AN ESTIMATION OF HEATING RATES IN SUB-ALPINE FIR LUMBER

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ABSTRACT

The objectives of this research were to explore the effects of moisture content on heating rates in sub-alpine fir lumber and to develop a user-friendly computer program to predict heating times during heat-treatment. A correction factor ϵ that can adjust the mass transfer coefficient based on the change of the moisture content was determined through the experiments. When moisture content, density, lumber size, initial and target temperatures, air velocity, dry-bulb and wet-bulb temperatures of the kiln are entered, the change of temperature with time can be predicted by the program. The results from the experiments and the data of previous publications confirmed that the program can be used to estimate heating times not only for sub-alpine fir, but also for other species. The results also indicated that heating wood with higher moisture content requires more energy and longer time than that with lower moisture content.

Keywords: Heat-treatment, heating rate, mass transfer.

INTRODUCTION

The advantage of wood heat-treatment is that it improves resistance to fungal decay without using wood preservatives (van Zuylen 1995). It is of interest to know how fast heat is transferred from the surface to the center of lumber during the heat-treatment process. Hou et al. (2002) theoretically calculated moisture and heat transfer in lumber during preheating. From their calculations, it takes about 3 h for the center of 4-cm-thick lumber to reach the ambient temperature during preheating in a kiln with 100% relative humidity. Tremblay et al. (2000) experimentally determined the convective heat and mass transfer coefficients for wood drying and indicated that the convective mass transfer coefficient was constant until the moisture content (*mc*) on the wood surface reached about 80%. Then it decreased more or less gradually as *mc* decreased.

When the heating medium is steam, i.e. when wet-bulb temperature (WT) depression is very small (from 0.6°C to 1.7°C), the heating times can be estimated accurately. However, inaccurate estimates are obtained when dry heat is applied (Simpson 2001; Gu and Garrahan 1984).

To improve the inaccurate estimates during dry heat, the effect of *mc* of sub-alpine fir lumber on heating rate is investigated, and a computer program that can predict the heating time is developed in this study. The program takes WT depression and air velocity (v) into account. Sub-alpine fir is used in the study because it usually exhibits large amounts of wood containing wet-pockets.

MATHEMATICAL FORMULATION

Lumber length is normally much greater than width and thickness, allowing a two-dimensional problem to be utilized in this study. The governing equation of energy conservation is as follows:

$$\frac{\partial\left(\rho_{wood} C_p T\right)}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \dot{q}_G \quad (1)$$

where T is the temperature, °C; k_x and k_y are the thermal conductivity in x and y coordinate directions, W/mK; $\dot{q}_G$ is the rate of heat generation per unit volume, W/m^3; ρ_{wood} is the basic density of the wood, kg/m^3; C_p is the specific heat of wood, J/kgK.

Free water has a higher thermal conductivity than bound water; thus it must be expressed as a function of *mc* (Siau 1995).

$$k = \rho_{wood}(0.200 + 0.38mc) + 0.0204) \quad mc < 0.4 \text{ and } T = 30°C \tag{2}$$

$$k = \rho_{wood}(0.200 + 0.52mc) + 0.0204) \quad mc > 0.4 \text{ and } T = 30°C \tag{3}$$

where k is the transverse thermal conductivity ($k_x = k_y = k$),W/mK.

The equations provided for k are all based on data taken at approximately 30°C. The following equation can be used for other temperatures (Siau 1995).

$$k = k_{30°C}\left[1 + 0.004(T - 30)\right] \tag{4}$$

The C_p as a function of *mc* can be expressed as follows (Siau 1995).

$$C_p = \frac{1260 + 4185mc}{1 + mc} \quad mc < 0.05 \text{ and } T = 30°C \tag{5}$$

$$C_p = \frac{1176 + 5859mc}{1 + mc} \quad 0.05 < mc < 0.30 \text{ and } T = 30°C \tag{6}$$

$$C_p = \frac{1678 + 4185mc}{1 + mc} \quad mc > 0.30 \text{ and } T = 30°C \tag{7}$$

