Modeling of moisture diffusion and heat transfer during softening in wood densification

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Abstract

Mechanical densification of wood involves compressing the wood in radial direction using heat, water and steam to produce a higher density surface exhibiting better mechanical properties. The densified wood is an environmentally friendly product that presents new opportunities for the wood products industry. Wood surface densification involves both soaking and heating. The objective of this study is to present a two-dimensional model of moisture diffusion and heat transfer during softening process in order to understand and control the degree of surface densification. The governing equations for diffusion process and heat transfer are solved numerically at non-steady state conditions. Experimental data was also collected on Aspen and Balsam fir specimens to determine the moisture profile. The model predicts suitably the moisture content and temperature in the soaking process. The results showed that the surface to be softened could be heated to a temperature of 80~90 ^{o}C in 3~5 minutes with an average moisture content of 25 percent in the surface layer.

Keywords: Softening, soaking, densification, moisture diffusion, heat transfer, modeling

1. INTRODUCTION

With the importance of wood in man's environment, the demand for hardwood used for furniture and interior materials keeps increasing. In Canada, coniferous woods account for about 80% of the total volume of merchantable timber. Compared with hardwoods, coniferous softwoods show low density and are generally soft. Therefore, to utilize softwoods for interior materials, it is necessary to improve their surface properties such as abrasion resistance and hardness as well as their dimension stability. Inoue *et al.* (1990) studied the improvement of surface properties of lumber by surface compression [1]. In comparison with untreated wood, abrasion resistance and hardness increased by 40 to 50% and 120 to 150%, respectively. Softening is an important step in the manufacture of surface-densified wood. Softening process involves soaking and heating of wood. It is vital to study and determine the distribution of moisture content and temperature across the thickness of a wood board in order to understand and control the degree of surface densification. This study was aimed at understanding the moisture diffusion and heat transfer in the coniferous wood boards during softening process, and eventually proper softening parameters can be determined and optimized.

2. MATHEMATICAL MODEL

2.1 Governing equations

At low temperature, moisture in wood mainly moves by a diffusion process that is driven by a gradient in the moisture content. Fick's second law offers one generalized method to describe the diffusion process [2, 3]. This approach allows the estimation of moisture gradients at any time during heating period. In the literature, the thermally induced mass transfer, which contributed considerably to the total moisture flux, was also taken into account in the model construction [4]. Moisture transfer should be considered a coupled process with heat transfer, or described by a non-isothermal diffusion model.

Non-isothermal diffusion was analyzed by different methods. Siau (1995) indicated that the thermodynamic model provided the best fit to the experimental data [5]. The model derived from non-equilibrium thermodynamics was presented by Nelson (1991) [6], and the steady state mass flux was shown as,

$$J_m = -k_m\left(\frac{dM}{dT}\frac{dT}{dx} + \frac{dM}{dx}\right) \tag{1}$$

The temperature gradient coefficient was given as,

$$\frac{dM}{dT} = \frac{H}{RT}\frac{\partial M}{\partial H}\frac{E_b}{T} \tag{2}$$

Where

$$k_m = G_m D\,, \tag{3}$$

$$E_b = 38{,}500 - 290M \tag{4}$$

Taking Eq. 1 as the starting point, the differentiated unsteady-state equation was derived as,

$$\frac{\partial M}{\partial t} = \nabla \cdot \left(D_{eff,T} \nabla T + D_{eff,M} \nabla M \right) \tag{5}$$

As a complete model for moisture movement, the energy balance equation is also required in addition to Eq. 5. Heat transport in wood occurs via heat conduction in all the three phases (free water, bound water, and vapor), and by convection through mass transportation. In the slow heating condition the vapor and free liquid bulk flows can be ignored, and the term of heat transfer by convection can also be omitted. With the simplification of conventional heat transfer, the heat balance equation was derived as,

$$\frac{\partial \left(\rho_{wood} c_{pwood} T \right)}{\partial t} = \nabla \left(\lambda_{eff} \nabla T \right) \tag{6}$$

In this study, the soaking process makes a two dimensional model necessary. In the experiments, the water was sucked into wood mainly in the thickness direction. However, the wood specimen was heated in two scenarios: heat transfer along specimen thickness from the boiling water, and heat transfer along specimen width from surrounding hot evaporated vapor. Thus, the cross section (i.e. width and thickness) of a specimen was taken into consideration in the model study.

