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Drying Western Red Cedar with Superheated Steam

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This exploratory study evaluated the possibility of drying 50-mm-thick western red cedar with superheated steam. Since there are no industrial facilities in Canada drying western red cedar with superheated steam, the study was designed to explore the potential of this technology in terms of lumber quality, moisture content distribution, and drying time. The experiments showed that the 50-mm-thick product can be dried in less than three days without jeopardizing lumber quality (in comparison with the two weeks that is currently required in conventional kilns), and the percentage of pieces that remained wet after drying was within the 10% to 15% range that is typically tolerated in industry.

Keywords Drying; Lumber; Superheated steam; Western red cedar

INTRODUCTION

Western red cedar (*Thuja plicata*) is a large softwood tree that could be up to 60 meters tall when mature. In British Columbia, it frequently grows with western hemlock and Douglas fir at low to mid-elevations along the coast and in the wet belt of the interior.^[1] Because of its natural resistance to decay, the wood may remain usable for over 100 years; thus native people have traditionally used this species for totem poles, canoes, and many other wood artifacts, such as arrow shafts, masks, and paddles.^[1]

Today, western red cedar is popular in western Canada for outdoor applications such as shingles, siding, decks, and fences,^[2] probably because of its superior dimensional stability and resistance to decay.^[3] According to the Coast Forest Products Association,^[4] western red cedar tends to be more stable because it has a lower shrinkage factor than other Canadian softwood species. The resistance to decay, on the other hand, is attributed to extractives in the hardwood with strong fungicidal toxicity (such as thujaplicins and polyoxyphenolic compounds).^[5]

When drying this species, however, internal checks and collapse are common defects.^[6] In addition, western red cedar is known to produce a relatively large percentage of wet pieces after drying.^[7] This is believed to be caused

by zones in the wood with anomalous high moisture content and low diffusion coefficient.^[8]

The typical solution for minimizing internal checks and collapse is drying slowly at relatively low temperatures.^[9] For example, anecdotal information from the local industry suggests that drying 50-mm-thick western red cedar typically takes two weeks in conventional kilns. This relatively long drying time in comparison with other available softwood species in Canada proposes a competitive disadvantage for many commercial applications. For this reason, drying with superheated steam has been proposed as a potentially viable alternative to dry this species.

The objective of this study, therefore, is to explore the potential of this technology for drying western red cedar towards a subsequent full-scale study or industrial implementation.

Drying with Superheated Steam

In simple words, drying with superheated steam consists of exposing a substance to water vapor at temperatures above the boiling point of water. At such temperatures, the water can literally boil within the substance, thus increasing the speed at which vapor can be removed from inside a porous material. For a detailed description of this technology the reader is referred to the book *Advanced Drying Technologies* by Kudra and Mujumdar.^[10]

Drying with superheated steam is a well-established industrial technology, with over 100 large-scale operations, but there are still only a limited number of commercial applications.^[11] Among those applications, at least at the laboratory scale, there are agricultural products,^[12,13,14] wood products,^[15,16] and inorganic materials.^[17,18] Mathematical models to describe the drying kinetic in superheated steam have also been reported in the literature.^[19,20] In particular, Elustondo et al. deduced the following semi-empirical model to describe the drying rate:

$$\frac{dMC}{dt} = -200 \cdot A \cdot \left(\frac{h}{\rho \cdot L \cdot \Delta H} \right) \cdot (T - T_w) \cdot \left(\frac{MC - B \cdot EMC}{MC_0 - B \cdot EMC} \right) \quad (1)$$

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where MC, MC₀, EMC are the actual, initial, and equilibrium moisture contents (%), T and T_W are the actual and boiling point temperatures (°C), t is the time (s), A and B are empirical fitting parameters (dimensionless), ρ is the wood basic density (kg/m³), ΔH is the water heat of evaporation (J/kg), L is the wood thickness (m), and h is the heat transfer coefficient of the superheated steam (W/m²·°C). For the particular case of drying 76-mm-thick hemlock in superheated steam, the fitting parameters were found in average A = 1.36 and B = 1.24.^[20]

If Eq. (1) provides an acceptable representation of the drying rate in drying softwood lumber with superheated steam, then the difference between T and T_W should control the drying rate in the initial phases of drying, and the difference between MC and EMC should control the drying rate in the final phases of drying. This principle is revisited in this study for developing drying schedules by trial and error.

