MECHANISMS RESPONSIBLE FOR THE EFFECT OF WET BULB DEPRESSION ON HEAT STERILIZATION OF SLASH PINE LUMBER

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ABSTRACT

Heat sterilization is often required to prevent spread of insects and pathogens in wood products in international trade. Heat sterilization requires estimating the time necessary for the center of the wood configuration to reach the temperature required to kill insects or pathogens. In these experiments on 1.0- and 1.8-in.- (25- and 46-mm-) thick slash pine, heating time at 160°F (71°C) increased exponentially with increase in wet bulb depression. The time required for the center of green 1.0-in.- (25-mm-) thick boards to reach 133°F (56°C) varied from 15 min at a low wet bulb depression near saturation to 438 min at the dry conditions of 50°F (27.8°C) wet bulb depression. For green 1.8-in.- (46-mm-) thick boards, the range was 38 to 198 min, and for air-dried 1.0-in.- (25-mm-) thick boards, the range was 9 to 23 min. When the wet bulb temperature in the kiln was below the desired target center temperature of 133°F (56°C), heating times were extended far beyond the times when it was not, which caused problems in attempts to estimate heating times. Surface temperatures during heating were found to decrease from evaporative cooling as wet bulb depression increased. A finite difference solution to the heat flow equations, solved for the boundary condition of a time-dependent change in surface temperature during heating, offers a good estimate of heating time when the wet bulb temperature of the heating air is above the desired target center temperature. An analysis was developed to estimate the surface transfer coefficient that describes this boundary condition.

Keywords: Heat sterilization, international trade, kiln-drying.

INTRODUCTION

Lumber, timbers, wood packaging, and other wood items are often heat sterilized to prevent the spread of insects and pathogens in international trade. In heat sterilization treatments, it is necessary to know when the center of the wood configuration reaches the temperature required to kill the insect or pathogen. This timing can be determined by measuring actual center temperatures with imbedded sensors during every heat sterilization treatment or by developing experimental data, possibly coupled with analytical methods, to develop estimates of heating times so that it is not necessary to actually measure center temperatures each time a sterilization is performed.

Previous research (Simpson 2001; also contains a literature review of heating wood) showed that when the heating medium is saturated steam, analytical methods based on the mathematics of heat conduction do quite well in estimating heating times because they depend on such variables as heating temperature, desired center temperature, initial temperature, dimensions, specific gravity, and moisture content. This research also showed that when the heating medium of saturated steam was replaced with dry air that allowed drying to proceed in conjunction with heating, heating times were extended considerably. This observation prompted a more thorough study of this effect (Simpson 2002), where the wet bulb depression was sequentially reduced from a low value at near saturation to as much as 50°F

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(28°C). The results showed that as wet bulb depression increased, the temperature at the surface of the wood decreased, compared with the dry bulb temperature and the time to heat the center increased. The increased heating time was presumed to be caused by cooling as water evaporated from the surface. The effect of cooling would be to reduce the temperature gradient from the surface inward, and since heating rate is proportional to temperature gradient, the heating time was increased. The purpose of this study was to examine the effect of surface cooling on heating time in a more quantitative way, based on the same experimental data reported by Simpson (2002), and incorporate it into a finite difference solution to the heat flow equation.

METHODS

Experimental

Slash pine lumber was obtained from a plantation in northern Florida and was received in the form of 8-ft- (2.4-m-) long, nominal 2- by 4-in.- (nominal 51- by 102-mm-) thick lumber freshly sawn and undried. Some of the lumber for the study was used in the thickness as received (1.8 in. (46 mm)), and the rest was planed to 1.0 in. (25 mm) thick. Board width averaged about 3.85 in. (98 mm).

Most of the experimental heating runs were conducted in a 1,500-board-foot (3.5-m^3) laboratory dry kiln at a dry bulb temperature of 160°F (71°C). The target levels of wet bulb depression for both the 1.0- and 1.8-in.- (25- and 46-mm-) thick lumber were 0, 5, 10, 15, 20, 30, and 50°F (0, 2.8, 5.6, 8.3, 11.1, 16.7, and 27.8°C), with corresponding equilibrium moisture content levels of 20%, 15.2%, 11.5%, 9.4%, 7.9%, 5.8%, and 3.2%. Because there was an excess of experimental material, several additional heating runs were conducted. With the 1.8-in.- (46-mm-) thick lumber, some target wet bulb depressions were missed by an undesirably wide margin. Therefore, two additional runs were conducted to fill in the large gaps between depression levels. Because high temperature dry kilns are common in the southern pine lumber industry, several heating runs were also included at a nominal dry bulb temperature of 240°F (116°C). For the 1.0-in.- (25-mm-) thick lumber, target wet bulb depressions of 60°F (33.3°C) and 110°F (61.1°C) were included, resulting in target wet bulb temperatures of 180°F (82.2°C) and 130°F (54.4°C). For the 1.8-in.- (46-mm-) thick lumber, the target wet bulb depression was 60°F (33.3°C). The center temperature of interest was 133°F (56°C) because at the time of this study, import–export regulations were requiring that this temperature be reached and held for 30 min. Air velocity was about 600 ft/min (3 m/s). All of these tests were conducted at green moisture contents. Because surface cooling during drying was anticipated to extend heating times, the question arose of whether or not heating times would also be extended if the drying during heating were reduced. With that question in mind, enough of the 1.0-in.- (25-mm-) thick boards were air-dried before heat treatment for six levels of wet bulb depression. Table 1 summarizes the experimental conditions.