For other temperatures (Siau 1995)

$$C_p = C_{p30°C}\left[1 + 0.004(T - 30)\right] \tag{8}$$

According to the Neuman (gradient) boundary condition:

$$-k\frac{\partial T}{\partial n}\Big|_r = h\left(T_s - T_\infty\right)\Big|_r + h_{ig}\dot{m}\Big|_r \tag{9}$$

where, *h* is the heat transfer coefficient, W/m^{2}K; T_s is the surface temperature, °C; T_∞ is the environment temperature, °C; h_{ig} is the latent heat of vaporization, J/kg; $\dot{m}$ is the moisture flux, kg/m^{2}s, and can be obtained as follows:

$$\dot{m} = h_m\left(\varepsilon\rho_s - \rho_\infty\right) \tag{10}$$

where h_m is the mass transfer coefficient, m/s; ε is a correction factor; ρ_s is the moisture concentration on the surface of wood, kg/m^3; ρ_∞ is the moisture concentration in the kiln, kg/m^3.

Since h_m is a function of v and h, they may be related by the Chilton-Colburn analogy (Pordage and Langrish 1999) and expressed as:

$$h_m = \frac{h}{\rho_g C_{pg}}\left(\frac{\Pr}{Sc}\right)^{\frac{2}{3}} \tag{11}$$

where, ρ_g is the density of the bulk gas, kg/m^3; C_{pg} is the specific heat capacity of the bulk gas, J/kgK; Pr is the Pradtl number, and Sc is the Schmidt number.

DETERMINATION OF THE CORRECTION FACTOR ε

The h_m obtained from Eq. (11) and ρ_s have a reference state defined as entirely free water at atmospheric pressure and ambient temperature. Since the free water on the surface of wood is reduced during the drying process, ρ_s cannot be defined as that of entirely free water. Therefore, a correction factor ε was employed to modify ρ_s. To determine the relationship between ϵ and *mc* of the wood, the following experiment was carried out.

A conditioning chamber with temperature kept constant at 60±1°C and relative humidity at 50 ± 1%, and a digital balance sensitive to 0.1 mg were used in the determination of factor ε. Fifty visually clear specimens at different *mc*'s were chosen for the tests. The specimens were cut to 50-mm (width) × 10-mm (thickness) × 100-mm (length) for transverse mass flux. Four edges of each specimen were coated with two layers of epoxy to restrict moisture movement. Then the specimens were placed in the chamber. During desorption (drying), the weight of each specimen was monitored with the digital balance. To obtain their oven-dry weights, the specimens were dried at 103 ± 2 °C to constant weight. The relationship between *mc* and ε is shown in Fig. 1.

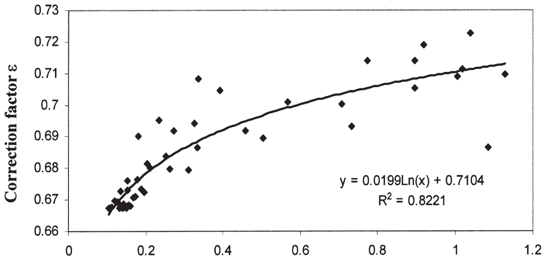

FIG. 1. The relationship between the *mc* and ε in sub-alpine fir at DT/WT = 60/56 °C (y = ε and x = *mc* in this equation).

As can be seen in Fig. 1, ε is reduced during drying process. It decreases rapidly after fiber saturation point.

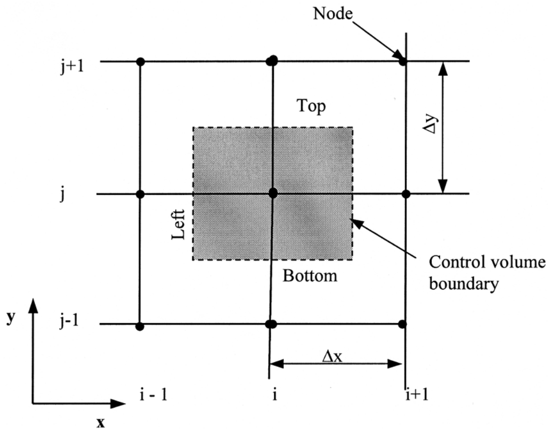

FIG. 2. Control volume for two-dimensional conduction.

