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Comparing Conventional and Vacuum Kiln-Drying of Hard Maple Lumber

Board Flatness and Drying Time

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Abstract

Vacuum drying technology can produce kiln-dried lumber at rates faster than conventional steam kiln-drying, resulting in reduced operating costs. Because of this, wood products manufacturers are increasingly becoming interested in vacuum drying technology, but the effects of this technology on the flatness of the resulting lumber are not known. This study compared the flatness of hard maple lumber when dried in a vacuum kiln with that of the same type of lumber dried in a conventional steam kiln. The drying schedules were also compared to quantify the difference in amount of time needed to dry the samples to the same moisture content. Paired samples of 1-in.- (25.4-mm-) thick flat-sawn boards were compared in this study. Half the samples were dried in a conventional steam kiln, and half were dried in a vacuum kiln. After the drying stage was complete, flatness of the two groups was measured using a flatness gauge. Although the vacuum-dried boards had less warp than the steam-dried boards in the rough-sawn condition, there were no statistically significant differences after planing. When the planed boards were acclimated to 12% moisture content, the narrowest vacuum-dried boards showed less residual warp than did the steam-dried boards, but that was not the case for wider boards. Also, the vacuum drying was found to take only about one-fifth the amount of time of the conventional steam drying.

Keywords: vacuum drying, kiln-drying, flatness, lumber

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Board Flatness and Drying Time

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Introduction

In 1904, Alexander Gray received a U.S. patent for a wood drying process he invented; this process involves the use of heat and vacuum cycling (Gray 1904). Historically, this technology was primarily used to dry specialty or niche wood products; however, in recent years, the use of vacuum technology to dry wood has seen a renewed interest. Because this process has been shown to produce quality lumber at faster drying rates and at reduced operating costs, the technology is being considered by more wood products manufacturers. However, the effects of this drying process on flatness of lumber are not known, and the faster drying rates of vacuum drying need to be quantified.

In conventional drying, diffusion (meaning the movement of moisture as vapor or liquid from an area of higher concentration to one of lower concentration) happens primarily in the transverse direction. Vacuum drying, on the other hand, involves reducing the boiling point of water in wood and removing the moisture by flow in the longitudinal direction. Longitudinal diffusion is 10 to 15 times faster than transverse diffusion, and diffusion in the radial direction is faster than in the tangential direction (Simpson 1991). Espinoza and Bond (2016) give an excellent overview of vacuum drying. They divide vacuum drying technology into conductive, cyclic, superheated steam, and dielectric heating methods and discuss the advantages and disadvantages of each. Conductive heating transfers heat through direct contact with metal plates. Cyclic drying involves repeating cycles of heat transfer by convection followed by a vacuum phase, during which moisture is removed. Forcing superheated steam under low pressure through a charge of stickered lumber will heat wood by convection, and moisture can be removed by circulating air. Dielectric methods use electromagnetic waves (microwaves or radio frequencies) to heat the wood.

Deviation from flatness is a category of warp that is caused by anisotropic shrinkage, growth stresses, or both. This category includes bow, twist, and cup (Bergman 2021). Bow typically results when a log is not sawn parallel to the bark, twist is caused by grain deviation along the length of a board, and cup is a result of differential shrinkage between the two faces of a board (Denig and others 2000). Improper thickness control and lack of restraint during drying can cause or aggravate deviation from flatness, the prevention of which is especially important in the production of high-quality hardwood lumber, such as that used in flooring and furniture (Boone and others 1993). The primary cause of deviation from flatness in this study is cup because the other types of degrade can be minimized by the selection and processing of the boards.

When thick and thin pieces are mixed across a course of lumber in a dry kiln, the thinner pieces are not restrained by the stickers. Thin lumber is then free to warp. Tolerance for drying defects, including moisture content variation, is exacting for hardwoods and softwoods used in furniture moldings and other trim. To meet the standards required, the first question when making drying decisions should always be “how will this decision affect quality?” Following this question, questions of how much time or energy can be saved should be asked.

