TRANSIENT ANALYSIS OF HEAT AND MASS TRANSFER DURING HEAT TREATMENT OF WOOD INCLUDING PRESSURE EQUATION

by

Souhila KADEM[b], Ramdane YOUNSI[a], Azziz LACHEMET[b], and Duygu KOCAEFE[a]*

[a] Department of Applied Sciences, University of Quebec,
Chicoutimi, Quebec, Canada
[b] Chemical Engineering Institute, University of Sciences and Technology
Algiers, Algeria

In the present paper, 3-D equations for coupled heat and mass conservation equations for wood are solved to study the transient heat and mass transfer during high thermal treatment of wood. The model is based on Luikov's approach, including pressure. The model equations are solved numerically by the commercial package Femlab for the temperature and moisture content histories under different treatment conditions. The simulation of the proposed conjugate problem allows the assessment of the effect of the heat and mass transfer within wood. A parametric study was also carried out to determine the effects of several parameters such as initial moisture content and the sample thickness on the temperature, pressure and moisture content distributions within the samples during heat treatment.

Key words: *heat and mass transfer, high-temperature wood treatment,*
mathematical modeling, Luikov's model, conjugate problem,
pressure equation

Introduction

In hygroscopic porous material like wood, mathematical models describing heat and moisture movement may be used to facilitate experimental testing and to explain the physicals mechanisms underlying such mass transfer process. The water or moisture content of wood is expressed as the weight of water present in the wood divided by the weight of dry wood substance. To increase the strength and rigidity, as well as to protect the wood against biological damage, most of the moisture must be removed.

The high temperature treatment of wood is different than the conventional drying. This technique offers an alternative to chemical treatment of wood which uses traditional oil (creosote and pentachloro-phenol) and chromated copper arsenate (CCA). These chemicals are toxic when released into the environment.

During the high temperature treatment process, various wood species with different moisture contents are heated slowly up to 200 °C-230 °C in hot gas. This treatment reduces the hydrophilic behavior of the wood by modifying the chemical structure of some of its

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* Corresponding author; e-mail: ryounsi@uqac.ca

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components. It also results in significant reduction of the hemicellulose content, thus improves the dimensional stability of the wood [1].

Currently thermal modification of wood has become well established procedure, and there are a growing number of industrial treatment centers in various countries [2]. Several physical mechanisms contribute to moisture migration during the process. For a porous solid matrix, with free water, bound water, vapour, and air, moisture transport through the matrix can be in the form of either diffusion or capillary flow driven by individual or combined effects of moisture, temperature and pressure gradients. The predominant mechanisms that control moisture transfer depend on the hygroscopic nature and properties of the materials, as well as the heating conditions and the way heat is supplied.

From the mathematical point of view, the high thermal treatment of wood can be treated as a simultaneous heat and mass transfer through a porous medium. The theory of transport phenomena in porous materials has been summarized by Luikov [3, 4], Bories [5], Whitaker [6], Ahiua and Yi [7], and Zhang [8]. The analysis of high thermal treatment of wood has been considered recently. Younsi *et al.* [9] analyzed the conjugate problem of heat and moisture transport in wood sample both experimentally and numerically. The classical Luikov model was used for the numerical formulation of the problem in wood only. Younsi *et al.* [10] considered heat treatment of wood by solving diffusion equation in wood and turbulent Navier-Stokes equation in the fluid field for thermowood technology. The experimental results and the model predictions were found to be in good agreement. A parametric study was presented. Kocaefe *et al.* [11, 12] compared the different models (diffusion, Luikov, and multiphase) for the high thermal treatment of wood. The authors showed that the diffusion model is very useful for industrial applications. The full description of the moist air and superheated steam drying models are given elsewhere [13-15]. The Luikov model is recognized as a reliable and still practical formulation, because it accounts for all forms of water-bonding and places no restriction on the moisture transfer mechanism, including whether it is a hygroscopic or no-hygroscopic.

