DO VERTICAL AIR GAPS AFFECT THE DRYING CHARACTERISTICS OF PACIFIC COAST HEMLOCK BABY SQUARES? RESULTS OF A PRELIMINARY STUDY.

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Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and amabilis fir (*Abies amabilis* (Dougl.) Forbes) are the most abundant species in the coastal area and the wet belts of British Columbia (BC). These two softwood species grow together and are marketed as Pacific Coast Hemlock (PCH). PCH lumber with a dimension of 105 x 105 mm in cross-section and at different lengths, commonly called baby squares, is widely used in Japanese traditional housing construction. About 95% of the BC PCH baby squares exported today to Japan are in green condition (Powles, 1995), which are further air-dried or kiln-dried by the Japanese users. During recent years, the Japanese demand for baby squares kiln dried in BC has greatly increased (Matsumoto, 1990; Kaila, 1991; Powles, 1995; Zhang et al., 1996). One reason for that is the dimensional stability of the dried product whereas another reason is the fact that shipping of dried squares can prevent mould which is likely to develop in warm storage environment in a vessel. Since lumber is exposed to view in traditional and modern Japanese houses, its aesthetic characteristics are very important.

PCH is a hard to dry species group due to the presence of wet pockets (Kozlik and Hamlin, 1972). Honeycomb, shake and nonuniformity of final moisture content are common kiln drying problems. There are various drying techniques that can be used to dry baby squares, namely, air drying, conventional and high temperature kiln drying. Air drying can produce a good quality product, but it takes approximately one year for the squares to reach about 15% final moisture content (Bramhall and Wellwood, 1976). High temperature drying of baby squares takes about four days (Dubois, 1991), but the uniformity of final moisture content is quite low and a considerable amount of degrade, like shake and internal checking will develop (Kozlik and Hamlin, 1972; Oliveira and Mackay, 1991; Dubois, 1991). Furthermore, the wood surface becomes darker thus, loosing its high color appeal to the Japanese customers. Conventional kiln drying of baby squares takes about 8 days (Avramidis and Mackay, 1988), and the final moisture content distribution within and between lumber pieces may vary considerably. The long drying cycle and the nonuniformity of final moisture content are the two major reasons why the BC industry has kept away from kiln drying baby squares.

Many attempts have been made over the past to address the PCH baby squares drying difficulties. Post-steaming (Dubois, 1991), density and moisture content pre-sorting (Zhang et al, 1996), just to name few, have been investigated as potential strategies to improve drying characteristics.

Stacking with vertical air gaps has been implemented in natural air drying of thick lumber, logs and squares where reduced drying times and improved final product quality have been observed (Thomas, 1939; Pratt, 1974). However, stacking with vertical air gaps has never been used in conventional kiln drying of lumber. By introducing vertical air gaps, four evaporation surfaces are created instead of the two original ones (top and bottom) and therefore, heat and mass transfer rates would be expected to increase and the kiln drying time to decrease.

Higher air velocities have been shown to increase lumber drying rates (Torgeson, 1940; Lyman, 1965; Price, 1981; Herzberg et al., 1985). One reason for that is the thickness reduction of the boundary layer by introducing more turbulent flow along the top and bottom lumber surfaces, which enhances the heat and mass transfer rates (Lyman, 1965; Carter, 1990). Another reason could be the fact that higher air velocity reduces the temperature drop across the lumber load. As air temperature decreases, the ability of air to transfer heat and absorb water is also reduced and consequently, longer drying times are needed (Carter, 1990). All past studies on the effect of air velocity were conducted on thin lumber, namely, thickness below 51 mm.

The objective of this study was to investigate the effect of vertical air gaps, air velocities and fan revolutions on drying characteristics of PCH baby squares.

Materials and Methods

One shipment of three hundred and thirty, 2.44 m long, pieces of green PCH was obtained from a local sawmill. The cross sectional dimensions of each lumber piece were 105 by 105 mm. There was no particular sawing pattern used in the cutting of lumber, so the annual rings of each piece had no specific direction.

For each run, twenty one pieces of green lumber were randomly selected from the shipment. Each green lumber provided three moisture content samples (MS), each 20 mm long, and two kiln specimens (KS), each 0.89 m long. The first 300 mm from both ends were discards (D) in order to eliminate air-dried end-sections (Figure 1). The average moisture content of the two consecutive MS samples were taken as the initial moisture content of the KS in between. Immediately after cutting, all KS's were coated with waterborne polyvinyl acetate sealant at both ends in order to minimize end-drying before and during drying processes. Two equidistant lines on