NUMERICAL SIMULATION

Both k and C_p vary with *mc* and T, and therefore an analytical solution to Eq. 1 can be very complex. Thus, a numerical simulation is used in this study. Several methods, such as finite difference, finite element, and control volume approaches, are available for discretizing the differential equations of heat conduction. The control volume approach (Kreith and Bohn 2001) was chosen in this study, and it considers the energy balance on a small volume within the boundaries of the problem.

With the control-volume method, as in Fig. 2, the temperatures for the internal control volumes were calculated by

$$T_{i,j,m+1} = \frac{T_{i,j,m} + \alpha\Delta t\left(\frac{T_{i+1,j,m+1}+T_{i-1,j,m+1}}{\Delta x^2} + \frac{T_{i,j+1,m+1}+T_{i,j-1,m+1}}{\Delta y^2} + \frac{\dot{q}_G}{k}\right)}{1+2\alpha\Delta t\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}\right)}$$

$$1 < i < M,\ 1 < j < N \qquad (12)$$

where, i, j, Δx and Δy are shown in Fig. 2; Δt is the time difference, s; α is the thermal diffusivity $= k/(\rho_{wood}C_p)$, m^2/s; m is the iteration; M is the number of nodes on the x axis; N is the number of nodes on the y axis.

A boundary condition of surface convection is specified at the each edge of the lumber during drying. In the case of a corner situation, a control volume of width Δx/2 and height Δy/2 is considered, and the temperatures for the corner can be calculated by

$$\left(\frac{k}{\alpha}\frac{\Delta x\Delta y}{4\Delta t} + k\frac{\Delta y}{2\Delta x} + k\frac{\Delta x}{2\Delta y} + k\frac{\Delta y}{2}h + \frac{\Delta x}{2}h\right)T_{i,j,m+1} =$$
$$= \frac{k}{\alpha}\frac{\Delta x\Delta y}{4\Delta t}T_{i,j,m} + k\frac{\Delta y}{2\Delta x}T_{-1,j,m+1} + k\frac{\Delta x}{2\Delta y}T_{i,j-1,+1} + \dot{q}_G\frac{\Delta x\Delta y}{4} + \frac{\Delta y}{2}hT_\infty$$
$$+ \frac{\Delta x}{2}hT_\infty + h_{ig}\dot{m}\left(\frac{\Delta x+\Delta y}{2}\right) \qquad (13)$$

In the case of an edge situation, a control volume of width Δx/2 and height Δy is employed and the temperatures for the edge can be calculated by

$$T_{i,N,m+1} = \frac{T_{i,N,m} + \frac{2\Delta t}{\Delta x^2\rho_{wood}C_p}\left\{k\left(\frac{T_{i+1,N,m+1}+T_{i-1,N,m+1}}{2} + T_{i,N-1,m+1}\right) + \dot{q}_G\frac{\Delta x^2}{2} + h\Delta x T_\infty + h_{ig}\dot{m}\Delta y\right\}}{1+\frac{2\Delta t}{\Delta x^2\rho_{wood}C_p}(2k+h\Delta x)}$$

where $1 < i < M$ (14)

A user-friendly computer program was developed to estimate the temperature profile during heating. When ***mc***, ρ_{wood} and lumber size, initial and target temperatures, v, DT and WT of the kiln are provided for the program, the change of temperature with time can be predicted as shown in Fig. 3. The temperature distribution during heating can be recorded at any time interval. Fig. 4 shows the temperature distributions at a time stage in a heating example.

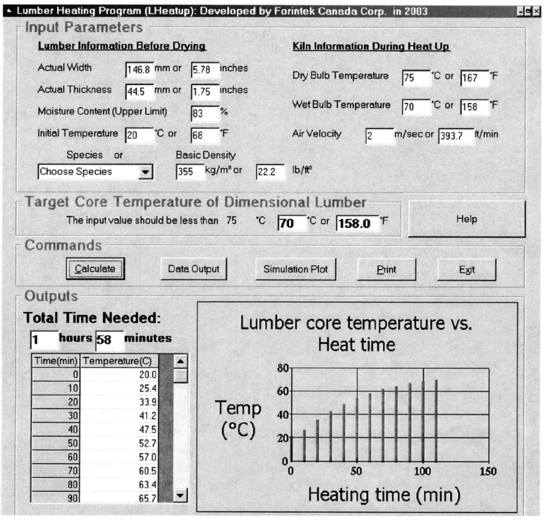

FIG. 3. Computer program to predict heating time.