The main goal of this study is to describe the high temperature thermal treatment of wood by introducing a simple 3-D model including gas pressure equation. In this way, transport is treated in all of three anatomical directions of wood (longitudinal, radial, and tangential). The advantage of this simple model is it contains less unknown constants, or in two words, we need less experimental work to determine the constants of the model, compared to multiphase model [16]. An effort was made to consider the moisture and/or temperature dependency of the thermodynamic physical, transport. Modeling and computer simulation are useful alternatives to expensive laboratory methods for assessing the heat treatment of wood. For comparative purposes, modeling and simulation allow the quantification of specific sources of variation that are impossible to isolate in practical heat treatment tests, where there is unavoidable variation in wood properties. The numerical scheme presented is also believed to be a useful tool when identifying material parameters required.
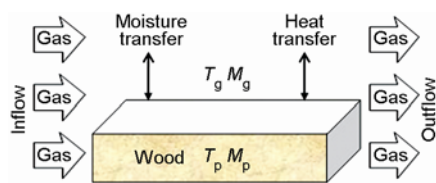

Figure 1. A schematic representation of the geometry

Mathematical formulation

The process of high thermal treatment of wood involves simultaneous transport of heat, and mass through a porous medium. The problem considers a sample of wood exposed to convective heating in an inert atmosphere. Figure 1 shows the geometry of the sample.

Assumptions

The assumptions for the coupled model are:
– the porous system is 3-D,
– the liquid water is incompressible, through the water percentage continuously decreases during the heating process,
– the shrinkage is neglected and no degradation of the solid occurs, and
– there is no heat generation inside the wood.

Governing equations

The Luikov model in 3-D was used to formulate the problem of heat and mass transfer in wood sample during heat treatment, which involves higher temperatures than the conventional drying. Based on these assumptions, the equations describing 3-D heat and moisture transfer in wood during heat treatment are:
– heat transfer

$$\rho\, c_q\, \frac{\partial T}{\partial t} = \vec{\nabla}\left[\left(k_q + \frac{\varepsilon\, \lambda\, k_m\, \delta}{c_m}\right)\vec{\nabla} T + \varepsilon\, \lambda\, k_m\, \vec{\nabla} U\right] \tag{1}$$

– moisture transfer

$$\rho\, c_m\, \frac{\partial U}{\partial t} = \vec{\nabla}\left[\left(\frac{k_m\, \delta}{c_m}\right)\vec{\nabla} T + k_m\, \vec{\nabla} U\right] \tag{2}$$

– gas flow

The air flow in the pores of wood structures is given by:

$$\frac{\partial m_g}{\partial t} = \vec{\nabla}\left[m_g\, \frac{K\, K_g}{\mu_g}\, \vec{\nabla} P_g\right] - \varepsilon c_M \rho\, \frac{\partial U}{\partial t} \tag{3}$$

Gas phase behaves like ideal gas, so:

$$P_g \varepsilon_g = \frac{m_g}{M_g}\, \mathrm{R} T \tag{4}$$

where T is the temperature, U – the moisture potential, t – the time, ρ – the dry body density, c_q – the heat capacity, k_q – the thermal conductivity, k_m – the moisture conductivity, ε – the ratio of vapour diffusion coefficient to total moisture diffusion, λ – the latent heat, δ – the thermal gradient coefficient, K – the permeability; K_g – the gas permeability, μ_g – the viscosity, and P_g – the pressure.

The initial and boundary conditions are:

$$-k_q\, \frac{\partial T}{\partial n} = h_q(T - T_g) + (1-\varepsilon)\, \lambda\, h_m(U - U_g) \quad \text{at} \quad \Omega \tag{5}$$

$$-k_m\, \frac{\partial U}{\partial n} = \left(\frac{k_m\, \delta}{c_m}\right)\frac{\partial T}{\partial n} + h_m(U - U_g) \quad \text{at} \quad \Omega \tag{6}$$

$$P = P_a \quad \text{at} \quad \Omega \tag{7}$$

where n is the spatial direction (x, y, z).

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Initially the material is assumed to be at uniform temperature and moisture content. Thus, the initial conditions can be expressed as:

$$T(x,y,z,0) = T_0 \ , \ M(x,y,z,0) = M_0 \ , \ P(x,y,z,0) = P_a \quad \text{at } t = 0 \tag{8}$$

$$T = T_0 \quad \text{at } t = 0 \tag{9}$$

$$U = U_0 \quad \text{at } t = 0 \tag{10}$$

where U_g is the gas moisture potential, T_a – the ambient temperature, h_q – the convective heat transfer coefficient, h_m – the convective mass transfer coefficient, Ω – the boundary surface for convective heat and mass transfer.

The moisture potential U is related to the moisture content C by:

$$C = c_m U \tag{11}$$

where c_m is a constant.