Each heating run included 33 boards arranged in three layers of 11 boards each. Temperature measurements were made on the center nine boards of the center layer. The layer above and the layer below were present so that the study boards were flanked by wet boards and thus more closely resembled boards in a large kiln filled with lumber.

The lumber was stacked on a kiln truck outside the kiln, which was already running at the target conditions, and thermocouples were inserted in the nine study boards. Each of these nine boards was fitted with two thermocouples, one inserted to the center and one placed on the surface (Fig. 1). The center thermocouple was inserted in a slightly oversized hole drilled into the edge of the board, and the hole was plugged with a round toothpick to minimize the influence of the outside kiln temperature on the measured center temperature. The surface thermocouples were held tightly to the board surfaces with plastic-headed (nonconducting) push pins and were pushed into even

TABLE 1. *Experimental heating conditions used in study. Temperatures listed are target temperatures and differ slightly from actual temperatures attained.*

1.0-in.- (25-mm-) thick boards		1.8-in.- (46-mm-) thick boards	
Heating temperature °F (°C)	Target wet bulb depression °F (°C)	Heating temperature °F (°C)	Target wet bulb depression °F (°C)
Heated at green moisture content			
160 (71)	0	160 (71)	0
	5 (2.8)		5 (2.8)
	10 (5.6)		10 (5.6)
	15 (8.3)		15 (8.3)
	20 (11.1)		20 (11.1)
	30 (16.7)		30 (16.7)
	50 (27.8)		50 (27.8)
240 (116)	60 (33.3)		—[a]
	110 (61.1)	240 (116)	60 (33.3)
Heated at air-dried moisture content			
160 (71)	0		
	10 (5.6)		
	15 (8.3)		
	20 (11.1)		
	30 (16.7)		
	50 (27.8)		

[a] Two additional runs at 160°F (71°C) were included with excess experimental material. Target wet bulb drpressions were 15°F (8.3°C) and 20°F (11.1°C). See Table 2 for actual temperatures.

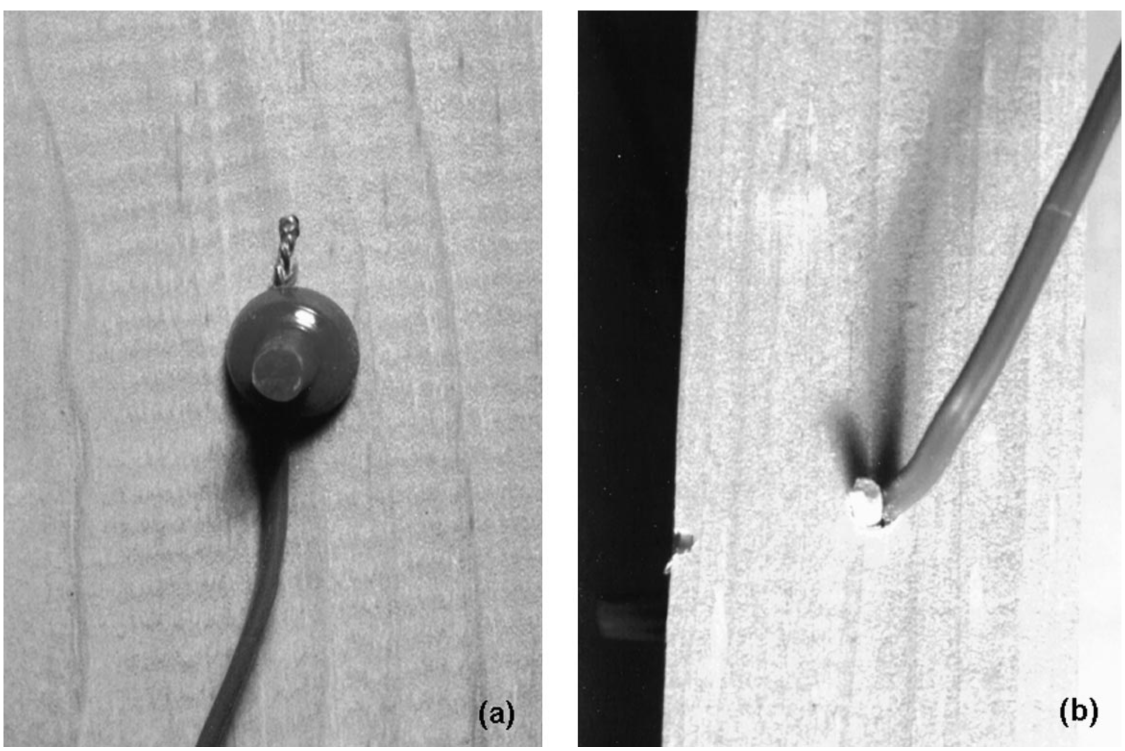

FIG. 1. Thermocouples placed on the surface (a) and in the center (b) of board.

closer contact with the surface by pressing down gently on the thermocouple junction. The nine boards were stacked edge-to-edge with the surface thermocouples on the undersides of the boards.

With all thermocouples in place, the kiln door was opened, the kiln truck wheeled in, and the door closed as quickly as possible to minimize recovery time of the desired kiln conditions after the door was closed. Both center and surface temperatures were read to a computer file at time intervals ranging from 0.5 to 2 min, depending on the expected rate of temperature rise. Runs were terminated after the last of the nine center temperatures reached 133°F (56°C). Each of the nine boards was weighed before and after heat treatment and then oven-dried for moisture content determination.