COMPARISONS OF THE RESULTS BETWEEN SIMULATION AND EXPERIMENTS

Comparing with experiment results

Sub-alpine fir fresh boards with dimensions of 5.08 × 15.24 × 91.44-cm were used in the experiment. A 2.5-mm-diameter hole was drilled from the edge into each board to the geometric center in which a 1.3-mm-diameter thermocouple was inserted. A round toothpick and silicon were used to seal the hole. To determine *mc* and ρ_{wood}, a small block (25.4 × 25.4 × 25.4 mm) where the thermocouple was placed was cut from the center of the lumber after the heating experiment.

Four heating runs with different DT/WT were carried out by a laboratory kiln with a capacity of 0.5 m^3. The v was kept at 3.8 m/s for all runs.

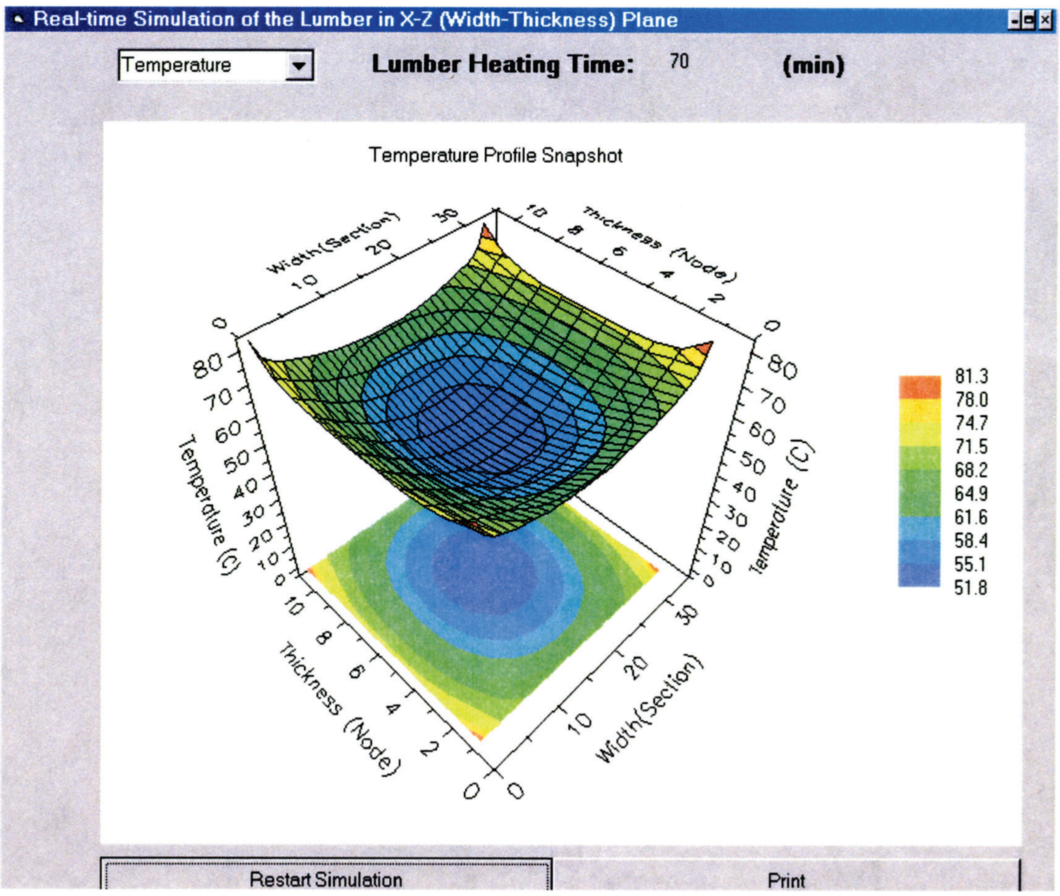

FIG. 4. Temperature distribution when heating time = 70 min.