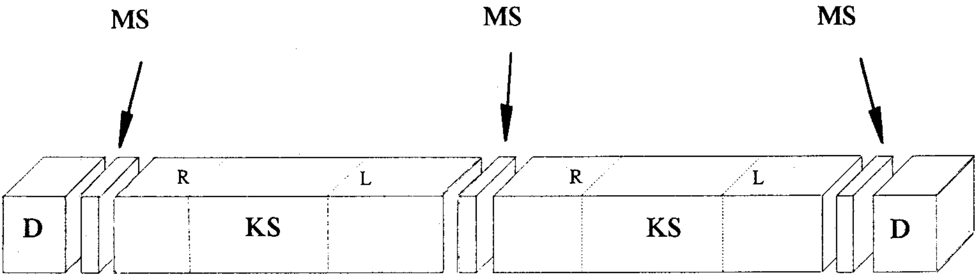


FIGURE 1. Cutting pattern of green lumber pieces.

each KS were drawn one on the top face and one of the side face and marked as R and L, respectively. The apparent thickness and width of each specimen at both R and L lines were measured before and after drying with a pair of digital caliper (± 0.01 mm) in order to calculate shrinkage percentages in both horizontal and vertical directions, and basic density (based on oven-dry weight and green volume). Each specimen was visually examined for end and surface checking and then weighed with a digital balance (± 0.001 g).

The laboratory kiln used in this study was capable of holding a 0.9 by 0.9 by 0.9 m lumber pile (about 0.76 m^3). The charge rested on a scale so that the change of weight and therefore, moisture content of the whole charge could be monitored over time. The aluminum stickers were 19 mm thick and there was no reversal of the air flow direction during drying. A schematic design of the lumber pile with a vertical air gap is shown in Figure 2. Thermocouples were also inserted in nine kiln specimens with pre-drilled holes, and readings were taken every hour via a temperature recorder (Figure 2).

The drying schedule used in this study was the one developed by Avramidis and Mackay (1988), as listed in Table 1. Vertical air gaps, fan revolutions and air velocities used in this study are listed in Table 2 for each run. Runs 1 to 12 were a "pseudo" two replication factorial experimental design (Table 3) because the basic densities of each run were not the same.

At the completions of each run, each specimen was re-weighed and visually evaluated for surface and end- checking. The apparent width and thickness of all

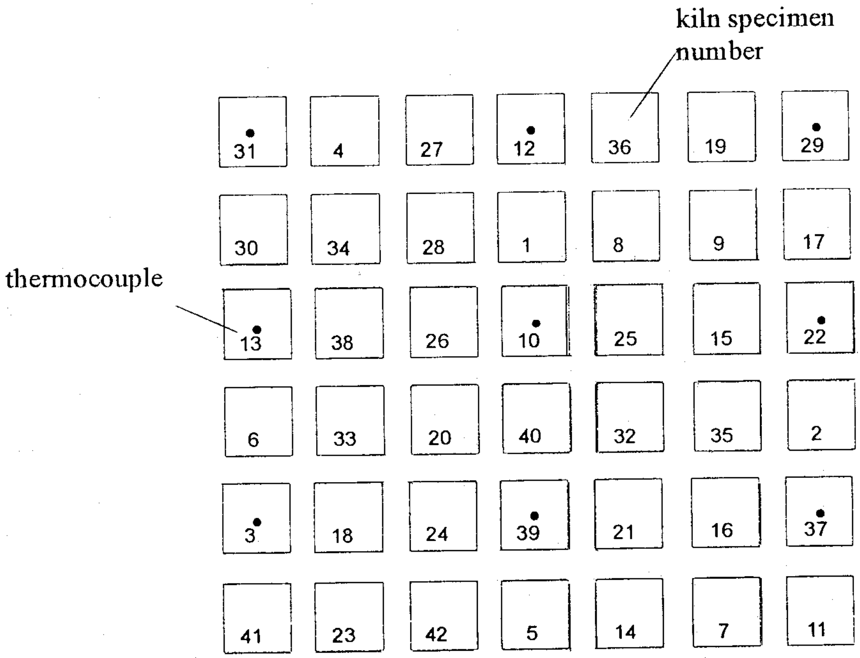


FIGURE 2. Lumber pile setup (with air gap).

TABLE 1. The drying schedule used in this study.

Time (h)	T_d (°C)	T_w (°C)	H (%)	M_{EMC} (%)	Mode
12	54.4	48.9	73	12.1	S
48	82.2	54.4	26	3.3	R
X	82.2	54.4	26	3.3	S
24	65.5	61.1	80	13	S

S = step, R = ramp, X = variable

TABLE 2. Vertical air gap, fan revolutions, and air velocities used for each run.

