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A high-temperature thermal treatment of wood using a multiscale computational model: Application to wood poles

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ABSTRACT

The present study is devoted to a numerical study with experimental validation of the high-temperature thermal treatment of three-dimensional wood pole. During the heat treatment process, the heat and mass transfer takes place between the solid and the drying medium, and the moisture evaporation occurs within the solid due to the capillarity action and diffusion. The development of the model equations, taking into account both bulk phases and interfaces of the multiphase system is described, starting from the microscopic scale. Fundamental to this model is the ability to quantify the effects of key material and geometric properties of the pole. The three-dimensional and unsteady-state mathematical model equations are solved numerically by the commercial package FEMLAB for the temperature and moisture content histories under different treatment conditions. A detailed discussion of the computational model and the solution algorithm is given. Heat treatment was applied on the test samples in an oven for three final temperatures (180, 200 and 220 °C). A series of experimental tests aimed at determination of heat treatment schedules kinetics curves and the temperature and moisture profiles and there time evolution were carried out. A very good agreement between the experimental and predicted results was obtained, implying that the proposed numerical algorithm can be used as a useful tool in designing high-temperature wood pole treatment processes.

1. Introduction

The advantages and economy of wood have led the world's utility industries to use a substantial number of wood poles to support overhead electrical power systems. Wood poles for power distribution and transmission have the advantage of requiring a relatively simple foundation system, and connections can be easily fabricated. In order to reduce moisture content in woods to a level low enough and to prevent undesirable biochemical reactions and microbiological growth, prolonged drying time and high temperature must often be used.

Heat treatment of wood at relatively high temperatures (in the range of 150–250 °C) is an effective method to improve biological durability of wood (Finnish Thermowood Association, 2003; Shi et al., 2007a,b; Momohara et al., 2003; Poncsak et al., 2006, 2007). The main objective is to reduce the hydrophilic behaviour of wood by the tridimensional modification of the chemical structure of some of its components through heat treatment in controlled atmosphere as a soft pyrolysis reaction. The process consists in starting from wood previously dried around 10–15% in humidity and to heat slowly in a specific chamber up to 210–240 °C in a nitrogen atmosphere with less than 2% in oxygen. Currently thermal modification of wood has become well established procedure, and there is a growing number of industrial treatment centers in various countries (Finnish Thermowood Association, 2003).

Moisture in wood exists in three phases: water vapour, bound water, and free water above the fiber saturation point (FSP) (Siau, 1984). Below FSP, water vapour exists in the cell cavities and bound water is found in the cell walls, in the hygroscopic range. The maximum bound water content is at the FSP and is limited by the number of sorption sites available. This may differ among species because their chemical compositions vary, but it is usually assumed that FSP is 30% water, based on the wood's dry weight at room temperature.

Several physical mechanisms contribute to moisture migration during drying. 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.

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Nomenclature

C_p	heat capacity (J/kg K)	t	time, s
D	diffusion coefficient, $m^2\,s^{-1}$	T	temperature, K
h	heat enthalpy, $J\,kg^{-1}$		
h_m	mass transfer coefficient, $m\,s^{-1}$	*Greek letters*	
h_q	heat-transfer coefficient, $W\,m^{-2}\,K^{-1}$	ρ	dry body density, $kg\,m^{-3}$
k_q	thermal conductivity, $W\,m^{-1}\,K^{-1}$	μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
K	permeability, m^2	φ	relative humidity of the drying gas
M	moisture content (%)	Ψ	coefficient for partial pressure of water vapour in wood
m_v	molar mass, $kg\,mol^{-1}$	Δh_{lv}	latent heat of vapourization, $J\,kg^{-1}$
n	normal		
Nu	Nusselt number	*Subscripts*	
P	partial water vapour pressure in wood, Pa	0	initial
P_{sv}	saturation water vapour pressure in wood, Pa	b	bound
Pr	Prandtl number	d	dry
R	ideal gas constant, $J\,mol^{-1}\,K^{-1}$	final	final
Re	Reynolds number	FSP	fiber saturation points
x, y, z	spatial directions, m	g	gas
Sc	Schmidt number	l	liquid
Sh	Sherwood number	v	vapour

High-temperature heat treatment of wood is a complex process involving simultaneous heat, mass and momentum transfer phenomena and effective models are necessary for process design, optimization, energy integration, and control (Fyhr and Rasmuson, 1997; Johanson et al., 1997; Pang, 1998). 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.

The development of the theory of transport phenomena in porous materials has been summarized by Luikov (1975, 1980) and Whitaker (1977). Luikov (1975) has developed a set of coupled partial differential equations to describe heat and mass transport in capillary-porous media by assuming that the transfer of moisture is analogue to heat transfer and that capillary transport is proportional to the moisture and temperature gradients. A dimensionless analysis of heat and mass transfer in a piece of wood was conducted by Younsi et al. (2006a) using the Luikov model. The influence of the governing parameters (Luikov, Posnov, Kossovitch and Biot numbers) on temperature and moisture fields within the wood sample was illustrated. This approach has been used by Thomas et al. (1980) and Irudayaraj et al. (1990). The solution, even numerical, is complicated, involving complex eigenvalues (Liu and Cheng, 1991). Lewis et al. (1996) and Malan and Lewis (2003) demonstrated the efficacy of the finite element numerical solution proceeding in solving highly non-linear drying systems. Murugesan et al. (2001) developed a theoretical model for brick drying in two dimensions based model on liquid, vapour and energy balances as well as on Darcy's law for capillary liquid mass flux and Fick's law for diffusive mass flux. (Oliveira and Haghighi, 1998) obtained the temperature and moisture contours for the drying of wood, considering a laminar boundary layer flow avec a solid. For the mathematical formulation, they used the Luikov model for solid and Navier–Stokes for fluid.

The analysis of high thermal treatment of wood has been considered recently. Younsi et al. (2006b,c) 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. A parametric study was presented. Kocaefe et al. (2007) 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.

In this study, a three-dimensional mathematical model for high temperature thermal treatment of wood poles has been developed to describe heat and mass transfer during the process. An effort was made to consider the moisture and/or temperature dependency of the thermodynamic physical, transport. Three moisture phases were accounted for: bound water and water vapour, which is the advantage of this model. The objectives of this work were to:

- Make a valid mathematical model that describes the heat and moisture transfer processes occurring during high thermal treatment of wood poles; and
- Validate the model by comparing the experimental results obtained by drying of stack of jack and red pines boards to the results obtained from the simulation.

2. Methods

The high thermal treatment process within wood can be interpreted as simultaneous heat and mass transfer with local thermodynamic equilibrium. The problem considers a sample of wood exposed to convective heating in an inert atmosphere. Fig. 1 shows

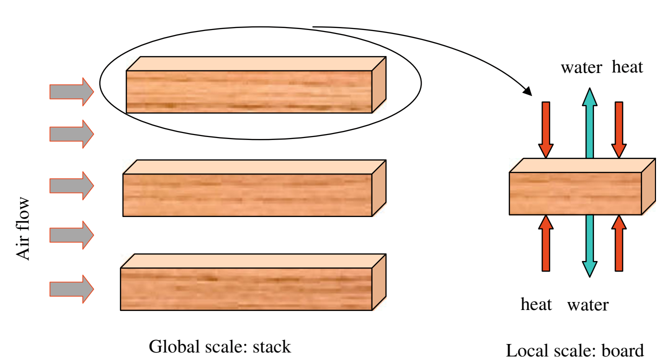

Fig. 1. Global schematic of the physical model.