Boundary conditions

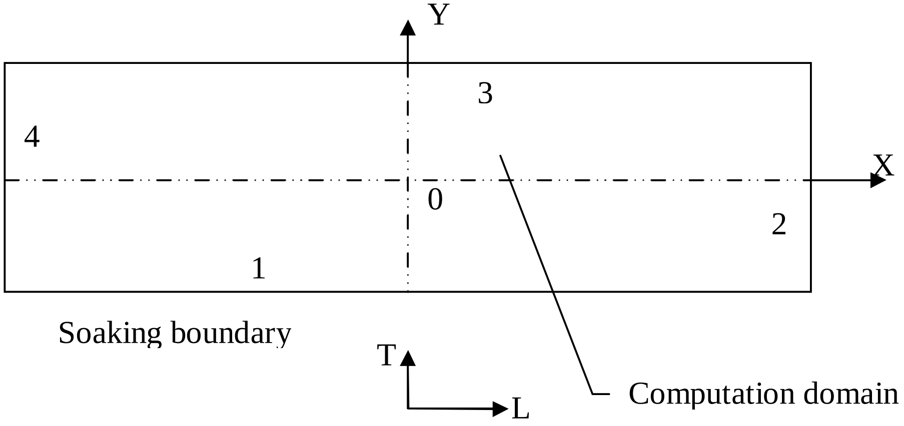

FIGURE.1. Configuration of 2-D model computation domain

In Figure 1, there were three types of boundary conditions. Boundary 1 was emerged into the water; boundaries 2 and 4 were heated by hot evaporated vapor; boundary 3 was exposed to open air. Using the relation between surface emission coefficient (*S*) and moisture transfer on the surface, the external surface, boundaries 2, 3, and 4 can be expressed as,

$$D \frac{\partial M}{\partial x} = -S \left(M - M_{\infty} \right) \tag{7}$$

The boundary condition for heat exchange could be written as,

$$\lambda_{eff}\ \frac{\partial T}{\partial x} = -h_{heat}\left(T - T_{\infty}\right), \text{ at the external surface} \tag{8}$$

At the boundary 1 (in water), the condition is imposed as:

$$M = M_{\max} \tag{9}$$

$$T = 100\ ^{o}\text{C}, \tag{10}$$

2.2 Numerical procedures

The non-isothermal model equations are solved numerically. The finite element method is used to discretize the mass diffusion and heat transfer equations. The weak form of Eq. 5 and Eq. 6 is expressed as,

$$\int_V \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \frac{\partial}{\partial t} \begin{bmatrix} M \\ \rho CpwoodT \end{bmatrix} = \int_V \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \frac{\partial}{\partial x} \begin{pmatrix} D_{Mx}\frac{\partial M}{\partial x} + D_{Tx}\frac{\partial T}{\partial x} \\ k_x \frac{\partial T}{\partial x} \end{pmatrix} + \int_V \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \frac{\partial}{\partial y} \begin{pmatrix} D_{My}\frac{\partial M}{\partial y} + D_{Ty}\frac{\partial T}{\partial y} \\ k_y \frac{\partial T}{\partial y} \end{pmatrix} \tag{11}$$

Following the procedure of integration by parts, Eq. 12 can be obtained:

$$\int_V \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \frac{\partial}{\partial t} \begin{bmatrix} M \\ \rho Cpwood \quad T \end{bmatrix} = \int_S \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \begin{pmatrix} D_{Mx}\frac{\partial M}{\partial x} + D_{Tx}\frac{\partial T}{\partial x} \\ k_x \frac{\partial T}{\partial x} \end{pmatrix} dS \; -$$

$$\int_V \frac{\partial}{\partial x} \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \cdot \begin{pmatrix} D_{Mx}\frac{\partial M}{\partial x} + D_{Tx}\frac{\partial T}{\partial x} \\ k_x \frac{\partial T}{\partial x} \end{pmatrix} dx - \int_V \frac{\partial}{\partial y} \begin{bmatrix} N_i & 0 \\ 0 & N_i \end{bmatrix} \cdot \begin{pmatrix} D_{My}\frac{\partial M}{\partial y} + D_{Ty}\frac{\partial T}{\partial y} \\ k_y \frac{\partial T}{\partial y} \end{pmatrix} dy \tag{12}$$

where N_i is the weighting function.