In hardwoods, drying defects such as surface and end checks, internal checking, end splits, and stain are considered more important than warp. Warp is not considered a major defect according to the 2023 National Hardwood Lumber Association grading rules (NHLA 2023), but because hardwood lumber grades are largely based on size and amount of clear face cuttings that can be obtained from a given board, warp affects grade.

Flatness is important not only in conventional flooring but also in engineered floors, which are constructed from layers of plywood or fiberboard to which top layers (lamellae) of solid wood are glued. When lamellae are made of solid sawn wood, drying to preserve flatness is especially important.

Objectives

The objectives of this study were to compare the flatness and the drying time of hard maple lumber dried in a vacuum kiln with that dried in a conventional steam kiln.

Methods

Sample Preparation

Five #1 grade hard maple logs, 8 ft 6 in. (2.6 m) long with diameters of 14 to 16 in. (360 to 410 mm) at the small end, were chosen for the study. These logs were harvested during the week of September 16, 2019, in Langlade County, Wisconsin. The logs were not end-coated. They were sawn on October 3, 2019, at a sawmill using a circular head saw and horizontal band resaw to produce 1-in.- (25.4-mm-) thick flat-sawn boards that ranged in width from 4 to 9 in. (100 to 230 mm).

Seven to nine clear sapwood boards that were free of discoloration were selected from each of the five logs. Each board was crosscut in half, and the halves were separated into two matching groups. One group was dried to 7% moisture content (MC) in a Southeastern Installation, Inc. (Lexington, North Carolina, USA) conventional steam kiln, and the second group was dried to 7% MC in a VacuPress (Vacuum Pressing Systems, Brunswick, Maine, USA) vacuum kiln (Fig. 1). The conventional steam kiln was a small research kiln. Its air flow, temperature, and relative humidity controls were more accurate than would be found in a typical commercial kiln. The kiln included top and side baffles to direct air flow through the charge of boards, but no top restraint was used because of kiln size limitations.

Because the study was conducted during a warm, humid week, the researchers chose to operate the conventional steam kiln with the T1-C5 schedule developed by the USDA Forest Service, Forest Products Laboratory for achieving the whitest color hard maple during summer months (Denig and others 2000) (Table 1). For the vacuum kiln, the VacuPress medium drying schedule shown in Figure 2 was used. The drying schedules of both kilns are presented in the units in which they were published. Kiln samples were used in both kilns to monitor moisture content during the drying process.

After drying, each sample board was again crosscut in half. One half of each board was used for a related color study (Lyon and others 2021), and then the remaining half was used for this flatness and drying time study. In total for both studies, 206 board feet (0.486 m^3) of lumber was used.

Sample Flatness Measurement

For comparison between drying processes, lumber flatness was determined using a flatness gauge digital indicator designed to measure short linear distances. To use the indicator, a series of aluminum braces of three widths, 4, 6, and 8 in. (101.6, 152.4, and 203.2 mm), were fabricated. The boards were separated into width classes and measured using the widest aluminum brace that fit on each board (Fig. 3). To accommodate the widest brace for each board, wane that interfered with the measurement was placed on the opposite side of the face being measured. Ultimately, this decision resulted in needing to use the absolute value of each board's "out-of-flat" measurement because some of the boards were measured as concave whereas others were measured as convex. This method did not account for the differences in thickness between the edges and centers of boards caused by differential radial and tangential shrinkage within a board, which might be substantial in wide boards.

Each board was measured in three conditions. First, the steam kiln and vacuum samples were measured in their rough-sawn form without any processing after leaving the kiln. Second, the samples were run through a surface planer and measured again. In the third and final condition, the planed samples were acclimated to the equilibrium moisture content of 12% MC in an environmental chamber and then brought back down to 7% MC and measured again.

Statistical Analysis

The analysis consisted of paired *t*-tests. Since the original sample boards were cut in half with half being dried in a conventional steam kiln and the other half dried in a vacuum kiln, the resulting pairs were created from the same board. This provided the best pairing, including similar grain, origin in the same location within a log, similar growth stresses, and other factors.