Mass transfer coefficient h_m and heat transfer coefficient h_q are determined from the expressions for laminar flow [17], respectively:

$$\text{Sh} = \frac{h_m L}{D} = 0.664 \, \text{Re}^{0.5} \, \text{Sc}^{0.33} \tag{12}$$

$$\text{Nu} = \frac{h_q L}{k_q} = 0.664 \, \text{Re}^{0.5} \, \text{Pr}^{0.33} \tag{13}$$

where Sh is the Sherwood number, Re – the Reynolds number, Sc – the Schmidt number, Nu – the Nusselt number, Pr – the Prandtl number, and L – the length of the sample.

These equations are non-linear, see eqs. (1-3), with boundary conditions given by eqs. (5) and (6) where T_g is not constant. Therefore, the equations have to be solved numerically.

Equations (1), (2), and (3) can be written in the generalized form:

$$\left. \begin{aligned} A_{11}\frac{\partial T}{\partial t} + A_{12}\frac{\partial U}{\partial t} + A_{13}\frac{\partial P_g}{\partial t} &= \vec{\nabla}\left[K_{11}\vec{\nabla}T + K_{12}\vec{\nabla}U + K_{13}\vec{\nabla}P_g \right] \\ A_{21}\frac{\partial T}{\partial t} + A_{22}\frac{\partial U}{\partial t} + A_{23}\frac{\partial P_g}{\partial t} &= \vec{\nabla}\left[K_{21}\vec{\nabla}T + K_{22}\vec{\nabla}U + K_{23}\vec{\nabla}P_g \right] \\ A_{31}\frac{\partial T}{\partial t} + A_{32}\frac{\partial U}{\partial t} + A_{33}\frac{\partial P_g}{\partial t} &= \vec{\nabla}\left[K_{31}\vec{\nabla}T + K_{32}\vec{\nabla}U + K_{33}\vec{\nabla}P_g \right] \end{aligned} \right\} \tag{14}$$

where A_{ij} and K_{ij} are coefficients.

The density (ρ), specific gravity (G_m), heat capacity (c_q), and thermal conductivities (k_{qx}, k_{qy}, k_{qz}) of moist wood were calculated using relations proposed by Simpson and Tenwold [18, 20] and Siau [19]:

$$\rho = 1000 \, G_m \left(1 + \frac{M}{100} \right) \tag{15}$$

The heat capacity and thermal conductivity of moist wood are functions of both moisture content and temperature [18]:

$$c_q = \frac{c_{p0} + 0.01\, c_{pw} M}{(1 + 0.01M) + A_c} \qquad (16)$$

where M [%] is moisture content, c_{pw} – the heat capacity of water, c_{p0} – the heat capacity of dry wood, and A_c – the parameter which is a function of moisture content and temperature. c_{p0} and A_c are given [18]:

$$c_{p0} = 0.1031 + 0.003867T \qquad (17)$$

$$A_c = M(-0.06191 + 2.36 \cdot 10^{-4} T - 1.33 \cdot 10^{-4} M) \qquad (18)$$

The thermal conductivities in different directions are [21]:

$$k_{qz} = k_{qy} = G_m(0.1941 + 0.004064M) + 0.01864 \ (k_{qx} = 2k_{qy} = 2k_{qz}) \qquad (19)$$

Heat of vaporization data from steam tables was fitted to a polynomial as a function of temperature and given as [21]:

$$\lambda = 2.792 \cdot 10^6 - 160T - 3.43T^2 \qquad (20)$$

The relative permeability of gas phase on the transversal plan [22] $K_{gy} = K_{gz}$:

$$K_{gy} = 0.95\left(1 - \frac{M}{M_{cr}}\right) + 0.05 \qquad (21)$$

The relative permeability of gas phase along the longitudinal direction [22] K_{gx}:

$$K_{gx} = 1 + \left(4\frac{M - M_{fsp}}{M_{sat} - M_{fsp}} - 5\right)\left(\frac{M - M_{fsp}}{M_{sat} - M_{fsp}}\right)^4 \qquad (22)$$

with

$$M_{fsp} = 0.325 - 0.001T \ [°C] \qquad (23)$$

Numerical solution

The governing equations are solved numerically with the commercial package Femlab [23]. The independence of the solution with respect to the grid size in the solid domain was studied for the final gas temperature of 220 °C and initial moisture content of 20%. A mesh consisting $40 \times 30 \times 30$ elements in wood domain with a time step of 180 s were used for all the subsequent computations considering both accuracy and computation time. The CPU time taken for simulating 24 h of heat treatment process is 1 h on Dell-Pentium 4, 3 GHz machine.