Analytical

The basic differential equations describing heat flow and moisture diffusion are similar, differing only in the driving force (temperature or moisture content gradient) and terminology for the coefficients (Crank 1975; Carslaw and Jaeger 1986). Furthermore, both analyses can incorporate a boundary condition where the surface does not come to immediate equilibrium with the surrounding conditions. In this study, the surface of the wood does not immediately attain the dry bulb temperature because of the evaporative cooling effect of drying when there is a wet bulb depression. When heating in a water-saturated environment, no drying or surface cooling occur, and the boundary condition is the attainment of immediate equilibrium. Previous work (Simpson 2001) demonstrated that the solution to the heat flow equation for the boundary condition of immediate surface equilibrium works well in estimating heating times in saturated steam.

In a previous study, Simpson and Liu (1991) developed a finite difference solution to the moisture diffusion equation, and this basic solution can be applied to heat treating. The boundary condition where the surface does not attain immediate equilibrium with the surroundings is

$$\delta T/\delta X = h(T_s - T_e) \qquad (1)$$

where T is temperature, T_s surface temperature at time t; T_e surface temperature at equilibrium (dry bulb temperature), X dimension (thickness), and h a constant of proportionality, that is, the ratio of the convection heat transfer coefficient to thermal conductivity (Carslaw and Jaeger 1986) between surface and internal flow (dimension^{-1}).

The finite difference solution, with the Eq. (1) boundary condition, is given in the Appendix. It consists of three equations—one each for the surface, center, and regions between the surface and center. Since the value of the proportionality constant h is unknown, the surface equation given in the Appendix cannot be used. However, Crank (1975) states that any algebraic formula that describes the surface condition as a function of time can be used. In this study, surface temperatures were measured as a function of time. So fitting these data to an algebraic function will provide the necessary surface equation to use with the two remaining finite difference equations. The solution was one-dimensional, which assumed that all heat flow was perpendicular to the wide face of the boards. Because of the width-to-thickness ratios of the boards and the edge-to-edge stacking in the kiln, this was a reasonable assumption.

The finite difference equations require values for thermal diffusivity, which depends on a number of factors such as moisture content, specific gravity, and temperature. The details of the methods for calculating thermal diffusivity are given in Simpson (2001).

RESULTS AND DISCUSSION

As the wet bulb depression increased in the heating experiments, the rate of drying was expected to increase. A consequence of the increased drying rate was surface cooling below the heating temperature of 160°F (71°C). This surface cooling is shown in Fig. 2a through 2c