Results

Lumber Flatness

Our null hypothesis was that the mean difference in warp (deviation from flatness) between the vacuum kiln-dried boards and steam kiln-dried boards was zero. Table 2 shows results of warp with all widths of boards analyzed together as one group. For each of the three unique conditions, rough, planed, and acclimated, only the rough condition showed significant difference at the 0.05 level. A *p*-value less than 0.05 is considered statistically significant, in which

Figure 1—Left: board sample halves stacked on stickers prior to processing in the conventional steam kiln. Right: board sample halves stacked on heating platens prior to processing in the vacuum kiln.

Table 1—White hard maple drying schedule (T1-C5)

Step	Moisture content (%)	Equilibrium moisture content (%)	Relative humidity (%)	Dry bulb (°F)[a]	Wet-bulb depression (°F)[a]
1	Above 30	11.8	68	105	14
2	25 to 30	9.8	58	105	20
3	20 to 25	7.6	44	115	35
4	15 to 20	4.1	22	120	45
5	<15	3.3	17	—	—

[a]°C = (°F – 32)/1.8

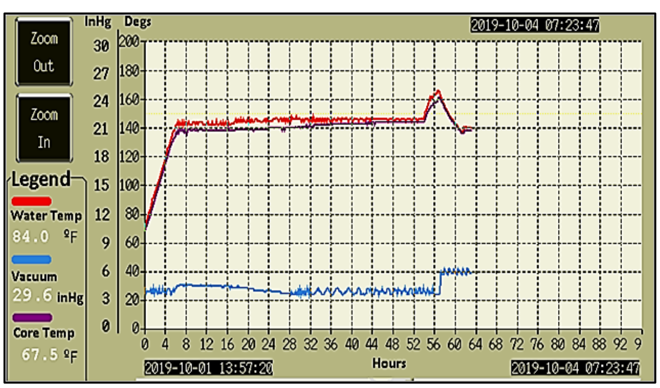

Figure 2—VacuPress drying schedule at medium setting.

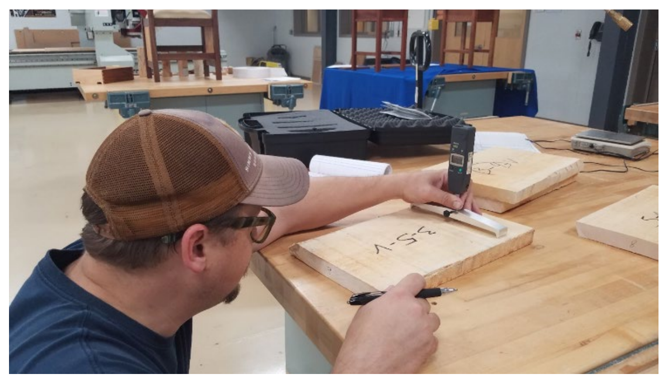

Figure 3—Measuring a sample for flatness. The aluminum brace attached to the indicator allowed the measurements to occur close to the edges of the board.

Table 2—Lumber warp paired *t*-test results for each unique condition — rough, planed, and acclimated

	Average warp (in. (mm))		
	Rough-sawn	Surface-planed	Planed, then acclimated to 12% moisture content
Vacuum kiln	0.015 (0.381)	0.0048 (0.122)	0.0098 (0.249)
Steam kiln	0.010 (0.254)	0.0053 (0.135)	0.0077 (0.196)
$p(T \leq t)$ one-tail	0.024[a]	0.190	0.158

[a]Significant at the 0.05 level.

case the null hypothesis was rejected. Simply stated, warp of the rough boards from the vacuum kiln was not the same as that of rough boards from the steam kilns; the boards from the vacuum kiln showed slightly more warp.

Neither the planed nor the acclimated boards showed a significant difference in warp between the vacuum kiln-dried and the steam kiln-dried boards when all widths were examined together. It is possible that any difference in warp was removed during the planing process because portions of the top and bottom surfaces were removed during planing. Although many factors are involved in the formation of drying defects, we wanted to reduce the number of variables considered in this study by using uniform material throughout and standardizing material preparation and drying schedules.