Results and discussion

Predicted high thermal treatment of aspen was carried out. The dimensions of the samples were 100 cm (length) × 10 cm (width) × 3.5 cm (thickness). The board was subjected to a hot gas of temperature 220 °C with 20 °C/h of heating rate, fig. 2. Initially the board was assumed to be at the ambient temperature of 25 °C and average moisture content 10-30%.
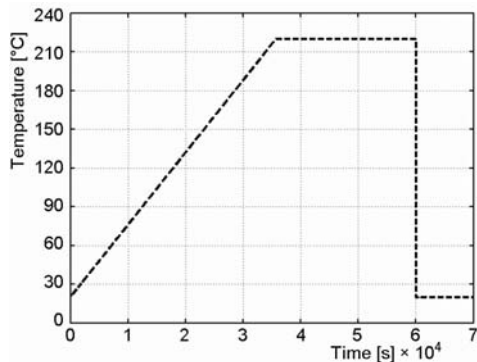
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Figure 2. Typical heat treatment schedule

The validation of the Luikov's model was already carried out by comparing the predictions of the model with the experimental results obtained during the high temperature treatment of jack pine wood. More detailed information on the validation is given elsewhere [15, 16].

During the high temperature heat treatment of wood, it is important to know how the temperature and moisture distribution change with time. This information can be used to adjust the treatment parameters and, consequently, to control the quality of final product more effectively. The mathematical model successfully predicts these profiles. In the model, the temperature and moisture distributions of the wood were calculated at each time step. The average moisture content, temperature and pressure of the material at any time step was determined by averaging the calculated moisture distribution, temperature, and pressure in the sample, respectively.

Figure 3 shows the time evolution of average temperature, pressure, and moisture content during high thermal treatment of the sample. During process, the temperature increases and the average moisture content decreases almost linearly with time, due to the influence of gas temperature. The pressure of gas increases because of evaporation. Evaporation of liquid moisture takes place from the wood sample surface by absorbing the heat of vaporization. The moisture migrates toward the external wood surfaces by means of capillary flow under the influence of moisture content gradient. When the moisture content reaches an equilibrium value, the pressure decreases to reach atmospheric value.
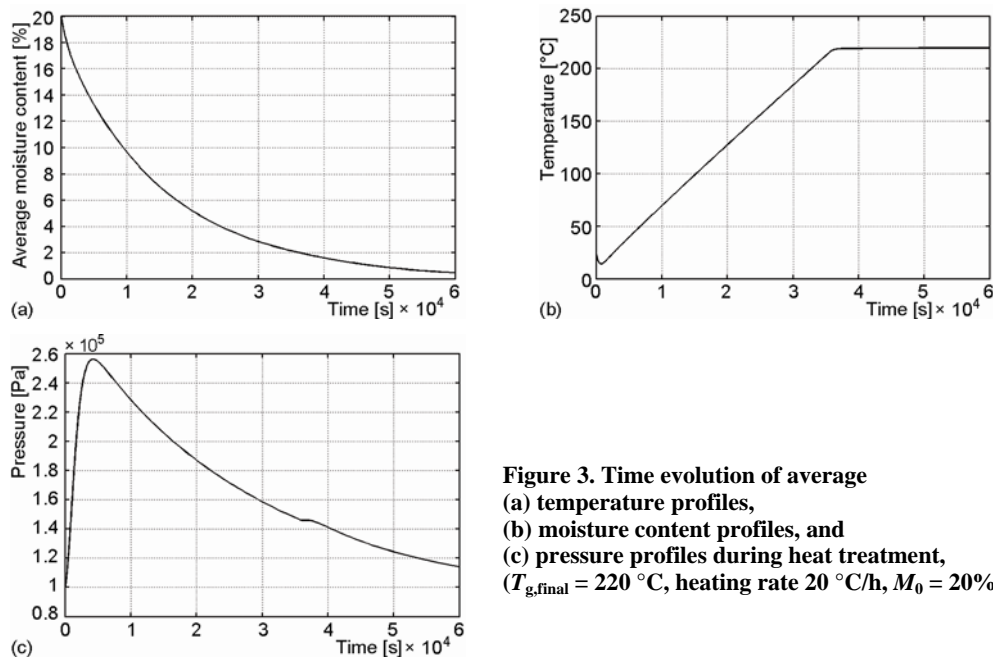

