Board stacking and kiln-drying

Stickers were placed uniformly in the stack and each of the 56 test boards was randomly placed throughout the stack. The stack consisted of more than 56 testing boards in order to fill up the kiln (500 BF). Every test board was weighed before stacking. Eight sample boards were used to control the drying schedule and were measured twice a day. It took 4 to 5 days to dry and equalize yellow-poplar boards, and 3 to 4 weeks to dry and equalize red oak boards. Drying was halted before and after the equalization treatment and all of the boards were weighed.

After equalization, the drying process was either stopped or continued by a conditioning treatment depending on the stress test outcome. If the stress test showed any indication of drying stress and tension set (casehardening), the conditioning phase was executed before the drying process was completed. All the boards were weighed again at the end of the process. Two 1-inch-long MC sections were cut 22 inches inside of each end from every board immediately after drying. The MC sections were ovendried at 103°C to determine the MC. The average of the two 1-inch sections from each board was used to estimate the final MC of each test board.

Results and discussion

MC variation

The coefficients of variation (COVs)[3] for the initial MC of red oak were less than the COVs for the initial MC of yel-

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[1] Hardwood lumber that is classified as 4/4 lumber is considered by the hardwood lumber industry to be lumber that has a minimum thickness specification of 1.000 inches.

[2] All MCs were calculated on a dry-weight basis, i.e., (initial weight – ovendry weight)/(ovendry weight).

Table 2. — MCs for two experiments at three stages of the drying process for two loads of red oak (Quercus spp.) and yellow-poplar (Liriodendron tulipifera) boards.[a]

	Initial MC				MC before equalizing				Final MC			
	Red oak		Yellow-poplar		Red oak		Yellow-poplar		Red oak		Yellow-poplar	
	1	2	1	2	1	2	1	2	1	2	1	2
	(%)											
Mean	73.96	87.64	79.28	80.16	7.34	6.48	8.47	9.23	7.28	7.61	5.15	7.50
SD	19.13	13.32	26.59	24.30	2.58	2.07	1.97	2.37	1.85	1.15	1.03	1.68
COV	27.0	15.2	33.5	30.3	35.2	32.0	23.2	25.6	25.3	15.1	19.9	22.3

[a]SD = standard deviation; COV = coefficient of variation.

Table 3. — Analysis of variance for final MC for red oak (Quercus spp.), first experiment.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	*p*-value
A: thickness	.00004903	1	.00004903	.2729	.6038
B: wood type	.00091854	1	.00091854	5.1122	.0283
C: growth rate	.00317104	1	.00317104	17.6488	.0001
AB	.00146473	1	.00146473	8.1521	.0063
BC	.00002445	1	.00002445	.1361	.7139
AC	.00051486	1	.00051486	2.8655	.0970
ABC	.00396145	1	.00396145	22.0479	<.0001
Error	.00862439	48	.00017968		
Total		55			

low-poplar (**Table 2**). The high value of the COVs in the yellow-poplar initial MC was due to a significant difference ($\alpha = 0.05$) between the initial MCs of heartwood and sapwood boards. Yellow-poplar sapwood lumber had an average initial MC greater than 90 percent, while heartwood lumber had an average initial MC less than 70 percent.

The COVs for the MC of red oak at the pre-equalizing stage were higher in both experiments than the COVs for the initial MC (**Table 2**). This difference in the COV may indicate that MC variation in the dried oak boards is a result of the kiln-drying process. The COVs for yellow-poplar MC at the equalizing stage were lower than the initial stage in both experiments. The difference in COVs by species between initial and pre-equalizing MC illustrates the challenges of kiln-drying red oak lumber. The difficulty of kiln-drying red oak lumber has been noted by others (Smith and Dittman 1960).

As expected after equalizing, the COVs for the final MC in both experiments for both species were lower than those at any other stages in the kiln-drying process. The COVs at the final stage were 25.3 and 15.1 percent for red oak, and 19.9 and 22.3 percent for yellow-poplar, compared to the higher values at the pre-equalizing stage of 35.2 and 32 percent for red oak, and 23.2 and 25.6 percent for yellow-poplar (**Table 2**). The MC range for red oak was reduced from 9 and 10 percent at the pre-equalizing stage to 5 and 7 percent after the equalizing treatment. For yellow-poplar, the range was reduced from 12 and 13 percent to 7 and 8 percent by equalizing treatment.

The changes in the COVs between the pre-equalizing and the final MCs for red oak further illustrate the importance of the equalizing stage for red oak lumber. The COV values of red oak for final MC went back to the initial stage, which demonstrated that the equalizing process reduced variation between the red oak boards during kiln-drying. There was a significant difference in the COVs between initial and final MCs for yellow-poplar, i.e., the COVs for the final MC of yellow-poplar were reduced significantly in both experiments. The drying process practiced for yellow-poplar appeared to be effective in reducing the MC variation between heartwood and sapwood lumber since the variation at the initial stage was mainly from the difference between heartwood and sapwood MCs.