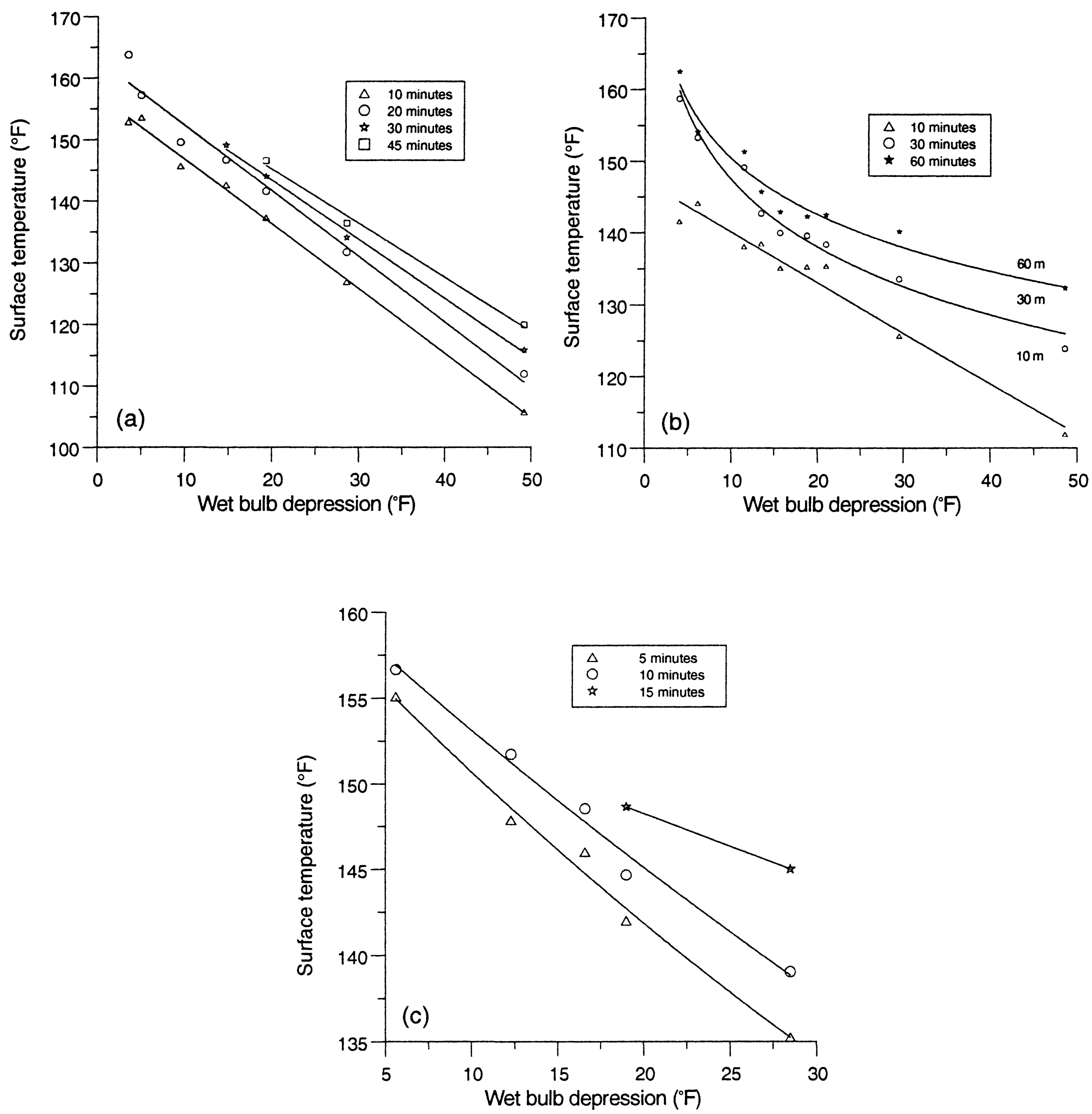

FIG. 2. Dependence of surface temperature on wet bulb depression at several times during the heating of slash pine (a) green, 1.0-in.- (25-mm-) thick, (b) green, 1.8-in.- (46-mm-) thick, and (c) air-dried, 1.0-in.- (25-mm-) thick at 160°F (71°C) (°C = (°F − 32)/1.8).

for 1.0-in.- (25-mm-) thick boards heated at green moisture content, 1.8-in.- (46-mm-) thick boards heated at green moisture content, and 1.0-in.- (25-mm-) thick boards heated at air-dried moisture content, respectively. In Fig. 2, the average surface temperature of the nine boards in each heating run is plotted against wet bulb depression at several times during heating. Figure 2 clearly shows that as wet bulb depression increased, surface temperature decreased. For example, with green 1.0-in.- (25-mm-) thick boards (Fig. 2a), surface temperature was about 157°F (69.4°C) after 20 min when the average wet bulb depression during the run was 3.5°F (1.9°C). When the wet bulb depression was 49°F (27.2°C), the surface temperature after 20 min was only 112°F (44.4°C), indicating the surface cooling due to evaporation of water from the surface during drying. Figure 2c shows that even after 1.0-in.- (25-mm-) thick boards were air-dried to approximately 15% moisture content, there was still surface cooling taking place, although, as expected, not as much as when the boards were heated at green moisture contents. Even though the air-dried boards were at approximately 15% moisture content, the equilibrium moisture content in the kiln was below that level (except for the minimum wet bulb depression; Table 2) and evaporation from the surface could still occur.

The results of the heating time experiments are summarized in Table 2, and the effect of the wet bulb depression on the time required to heat the center of the boards to 133°F (56°C) is shown in Fig. 3. Heating time increased as wet bulb depression increased. For 1-in.- (25-mm-) thick boards heated at green moisture content (Fig. 3a), heating time increased from about 15 min at a wet bulb de-

TABLE 2. *Results of heating time experiments and differences between experimental and calculated heating times with 1.0- and 1.8-in.- (25- and 46-mm-) thick slash pine heated at target temperatures of 160°F (71°C) and 240°F (116°C).*

Wet bulb depression (°F)	Average dry bulb temp. (°F)	Average wet bulb (°F)	Initial moisture content (%)	Moisture content after heating (%)	Time for center to reach 133°F (min)			h (cm^{-1})
					Exp.	Calc.	Difference (%)	
Heated at green moisture content								
1.0-in.- (25-mm-) thick								
3.5	160.3	156.8	111	109	15.1	14.0	7.3	5.1
5.0	158.9	153.9	109	111	15.4	13.9	9.7	4.4
9.5	158.4	148.9	116	114	18.7	16.5	11.8	2.7
14.7	159.6	144.9	120	117	20.9	17.3	17.2	2.0
19.3	160.0	140.7	109	106	26.2	20.9	20.2	1.4
28.6	159.8	131.2	106	75	109.0	36.5	66.5[a]	0.213
49.2	160.0	110.8	106	34	438.0	159.0	63.7[a]	0.0526
68.5	241.2	172.7	113	110	9.9	8.5	14.1	1.3
105.5	238.7	133.6	118	95	48.0	21.0	56.3[a]	0.167
						Avg.	13.4	
1.8-in.- (46-mm-) thick								
4.0	160.6	156.6	100	98	38.0	37.7	0.8	4.5
6.1	159.7	153.6	112	110	42.7	39.7	7.0	3.0
11.5	159.0	147.5	90	90	46.6	45.6	2.1	2.6
13.5	159.2	145.7	93	93	51.6	51.3	0.6	1.8
15.7	159.7	144.0	81	79	57.0	59.5	4.4	1.6
18.8	159.3	140.5	88	84	60.0	59.0	1.7	1.3
21.0	161.4	140.4	80	79	63.5	62.5	1.6	1.2
29.5	161.0	131.5	68	62	102.0	74.0	27.5[a]	0.420
48.6	160.1	111.5	76	57	198.0	100.0	49.5[a]	0.223
57.4	232.7	175.3	109	104	25.1	25.8	2.8	2.01
						Avg.	2.6	
Heated at air-dried moisture content								
1.0-in.- (25-mm-) thick								
5.6	157.4	151.8	15.3	15.3[b]	8.7	10.0	14.9	Infinite
12.3	158.6	146.3	14.4	10.9[b]	10.2	11.7	14.7	9.8
16.6	159.1	142.5	15.4	9.3[b]	11.3	12.3	8.8	6.3
19.0	157.3	138.2	15.2	8.6[b]	14.2	14.3	0.7	3.4
28.5	158.4	129.8	15.6	6.6[b]	18.1	—[a]	—	—
48.8	160.5	111.6	15.5	3.6[b]	23.0	—[a]	—	—
						Avg.	9.6	

[a] Averages do not include runs where wet bulb temperature was below the desired center temperature of 133°F (56°C).
[b] Equilibrium moisture content conditions in kiln.