**Figure 3. Time evolution of average
(a) temperature profiles,
(b) moisture content profiles, and
(c) pressure profiles during heat treatment,
($T_{g,final}$ = 220 °C, heating rate 20 °C/h, M_0 = 20%)**

Figure 4 illustrates the behavior of temperature, pressure, and moisture content profiles inside the sample for $t = 8$ h and 16 h. It is clearly seen that all the profiles are symmetrical as expected since all external surfaces of the sample are subjected to the same boundary conditions. The moisture gradient decreases as the distance from the heat exposed surfaces increases, *i. e.*, the closer to the surface of the board, the lower the moisture content will be. It can be verified that larger moisture gradients occur for lower time, tending to zero at the end of the process, when the wood reaches its equilibrium moisture. The final pressure reaches atmospheric value when all moisture content was evaporated. The temperatures at the boundary surfaces are slightly higher than those at the interior of wood at different times. The heated gas stream is the only heat source and is in contact with the wood at the surfaces.
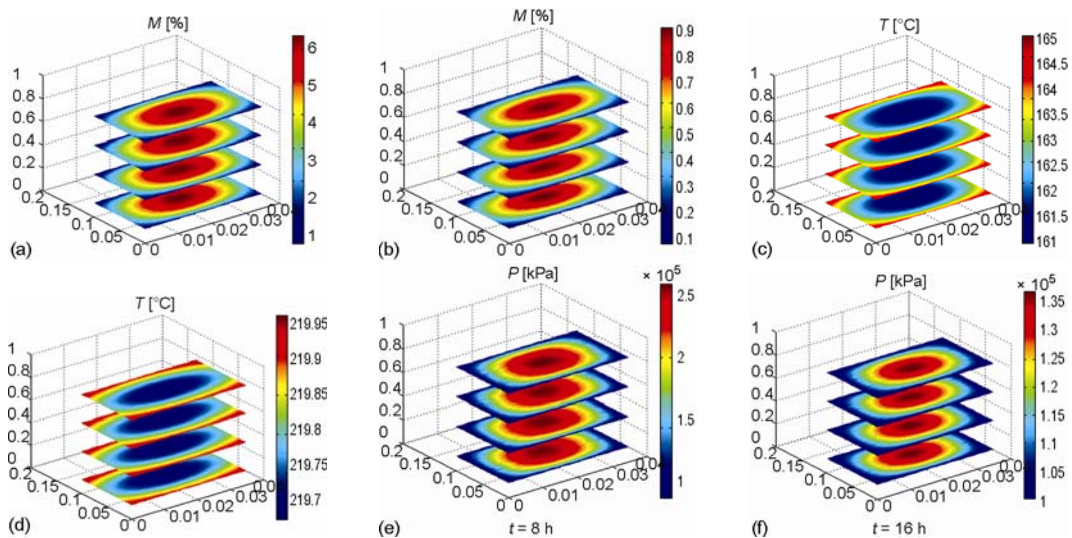

Figure 4. Spatial profiles of (a) temperature, (b) moisture content, and pressure during heat treatment ($T_{g,final}$ = 220 °C, heating rate 20 °C/h, M_0 = 20%) *(for color image see journal web-site)*

A series of simulations were carried out at different initial average moisture contents (M_0) of 10%, 20%, and 30% keeping the other conditions constant. The heating rate was maintained at 20 °C/h, and the final gas temperature was taken as 220 °C. The influence of initial moisture content of wood on temperature, moisture content, and pressure *vs.* time data is presented in fig. 5. It can be seen from the figure that there are slight differences between the temperatures of the samples: lower the initial moisture content of the sample, higher is the temperature. Obviously, vaporization has a cooling effect. Since the humidity of the gas is kept constant, high initial moisture content means higher moisture gradients at the surface and high pressure due to evaporation. Therefore, vaporization rate at the surface will be higher for the sample with high moisture content which leads to lower temperatures. As expected, the time necessary for moisture removal is greater if the initial moisture content of the sample is higher when the other treatment conditions are kept constant.