Runs	air gap (mm)	fan revolutions (rpm)	air velocities (m/s)
Run 1	0	620	2.54
Run 2	10	620	2.43
Run 3	20	620	2.25
Run 4	0	1220	5.08
Run 5	10	1220	4.79
Run 6	20	1220	4.47
Run 7	0	620	2.54
Run 8	10	620	2.43
Run 9	20	620	2.25
Run 10	0	1220	5.08
Run 11	10	1220	4.79
Run 12	20	1220	4.47
Run 13	20	1380	5.08
Run 14	20	710	2.54

TABLE 3. The experimental design

fan revolutions (rpm)	vertical air gap (mm)		
	0	10	20
620	Run 1 Run 7	Run 2 Run 8	Run 3 Run 9
1220	Run 4 Run 10	Run 5 Run 11	Run 6 Run 12

specimens at the R and L line locations were measured again in order to calculate the horizontal and vertical shrinkage of each specimen. Then, each specimen was sectioned in the middle to obtain six (even number) or four (odd number) slabs, about 25 mm thick, in order to determine the average final moisture content (a), moisture content profiles in the vertical (b) and horizontal (c) directions, the top bottom, side and core moisture contents (d), and the drying stresses in the horizontal (e) and vertical (f) direction, respectively (Figure 3).

Results and Discussion

The average initial ($M_{initial}$) and final moisture content (M_{final}), basic densities and kiln residence time for each run are listed in Table 4. The average $M_{initial}$ of each run was in the range of 45.2 to 63.6%, and average M_{final} of each run was in the range of 13 to 17.4%. In order to exclude the drying time difference caused by the $M_{initial}$ and M_{final} variability between runs, the drying times were calculated from the drying curves which were re-adjusted to a $M_{initial}$ and M_{final} of 48% and 17%, respectively, for all runs. At the same $M_{initial}$, some of the runs had already been dried for more than 20 hours and some runs had just started their drying cycle. The main difference between these runs was the temperature level at the geometric centre of the lumber specimens. Based on the readings from the thermocouples, it was determined that the temperature in the centre was raised to the highest level within 4 hours for all the runs and all locations within the kiln charge (Figure 4). In order to exclude the temperature differences at the 48% moisture content level, 4 hours were subtracted from the kiln drying time of each run which was just started. For Runs 6, 7, 10 and 13, extra hours were estimated and added to the total drying times based on the average drying rate values. The adjusted drying times are listed in Table 4 (column 6).

Basic densities of each run were in the range of 362 to 451 kg/m^3. It can be seen that, the higher the basic density, the longer the drying time was (Table 4). For the same fan revolutions and vertical air gaps, Run 10 showed a 15% reduction in drying time when compared to Run 4, whereas, Run 9 resulted in a 27% reduction of drying time when compared to Run 3. This density/ time relation is in agreement with the hemlock drying results reported by Kozlik and Ward (1981), Avramidis and Oliveira (1993), Zhang et al. (1996).

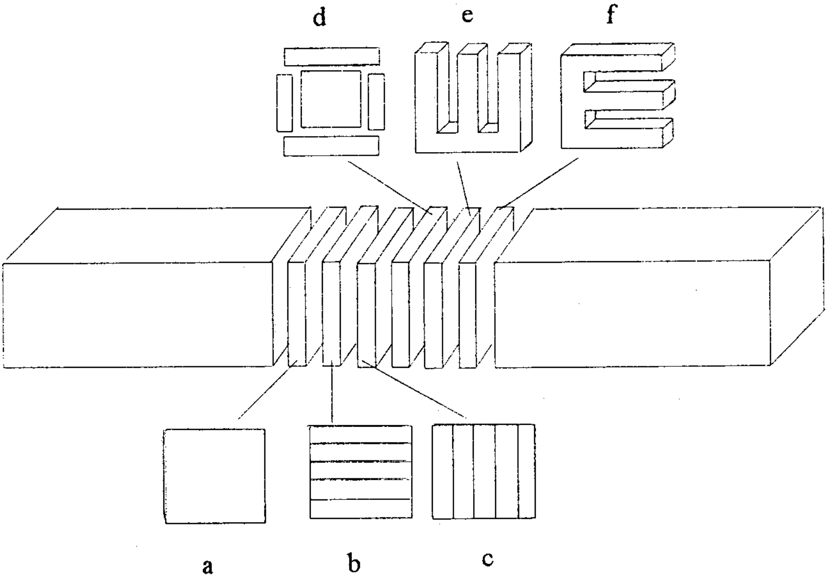


FIGURE 3. Sawing pattern of each kiln specimen after drying

TABLE 4. The average $M_{initial}$, M_{final}, basic density, kiln residence time (KRT) and adjusted kiln drying time (AKDT) for each run.

