HEATING PERFORMANCE OF FROZEN LODGEPOLE PINE LUMBER

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Abstract. This study was undertaken to determine the heating process of frozen lodgepole pine (*Pinus contorta*) lumber because many regions in Canada have to heat-treat or dry frozen lumber in the winter. Because phytosanitary regulations require that lumber products be heat-treated before delivery to customers (core wood temperature of 56°C for 30 min), it is important to determine the time required to reach this criterion. In this study, 10 heating runs were made with different initial moisture contents (MCs) and temperatures using a laboratory kiln humidified with low-pressure steam or cold water spray. To simulate the performance of frozen lumber, the existing heating model for unfrozen lumber was modified by adding a phase-change analysis and was verified using the data from laboratory experiments. The experimental results combined with the model predictions indicated that the thawing time was increased for frozen lumber with higher initial MC. The modified model satisfactorily estimates heating times for frozen lodgepole pine lumber.

Keywords: Frozen lumber, heating performance, model prediction, thawing time.

INTRODUCTION

With a view to optimizing the heat treatment process, operators must accurately predict the time that is required for the core of the lumber to reach a certain value. Simpson (2001) estimated heating times for round and rectangular cross-sections of wood using the equations developed by MacLean (1930, 1932). The results showed that heating times can be predicted accurately when the kiln was humidified by steam with a small wet-bulb temperature depression. However, inaccurate estimates were obtained when the lumber was heated in the kiln without a humidification system. Simpson (2004) developed equations using a two-dimensional finite-difference heat flow analysis. Those equations were successfully used to predict heating up times for ponderosa pine and Douglas-fir timber squares. Simpson et al (2003) compared heating times between solid piling and stickered piling. Depending on species and size, the solid piling increased heating time by a factor of 2-10 compared with stickered piling. Simpson et al (2005) and Simpson (2006) also explored the effect of size, species, and wet-bulb depression on heating times at 71°C. The time required to heat the center of lumber with saturated steam was estimated using heat conduction equations for a number of combinations of these variables. Cai (2005) examined the impact of initial moisture content (MC) in lumber on heating rates and developed a computer program to predict heating times during heat treatment.

However, all of the previously mentioned studies dealt with unfrozen lumber. While free water exists in wood in the form of ice in frozen lumber, the MC of wood influences the percentage of ice in the lumber. In view of the fact that the thermal conductivity of ice differs from that of water, it is important to investigate the heating behavior in frozen lumber to design an optimum kiln drying/heat treatment schedule. Limited studies have presented experimental and calculated values regarding heating times for frozen

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veneer logs (Steinhagen 1977, 1986; Steinhagen and Lee 1988). Using a commercial software program (COMSOL), an estimation of heating times for frozen logs and lumber was investigated by Peralta and Bangi (2006). However, the complexity of the commercial software makes application difficult.

The major objectives of the project were: 1) to adapt an existing heating model for unfrozen lumber (Cai 2005) to simulate the heating performance in frozen lumber; and 2) to verify the model using the experimental data.

MATERIALS AND METHODS

Specimen Preparation and Pilot Kiln

Green lodgepole pine (*Pinus contorta*) 38 mm × 89 mm × 3-m lumber, which was separated into wet and dry sorts, was supplied by a mill located in the Interior of British Columbia. The average initial MC for the dry sort was 20.5% (SD = 4.2%) and that for the wet sort was 63.2% (SD = 33.4%). The specimens (about 2000 pieces) were block-piled to minimize moisture loss during transportation and storage. Each 3-m specimen was cut into a 2.44-m long section. Individual initial MC was determined by oven-drying wood discs that were trimmed from each end of the specimens (Cai and Oliveira 2007). Individual width and thickness of specimens were determined using a caliper.

Lumber from the dry and wet sorts was divided into two groups. One was acclimatized at –8°C (high temperature group) while the second was acclimatized at –25°C (low temperature group). Although the specimens were cooled to –8° and –25°C, their temperatures at the beginning of drying were slightly higher (Table 1) because the specimens were exposed to ambient temperatures for a short period during the preparation of each drying run.

The laboratory kiln used in this study had a volume of 5.9 m^3. Heat was supplied by two 48-kJ/s heater coils, and a low pressure steam and cold water spray system was used for humidification. The steam was provided by a boiler with a preset pressure of 103 kPa. The cold water spray was supplied provided by a pump at 6.9 MPa.