Using the model, the average temperatures, pressure, and moisture content distributions at different times can be predicted for any size wood sample. Simulations were carried out for three different sample sizes. For these simulations, the length of the sample was kept constant (1 m). The geometrical ratio (thickness/width) of the samples was taken as 0.35, 0.55, and 0.75.
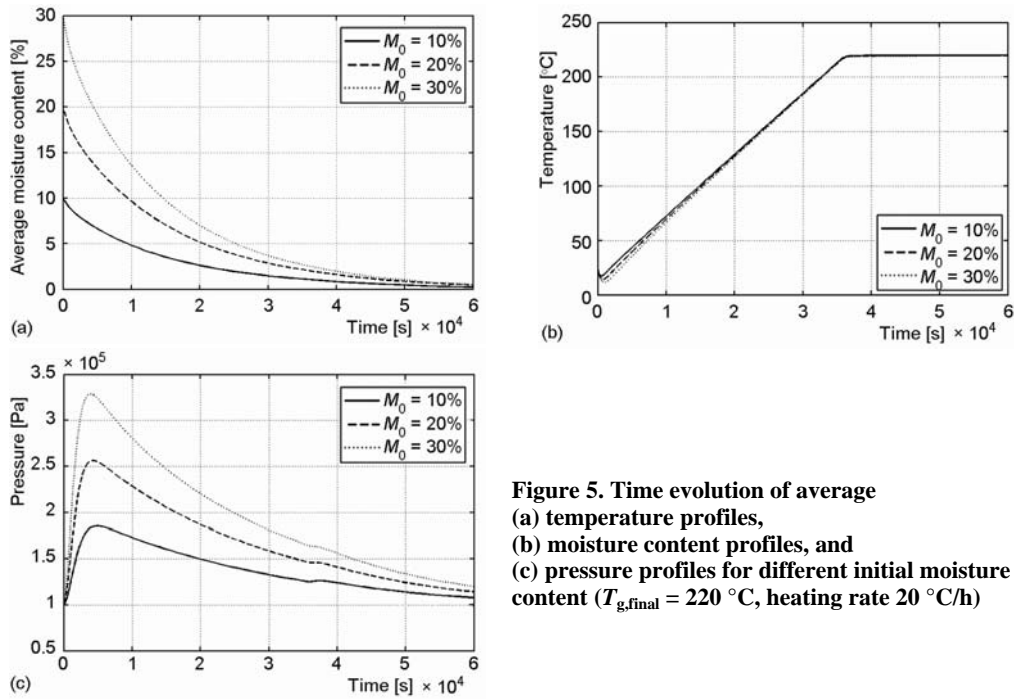
**Figure 5. Time evolution of average
(a) temperature profiles,
(b) moisture content profiles, and
(c) pressure profiles for different initial moisture
content ($T_{g,final} = 220$ °C, heating rate 20 °C/h)**

Figure 6 compares the temperatures, pressure, and moisture content of the samples for different sample sizes. As expected, the temperature is lowest for the largest sample, and
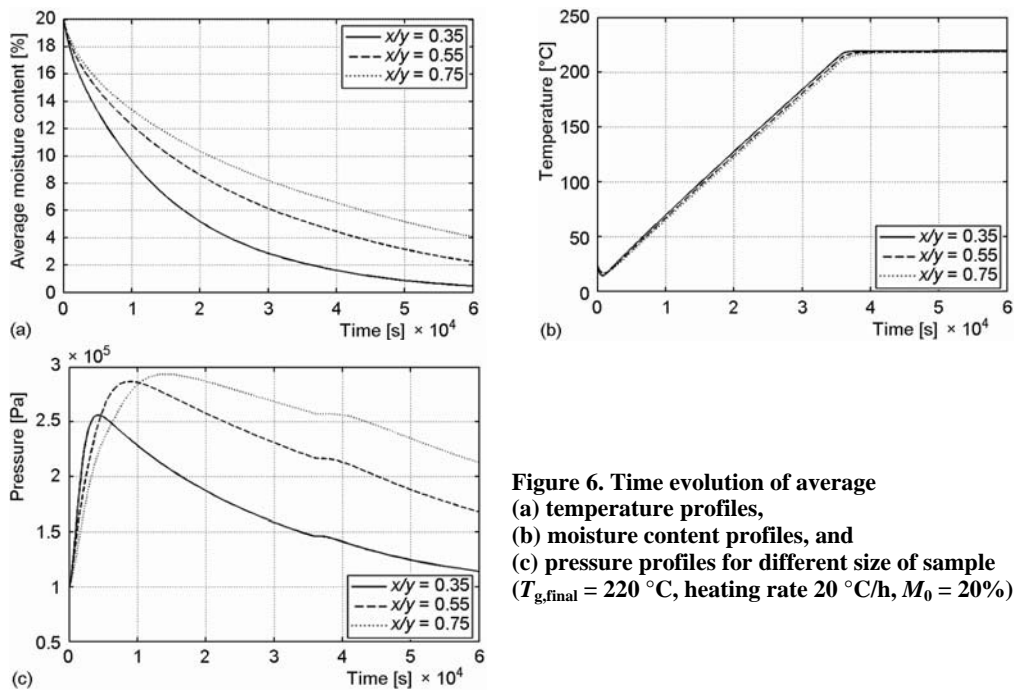