RUN	$M_{initial}$ (%)	M_{final} (%)	basic density (kg/m^3)	KRT (hours)	AKDT (hours)*
Run 1	48.7	14.5	410	182	108
Run 2	58.7	13.7	415	185	94
Run 3	50.0	13.0	417	196	115
Run 4	60.4	14.1	415	205	107
Run 5	63.6	14.7	451	214	106
Run 6	47.2	14.4	406	167	93
Run 7	45.2	15.3	440	188	120
Run 8	48.3	14.2	427	221	117
Run 9	50.4	15.8	362	150	84
Run 10	46.7	14.9	368	154	94
Run 11	72	14.8	443	207	99
Run 12	58.7	15.4	438	191	99
Run 13	56.2	17.4	414	161	92
Run 14	47.9	16.4	434	177	106

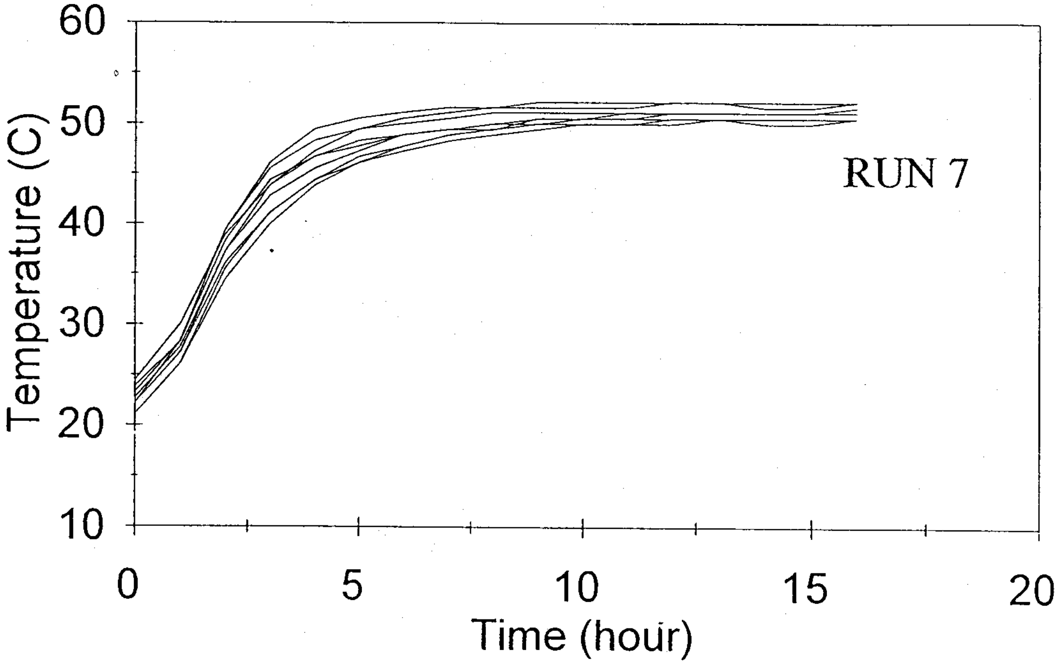
* The 24-hours conditioning period is excluded.

The Effect of Vertical Air Gaps on Drying Time

For the same fan revolutions (620 rpm), comparing Run 1 (control) to Run 2 (10 mm air gap), it can be seen that there is a distinct air gap effect on drying time since the total drying time of the latter was reduced by about 13%. In both runs the average basic density was approximately the same, but in Run 2 the air velocity was slightly lower (about 4% less) which further supported the effect of a 10 mm air gap. However, when Run 3 (20 mm air gap) is compared to Run 1 (control) and Run 2 (10 mm air gap), the effect of the vertical air gap disappears. The air velocity in Run 3 was approximately 11% and 7% lower compared to Run1 and Run 2, respectively. The air velocity difference may have resulted in an overshadowing effect of the 20 mm air gap on the drying time.

For the same fan revolutions (1220 rpm,), comparing Run 4 (control) to Run 11 (10 mm air gap, Figure 5), it can be seen that the introduction of a 10 mm vertical air gap in the latter resulted in a drying time reduction of about 7% even though the basic density of the former was approximately 4% higher. Drying time in Run 6 (20 mm air gap) compared to Run 4 (control) was reduced by 12% and in Run 12 (20 mm air gap) when compared to Run 4 (control), it is seen that drying time is reduced by 7%. The positive effect of the vertical air gap in the latter case is further supported by the higher basic density of Run 12.