Run 1: The boards were heated with DT = WT = 80°C, and the results are shown in Fig. 5.

Run 2: The boards were heated with DT = WT = 60°C, and the results are shown in Fig. 6.

Run 3: The boards were heated with DT = 80°C, WT = 72°C, and the results are shown in Fig. 7.

Run 4: The boards were heated with DT = 80°C, WT = 56°C, and the results are shown in Fig. 8.

There were two specimens in Runs 1, 2, and 4 and three specimens in Run 3. Each specimen had five testing sections with five thermocouples. The T and *mc* in Figs. 5 to 8 are the average of the five values from these five testing sections. Figures 5 to 8 show that the calculations agree with the experimental results well.

Comparison with the experiment results in previous publications

Heating time data from Simpson (2001) was used to check the calculation results as shown in Tables 1 and 2. The v in the calculations were assumed to be 3.8 m/s. Tables 1 and 2 show that the calculation is capable of predicting heating times in thicker stock to within ± 23%. There were greater errors in thinner boards. Some errors probably occurred in placing the thermocouples in the exact geometric center of the boards (Simpson 2001).

Heating time data from a previous Forintek publication (1991) were used to check the calculation results as shown in Table 3. As have been seen in Table 3, the calculation predicts heating times in these boards to within ± 22%.

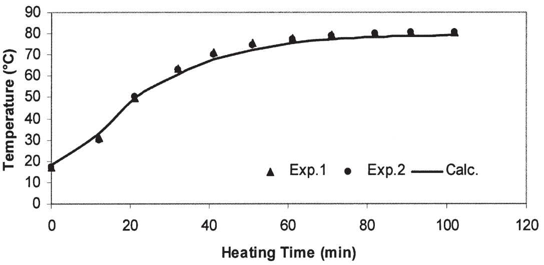

FIG. 5. Calculation VS. experiment when DT = WT = 80°C and *mc* = 0.42.

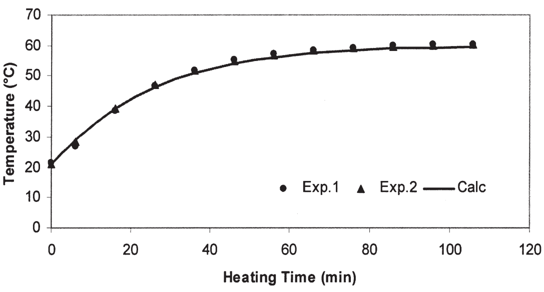

FIG. 6. Calculation VS. experiment when DT = WT = 60°C and *mc* = 0.63.

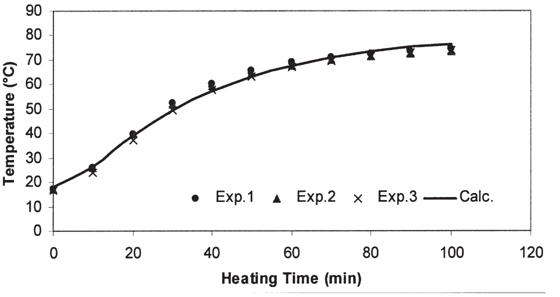

FIG. 7. Calculation VS. experiment when DT = 80°C,WT = 72°C, ***mc*** = 0.42.

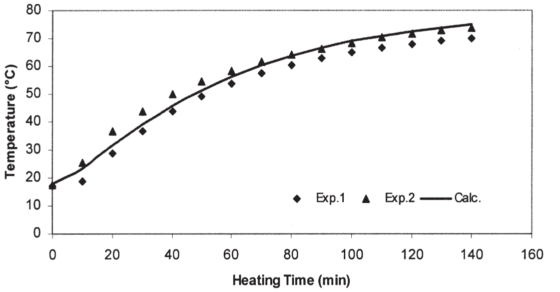

FIG. 8. Calculation VS. experiment when DT = 80°C, WT = 56°C, *mc* = 0.63.