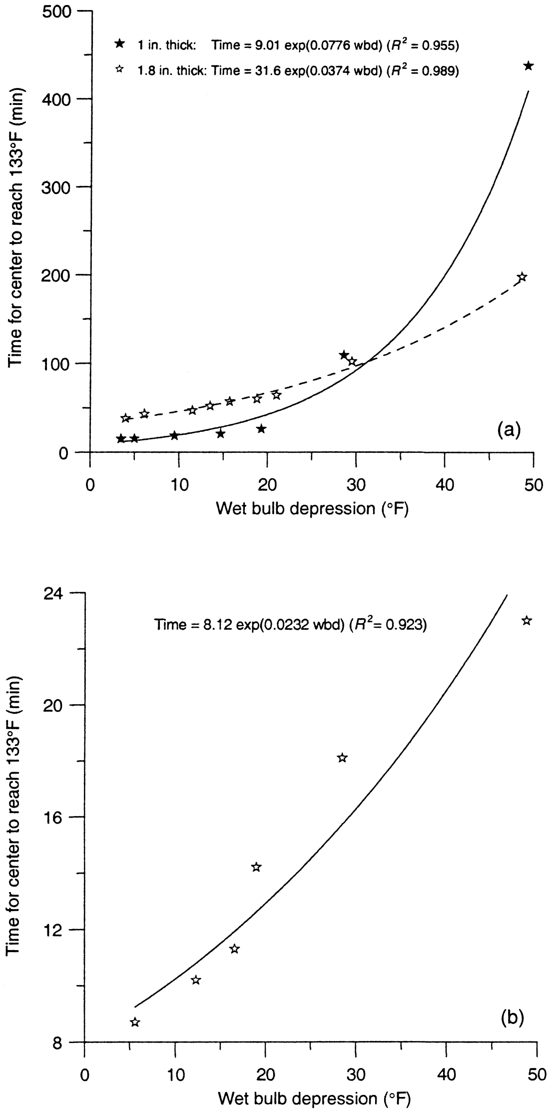

FIG. 3. Dependence of the time required for the center of slash pine boards (a) green and (b) air-dried to reach 133°F (56°C) on wet bulb depression (wbd) when heated at 160°F (71°C). [°C (temperature) = (°F − 32)/1.8; °C (wbd) = °F/1.8]

pression of 3.5°F (1.9°C) to about 26 min at a wet bulb depression of 19.3°F (10.7°C) to 438 min at a wet bulb depression of 49.2°F (27.3°C)—for an increase factor of 29 between the two extremes. For 1.8-in.- (46-mm-) thick boards heated at green moisture content (Fig. 3a), heating time increased from 38 min at a

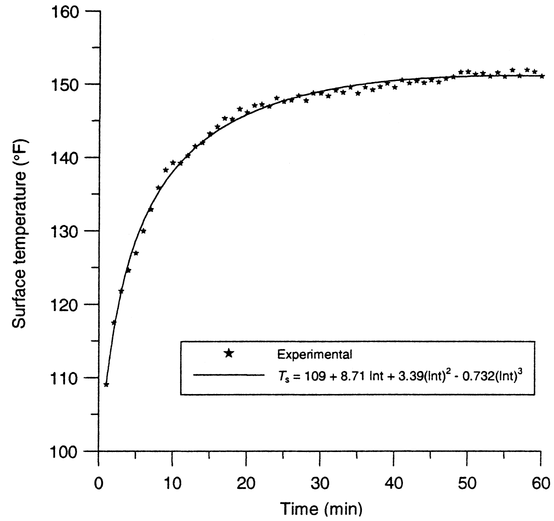

FIG. 4. Increase in surface temperature (T_s) of 1.8-in.- (46-mm-) thick slash pine heated at 160°F (71°C) dry bulb and 11.5°F (6.4°C) wet bulb depression. [°C (temperature) = (°F − 32)/1.8; °C (wbd) = °F/1.8]

wet bulb depression of 4.0°F (2.2°C) to 198 min at a wet bulb depression of 48.6°F (27.0°C), a factor of 5.2. For 1.0-in. (25-mm) boards heated at air-dried moisture content (Fig. 3b), heating time increased from 8.7 to 23 min, a factor of 2.6 (Fig. 3b).

Figure 4 is an example of the change in surface temperature with time—in this case for green 1.8-in.- (46-mm-) thick boards heated at 160°F (71°C) dry bulb temperature and an 11.5°F (6.4°C) wet bulb depression. The following logarithmic function worked well in expressing surface temperature as a function of time:

$$T_s = a + b(\ln t) + c(\ln t)^2 + d(\ln t)^3 \quad (2)$$

where T_s is surface temperature (°F (°C)); a, b, c, d are coefficients derived from least squares fitting (Table 3); and t is time in minutes.

Equation (2) was used to calculate the surface temperatures in the finite difference analysis given in the Appendix. The experimental times required to reach the desired center temperature of 133°F (56°C) are given in Table 2, and the times calculated with the finite differ-

TABLE 3. *Least squares coefficients for relationship between surface temperature and time. Surface temperature = a + b(ln t) + c(ln t)^2 + d(ln t)^3.*

