EFFECT OF ULTRASONIC VIBRATION ON CONVECTIVE HEAT TRANSFER BETWEEN WATER AND WOOD CYLINDERS

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ABSTRACT

A study has been conducted to examine the effect of ultrasonic vibration on convective heat transfer of wooden cylinders. Forty fully saturated and air-dried cylindrical wood specimens were partially submerged in a heated water bath of 59.8 C (with and without ultrasound). The temperature versus time relationship at the center of the cylinders was monitored. Results indicate that ultrasound significantly influenced the heat transfer to wooden cylinders.

Keywords: Ultrasound, heat transfer, cylinders.

INTRODUCTION

Declines of the large old-growth timber supply have resulted in increased emphasis on the manufacturing of a wide variety of composite veneer wood products. Examples of these composite wood products are plywood, laminate veneer lumber, microlam, and paralam.

The basic wood elements for these products are the veneers that are peeled from logs by turning the log about its longitudinal axis against a fixed knife. Prior to the peeling operation, it is common practice to immerse the logs in warm water (60 C) to soften the wood. Temperature profiles and heating times at different distances from the surface of wood poles were reported by Maclean (1952). Core heating times for frozen and unfrozen logs submerged in agitated water were investigated, and a computer program to describe their temperature history was created (Steinhagen 1977; Steinhagen et al. 1980, 1987). The time required for the soaking procedure can potentially be reduced if the heat transfer mechanism between the warm water and the wood is improved.

Ultrasonic vibration (50 kHz) has been shown to affect radiant and conductive heat transfer systems (Fairbanks and Otsuka 1978; Fairbanks 1979). Other studies have shown that ultrasound (28 kHz) also affected the heat transfer from copper cylinders to water (Hoshino and Yukawa 1977), from flat copper plates to water (Yukawa et al. 1976) and from heated platinum wire to water (Hoshino et al. 1976). Sastry et al. (1989) also showed that ultrasonic vibration increased the fluid to particle convective heat transfer coefficients of mushroom-shaped aluminum transducer particles of three different sizes at three different energy input levels.

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This paper describes an exploratory investigation to examine the effect of ultrasonic vibration on convective heat transfer of 1) fully saturated and 2) room-conditioned cylindrical wood specimens. The latter specimens also provided information on the effect of water uptake on heat transfer.

MATERIALS AND METHODS

Forty kiln-dried defect-free Douglas-fir specimens were sampled for this study. The specimens were cylindrical in shape with a diameter of 38 mm and a length of 254 mm. The specimens were conditioned at room temperature and humidity to an average moisture content of 9%. The weight of each specimen was measured prior to testing.

The specimens were randomly divided into the following four groups of 10 specimens:

1) Group A — Air-dried and heated in a water bath without ultrasound;
2) Group AU — Air-dried and heated in a water bath with ultrasound;
3) Group S — Fully saturated and heated in a water bath without ultrasound;
4) Group SU — Fully saturated and heated in a water bath with ultrasound.

Specimens from Groups S and SU were placed in an impregnation apparatus until they were fully saturated with water. The impregnation procedure involved placing the specimens in a cylinder and introducing a vacuum into the system for 48 hours. Water was then introduced into the cylinder while the system was still under vacuum. The system was then pressurized to 410 cm-Hg (80 psi) for 48 hours. After the impregnation, the weight of each specimen was measured to determine the degree of saturation.

A precision copper/constantan (Type T) teflon insulated thermocouple, 0.81 mm diameter, was inserted into the center of each specimen through a small hole (2 mm in diameter and 19 mm deep) drilled from the side of the specimen. After the thermocouple had been inserted, the hole was filled with wood chip fibers and then sealed with a silicon adhesive to prevent penetration of the warm water into the specimen through the hole.

The water bath of a commercial ultrasonic cleaner that operated at a frequency of 50–55 kHz was used in this phase of the experiment. The temperature of the water was maintained at 59.8 C by circulating warm water (60 C) through a closed-loop copper piping system submerged in the water bath. The water bath was then covered with a styrofoam cover to minimize temperature gradient above the waterline and mass loss through exposed surface. The distance between the cover and the surface of the water was approximately 60 mm. The temperature above the waterline was found to be approximately 52 C. The temperature of the water in the bath was checked to be uniform.