The finite element approximation can be derived by considering

$$M(x,y) = [N]\{M\} \tag{13}$$

$$T(x,y) = [N]\{T\} \tag{14}$$

where M, T represents the nodal point values with respect to time. Substitution of these finite element approximations into the weak form gives,

$$\sum \int_{Ve} [C] dV \ \frac{\partial}{\partial t} \begin{Bmatrix} M_e \\ T_e \end{Bmatrix} + \sum \int_{Ve} [S] dV \begin{Bmatrix} M_e \\ T_e \end{Bmatrix} = \sum \int_{Se} [B] dS \tag{15}$$

where $$[C] = [N]\rho c_p [N] \tag{16}$$

$$[S] = [N'] D_{eff} [N'] \tag{17}$$

Eq. 18 can be obtained, in terms of central time difference,

$$\left(\frac{1}{2}[S]+\frac{1}{\Delta t}[C_t]\right)\begin{Bmatrix} M_e \\ T_e \end{Bmatrix}^{n+1} = [B]^{n+\frac{1}{2}} + \left(\frac{1}{\Delta t}[C_t]-\frac{1}{2}[S]\right)\begin{Bmatrix} M_e \\ T_e \end{Bmatrix}^{n} \tag{18}$$

A computer code was developed to solve above algebraic equations.

3. EXPERIMENTAL

Aspen (*Populus tremuloides* Michx.) and Balsam fir (*Abies balsamea* (L.) Mill.) specimens were used for moisture distribution tests. The dimension of each specimen was 280 mm long, 25 mm thick and 37 mm wide. All specimens were stored in a conditioning chamber set at 20^{o}C and 65% relative humidity prior to the tests. In the soaking process, the water was heated to the boiling point, and then a specimen was put on the top of a shelf in the water with 1mm of the specimen in the radial direction (thickness) being emerged into the water. The whole soaking process took approximately 5 minutes. After soaking, the specimen was cut into several small slides along the thickness to determine the moisture profiles.

4. RESULTS AND DISCUSSION

4.1 Model validation

During softening in wood densification, it is important to know how the heat and moisture transfer distributed within the surface of the wood. This information can be used to adjust the treatment for densification parameters, and to control the quality of final product more effectively. The proposed model predicted the moisture and temperature profile very well. The test results are shown in Figures 2 and 3 for aspen and balsam fir, respectively. The soaking depth of a specimen shown in the figures is approximately 8 mm for both species. The average moisture content distribution along the thickness for aspen after soaking process was increased non-uniformly from unsoaked surface. In case of balsam fir the average moisture content distribution along the thickness was increased uniformly from unsoaked surface.