Wet bulb depression (°F)	Average dry bulb temp. (°F)	Coefficients a	b	c	d	Standard error of the estimate
		Heated at green moisture content				
1.0-in.- (25-mm-) thick						
3.5	160.3	120	10.3	2.78	−0.435	1.483
5.0	158.9	117	18.5	0.706	−0.802	1.044
9.5	158.4	109	27.2	−5.98	0.476	1.914
14.7	159.6	118	17.2	−3.97	0.459	1.417
19.3	160.0	112	17.1	−3.55	0.375	1.607
28.6	159.8	104	12.9	−1.44	0.078	1.660
49.2	160.0	91	4.00	1.14	−0.054	1.396
68.5	241.2	137	28.5	−2.22	−0.93	1.183
105.5	238.7	115	5.73	−0.094	0.383	3.062
1.8-in.- (46-mm-) thick						
4.0	160.6	121	−10.2	12.5	−1.86	1.727
6.1	159.7	121	4.45	4.44	−0.866	1.742
11.5	159.0	109	8.71	3.39	−0.732	0.669
13.5	159.2	122	12.2	−2.83	0.314	1.747
15.7	159.7	109	19.9	−4.80	0.481	1.120
18.8	159.3	111	19.2	−4.83	0.498	1.582
21.0	161.4	111	23.4	−7.91	0.990	1.380
29.5	161.0	131	−11.5	4.88	−0.370	1.790
48.6	160.1	110	−10.6	6.15	−0.550	1.130
57.4	232.7	129	23.4	2.07	−1.28	3.747
		Heated at air-dried moisture content				
1.0-in.- (25-mm-) thick						
5.6	157.4	136	9.95	2.92	−1.51	0.650
12.3	158.6	131	19.15	−7.41	1.28	0.995
16.6	159.1	131	14.39	−3.29	0.225	1.140
19.0	157.3	123	17.23	−5.10	0.793	1.822
28.5	158.4	124	11.57	−4.37	1.072	1.510
48.8	160.5	116	13.0	−2.43	0.517	1.050

ence analysis are also given. When the wet bulb temperature was above 133°F (56°C), the agreement between the experimental times and calculated times was excellent for the green 1.8-in.- (46-mm-) thick boards, averaging only 2.6% difference. Agreement was not as good for the green 1.0-in.- (25-mm-) thick boards, averaging 13.4% difference (calculated times less than experimental times). Agreement for the air-dried 1.0-in.- (25-mm-) thick boards was 9.6%. The overall results do confirm that the finite difference equations provide a good framework for estimating heating times provided the variation of surface temperature with time is known and the wet bulb temperature is above the desired center temperature. Figure 5 shows two example graphs comparing the experimental and calculated rise in center temperature with time during heating—green 1.0 in. (25 mm) thick, 5.0°F (2.8°C) wet bulb depression, and green 1.8 in. (46 mm) thick, 15.7°F (8.7°C) wet bulb depression.

When the wet bulb temperature is below the desired center temperature of 133°F (56°C), there is no longer agreement between experimental and calculated times for the center to reach 133°F (56°C) (Table 2). Figure 6 shows that this disagreement begins as the center temperature approaches the wet bulb temperature of 131.7°F (55.4°C) after 50 to 75 min.

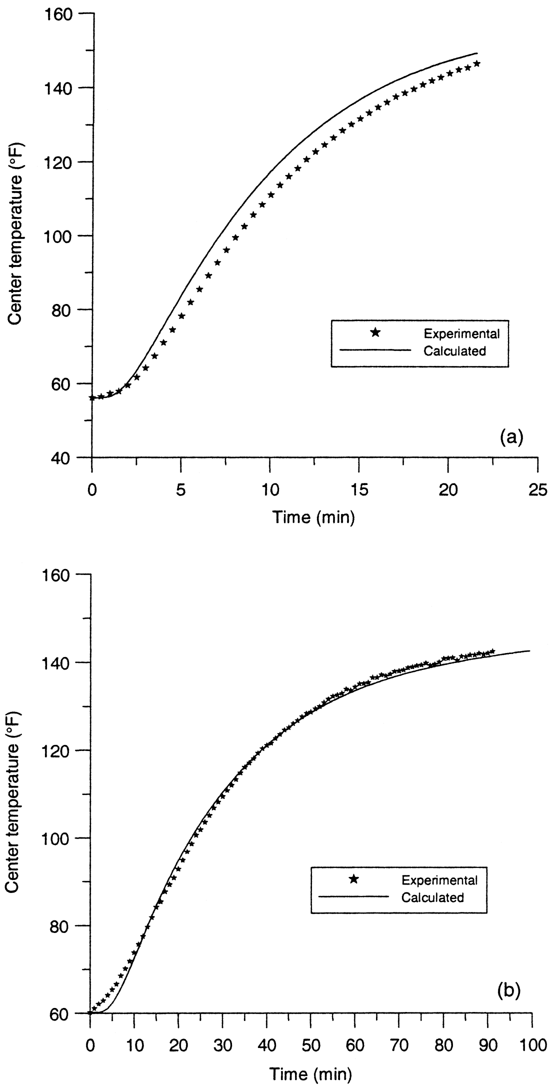

FIG. 5. Experimental and calculated increase in center temperature of slash pine with time while heated at 160°F (71°C) dry bulb: (a) 1.0-in.- (25-mm-) thick, 5.0°F (2.8°C) wet bulb depression; (b) 1.8-in.- (46-mm-) thick 15.7°F (8.7°C) wet bulb depression. [°C (temperature) = (°F − 32)/1.8; °C (wbd) = °F/1.8]

As Fig. 3 shows, the increase in heating time with increase in wet bulb depression is relatively small at the lower values of wet bulb depression. But at the larger values of wet bulb depression, the increase was quite large when heating was done at green moisture content and followed an exponential relationship.