MATERIALS AND METHODS

The drying tests were performed in a laboratory-scale superheated steam vacuum drier (property of FPInnovations, British Columbia, Canada). The drier was basically a 5-m-long by 1.2-m-diameter stainless-steel tube connected to an external vacuum pump for controlling the chamber pressure, and an external hot-oil heating system for controlling the steam temperature. Inside the drier, there were 11 32-cm-diameter fans in a line capable of providing steam velocities of 20 m/s if the absolute pressure was below 0.5 bars.

The fans were located in the top half of the stainless-steel tube, while the lumber was arranged in a rectangular stack placed in the bottom half. This reduced the net volume of the drier to a rectangular 0.7 m by 0.7 m by 5 m chamber with capacity for approximately 1 m³ of lumber, depending on the width and thickness. In the case of this study, the lumber dimensions were 50 mm by 150 mm; thus there was enough space in the chamber to accommodate 24 boards arranged in six layers separated by 19 mm stickers.

For illustration, Fig. 1 shows a photograph of a 24-piece lumber stack before it was introduced in the kiln. A local sawmill provided a 208-piece package of freshly cut 50 mm × 150 mm × 5 m western red cedar lumber, thus containing enough material for eight consecutive drying runs. Run #3, unfortunately, had to be aborted because of technical issues.

Since the authors were not aware of any Canadian companies currently drying western red cedar with superheated steam, the experiments were not designed to perform a statistical analysis of the process, but rather to explore the potential of this technology as a viable industrial alternative. Consequently, the comparisons were made with lumber coming from the same package, and the results were assessed by following common industrial practices.

FIG. 1. Picture of a 24-piece lumber stack before it was introduced in the kiln.

More specifically, lumber quality was assessed through visual observations based on a grader's personal perception of drying degrade, and the lumber moisture content at the end of drying was measured with a commercial Wagner L620 digital MC meter every 25 cm along the upper and lower surfaces of each board. Of course, there was a certain error associated with measuring lumber moisture content with electric capacitance meters,^[21] but these values are widely accepted in industry for quality control.

For measuring the average lumber MC during drying, the controller had available 10 in-kiln MC sensors based on the principle of electric conductivity. Each of these sensors was basically a long cable with a couple of metallic pins at the end that were inserted into the core of the lumber. As an example, Fig. 2 shows a picture of an in-kiln MC sensor inserted in a board before drying.

The initial moisture content was not necessary for controlling the process, but it was estimated for reference after drying. The initial moisture content (MC₀) was estimated through the following equation on the basis of the initial weight (W₀) and final weight (W):

$$MC_0 = \left(\frac{W_0}{W} \right) \cdot (MC + 100) - 100 \quad (2)$$

Drying Schedules

The drying rate in superheated steam drying is typically controlled through the temperature and pressure of the steam. To draw a comparison with conventional drying, the temperature of the steam is the equivalent of the dry-bulb temperature, and the pressure of the steam determines the boiling point of water, which can be compared with the wet-bulb temperature.

FIG. 2. Picture of an in-kiln MC sensor inserted in the lumber before drying.

As a standard feature of the drier, however, the controller offered a method to generate drying schedules based on the combination of two tables, namely the temperature table (T) and the relative pressure table (RH), where RH was defined as the ratio between the pressure of the steam (P) and equilibrium vapor pressure (P_{eq}) at the same temperature:

$$RH = \frac{P}{P_{eq}} \quad (3)$$

In the analogy with conventional drying, RH would be the equivalent of relative humidity, which is defined as the ratio between partial vapor pressure in air and equilibrium vapor pressure at the same temperature.