Heating Process

Each heating run consisted of 192 pieces of 38 mm × 89 mm × 2.44-m specimens. To

Table 1. Conditions and results for heating frozen lumber.

Run no.	Description	Initial temp (°C)	Initial MC (%)	Thickness (mm)	Width (mm)	Time to 56°C (h) Exp.[a]	Calc.[b]	Deviation[c] (%)	Results shown in figure
1	Without humidification	−4.1	23.6	42.8	98.9	3.03	3.08	−1.65	4
2	Without humidification	−6.7	87.7	41.8	99.9	3.58	3.82	−6.70	4
3	Without humidification	−18.4	23.8	42.5	98.9	3.00	3	0.00	5
4	Without humidification	−18.5	76.5	41.3	99.2	3.75	3.68	1.87	5
5	Steam spray	−5.3	26.2	41.8	99.4	2.83	2.75	2.83	6
6	Steam spray	−5.7	82.1	41.4	100.0	2.96	2.92	1.35	6
7	Steam spray	−18.5	19.4	42.2	99.6	2.83	2.75	2.83	7
8	Steam spray	−23.2	76.9	42.5	99.7	3.04	3	1.32	7
9	Cold water spray	−7.4	25.7	42.8	98.9	2.57	2.67	−3.89	8
10	Cold water spray	−8.0	96.7	41.2	99.6	3.18	3.17	0.31	8

[a] Exp. = experimental data.
[b] Calc. = calculated values using the modified model.
[c] Deviation = (experiment – calculation)/experiment × %.

monitor the temperatures in the core of the lumber, a hole with 2.5-mm dia and 24-mm depth was drilled from the edge toward the center of each specimen and a 1.3-mm-dia J-type thermocouple inserted (Fig 1). A round toothpick and silicone glue were used to seal the hole. Twenty-four square-edge (without wane) specimens were randomly selected from the lumber pile for monitoring core temperatures. An accelerated schedule (Table 2) was used for the heating process.

Three heating scenarios (humidified with low pressure steam, humidified with cold water spray, and without humidification) were carried out as illustrated in Fig 2. Because the freezer used to acclimatize the specimens to –25°C failed before producing the subgroup to be tested with cold water spray, 6 and 4 runs were carried out for the high temperature group and low temperature group, respectively (Fig 2).

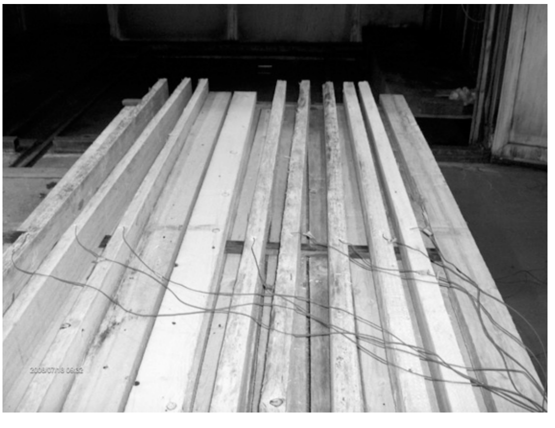

Figure 1. Thermocouples inserted into specimens.

Table 2. Accelerated schedule.

Ramp time (h)	Step time (h)	Total time (h)[a]	Dry bulb temperature (°C)	Wet bulb temperature (°C)	Air velocity (m/s)
4	—	4	88	83	3
2	—	6	93	77	3
—	50	60*	93	77	3

[a] Total kiln time depends on moisture content. Kiln stops when the target moisture content is reached.

Modification of the Existing Model

An existing heating model (Cai 2005) is capable of predicting heating times to reach 56°C based on lumber size, initial temperature, MC, dry/wet bulb temperatures, and air velocity. Because the model was developed to predict heating rates for unfrozen lumber, it needed to be adapted for frozen lumber.

When frozen lumber is heated in a dry kiln, ice is progressively melted from shell to core as a result of heat transfer from the hot air to the lumber surface. Heat flows by convection from the hot air to the surface of the lumber and by conduction through the frozen and unfrozen zones. During this process, the heat partially serves to warm the lumber and partially works to melt the ice by latent heat at the frozen–unfrozen interface. Thus, basically two calculations are used in this modified model.