For the same air velocity conditions, Run 13 can be compared to Runs 4 and 10 (air velocity 5.08 m/s, Figure 6), and Run 14 can be compared to Runs 1 and 7 (air velocity 2.54 m/s, Figure 7). In Run 13, the drying time was reduced by about 14% when compared to the same density control, namely, Run 4. When compared



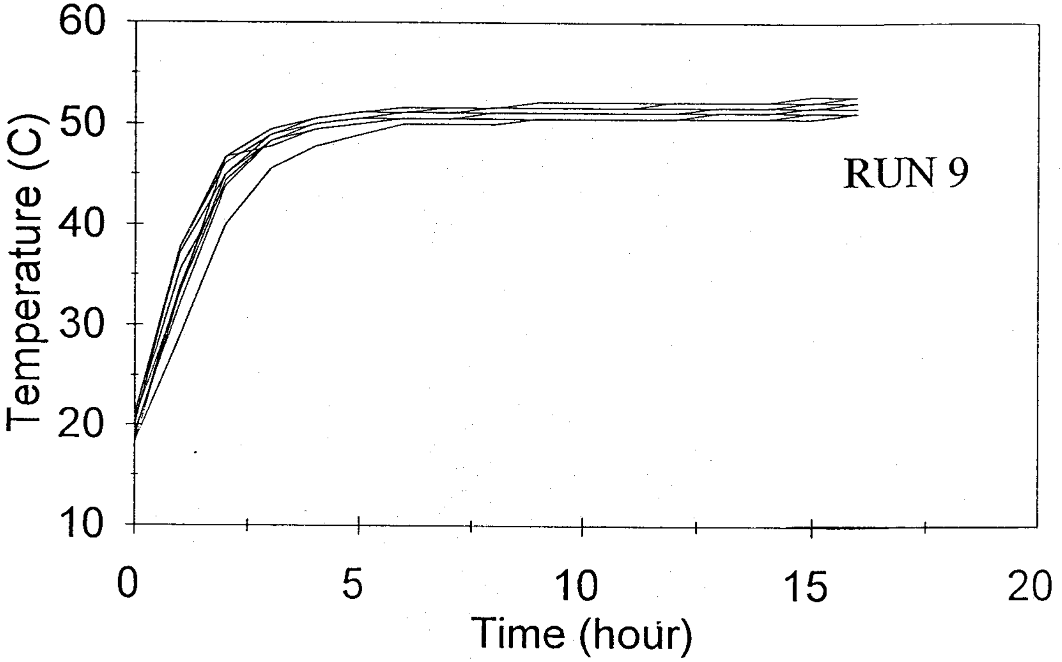


FIGURE 4. Typical centre temperature versus time for Run 7 (a) and Run 9 (b).

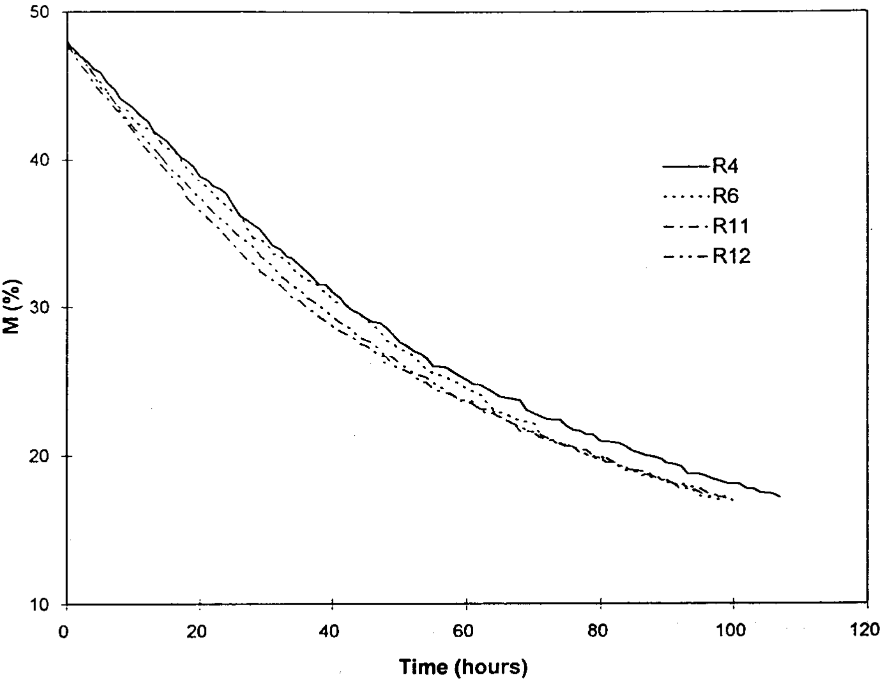


FIGURE 5. Adjusted average moisture content versus time for Runs 4, 6, 11 and 12.

to the replication control, Run 10, no drying time reduction could be observed. However, the density of Run 13 was approximately 19% higher than that in Run 10. This difference is large enough to overshadow the effect of the vertical air gap. At the 2.54 m/s air velocity, Run 14 which had a 20 mm air gaps, resulted in a drying time reduction of about 12% when compared to Run 7 of similar basic density. When compared to Run 1, the time reduction was almost nil. That could have been affected by the higher basic density of Run 14. In general, the kiln drying time can be reduced by about 15% when baby squares are stacked with 10 to 20 mm air gaps. However, the kiln capacity is reduced by 8% if the gap is 10 mm and 15% if the gap is 20 mm. From an economic point of view, stacking lumber with a 10 mm air gap is the best option since the volume output per year will increase by about 4.2% when both capacity and drying time reductions are considered.