The controller offered the possibility of choosing among 10 T and 10 RH preprogramed schedules that were implemented through six successive steps controlled by MC and/or drying time. The schedule steps started with a heating period controlled by time, continued with four successive steps in which T and RH were linearly updated depending on the lumber MC (although they could be also updated by time), and ended with a conditioning stage also controlled by time.

RESULTS AND DISCUSSION

All of the drying schedules tested in this study are reported in Table 1. In addition, Table 2 reports the same

schedules, but transformed into equilibrium moisture content (EMC) and the equivalent of wet-bulb depression (ΔT). The equilibrium moisture content was calculated through Hailwood and Horrobin's equation^[22] on the basis of the RH parameter, which is thermodynamically identical to the definition of relative humidity in air. The equivalent of wet-bulb depression was defined as the difference between the temperature of the steam and the boiling point of water ($T - T_w$).

The initial and final MC distributions are reported in Figs. 3 and 4, respectively. Figure 3 reports the initial MC distributions calculated from the measured final MC and initial and final weights, and Fig. 4 reports the final MC distributions measured with the hand-held MC meter.

From Fig. 3, it is apparent that the combined MC distributions of all runs tend to describe a log-normal probability curve. Nevertheless, it was not the purpose of this study to report a statistical analysis of the process. For the purpose of this exploratory study, the final MC distributions were reported by sorting the lumber into three MC groups that are customarily associated with lumber quality in industry. These three MC groups were defined as follows:

- Wets: Pieces that finalize drying with average MC > 20%. This is a real definition in industry because most sawmills have the capability to measure final MC after drying. If the MC is higher than a certain threshold, then sawmills automatically reject those pieces into a lower grade.
- Over-dried: Pieces that finalize drying with average MC < 10%. Even though sawmills do not automatically reject pieces based on low MC, it is generally accepted in industry that MC below a certain threshold tend to be associated with unacceptable distortion and problems at the planer.
- On-range: Pieces that finalize drying with average MC between 10% and 20%.

It must be pointed out that the 10% and 20% thresholds are arbitrary definitions based on the authors' experience in working with this species of lumber. The results of initial and final MC, drying time, overall drying rate, and percentages of wets and over-dried for the different schedules are reported in Table 3.

For the first run, it was assumed that the mildest conditions recommended by the manufacturer should result in one of the best qualities possible with its piece of equipment. Consequently, the drying schedule for Run #1 was created automatically from the tables by selecting schedules 1 for T and schedule 1 for RH. These schedules represent the lowest temperature and highest relative pressure recommended by the manufacturer.

The results of Run #1 basically confirmed that assumption. From 24 boards, only four developed some warp and three developed new checks after drying, and the magnitude

TABLE 1
Superheated steam drying schedules based on the T and RH parameters

Steps	Run #1		Run #2		Run #4		Run #5		Run #6		Run #7		Run #8	
	T °C	RH %	T °C	RH %	T °C	RH %	T °C	RH %	T °C	RH %	T °C	RH %	T °C	RH %
4 hrs	50	97	50	95	50	95	50	96	50	96	60	97	60	97
40% MC	50	95	50	89	50	90	50	91	50	93	60	94	60	92
30% MC	55	89	55	80	55	82	55	84	55	87	65	89	65	86
20% MC	60	72	60	72	60	75	60	76	60	75	70	78	70	78
15% MC	65	42	65	70	65	74	65	75	65	74	75	77	75	77
15 hrs	55	50	55	80										

T: Steam temperature; RH: Steam relative pressure.