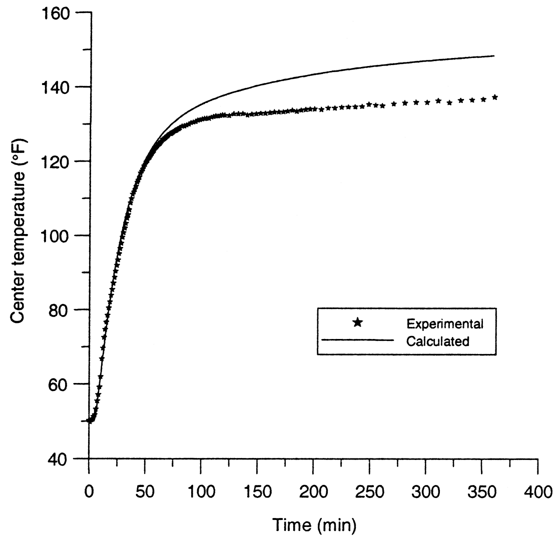

FIG. 6. Comparison of experimental and calculated increase in center temperature of green 1.0-in.- (25-mm-) thick slash pine when the wet bulb temperature was below the desired center temperature (160°F (71°C) dry bulb; 28.6°F (15.9°C) wet bulb depression). [°C (temperature) = (°F − 32)/1.8; °C (wbd) = °F/1.8]

The point where the heating time begins to increase sharply with wet bulb depression is when the wet bulb temperature in the kiln is about equal to the desired center temperature of 133°F (56°C). In the heating runs listed in Table 2, those where the wet bulb temperature was below 133°F (56°C) (wet bulb temperature targeted for either 110°F or 130°F (43.4°C or 54.5°C)) showed sharply longer heating times than runs where the wet bulb temperature was greater than 133°F (56°C).

Figure 7 illustrates the progression of surface and center temperatures when the wet bulb temperature was less than the desired center temperature. In this example, the dry bulb temperature was 160°F (71°C), the wet bulb was depression 49.2°F (27.3°C), wet bulb temperature was 110.8°F (43.8°C), and green 1.0-in.- (25-mm-) thick boards were used. The center temperature rose to the wet bulb temperature relatively quickly (in about 50 min). Then it gradually increased, but even after 800 min, it was only about 140°F (60.0°C). The surface temperature rose quickly to about

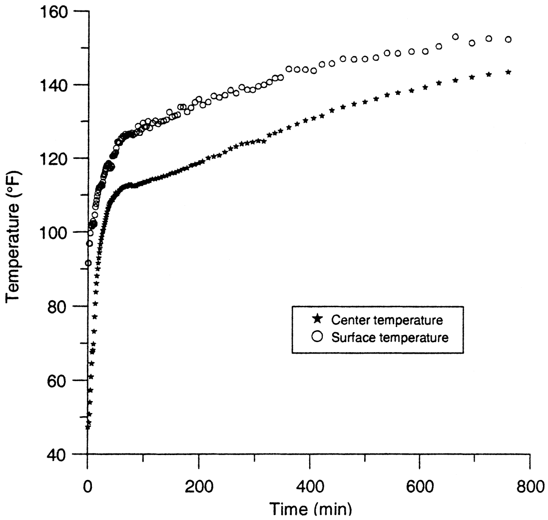

FIG. 7. Increase in surface and center temperatures when 1.0-in.- (25-mm-) thick slash pine boards were heated at 160°F (71°C) dry bulb temperature with a 49.2°F (27.3°C) wet bulb depression. [°C (temperature) = (°F − 32)/1.8; °C (wbd) = °F/1.8]

125°F (51.7°C) and then gradually rose to about 150°F (65.6°C) after 800 min. In contrast, when the wet bulb depression was only 3.5°F (1.9°C), the center reached 110.8°F (43.8°C) in about 11 min and 133°F (56°C) in about 15 min. And the surface temperature reached 160°F (71°C) in about 12 min.

The results suggest that there are two causes that extend heating times beyond those for heating in a saturated steam environment. The first is the surface cooling effect that results from the increased drying when wet bulb depression is increased. This reduces the surface-to-center temperature gradient, and because this temperature gradient is the driving force for heat conduction, heating time increases. Secondly, if the wet bulb temperature is less than the desired center temperature, the heating time may be increased because of evaporative cooling in the center during drying. Heating time to 133°F (56°C) (at 160°F (71°C) dry bulb temperature) increased by a factor of 29 from a wet bulb depression of 3.5°F (1.9°C) to a wet bulb depression of 49.2°F (27.3°C) for green 1.0-in.- (25-mm-) thick boards. But the increase between those two extremes was only a factor of 5.2 for the green 1.8-in.- (46-mm-) thick boards. The reason for this is that as thickness increases, internal transfer mechanisms play a more important role compared with surface heat and mass transfer mechanisms (Fleischer 1953).

The results in Table 2 also show that heating times were extended at a wet bulb temperature below 133°F (56°C) even when the heating temperature was 240°F (116°C). With green 1.0-in.- (25-mm-) thick boards and a wet bulb temperature of 172.7°F (78.2°C), heating time was 9.9 min. But when the wet bulb temperature was 132.6°F (56°C), the heating time was 48 min.

The moisture content data in Table 2 show the extent of drying when the wet bulb depression is large. When the green 1.0-in.- (25-mm-) thick boards were heated with wet bulb temperatures above 133°F (56°C), there was little decrease in moisture content during heating. Moisture contents were reduced by only a few percent during drying. In contrast, with the two wet bulb temperatures below 133°F (56°C), moisture contents were reduced from slightly more than 100% to 75% and 34% for wet bulb temperatures of 131.2°F (55.1°C) and 110.8°F (43.8°C), respectively.