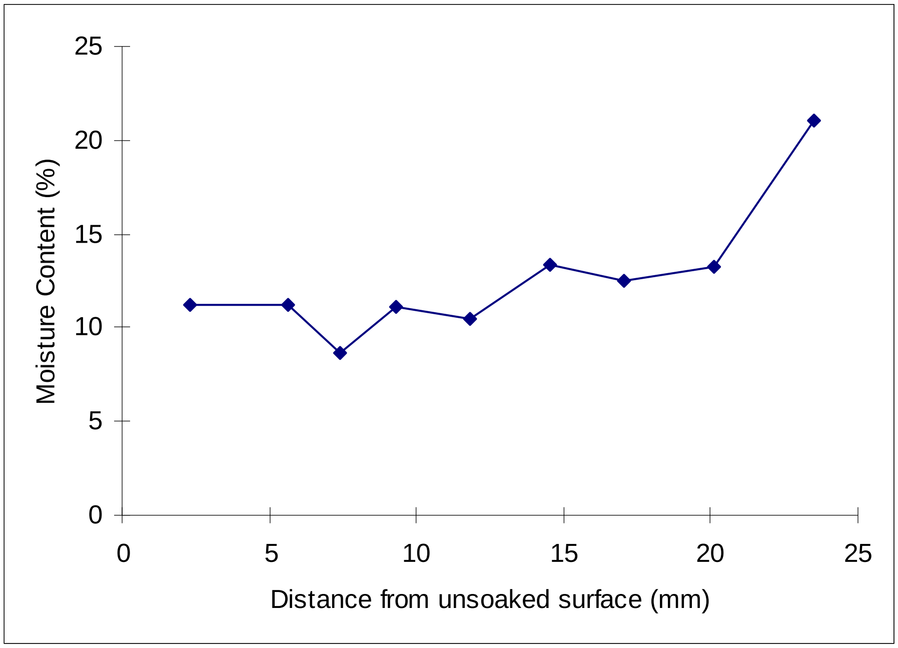

FIGURE.2. Distribution of average moisture content along thickness for three aspen specimens after soaking process

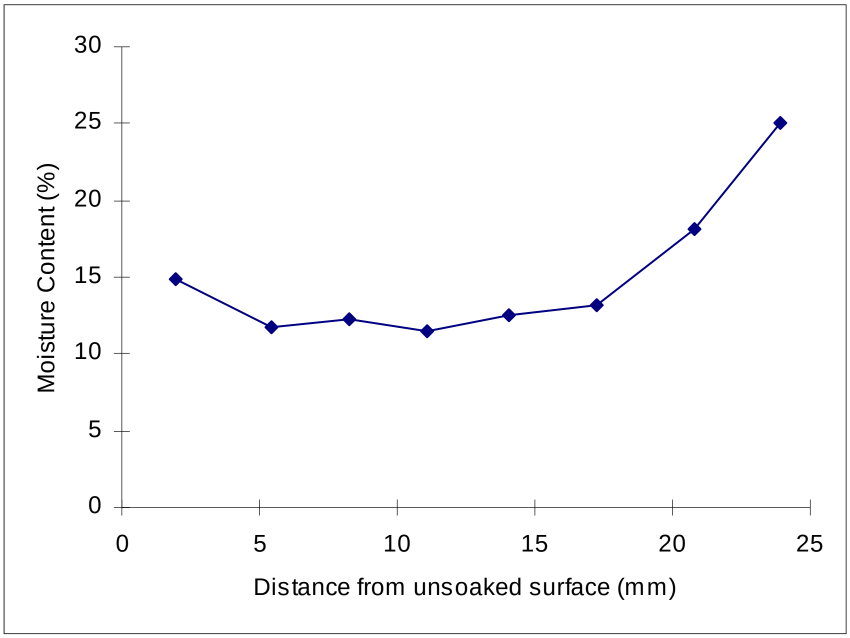

FIGURE. 3. Distribution of average moisture content along thickness for three balsam fir specimens after soaking process

Experimental results of the moisture profile of wood in the soaking process compared to verify the model calculation. To simulate the soaking process by model calculation, the following diffusion coefficient was used in the model for wood [4],

$$D_{eff,M} = 4.78 \times 10^{-5} \exp(-3574/T) \tag{19}$$

Thermal conductivity of wood with moisture content was approximated by the following empirical equation [7]:

$$k = G(0.2 + 0.004M) + 0.024 \tag{20}$$

Where *G* is the specific gravity based on volume at moisture content *M*.
The heat capacity of wet wood is a function of both moisture content and temperature. Koumoutsakos (2001) showed that the heat capacity was not related to wood species and density, and was assumed to be constant over the temperature range of interest [7],

$$Cp_{wood} = (1176 + 5859M)/(1 + M) \tag{21}$$

The results of model simulation and corresponding experimental data are shown in Fig. 4 and 5. Both figures show a very good model prediction of temperature and moisture distribution. Fig. 4 illustrates that the temperature gradient along the thickness is minimal; this can be explained by the effect of hot evaporated vapor surrounding the wood. In Fig. 5, the thickness wetted by soaking in model calculation is also approximately 8 mm.