TABLE 2
Superheated steam drying schedules based on the EMC and ΔT parameters

Steps	Run #1		Run #2		Run #4		Run #5		Run #6		Run #7		Run #8	
	E %	ΔT °C	E %	ΔT °C	E %	ΔT °C	E %	ΔT °C	E %	ΔT °C	E %	ΔT °C	E %	ΔT °C
4 hrs	24	1.7	22	2.2	22	2.2	23	2.0	23	2.0	23	1.3	23	1.3
40% MC	22	2.2	18	3.5	19	3.3	19	3.1	20	2.6	20	2.0	19	2.5
30% MC	18	3.4	14	5.7	15	5.1	15	4.6	17	3.9	17	3.1	15	3.9
20% MC	11	7.9	11	7.9	12	7.0	12	6.7	12	7.0	12	6.0	12	6.0
15% MC	6	19	11	8.5	12	7.3	12	7.0	12	7.3	12	6.3	12	6.3
15 hrs	8	15	14	5.7										

E: EMC (equilibrium moisture content); ΔT : Wet-bulb depression.

of these defects were close to negligible for industrial standards. This, of course, was based on the grader's opinion, but it allowed defining a reference quality to compare the results obtained with the other schedules. To visualize the meaning of this reference, Fig. 5 shows some boards that approximately represent the type lumber quality that was observed in Run #1.

FIG. 3. Initial MC distributions as calculated from weights and final MCs.

The results in terms of drying time and MC distribution were also promissory. Total drying time was 59 hr, and the percentage of wets was 12.5%. In western Canada, for example, the same lumber is dried in approximately two weeks and results in approximately 10% and 15% of wet lumber. On the negative side, the percentage of over-dried pieces was 16.7%. Over-dried lumber is certainly not desirable in industry because it tends to increase shrinkage and distortion.

For Run #2, the expectation was to reduce both drying time and the percentage of over-dried lumber. It was expected from Eq. (1) that increasing ΔT from approximately 2.8°C to 4.6°C in the initial phase would almost duplicate the initial drying rate, while increasing EMC from approximately 8% to 14% in the conditioning stage would considerably reduce the percentage of over-dried lumber. The results again confirmed the assumption, total drying time reduced from 59 hr to 39 hr, and the percentage wets reduced to 0%.

On the negative side, the quality of the lumber after Run #2 was surprisingly low. It was not the amount of pieces with drying defects that considerably increased, but the magnitude of the checks. In simple words, some pieces of lumber were practically split in the middle. As an example,

FIG. 4. Final MC distributions as measured with a hand-held MC meter.

Fig. 6 shows the magnitude of the checks that were observed in some boards after Run #2. Increasing EMC from 8% to 14% in the conditioning stage also had negative consequences. Even though the percentage of over-dried lumber reduced to zero, the percentage of wet lumber increased proportionally to 25%.

For the following runs, the objective was to gradually reduce ΔT in the initial phase until the quality became closer to the high quality that was obtained in Run #1. In

FIG. 5. Picture of boards representing the type of lumber quality obtained in Run #1.

addition, it was decided to remove the conditioning stage from the schedule and replace it by a 12% EMC in the final MC step. This was done to prevent the lumber from accidentally over-drying in practice if the in-kiln MC sensors were placed, by chance, on an unrealistic number of wet spots.

It was found that both the overall drying rate and the magnitude of checks reduced consistently from Run #2 to Run #6 as the ΔT was reduced from approximately 4.8°C to 3.3°C in the initial phase. In Run #6, in particular, the quality of the lumber was not different from the quality obtained in Run #1. The percentages of wet lumber were difficult to compare due to the experimental error, but there was no clear evidence of any significant differences other than a lower percentage of over-dried lumber in Run #6.

The remaining two runs were used to test the principle described by Eq. (1). For both Run #7 and Run #8, the T was increased 10°C with respect to Run #6; however, for Run #7 the RH was modified to obtain approximately the same EMC than in Run #6, while for Run #8 the RH was modified to obtain approximately the same initial ΔT

TABLE 3
MC distribution comparison among the different drying runs

	Run #1%	Run #2%	Run #4%	Run #5%	Run #6%	Run #7%	Run #8%
Initial MC (%)	41.8	37.1	45.6	46.7	36.5	41.6	39.0
Final MC (%)	13.5	16.2	13.4	15.4	15.3	11.7	15.3
Drying time (hr)	59	39	61	63	46	83	49
Drying rate (%/hr)	0.48	0.54	0.53	0.50	0.46	0.36	0.48
Wets (%)	12.5	25.0	12.5	16.7	16.7	8.3	16.7
Over-dried (%)	16.7	0.0	12.5	4.2	4.2	62.5	8.3

Drying rate: (initial MC – final MC)/drying time; Wets: MC > 20%; Over-dried: MC < 10%.