Simulating the heating process using a numeric method. The existing heating model is used to estimate the temperature increase in the lumber during heat treatment. The governing equation for the conservation of energy is as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) \quad (1)$$

where T is the air temperature (°C); k_x and k_y are the thermal conductivities in x and y coordinate

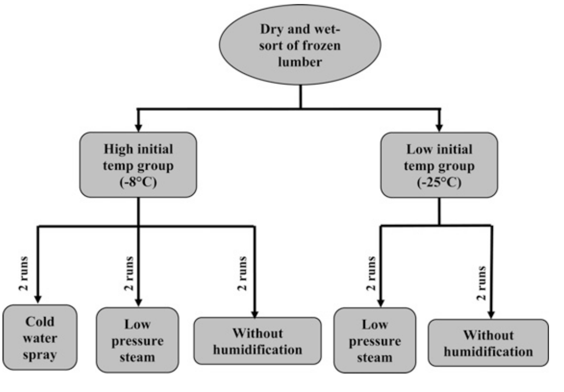

Figure 2. Initial frozen temperatures and scenarios used for 10 heating runs.

directions (W/m·K); ρ is the basic density of wood (kg/m^3); and C_p is the specific heat of wood (J/kg·K).

The boundary condition for Eq 1 can be described by:

$$-k\frac{\partial T}{\partial n}|_r = h(T_s - T_\infty)|_r + h_{ig}\dot{m}|_r \qquad (2)$$

where h is the heat transfer coefficient; W/m^2·K; T_s is the lumber surface temperature (°C); T_∞ is the kiln temperature (°C); h_{ig} is the latent heat of vaporization (J/kg); and $\dot{m}$ is the moisture flux (kg/m^{2}s).

Eq 1 is numerically solved (finite differences method) to develop temperature profiles in the wood as a function of time.

Estimating the thawing times using an approximate analytic solution. The following equation was used for the approximate analytic solution (Cai and Garrahan 2008):

$$\frac{T_\infty - T_\varepsilon}{\rho L_{wood}} t = \frac{1}{h_0}\varepsilon + \frac{\varepsilon^2}{2k} \qquad (3)$$

where T_∞ is the air temperature in the kiln (°C); T_ε is the temperature of unfrozen lumber adjacent to the frozen–unfrozen interface (°C); ρ is the density of wood (kg/m^3); L_{wood} is the latent heat of fusion of the frozen wood (J/kg); t is the thawing times (s); h_0 is the heat transfer coefficient (W/m^{2}K) on the air–wood interface; ε is the distance (m) from the surface to the frozen–unfrozen interface, which is a function of time (t); and k is the thermal conductivity of wood (W/m·K).

Combining the approximate analytic solution (Eq 3) and the heating model (Eq 1), a computer program was developed to estimate the temperatures during the heating of frozen lumber. When initial MC, density, dimension, initial temperature of the lumber, air velocity, and dry/wet-bulb temperatures of the kiln are entered the program, the change of temperature over time can be predicted.

RESULTS AND DISCUSSION

Heating Results

The results for heating frozen lodgepole pine lumber are shown in Table 1 and Figs 3-8. The data shown in Table 1 represent the average of 24 thermocouples inserted in 24 specimens.

a. When frozen lumber with a high MC was heated, the heating curve was flat near 0°C because the energy (latent heat) was being used to melt the ice in the core of lumber.
b. The thawing time and time to reach 56°C increased for frozen lumber with a higher initial MC. The average time to reach 56°C was 2.85 h for the low MC group (19–27%) and 3.3 h for the high MC group (70–98%).
c. The wet-bulb temperature depression in the runs without a humidification system was greater compared with the runs humidified by cold water or steam spray.

Validation of the Model

Using average initial MC, density, dimension, initial temperature of the lumber, air velocity, and dry/wet-bulb temperatures of the kiln as input variables for the model, the times to reach the temperature of 56°C in the core of the lumber were calculated as shown in Table 1. The deviations for the heating times between the experimental and calculated values were within ±7%. The temperature profiles were estimated and are shown in Figs 4-8. These figures show that the differences between calculated curves using the modified model and the experimental data are within an acceptable range. However, discrepancies between the experimental and calculated curves near 0°C can be observed in Figs 4, 5, and 6. These differences can be attributed to errors caused by the determinations of initial MC. The initial MC discs were trimmed from both ends of the specimens, while the thermocouples were inserted into the middle of the specimens (Fig 1). Along a length of lumber, MC can vary significantly.