**Figure 6. Time evolution of average
(a) temperature profiles,
(b) moisture content profiles, and
(c) pressure profiles for different size of sample
($T_{g,final} = 220$ °C, heating rate 20 °C/h, $M_0 = 20\%$)**

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highest for the smallest sample for any given time. As the sample size increases the distance the heat has to travel increases before it reaches the center point. Since the thermal conductivity of the wood is very low, the differences in the temperatures can be seen clearly. The reduction of average moisture content becomes much faster as the sample thickness decreases which leads to lower pressure. In order to drive the moisture out of the sample, the moisture present in the interior part of the sample has to diffuse to the surface. The moisture is removed from the wood at the surface and carried away by the gas. As the sample size increases, the diffusion process takes longer. Under the same heat treatment conditions, it leads to samples with different final moisture contents and pressure. Therefore, the size of the sample has to be considered when treatment schedules are prepared. The present model can give a very good estimation of the time required for the treatment of a sample with any size and shape.

Conclusions

A coupled heat and mass transfer model has been used to achieve a better understanding of the high temperature heat treatment of wood and to determine its influence on several parameters that control the process. This study is carried out by solving 3-D Luikov model. The Femlab software was used to solve the coupled system of partial differential equations. This model can be an important tool for the design of new furnaces, for the analysis of problems encountered in existing furnaces, and optimization of their operation. Computational methods can considerably reduce costly experimental time and increase the understanding of wood heat treatment processes by allowing researchers to look inside the furnace and inside the wood piece. Experimental work is in progress to validate the numerical predictions.

Nomenclature

C – concentration, [kgm^{-3}]
c_m – moisture capacity, [kg$_m$kg^{-1}°M^{-1}]
c_q – heat capacity, [Jkg^{-1}K^{-1}]
D – diffusion coefficient, [m^{2}s^{-1}]
G_m – specific gravity
g – gravitational acceleration, [ms^{-2}]
h_m – convective mass transfer
     coefficient, [kg$_m$m^{-2}s^{-1}°M^{-1}]
h_q – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
K – intrinsic permeability, [m^2]
K_g – relative permeability, [m^2]
k_m – moisture conductivity, [kg$_d$m^{-1}s^{-1}°M^{-1}]
k_q – thermal conductivity, [Wm^{-1}K^{-1}]
M – moisture content, [(%) kgH$_2$O kgsolid^{-1}]
M_g – molar mass, [kgmol^{-1}]
Nu – Nusselt number, (= $h_q L/k_q$)
n – normal, [–]
P – pressure, [Pa]
Pa – atmospheric pressure, [Pa]
Pr – Prandtl number, (= $\mu c_q/k_q$)
R – gas constant, [Jmol^{-1}K^{-1}]
Re – Reynolds number (= VD/ν)
Sc – Schmidt number (= ν/D)
Sh – Sherwood number (= hL/D)

T – temperature, [K]
U – moisture potential, [°M^{-1}]
V – velocity, [ms^{-1}]

Greek symbols

δ – thermal gradient coefficient, [kg$_m$kg^{-1}K^{-1}]
ε – ratio of vapor diffusion coefficient to
     coefficient of total moisture diffusion, [–]
λ – latent heat of vaporization, [Jkg^{-1}]
μ – dynamic viscosity, [kgm^{-1}s^{-1}]
ν – cinematic viscosity, [ms^{-2}]
ρ – dry body density, [kgm^{-3}]
Ω – boundary surface of the computational
     domain

Subscripts

0 – initial
a – ambient
d – dry
f – fluid
g – gas
m – moisture
p – product
sat – saturation

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