The effect of air velocity on lumber drying time

Comparing Run 3 (air velocity was 2.25 m/s) to Run 6 (air velocity was 4.47 m/s) both with the same vertical air gaps and basic densities (Figure 8), we can see that Run 6 showed a 21-hour reduction in drying time. This 18% reduction of drying time in Run 6 was the result of the higher air velocity since the average lumber basic densities in both runs were nearly the same. By comparing Run 12 (air velocity 4.47 m/s, air gap 20 mm) to Run 3 (air velocity 2.25 m/s, air gap 20 mm, Figure 8), again with similar basic densities, it can be seen that the drying time of Run 12 exhibited a 14% reduction. The effect of velocity was furthermore supported by the fact that lumber specimens in Run12 had an average basic density about 5% higher than that of Run 3. The same positive effect of air velocity on drying time can also be realized when comparing Run 11 to Run 8, both with a 10 mm vertical air gap. The drying time reduction in this case was about 15%. However, comparing Run 1 (air velocity 2.54 m/s) to Run 4 (air velocity 5.08 m/s), both with no air gaps, it can be seen that the air velocity had no effect on drying time, even though basic densities were the same. No further comparison can be made between the rest of runs with respect to the effect of air velocity on drying times because of the large differences in basic densities between them.

From the above discussion, it can be concluded that increasing air velocity will result in an approximately 15% drying time reduction for PCH baby squares when vertical air gaps are present. That is in agreement with the way air velocity is expected to affect drying times according to the results reported by Mackay (1984), Herzberg et al. (1985) and Mitchell and Bigbee (1989).

In the case of thick lumber with no vertical air gaps, higher air velocities did not seem to reduce drying times. The explanation for this unexpected result could be as follows: the increased air velocity results in increased air capacities to absorb moisture in a given time period. If the moisture evaporation rate from wood is lower than the surface moisture removal rate by the circulating air, then high air velocity is ineffective and wasteful. According to Fourier's and Fick's laws, the rate of heat and moisture transferred varies inversely to the length of the flow path and is directly proportional to the effective evaporation area (Siau, 1984). In this study, the moisture evaporation rate was very low because of the large lumber thickness. Thus, the main factor affecting drying time was the wood internal resistance. Therefore,

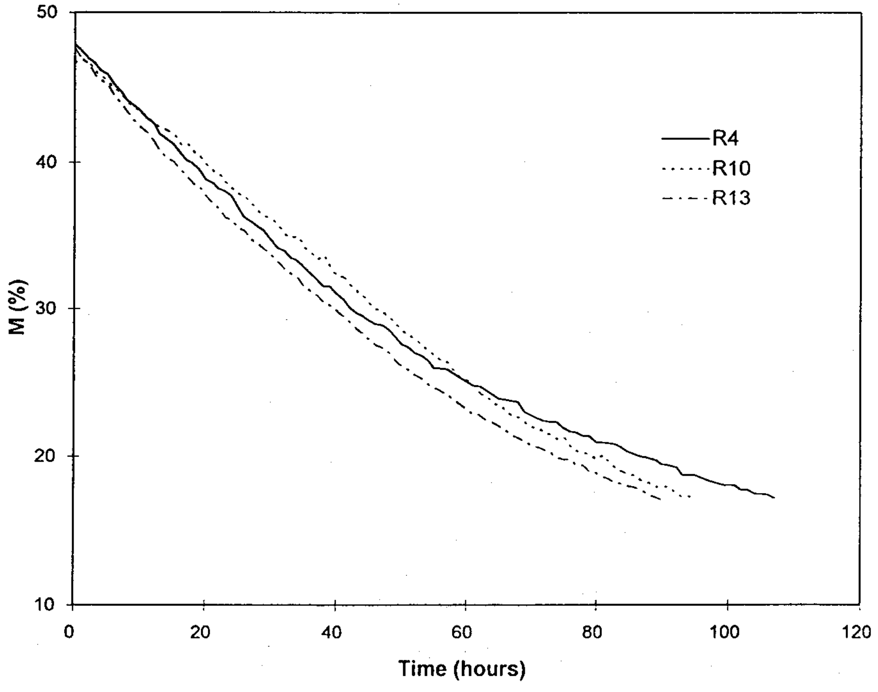


FIGURE 6. Adjusted average moisture content versus time for Runs 4, 10 and 13.