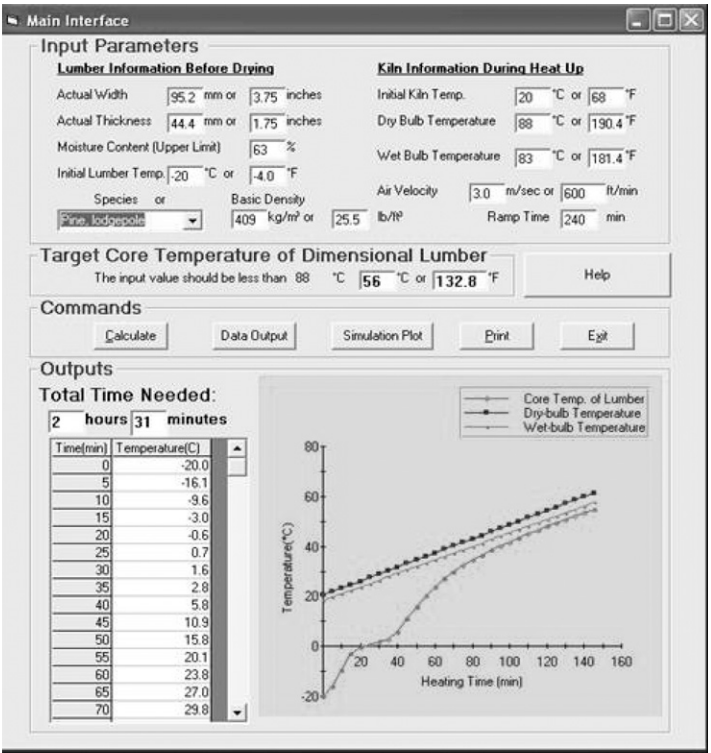

Figure 3. Interface for calculating time to reach 56°C in frozen lumber.

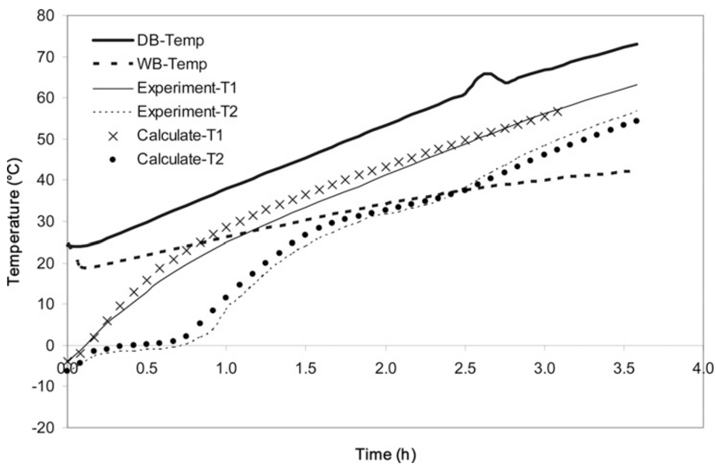

Figure 4. Frozen lumber (high temperature group) heated in the kiln without humidification (T1 = 23.6% MC and T2 = 87.7% MC).

CONCLUSIONS

The results of the experiments and the model simulation indicated that the thawing time and time to reach 56°C increased for frozen lumber with a higher initial MC. When frozen lumber with a high MC is heated, the heating curve is flat near 0°C because the energy (latent heat) is being used to melt the ice in the core of lumber.

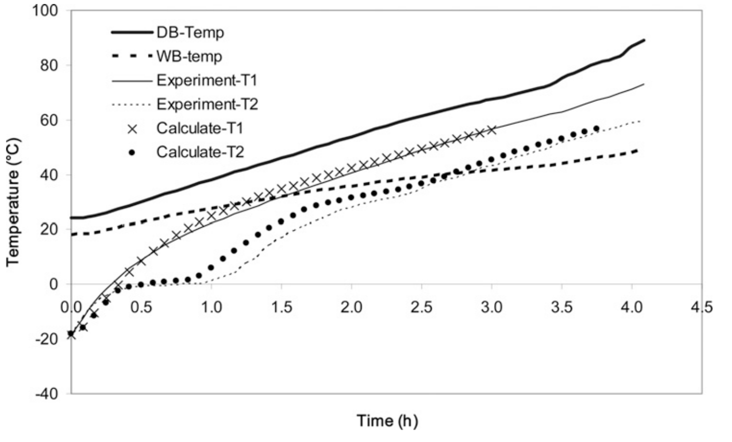

Figure 5. Frozen lumber (low temperature group) heated in the kiln without humidification (T1 = 23.8% MC and T2 = 76.5% MC).