For each of the experimental runs, one specimen was placed in the water bath of the ultrasonic cleaner. As shown in Fig. 1, the specimen was partially submerged such that a distance of 2 mm measured vertically along the diameter of the specimen was exposed to air. The limitation of the equipment prevented completely submerging the entire specimen. The temperature at the exposed surface was measured, which reached a temperature of approximately 52 C shortly after the specimen was placed in the water bath. The temperature rise in the center of each specimen was monitored as a function of time at a sampling rate of one reading per fifteen seconds.

Immediately after testing, the specimens were blotted to remove excess surface water and weighed to determine the water uptake. The specimens were then oven-dried at a temperature of 103 C ± 2 C for 24 hours. The oven-dry weights of the specimens were measured.

ANALYSIS

The heat transfer of cylinders in a heated water bath is a transient heat-conduction problem with a convection boundary condition at the surface of the cylinder. Assuming that the influence of the temperature difference be-

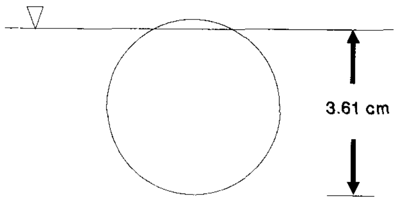

FIG. 1. A partially submerged test specimen.

tween the exposed and submerged surface of the wooden cylinder is small and since the cylinder's length to diameter ratio was more than 1.9 (Siau 1984), the differential equation for radial heat flow into the center of the cylinder expressed in cylindrical coordinates is given by (Holman 1986):

$$\frac{\partial T}{\partial t} = D_h\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \qquad (1)$$

where

T = the temperature of the cylinder as a function of position and time, °C

t = time, s

r = the location of the point of interest expressed as the distance measured along the radius from the center of the cylinder, cm

D_h = the thermal diffusivity of wood, $\frac{cm^2}{s}$.

The initial condition and the boundary conditions are:

$$\begin{aligned} T &= T_0 && @\, t = 0 \\ \frac{\partial T}{\partial r} &= 0 && @\, r = 0 \qquad (2) \\ \frac{\partial T}{\partial r} &= -\frac{h}{k_T}(T - T_\infty) && @\, r = a \end{aligned}$$

where

h = the convective heat transfer coefficient, $\frac{cal}{cm^2\ s\ °C}$

k_T = the thermal conductivity of wood, $\frac{cal}{cm\ s\ °C}$

T_∞ = the temperature of the surrounding medium, °C

a = radius of the cylinder, cm.

An approximate solution to Eq. (1) for the temperature at the center of a long cylinder is given in Holman (1986) as:

$$\frac{T - T_\infty}{T_0 - T_\infty} = C_B \exp\left(\frac{-A_B^2 D_h t}{a^2}\right) \qquad (3)$$

where

$$\frac{A_B J_1(A_B)}{J_0(A_B)} = \text{Biot Number} = \frac{ha}{k_T}$$

$$C_B = \frac{2J_1(A_B)}{A_B[J_0(A_B)^2 + J_1(A_B)^2]}$$

J_0 and J_1 are zeroth and first order Bessel functions of the first kind, respectively.

Equation (3) is a single term solution to Eq. (1). It is within ±1% of the complete solution provided that the Fourier Number, $\frac{D_h t}{a^2}$, is greater than 0.2 (Holman 1986). D_h can be estimated by (Siau 1984):

$$D_h = \frac{k_T}{c\rho} \qquad (4)$$

where

$$k_T = [G(4.80 + 0.09M) + 0.57] \times 10^{-4}\frac{cal}{cm\ °C\ s} \quad \text{for } M < 40\%;$$

$$k_T = [G(4.80 + 0.125M) + 0.57] \times 10^{-4}\frac{cal}{cm\ °C\ s} \quad \text{for } M > 40\%;$$

G = specific gravity of the wood,

M = moisture content of the wood, %

ρ = density of the wood, $\frac{g}{cm^3}$

c = specific heat $= \frac{0.0268 + 0.0011T + 0.01M}{1 + 0.01M}, \frac{cal}{g\ °C}$.