Sources of variation

For lumber dried in a commercial kiln, there are additional factors that affect the final MC other than the ones examined in this study. For example, the board location within the stack and the variation in airflow and temperature within the kiln may add variability in the final MC. By doing this study in a small research kiln with good stacking, control, and air flow, we feel that we have reduced some of the variability that is not directly related to the controlled variables and improved the sensitivity of the test to the treatment variables.

Red oak. — There was strong statistical evidence from the duplicate experiments (*p*-value = 0.0283; *p*-value = 0. 0158) that the final MC of red oak was affected by lumber that was classified as either heartwood or sapwood (**Tables 3** and **4**). The final MC of heartwood lumber was significantly higher ($\alpha = 0.05$) than sapwood lumber after kiln-drying (**Tables 5** and **6**). The average final MCs of heartwood boards were 7.8 and 8.0

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[3] The COV is defined as the quotient of the sample standard deviation and sample average. The COV is a useful statistic when the data are subject to varying sample averages that may have a large scale. The COV gives the analyst a statistic for comparing relative variability between factors. The sample standard deviation is affected by the scale of the raw data, which may affect comparison of standard deviations for parameters with large differences in scale.

Table 4. — Analysis of variance for final MC for red oak (Quercus spp.), second experiment.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	*p*-value
A: thickness	.00004420	1	.00004420	.3434	.5606
B: wood type	.00080584	1	.00080584	6.2604	.0158
C: growth rate	.00001112	1	.00001112	.0864	.7701
AB	.00002313	1	.00002313	.1797	.6735
BC	.00011950	1	.00011950	.9284	.4677
AC	.00006899	1	.00006899	.5359	.3401
ABC	.00001503	1	.00001503	.1167	.7341
Error	.00617857	48	.00012872		
Total	.00726485	55			

Table 5. — Final average MC data for red oak (Quercus spp.), first experiment.

	Heartwood		Sapwood	
Growth rate	< 1.13 in. thick	≥ 1.13 in. thick	< 1.13 in. thick	≥ 1.13 in. thick
	- - - - - - - - - - - -	- - - - - - - - (%)	- - - - - - - - - - - -	- - - - - - - -
Slow: < 5 rings/in.	6.33	7.41	6.31	6.07
Fast: ≥ 5 rings/in.	10.26	6.76	6.61	6.52

Table 6. — Final average MC data for red oak (Quercus spp.), second experiment.

	Heartwood		Sapwood	
Growth rate	< 1.13 in. thick	≥ 1.13 in. thick	< 1.13 in. thick	≥ 1.13 in. thick
	- - - - - - - - - - - -	- - - - - - - - (%)	- - - - - - - - - - - -	- - - - - - - -
Slow: < 5 rings/in.	7.97	8.39	6.94	7.32
Fast: ≥ 5 rings/in.	7.71	7.89	7.47	7.19

percent for the first and second load test, and they were 6.8 and 7.2 percent for the sapwood boards in the first and second load tests. Approximately 1 percent MC difference between heartwood and sapwood boards occurred after drying. This MC difference may be caused by the difference in the anatomical characteristics of heartwood and sapwood. Heartwood tends to dry slower than sapwood due to some depositions formed in the vessels during the transition from sapwood to heartwood (Hoadley 1980). The difference in final MC between heartwood and sapwood boards may reduce with the time of equalization. The time required to equalize red oak will be dependant on the variation and amount of heartwood and sapwood, and this is why equalization times can be so varied in red oak.

Variations in board thickness after cutting have been found to be a substantial problem in the sawmill industry. The presence of a couple of thick boards in one kiln stack can adversely affect all of the pieces in the stack (Brown 1982). The effect from lumber thickness variation on final MCs is of more interest to both primary and secondary wood manufacturers. The focus of this research was to investigate the effect of between-board thickness variation on final MC.

Two levels of board thickness (thin/thick) were examined for the effect on the final MC. Results from the two red oak experiments showed no statistical significant effect (**Tables 3** and **4**). In the first drying experiment of red oak lumber, the result of the individual effects of wood type (p-value = 0.0283) and growth rate (p-value = 0.0001) was confounded by the significance of the interaction of thickness and wood type (**Table 3**). The interaction of thickness, wood type, and growth rate was also significant (p-value < 0.0001) (**Table 3**). These interactions were not significant in the second experiment (**Table 4**). Only the main effect of wood type was statistically significant (p-value = 0.0150) in the second red oak experiment. The inconsistent results of the red oak experiments may indicate some of the problems in controlling MC variability in kiln-drying red oak (*Quercus* spp.) lumber. Due to anatomical structure and density, it is more difficult to move moisture through red oak than many other species. In addition, red oak has a great range of property variability. More long-term experiments on red oak may be required to improve the science of drying red oak lumber. Future experiments may also examine traditional control strategies for drying red oak lumber.