The constant of proportionality h in Eq. (1) can be determined if the times required to reach the desired center temperature are known. The finite difference equations can be used with trial and error values of h substituted into the surface temperature Eq. (1A) in the Appendix until the calculated time equals the experimental time. The value of h when the times are equal is the applicable value, and values (160°F (71°C) dry bulb temperature) for the different wet bulb depressions are shown in Fig. 8 and Table 2 (only for conditions where the wet bulb temperature was above 133°F (56°C)). The value of h decreases with increasing wet bulb depression in an approximately exponential way, indicating that as wet bulb depression decreases, the rate of surface heating increases. The extreme is illustrated for air-dried 1.0-in.- (25-mm-) thick boards in Table 2, where h is infinite for the

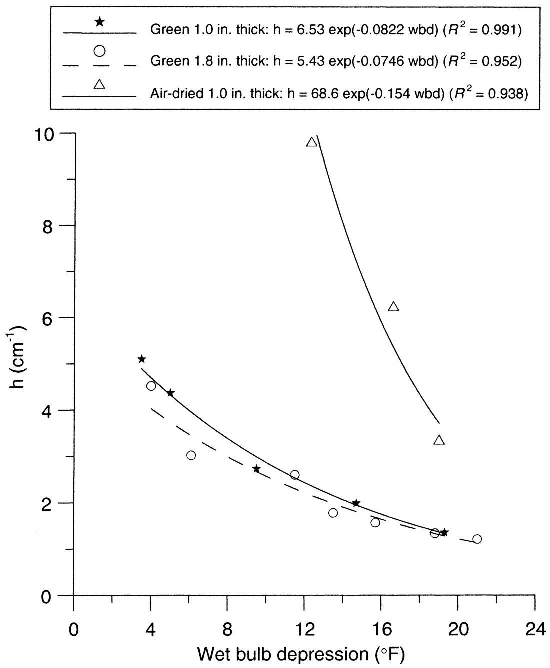

FIG. 8. Dependence of surface transfer coefficient *h* on wet bulb depression (wbd). [°C (temperature) = (°F − 32)/1.8; °C (wbd) = °F/1.8]

condition when both the moisture content of the wood and the equilibrium moisture content of the kiln air are 15.3%. These conditions approximated no surface drying and no surface cooling, and therefore, the boundary condition approximated that of immediate surface temperature equilibrium, which corresponds to an infinite value of *h*. The utility of knowing the functional form (Fig. 8) of the *h* compared with wet bulb depression relationship is that now we can calculate an estimate of *h* for any wet bulb depression in the range of the experiment (that is, for wet bulb depressions between about 4°F and 20°F (2.2 and 11.1°C) at 160°F (71°C) dry bulb temperature for 1.0- and 1.8-in.- (25- and 46-mm-) thick slash pine) and use it in the finite difference equations in the Appendix. A broader knowledge of how *h* varies with dry bulb temperature, thickness, and species would be useful in estimating heating times at varying wet bulb depressions without the need to measure surface or internal temperatures.

SUMMARY AND CONCLUSIONS

This study investigated the effect of wet bulb depression, at constant dry bulb temperature, on the time required to heat the center of green 1.0- and 1.8-in.- (25- and 46-mm-) thick slash pine boards to 133°F (56°C). The expectation was that as wet bulb depression increased, drying rate would increase and result in a surface cooling effect that would slow heating compared with conditions where little or no drying occurred. Measurements showed that surface cooling increased as wet bulb depression increased. The time required for the center to reach 133°F (56°C) increased exponentially with wet bulb depression at a constant dry bulb temperature of 160°F (71°C). The increase was greater for the 1.0-in.- (25-mm-) thick boards than for the 1.8-in.- (46-mm-) thick ones. When the wet bulb temperature was less than the desired center temperature, the time required for the center to reach the desired temperature was greatly extended beyond the time required when the wet bulb temperature was greater than the desired center temperature. Boards that had been air-dried to 15% moisture content before heating also showed these effects but to a lesser degree than boards heated at green moisture content.

This study also showed that a finite difference solution to the one-dimensional heat flow equation, solved for the boundary condition of time-dependent rise of the surface temperature during heating, can offer a good estimate of heating time provided the target center temperature is above the wet bulb temperature in the heating chamber. Future analytical work should include consideration of the case where the target center temperature is below the wet bulb temperature in the heating chamber. An analysis was developed to estimate the surface transfer coefficient that describes the boundary condition of time-dependent surface temperature rise during heating.

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APPENDIX: FINITE DIFFERENCE SOLUTIONS

The finite difference solution equations for heat flow consist of three parts. The indexing system is $T_{i,j}$, where i is the thickness direction (x) increment (21 thickness divisions used) and j is the time (t) increment (0.01-second intervals).

1. Surface temperature T_0:

$$T_{0,j+1} = T_{0,j} + 2R\alpha_{0,j}(T_{1,j} - T_{0,j} - h\,\Delta x(T_{0,j} - T_e)) \quad (1A)$$

where α is thermal diffusivity (dimension^2/time), and $R = \Delta t/(\Delta x)^2$.

We do not know values for h in Eq. (1A), so we cannot use it to calculate surface temperatures. Instead, we use the least squares estimate of Eq. (2) in the text that represents the measured surface temperatures:

$$T_0 = a + b(\ln t) + c(\ln t)^2 + d(\ln t)^3$$

2. Interior temperature T_i:

$$T_{i,j+1} = T_{i,j} + R(\alpha_{i+0.5,j}(T_{i+1,j} - T_{i,j}) - \alpha_{i-0.5,j}(T_{i,j} - T_{i-1,j}))$$

3. Center temperature T_n:

$$T_{n,j+1} = T_{n,j} + 2R\alpha_{n-0.5,j}(T_{n-1,j} - T_{n,j})$$