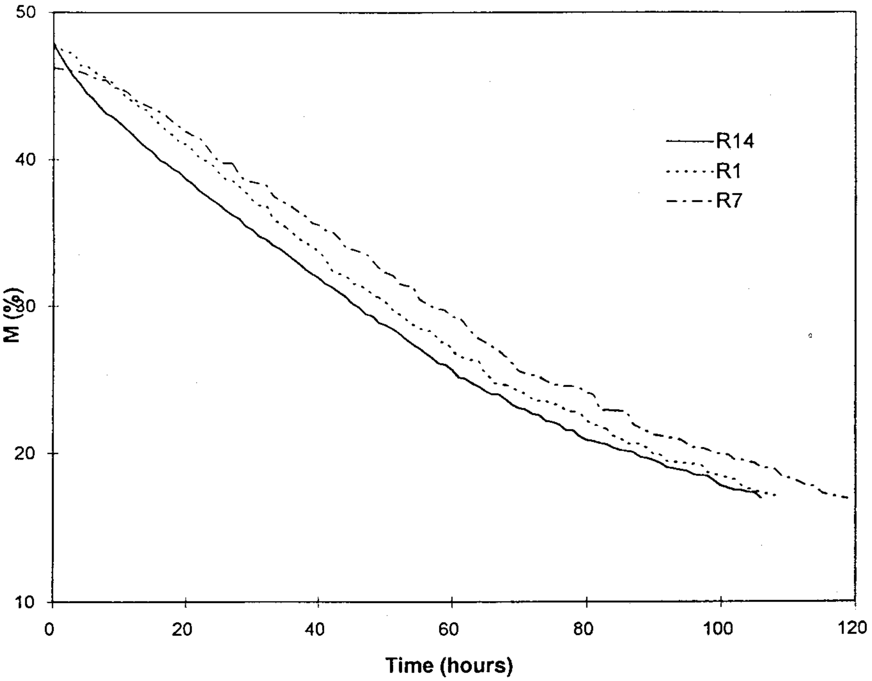


FIGURE 7. Adjusted average moisture content versus time for Runs 1, 7 and 14.

the benefit of higher air velocity could have been offset by the wood thickness. However, the effect that overshadowed the velocity effect was probably eliminated when vertical air gaps were introduced to the system by creating more surface area for water evaporation.

Lumber drying quality

The moisture content difference between core and shell in kiln dried lumber is considered important especially for lumber that is to be remanufactured. Table 5 contains the average moisture content differences between core and shell for each run. It can be seen that the differences ranged between 5.2 and 7.6%, the latter being for Run 13 where the average M_{final} was 17.4%, which is much higher than the target M_{final} of 13%. A two-way analysis of variance showed that vertical air gaps, fan revolutions and their interaction had no effect on moisture content difference between core and shell in the dried specimens and all runs at the 95% confidence level.

TABLE 5. The average moisture content difference (%) between core and shell (M_{c-s}) for each run.

R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
5.7	5.2	5.2	5.7	6.5	6.2	5.7	5.3	5.3	5.2	5.3	5.9	7.6	6.2

The range of moisture content distribution within each of the specimens in the vertical and horizontal directions was quite similar in the 14 runs. In the vertical direction the range was 4.7 to 8.6 % and in the horizontal direction it was 5.1 to 7.9 %.

Since the percent of shrinkage is directly related to the M_{final}, which was not the same in all 14 runs, the shrinkages were estimated for a M_{final} of 17% (Table 6). Two-way analysis of variance that was run using the estimated shrinkage percentage revealed that there was no effect of vertical air gaps, fan revolutions and their interaction on both with and thickness shrinkage at the 95% confidence level.

Mild casehardening was found among dried specimens. Table 7 lists the number of casehardened specimens in the vertical and horizontal directions in all runs. It is clear that vertical air gaps, fan revolutions and their interaction had no apparent effect on the number of casehardened specimens.

Only surface checking, splitting, shake, wet pockets and compression wood were found in some specimens. Because shake, wet pockets and compression wood are related to the wood natural properties, they are not considered as drying defects. According to the standards (NLGA,1991), surface checking is allowed for construction lumber. Therefore, only splitting is considered when grading lumber. In this study, lumber was divided into three categories based on drying degrade, namely, A----no or slight degrade (split 0 -100 mm). B----medium degrade (split 101-300 mm). C----severe degrade (split 301- 890 mm). The quality classification for the

TABLE 6. Actual shrinkage (S_{act}) and estimated shrinkage (S_{est}) at a final moisture content of 17%.

RUN	S_{act} (%)		S_{est}(%)	
	horizontal	vertical	horizontal	vertical
Run 1	2.7	2.7	2.3	2.2
Run 2	3.3	2.5	2.6	2.0
Run 3	3.0	2.3	2.3	1.8
Run 4	2.7	2.7	2.2	2.2
Run 5	3.0	2.5	2.5	2.1
Run 6	2.6	2.6	2.1	2.2
Run 7	2.8	2.0	2.4	1.8
Run 8	3.1	2.9	2.5	2.4
Run 9	3.2	2.5	2.9	2.3
Run 10	3.3	2.2	2.9	1.9
Run 11	3.2	2.2	2.7	1.9
Run 12	3.6	2.8	3.2	2.5
Run 13	3.0	2.4	3.1	2.5
Run 14	2.8	2.6	2.7	2.5

14 runs is shown in Table 8. A two-way analysis of variance that was run using the percent of A grade in all runs showed that vertical air gaps, fan revolutions and their interaction had no effect on lumber drying quality at the 95% confidence level.