A COMPARISON OF HEATING CURVES BETWEEN NORMAL AND WET WOOD

It can be seen from Eq. (9) that the boundary condition is affected by $\dot{m}$ during heating. Since heat is consumed by vaporizing moisture, the greater $\dot{m}$ occurs, the lower T is. In addition, *mc*

TABLE 1. *Data on heating aspen and red maple to center temperature of 54 °C with steam spray at temperature of 85 °C.*

Species	Thickness (m)	Width (m)	Moisture content (%)	Density (kg/m³)	Initial temp. (°C)	Experiment[1] time (min)	Calculated[2] time (min)	Deviation[3] (%)
Aspen	0.1321	0.1397	85	411	14.44	133	125	6.02
	0.1499	0.1524	89	432	13.89	171	155	9.36
Maple	0.1524	0.1651	62	560	11.11	201	177.33	11.78
	0.1524	0.1778	71	543	7.78	214	199.67	6.70
	0.1422	0.1422	53	525	13.89	142	134.33	5.40
Absolute average								***7.85***
Aspen	0.0813	0.0889	95	373	16.11	46.6	53.33	–14.44
Maple	0.0813	0.1549	73	483	14.44	70.8	80	–12.99
	0.0737	0.1092	81	527	15.56	60.0	63.33	–5.55
	0.0813	0.1778	39	530	14.44	88.2	86	2.49
	0.0813	0.1905	80	523	15.00	94.2	86	8.70
Absolute average								***8.84***
Aspen	0.0279	0.1143	82	397	17.22	17.0	12	29.41
	0.0279	0.160	91	418	18.33	13.2	11.67	11.59
	0.0305	0.1143	90	423	20.0	13.5	14.33	–6.15
	0.033	0.1473	116	382	20.0	14.3	16	–11.89
	0.0305	0.0940	109	379	20.0	10.4	15.67	–50.67
Maple	0.0236	0.1397	53	520	15.56	8.3	8.67	–4.46
	0.0279	0.1753	74	523	16.11	14.0	12.33	11.93
	0.0279	0.1549	68	524	17.78	12	12	0.00
	0.0305	0.1702	72	501	16.67	11.1	14	–26.13
	0.0279	0.1092	50	537	17.22	10.6	12.33	–16.32
	0.0279	0.1346	46	536	17.78	11.7	11.33	3.16
	0.0279	0.1473	57	544	18.89	12.8	11.67	8.83
	0.0279	0.1473	68	534	17.22	16.5	12.33	25.27
	0.0305	0.1041	60	470	20.56	10.8	13.67	–26.57
	0.0305	0.2032	86	509	19.44	15.4	14	9.09
Absolute average								***16.10***

1. Experiment data from Simpson (2001)
2. Calculated by using this program
3. Deviation = (experiment-calculation)/experiment×%

also affects k and C_p as shown in Eqs. (2), (3), (5), (6) and (7). Comparing the heating times of higher *mc* sections and that of lower ***mc*** sections in sub-alpine fir lumber, it can be seen that the heating time for higher *mc* wood is longer than that for lower *mc* wood (Fig. 9). In this case, the *mc* of lower section was 0.42 and that of higher section was 0.95 while DT/WT were 80/72 °C.

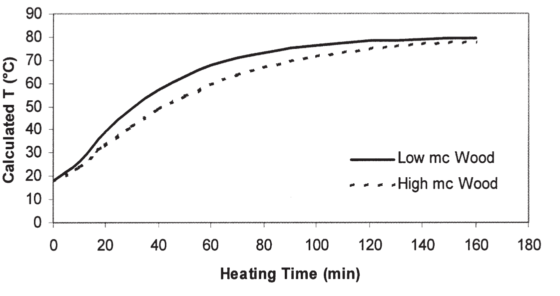

FIG. 9. A comparison of hearting curves between low *mc* wood (*mc* = 0.42) and high mc wood (*mc* = 0.95).