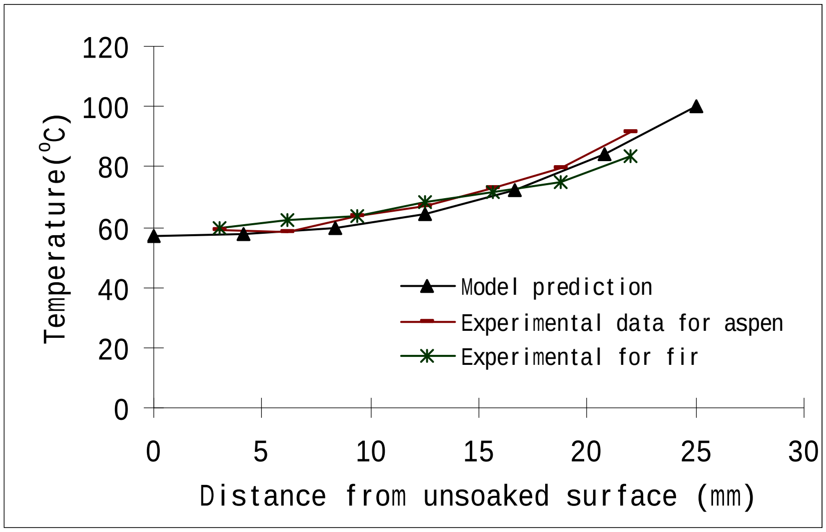

FIGURE. 4. Predicted temperature distribution by model calculation

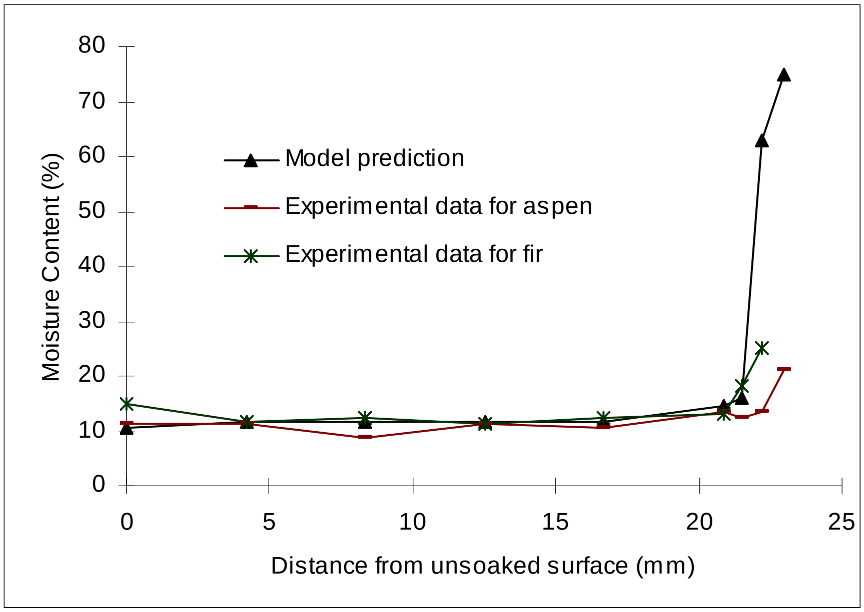

FIGURE. 5. Predicted moisture distribution by model calculation

5. CONCLUSIONS

From the above analysis and comparison between model prediction and experimental data, it can be concluded that:

(1) The principal mechanism of moisture movement in the soaking process is the diffusion of moisture caused by moisture and temperature gradients, also the numerical model for moisture and heat transfer can be suitably used to predict the variables of moisture content (*M*) and temperature (*T*) in the soaking process.

(2) The boundary conditions selected can accurately describe the moisture and heat transfer processes through the material surfaces.

(3) The average moisture content in the surface layers was approximately 25%.

(4) The surface of a specimen to be softened could be heated to a temperature of 80°C to 90°C in 3-5 minutes for these two species. The temperature of the opposite face layers was approximately 60°C.

6. NOMENCLATURES

C_p	heat capacity, $J / Kg.K$
D_{eff}	effective diffusion coefficient, m^2/s
E_b	activation energy, $J/\ mol$
G	specific gravity
h_{heat}	heat transfer coefficient, $W / m^2.K$
ΔH	latent heat, J / kg
H	relative humidity
J	fluxes of moisture, $kg/m^2 .s$
J_e	fluxes of enthalpy, W/m^2
k	thermal conductivity
k_m	heat transfer coefficient, m / s
M	moisture content
R	gas constant, $J/mol.K$
S	surface emission coefficient, m/s
T	temperature
ρ	density of liquid, kg/m^3
λ_{eff}	thermal conductivity, W/m.K

7. ACKNOWLEDGMENT

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