When the boards were sorted into width groups, we saw some interesting results (Table 3). In the rough group, significant differences in flatness between the vacuum kiln-dried boards and the steam kiln-dried boards were found in each width group, with warp significantly greater in the steam kiln-dried boards (Table 3). Those differences were not found in the planed groups of boards. As mentioned earlier, warp was probably decreased during the planing process because material was removed from the top and bottom of each board.

There were mixed results in the planed then acclimated groups of boards. The 4-in.-wide group showed significant differences in flatness between the vacuum kiln-dried boards and the steam kiln-dried boards with warp significantly greater in the steam kiln-dried boards (Table 3). In contrast, the 6- and 8-in.-wide groups did not show significant differences in flatness between the vacuum kiln-dried boards and the steam kiln-dried boards even though warp was greater in the vacuum kiln-dried boards (Table 3).

Boards that do not remain flat will cup or warp toward their bark side. This is caused by differential shrinkage in the radial and tangential directions. For wider boards, the differential shrinkage between the top face (bark side) is greater than the differential shrinkage of the bottom face (pith side), causing more warp in wider boards.

Drying Schedules

Samples in the vacuum kiln were dried in 58 h using a vacuum of 3.92 inHg (13.3 kPa). When the kiln temperature and wood core reached 140 °F (60 °C), they were maintained at 140 °F for 8 h to equalize the moisture content in the lumber. Then the kiln temperature was adjusted to 160 °F (71 °C) to bring the wood core up to 160 °F, resulting in a lumber moisture content of 7%.

Samples in the conventional steam kiln were dried in 288 h using the T1-C5 schedule. The conventional steam kiln dried the lumber using two 2-hp (1,491-W) fans that averaged an air speed of 500 ft/min (152.4 m/min) during the kiln schedule. Although vacuum drying required only one-fifth the time needed by conventional steam drying, the loading and unloading of a vacuum kiln that uses platens is significantly more labor intensive than loading and unloading a conventional kiln or a vacuum kiln that does not use platens.

Conclusions and Suggestions for Further Study

In summary, no statistical differences were found in the dried boards after planing, but after the boards were acclimated to 12% MC, the 4-in.-wide vacuum-dried boards had less warp than the 4-in.-wide steam kiln-dried boards. The wider (6- and 8-in.) boards still had no statistically significant differences in warp after acclimating to 12% MC.

Drying in a vacuum kiln required only one-fifth the amount of time of conventional kiln-drying to bring the boards to the same moisture content. However, the savings from more rapid drying might be offset by the increased labor cost incurred in the loading and unloading of the vacuum kiln. Because we did not collect the data necessary to support or refute this claim, a follow-up study should include those measurements.

Table 3—Lumber warp paired *t*-test results for each unique condition — rough, planed, and acclimated, sorted by lumber width[a]

	Average warp in. (mm)								
	Rough-sawn			Surface-planed			Planed, then acclimated to 12% moisture content		
	4 in. wide	6 in. wide	8 in. wide	4 in. wide	6 in. wide	8 in. wide	4 in. wide	6 in. wide	8 in. wide
Vacuum kiln	0.011 (0.279)	0.020 (0.508)	0.015 (0.381)	0.003 (0.068)	0.005 (0.131)	0.014 (0.344)	0.004 (0.109)	0.015 (0.386)	0.016 (0.402)
Steam kiln	0.034 (0.864)	0.064 (1.626)	0.082 (2.083)	0.003 (0.067)	0.006 (0.148)	0.017 (0.425)	0.008 (0.207)	0.008 (0.192)	0.006 (0.141)
$p(T \leq t)$ one-tail	0.000[b]	0.000[b]	0.003[b]	0.447	0.271	0.272	0.000[b]	0.053	0.105

[a]1 in. = 25.4 mm.

[b]Significant at the 0.05 level.

An industry survey to determine the range of flatness that is acceptable in the industry would also be useful to determine the likelihood of acceptance of vacuum drying.

A follow-up study could also include measurements to determine the effects of differential shrinkage across a board and could also include data on the placement of boards in the conventional kiln to determine if the absence of top restraint might have affected the results.

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