TABLE 1. *Experimental results.*

Specimen No.	Group	G	M (%)	Water uptake (g)	β_1	β_0	R^2
1	A	0.421	9.01	10.40	−0.00206	−0.34473	0.953
2	A	0.412	8.57	8.24	−0.00080	−0.58904	0.856
3	A	0.529	9.89	8.41	−0.00181	−0.42902	0.955
4	A	0.425	9.50	10.16	−0.00087	−0.69755	0.871
5	A	0.403	8.65	8.71	−0.00097	−0.75059	0.827
6	A	0.528	9.58	9.18	−0.00124	−0.49938	0.943
7	A	0.432	9.18	9.50	−0.00174	−0.45438	0.943
8	A	0.432	8.10	8.43	−0.00129	−0.54993	0.923
9	A	0.530	9.83	11.06	−0.00194	−0.45931	0.957
10	A	0.424	9.29	8.86	−0.00185	−0.47207	0.932
11	AU	0.539	9.38	7.87	−0.00221	−0.41022	0.946
12	AU	0.413	7.93	6.37	−0.00260	−0.37657	0.957
13	AU	0.532	9.48	8.06	−0.00272	−0.38376	0.966
14	AU	0.529	9.39	7.81	−0.00187	−0.49007	0.936
15	AU	0.526	9.35	7.99	−0.00205	−0.38045	0.960
16	AU	0.553	9.69	7.61	−0.00166	−0.44147	0.955
17	AU	0.526	9.49	8.45	−0.00192	−0.42964	0.957
18	AU	0.549	9.70	8.09	−0.00199	−0.43052	0.957
19	AU	0.554	9.19	7.95	−0.00221	−0.36053	0.965
20	AU	0.530	9.25	9.43	−0.00151	−0.43341	0.968
21	S	0.512	7.63	−12.00	−0.00124	−0.05992	0.996
22	S	0.519	8.40	−9.89	−0.00126	−0.04560	0.998
23	S	0.548	9.23	−15.50	−0.00124	−0.07551	0.996
24	S	0.417	8.30	−6.55	−0.00157	0.00439	0.999
25	S	0.522	7.28	−10.88	−0.00138	−0.05230	0.999
26	S	0.525	8.94	−5.62	−0.00144	−0.01026	0.999
27	S	0.501	9.12	−6.07	−0.00139	−0.03677	0.999
28	S	0.531	8.76	−9.70	−0.00148	−0.03191	0.997
29	S	0.520	8.61	−5.71	−0.00152	−0.02550	0.996
30	S	0.537	8.56	−7.84	−0.00135	0.01615	0.999
31	SU	0.513	7.17	−9.36	−0.00188	0.01533	0.983
32	SU	0.521	8.90	−7.36	−0.00198	−0.02420	0.996
33	SU	0.538	8.22	−5.14	−0.00218	0.08162	0.994
34	SU	0.505	8.83	−8.49	−0.00207	0.08005	0.991
35	SU	0.556	7.03	−4.69	−0.00200	0.03365	0.983
36	SU	0.523	8.75	−7.37	−0.00225	0.08002	0.985
37	SU	0.539	8.63	−3.01	−0.00218	0.07199	0.989
38	SU	0.541	9.28	−10.32	−0.00198	0.02638	0.989
39	SU	0.430	9.16	−6.51	−0.00225	0.05507	0.980
40	SU	0.498	8.83	−8.42	−0.00205	0.05774	0.992

Note: M refers to the moisture content of the specimen prior to testing.

For air-dried wood with a moisture content of 10%, a specific gravity of 0.4, and a temperature of 50 C, D_h equals 0.0075; therefore, the condition that $\frac{D_h t}{a^2} > 0.2$ is met when t is greater than 96 s. Using a nonlinear least squares fit routine, Eq. (3) can be fitted to the data corresponding to $t > 96$ s to estimate A_B.

However, it is clear from Eq. (4) that D_h is a function of both the temperature and moisture content in the wood, which varies with time during the experiment. Therefore, it is not possible to obtain a proper estimate of the heat transfer coefficient, h, by fitting Eq. (3) to the data.