Conclusions

The conclusions from this research are summarized below:

1. Higher basic density results in longer drying time, therefore, density sorting before drying is an effective way to reduce lumber drying time and the number of over-dried and under-dried specimens.

2. When PCH baby squares are stacked with vertical air gaps, higher air velocities canreduce their kiln drying time.

3. Vertical air gaps will reduce kiln drying times for PCH baby squares of similar basic density.

4. Vertical air gaps, fan revolutions and air velocities have no significant effect on moisture content differences between core and shell, drying quality, drying stresses and shrinkage percentage in kiln dried PCH baby squares.

Since this research was carried out in a small scale laboratory kiln, the research results might not be representative of a full scale commercial situation. Therefore, a full scale research project is recommended to further investigate the effects of vertical air gaps on the drying characteristics of PCH baby squares.

TABLE 7. The total number of casehardened specimens in the vertical (V) and horizontal (H) direction in the replication runs.

fan revolutions (rpm)	vertical air gap (mm)					
	0		10		20	
	V	H	V	H	V	H
620	5* 11 16	4** 9 13	1 1 2	3 1 4	0 3 3	1 7 8
1220	2 5 7	4 2 6	2 6 8	1 6 7	3 0 3	2 1 3

*first row corresponds to initial runs.
**second row corresponds to replications.

TABLE 8. Degrade of dried lumber for each run.

RUN	A		B		C	
	number of specimens	(%)	number of specimens	(%)	number of specimens	(%)
Run 1	41	97.6	0	0	1	2.4
Run 2	35	83.3	3	7.1	4	9.5
Run 3	37	88.1	1	2.4	4	9.5
Run 4	36	85.7	1	2.4	5	11.9
Run 5	39	92.9	1	2.4	2	4.8
Run 6	36	85.7	1	2.4	5	11.9
Run 7	38	90.5	2	4.8	2	4.8
Run 8	33	78.6	0	0	9	21.4
Run 9	36	85.7	0	0	6	14.3
Run 10	40	95.2	0	0	2	4.8
Run 11	41	97.6	0	0	1	2.4
Run 12	40	95.2	0	0	2	4.8
Run 13	39	92.9	1	2.4	2	4.8
Run 14	38	90.5	1	2.4	3	7.1

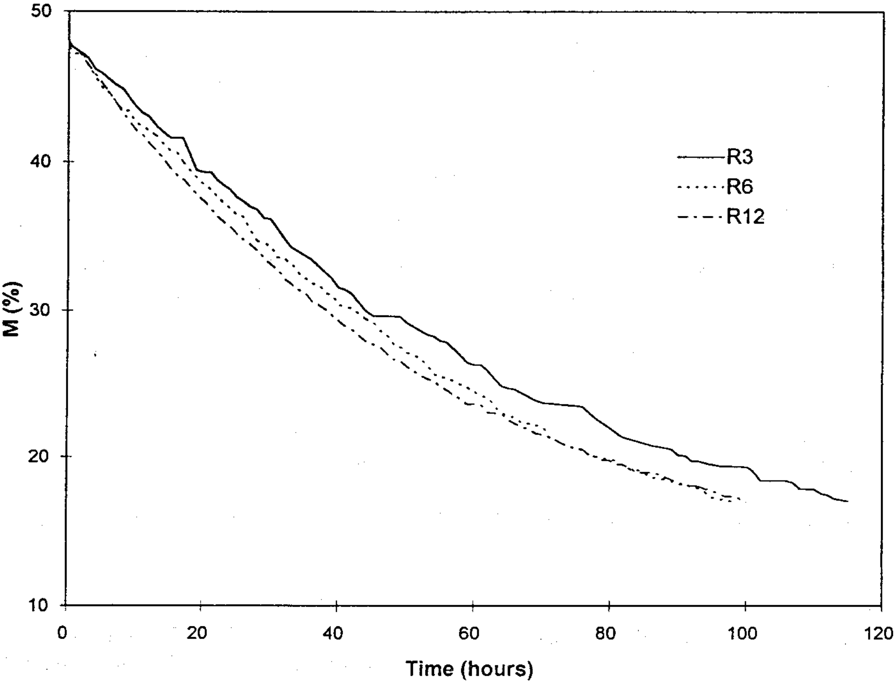


FIGURE 8. Adjusted average moisture content versus time for Runs 3, 6 and 12.

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