FIG. 6. Picture of a board representing the magnitude of the checks obtained in Run #2.

than in Run #6. Consistent with Eq. (1), reducing the initial ΔT in Run #7 resulted in a lower drying rate, even though EMC was the same as in Run #6.

As a final note, it could be added that Run #7 unintentionally tested the benefits of using a relatively high EMC in the final MC step of the schedule. It is probable that the in-kiln MC sensors in Run #7 accidentally overrepresented wet pieces, thus lumber dried for 83 hr. Even though the lumber considerably over-dry according to the definition used in this study ($MC < 10\%$), Fig. 7 shows that only two pieces ended with MC slightly below 9% (as measured after drying with a hand held MC meter).

Notes on Industrial Implementation

One of the conclusions of this study is that the results in term of lumber quality were very sensitive to small

FIG. 7. Detailed final moisture content distribution measured in Run #7.

variations in the wet-bulb depression. It was found that by using between 2.2°C and 3.4°C wet-bulb depression the process produced negligible quality degrade, but by using between 3.5°C and 5.7°C wet-bulb depression the process produced unacceptable checks.

This must be taken into consideration when scaling up these laboratory results to industrial driers with considerable temperature drop across the load. In industrial driers, the dry-bulb reduces as the vapor flows throughout the lumber stack, and this in turn reduces the wet-bulb depression.

Other problems with the industrial implementation could be operation and capital costs. Superheated steam technology may be more complex to operate and maintain due to the need of vacuum. In addition, superheated steam driers are comparatively more expensive than conventional kilns.

For example, the manufacturer of the equipment used in this study provided a detailed quotation for an industrial scale drier. As of August 2012, a drier with capacity for 53 m^3 would cost approximately \$500,000 (excluding foundation and rails). If it were confirmed in industry that superheated steam reduces drying time from two weeks to three days, then this means that \$500,000 would buy the equivalent of a 250 m^3 conventional kiln.

Of course, it would be difficult to determine here if this is competitive or not. However, it could be argued that having the capability of drying small volumes in short periods of time could be advantageous for stock management if different high value products need to be dried discontinuously throughout the year.

CONCLUSIONS

This exploratory study evaluated the possibility of drying 50-mm-thick western red cedar in superheated steam. Since the authors were not aware of any industrial facilities currently using superheated steam for western red cedar, the study was designed to explore the potential of this technology in terms of drying time, lumber quality, and moisture content distribution. The results were very promising from the industrial viewpoint. The experiments showed that the 50 mm lumber can be dried in less than three days without jeopardizing quality, in comparison with the two weeks that is currently required in conventional kilns, and the percentage of pieces that remain wet after drying seems to be within the 10% to 15% range that is typically tolerated in industry.

The lumber quality, in the opinion of the authors, seemed to be superior to the quality that is typically observed after conventional drying. From visual observations, it was found that the magnitude of warp and checks was almost negligible when very low wet-bulb depressions were used in the first stages of drying. The problem, however, was that these results were very sensitive to small variations in the wet-bulb depression. It was found that by using between 2.2°C and 3.4°C wet-bulb depression, the process produced negligible quality degrade, but by

using between 3.5°C and 5.7°C wet-bulb depression the process produced unacceptable checks. This must be taken into consideration when scaling up laboratory results to industrial driers with considerable temperature drop across the load. From the lessons learned in this study, relatively small temperature differences in the first phases of drying could be the difference between negligible and unacceptable checks.

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