Yellow-poplar. — The results of the study were more consistent for yellow-poplar lumber (**Tables 7** and **8**). There was a lack of statistical evidence to suggest that any of the factors studied had a significant effect on the final MC of yellow-poplar lumber. The initial MCs of heartwood and sapwood were significantly different, but the final MCs were not significantly different (**Tables 9** and **10**), which may indicate that there is no benefit to be gained by sorting poplar based on heartwood or sapwood before the drying process.

Conclusions

The COVs in MCs for red oak and yellow-poplar were different during the kiln-drying process. For red oak, higher COV values at the pre-equalizing stage relative to the COVs at the initial stage indicated that variability between red oak board MCs increased at a certain stage during the kiln-drying process. A significant reduction in the COVs for the final MC of red oak lumber after equalizing illustrates the importance of this step when drying red oak. The COVs of yellow-poplar MC were significantly reduced throughout the entire drying process.

There was statistical evidence to suggest that the final MC of red oak lumber was affected by its classification as either heartwood or sapwood lumber. The final MC of heartwood lumber was significantly higher than sapwood lumber after kiln-drying. The second kiln-dry-

Table 7. — Analysis of variance for final MC for yellow-poplar (Liriodendron tulipifera), first experiment.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	*p*-value
A: thickness	.00030504	1	.00030504	3.0657	.0863
B: wood type	.00005149	1	.00005149	.5175	.4754
C: growth rate	.00007383	1	.00007383	.7420	.3933
AB	.00006069	1	.00006069	.6100	.4386
BC	.00029762	1	.00029762	2.9911	.1803
AC	.00018397	1	.00018397	1.8489	.0901
ABC	.00004884	1	.00004884	.4909	.4869
Error	.00477609	48	.00009952		
Total	.00579759	55			

Table 8. — Analysis of variance for final MC for yellow-poplar (Liriodendron tulipifera), second experiment.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F	*p*-value
A: thickness	.00000138	1	.00000138	.0046	.9461
B: wood type	.00008257	1	.00008257	.2757	.6019
C: growth rate	.00000186	1	.00000186	.0062	.9375
AB	.00025118	1	.00025118	.8388	.3643
BC	.00038903	1	.00038903	1.2991	.3003
AC	.00032835	1	.00032835	1.0965	.2600
ABC	.00000618	1	.00000618	.0206	.8864
Error	.01437416	48	.00029946		
Total	.01543470	55			

Table 9. — Final average MC data for yellow-poplar (Liriodendron tulipifera), first experiment.

	Heartwood		Sapwood	
Growth rate	< 1.13 in. thick	≥ 1.13 in. thick	< 1.13 in. thick	≥ 1.13 in. thick
	- - - - - - - - - - - -	- - - - - - - - - - - - (%)	- - - - - - - - - - - -	- - - - - - - - - - - -
Slow: < 5 rings/in.	4.79	6.01	4.92	5.35
Fast: ≥ 5 rings/in.	4.65	4.79	5.32	5.41

Table 10. — Final average MC data for yellow-poplar (Liriodendron tulipifera), second experiment.

	Heartwood		Sapwood	
Growth rate	< 1.13 in. thick	≥ 1.13 in. thick	< 1.13 in. thick	≥ 1.13 in. thick
	- - - - - - - - - - - -	- - - - - - - - - - - - (%)	- - - - - - - - - - - -	- - - - - - - - - - - -
Slow: < 5 rings/in.	7.38	7.29	8.03	7.22
Fast: ≥ 5 rings/in.	7.40	8.40	7.12	7.14

ing experiment on red oak lumber indicated that in addition to wood type (heartwood/sapwood), a growth rate, thickness, and wood type interaction confounded the inference of experimental conclusions. The difference in the results of duplicate experiments may illustrate some of the challenges of kiln-drying red oak lumber, i.e., anatomical complexities within red oak lead to differing and inconsistent effects on the final kiln-dried MC.

There was a lack of statistical evidence to suggest that growth rate, wood type, or thickness had an effect on the final MC of yellow-poplar lumber. It is likely that because of the fast drying rate of yellow-poplar that some equalization occurs during the drying process. In other words, red oak is probably dried at a maximum rate of moisture transfer from the center of the board to the surface of the board, while yellow-poplar is more stable and uniform during the schedule.

This study illustrates the differences in sources of variation that influence the final MC of kiln-dried red oak and yellow-poplar lumber. The study added value to the science of kiln-drying by presenting empirical evidence on sources of variation that may influence the final MC of kiln-dried red oak and yellow-poplar lumber.

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