An alternative approach is taken where each

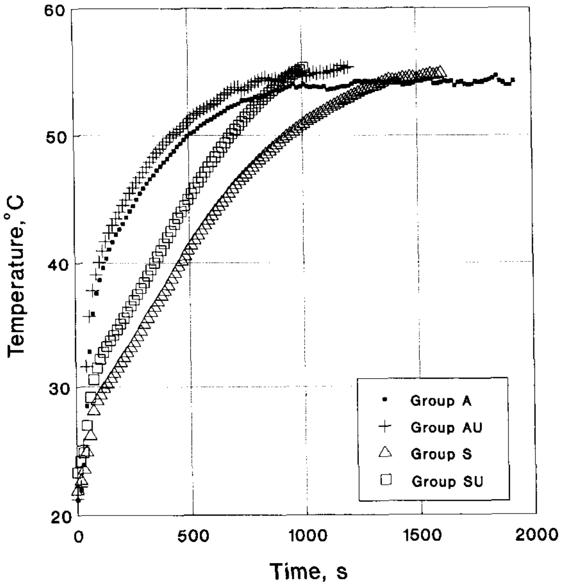

FIG. 2. The average temperature versus time relationships for the four groups.

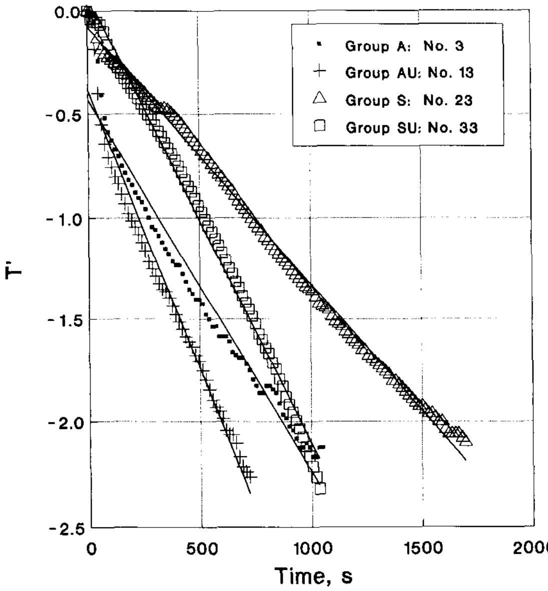

FIG. 3. Typical normalized and transformed temperature versus time relationships.

experimental temperature versus time relationship is normalized and transformed as $T' = \ln\left(\frac{T - T_\infty}{T_0 - T_\infty}\right)$. A regression line of the form given in Eq. (5) was fitted to the normalized and transformed data.

$$\ln\left(\frac{T - T_\infty}{T_0 - T_\infty}\right) = \beta_0 + \beta_1 t \tag{5}$$

The slope of each regression line, β_1, is related to the rate increase of the transformed temperature at the center of the cylinder as a function of time. Analysis of variance was performed on β_1 for the four groups. Using the water uptake as the independent variable, analysis of covariance was also performed on the four groups of β_1 values.

RESULTS AND DISCUSSION

Table 1 shows the specific gravity, moisture content (prior to testing), and water uptake of the specimens. It is clear that the specimens in the dry category picked up water during the experiment and the specimens in the fully saturated category lost water during the experiment, the latter being probably the result of losing moisture from the air-exposed surface of the specimen. The mass loss in the specimens of Group S and SU ranged from 0.85% to 4.26% of the fully saturated mass. The amount of mass loss is judged to be consistent with the amount of exposed surface and the environmental conditions above the waterline.

Figure 2 shows average temperature versus time relationships for the four groups. Each point on the graph was obtained by averaging the temperature at a particular time of the ten specimens from a group. The results suggest that the combined conductive and convective heat transfer processes in the fully saturated groups and in the air-dried groups are distinct. On the average, the air-dried groups reached temperatures between 30 C and 50 C faster than the fully saturated groups. This may be explained by the water uptake of the air-dried specimens, which contributed to the conductive heat transfer process.

Direct comparison of the heating times obtained in this study to the values reported by Maclean (1952) and Steinhagen (1977) cannot be made because of differences in species,

TABLE 2. *Results of analysis of variance of* β_1.