CONCLUSIONS

A computer program predicting the heating times in sub-alpine fir lumber was developed. The results from the experiments and the data of

TABLE 2. *Data on heating aspen and red maple to center temperature of 54 °C with 85 °C dry-bulb temperature and 54 °C wet-bulb temperature.*

Species	Thickness (m)	Width (m)	Moisture content (%)	Density (kg/m³)	Initial temp. (°C)	Experiment[1] time (min)	Calculated[2] time (min)	Deviation[3] (%)
Aspen	0.1422	0.1372	88	400	14.44	294	227.33	22.68
	0.1549	0.1549	83	414	11.67	294	281.00	4.42
Maple	0.1422	0.1372	54	532	15.56	235	222.00	5.53
	0.1803	0.1549	65	569	12.78	402	311.33	22.55
	0.1676	0.1549	66	546	11.67	347	305.33	12.01
Absolute average								***13.44***
Aspen	0.0787	0.0889	76	379	17.78	129.0	99.33	23.00
	0.0762	0.114	83	451	16.67	145.3	148.33	–2.09
Maple	0.0737	0.1092	84	543	16.67	170.5	158.67	6.94
	0.0787	0.1549	75	525	16.11	166.0	198.67	–19.68
	0.0787	0.1905	78	535	16.11	198.0	217.33	–9.76
	0.0787	0.1778	39	521	17.78	147.3	174.67	–18.58
Absolute average								***13.34***
Aspen	0.0279	0.160	94	416	19.44	45.0	41.00	8.89
	0.0279	0.1143	77	397	20	49.3	39.67	19.53
	0.0305	0.0965	149	349	20	30.9	63.33	–104.95
	0.0330	0.1473	145	356	22.78	58.0	59.33	–2.29
	0.0305	0.114	78	417	25.56	37.4	42.67	–14.09
Maple	0.0305	0.1549	62	530	18.33	75.7	47.67	37.03
	0.0330	0.1702	68	505	18.33	88.6	52.33	40.94
	0.0254	0.1473	52	526	18.33	48.7	33.33	31.56
	0.0234	0.1422	48	522	20	62.0	27.67	55.37
	0.0279	0.1092	49	533	20.56	45.0	40.67	9.62
	0.0305	0.1753	61	518	19.44	29.7	43.33	–45.89
	0.0305	0.1651	87	516	20	78.0	53.00	32.05
	0.0279	0.2057	91	513	22.22	56.5	42.67	24.48
	0.0279	0.1067	41	533	22.78	26.1	36.33	–39.20
	0.0279	0.1346	46	536	23.89	38.1	34.33	9.90
	0.0305	0.1473	70	562	22.78	39.1	49.67	–27.03
Absolute average								***31.43***

1. Experiment data from Simpson (2001)
2. Calculated by using this program
3. Deviation = (experiment-calculation)/experiment×%

previous publications confirmed that the program can be used to estimate heating times in multiple wood species. The program is capable of predicting heating times in thicker stock to within ± 23% of observed values and provides a powerful way to take into account the effects of all the variables that affect heating time, such as density, moisture content, initial and desired temperatures, and cross-sectional dimensions of the lumber, air velocity, dry-bulb and wet-bulb temperatures in the kiln. Future work is required to expand the calculation for heating of frozen lumber and further verify the calculation by industrial experiments.

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TABLE 3. *Data on heating different species to center temperature of 70 °C with DT = WT = 75 °C for lumber of size 75mm × 150mm × 2.4m (v = 2 m/s).*

Species	Initial Temp. (°C)	MC (%)	Density (kg/m³)	Exp. time[1] (min)	Calc. time[2] (min)	Deviation[3] (%)
Douglas fir	20.5	59.5	430	169	180.33	–6.70
Spruce/pine	18.5	62.5	370	151	173.67	–15.01
Sitka spruce	18.5	56.5	380	150	171	–14.00
Hem fir	19	97	420	210	207.67	1.11
White pine	28	108	350	239	185.33	22.46
Eastern hemlock	25.5	110.5	385	226	199	11.95
Eastern spruce	32	28.5	425	127	150.33	–18.37
Balsam fir	26	88	325	160	171	–6.88
Larch	22.5	56.5	465	213	181.67	14.71
Absolute average						***12.35***

1. Experiment data from Forintek (1991).
2. Calculated by using this program.
3. Deviation = (experiment-calculation)/experiment×%.

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