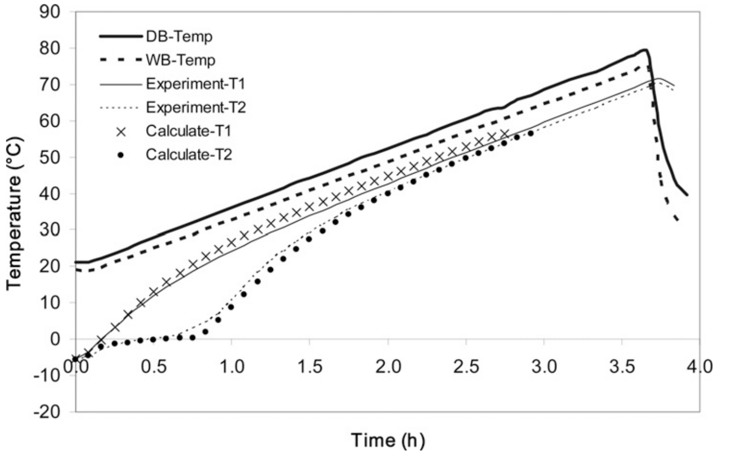

Figure 6. Frozen lumber (high temperature group) heated in the kiln with steam (T1 = 26.2% MC and T2 = 82.1% MC).

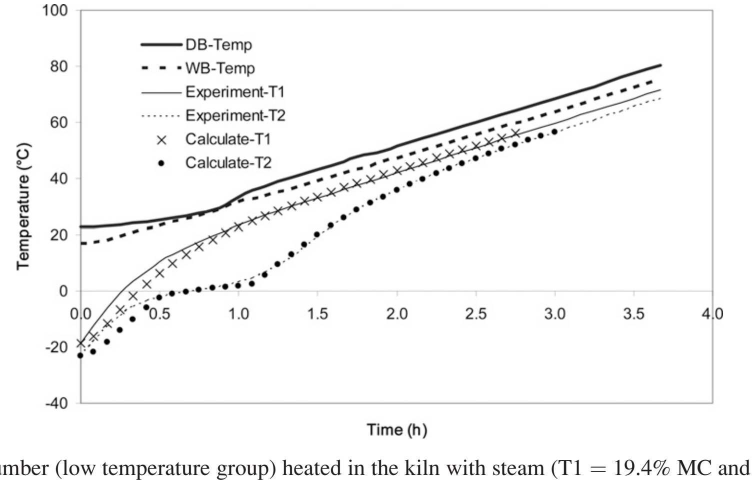

Figure 7. Frozen lumber (low temperature group) heated in the kiln with steam (T1 = 19.4% MC and T2 = 76.9% MC).

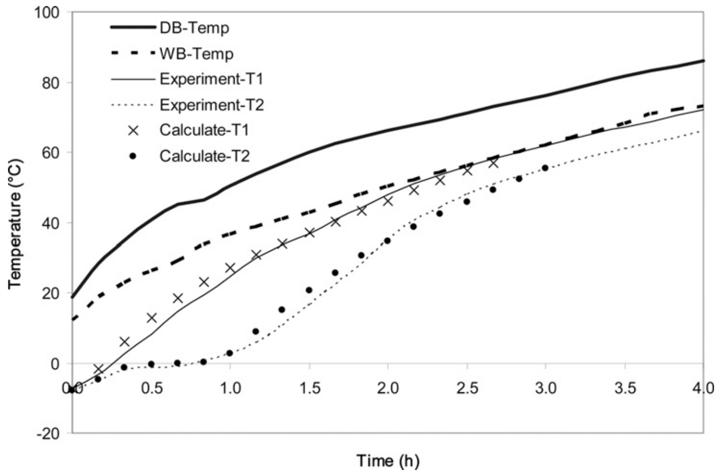

Figure 8. Frozen lumber (high temperature group) heated in the kiln with cold water spray (T1 = 25.7% MC and T2 = 96.7% MC).

The modified model in this study is capable of satisfactorily predicting the heating time required for frozen lodgepole pine lumber.

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