Source	Degree of freedom	Sum of squares	Mean square	F Value	$F_{critical}$ ($\alpha = 0.05$)
Model	3	0.00000431	0.00000144	14.33	$F_{3,36,1-\alpha} \simeq 2.92$
Error	36	0.00000361	0.00000010		
Total	39	0.00000792			

Group	Mean	Standard deviation of treatment mean	95% confidence interval of treatment mean	
A	−0.001462	0.0001002	(−0.001666, −0.001258)	*
AU	−0.002077	0.0001002	(−0.002281, −0.001873)	**
S	−0.001394	0.0001002	(−0.001598, −0.001190)	*
SU	−0.002087	0.0001002	(−0.002291, −0.001883)	**

Note: * and ** indicate Groups A and S are not significantly different and Groups AU and SU are not significantly different, but Groups A and S are significantly different from Groups AU and SU.

moisture contents, and specimen sizes. Using the data reported by Maclean (1952) and Steinhagen (1977), calculations of the times required to reach 55 C from ambient, 19 mm deep from the surface of a submerged bolt 406 mm in diameter, resulted in heating periods approximately 4 to 6 times longer than the ones obtained in this study.

Typical normalized and transformed temperature versus time relationships for specimens from the four groups are shown in Fig. 3. Also shown in Table 1 are the β_0, β_1 and the coefficient of determination (R^2) values of the specimens. The R^2 values range from 0.827 to 0.999. The regression lines in the form of Eq. (5) fitted through the data of typical specimens are also shown in Fig. 3. It is apparent that Eq. (5) fits the data relatively well.

Table 2 shows the results of an analysis of variance of β_1 for the four groups. At a 95% significance level, results indicate that the β_1 values for Groups AU and SU are significantly different from the β_1 values for Groups A and S. However, the β_1 values between Groups A and S are not significantly different and the β_1 values between Groups AU and SU are not significantly different either. Therefore, combined β_1 values from Groups A and S can be compared with combined β_1 values from Groups AU and SU. The ratio between the mean β_1 values from Groups AU and SU (with ultrasonic treatment) to the mean β_1 values from Groups A and S (without ultrasonic treatment) is 1.46. This result supports the initial hypothesis that ultrasonic vibrations positively affect the rate increase of temperature in the center of the specimens. The positive effect on the rate of increase of temperature could be

TABLE 3. *Results of analysis of covariance of* β_1.

Source	Degree of freedom	Adjusted sum of squares	Mean square	F value	$F_{critical}$ ($\alpha = 0.05$)
Model	4	0.00000434	0.00000109	10.63	$F_{4,35,1-\alpha} \simeq 2.69$
Error	35	0.00000358	0.00000010		
Total	39	0.00000792			

Group	Adjusted mean	Standard deviation of adjusted mean	95% confidence interval of adjusted mean	
A	−0.001497	0.0001179	(−0.001737, −0.001257)	*
AU	−0.002105	0.0001120	(−0.002333, −0.001877)	**
S	−0.001372	0.0001078	(−0.001591, −0.001153)	*
SU	−0.002046	0.0001239	(−0.002298, −0.001794)	**

Note: * and ** indicate Groups A and S are not significantly different and Groups AU and SU are not significantly different but Groups A and S are significantly different from Groups AU and SU.

attributed to the collapse of the thermal boundary layer due to the interfacial instability produced by the acoustic streaming and the shock waves produced by cavitation in the water, both being the results of ultrasonic energy.

Table 3 shows the results of an analysis of covariance of β_1 for the four groups with the water uptake as the independent variable. The adjusted mean and the standard error of the adjusted means for the four groups are also shown. The ratio between the adjusted mean of β_1 values from Groups AU and SU (with ultrasonic treatment) to the adjusted mean of β_1 values from Groups A and S (without ultrasonic treatment) is 1.45. Examination of the confidence interval of the adjusted mean at a 95% significance level resulted in the same conclusion as the analysis of variance.

CONCLUSION

Ultrasonic excitation increased the rate of temperature rise in submerged wooden cylinders during heating. Regression of the normalized and transformed temperature versus time relationship at the center of the cylinders provided information on the rate of increase of T′. The influence of ultrasonic vibrations on the rate increase of T′ at the center of the cylinder was found to be significant. The rate of increase of T′ at the center of the cylinder between the air dried and the saturated groups was found to be insignificant. Ultrasound can possibly be used to improve heat transfer in submerged timber (e.g., logs) during preconditioning for veneer production.

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