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Computational modelling of heat and mass transfer during the high-temperature heat treatment of wood

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Abstract

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. In the current work, the three-dimensional Navier–Stokes equations along with the energy and concentration equations for the fluid coupled with the energy and mass conservation equations for the solid (wood) are solved to study the conjugate heat treatment behaviour. Whitaker's continuum approach has been used to obtain the equations for the liquid and vapour migration within the solid. Three moisture phases are accounted for: free water, bound water, and water vapour. The model equations are solved numerically by the commercial package FEMLAB for the temperature and moisture content histories under different treatment conditions. The model validation is carried out via a comparison between the predicted values with those obtained experimentally. The comparison of the numerical and experimental results shows good agreement, implying that the proposed numerical algorithm can be used as a useful tool in designing high-temperature wood treatment processes.

Keywords: Simultaneous heat and moisture transfer; High-temperature wood treatment; Multiphase model; Mathematical modelling; Validation

1. Introduction

The conjugate heat and moisture transfer from a solid body in a convection environment has many applications in industry. The simultaneous heat and mass transfer through a porous medium plays an important role in wide engineering applications such as drying, food processing, designing solar houses, etc.

In order to reduce moisture content in woods to a level low enough, to prevent undesirable biochemical reactions and microbiological growth, prolonged drying time and high temperature must often be used [1–4].

High temperature heat treatment of wood is a complex process involving simultaneous heat, mass and momentum transfer phenomena and the effective models are necessary for process design, optimization, energy integration, and control.

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. In this regard, there is a need to assess the effects of the heat and mass transfer within the wood on the transfer in the fluid adjacent to it.

The development of the theory of transport phenomena in porous materials has been summarized by Luikov [5,6] and Whitaker [7]. Luikov [5] has developed a set of coupled partial differential equations to describe a heat and mass transport in capillary porous media by assuming that the transfer of moisture is analogue to heat transfer and that

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Nomenclature

C	concentration, kg m^{-3}
C_p	heat capacity, J kg^{-1} K^{-1}
D	diffusion coefficient, m^2 s^{-1}
g	gravitational acceleration, m s^{-2}
h	heat enthalpy, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
K	permeability, m^2
M	moisture content, kg H_2O (kg solid)$^{-1}$
m_v	molar mass, kg mol^{-1}
n	normal
P	partial water vapour pressure in wood, Pa
P_{sv}	saturation water vapour pressure in wood, Pa
R	ideal gas constant, J mol^{-1} K^{-1}
t	time, s
T	temperature, K
$\mathbf{V}$	velocity, m s^{-1}
ρ	dry body density, kg m^{-3}
δ	attenuation factor in the effective diffusivity
μ	dynamic viscosity, kg m^{-1} s^{-1}
φ	relative humidity of the drying gas
Ψ	coefficient for partial pressure of water vapour in wood
ΔH_{lv}	latent heat of vaporisation, J kg^{-1}

Subscripts

0	initial
b	bound
f	free water
final	final
FSP	fiber saturation points
g	gas
l	liquid
v	vapour

capillary transport is proportional to moisture and temperature gradient. A dimensionless analysis of heat and mass transfer in a piece of wood was conducted by Younsi et al. [8] using the Luikov model. The influence of the governing parameters (Luikov, Posnov, Kossovitch and Biot numbers) on temperature and moisture fields within wood sample was illustrated.

This approach has been used by Thomas et al. [9] and Irudayaraj [10]. But the solution, even numerical, is complicated, involving complex eigenvalues [11]. Malan et al. [12] and Lewis et al. [13] demonstrated the efficacy of the finite element numerical solution proceeding in solving highly non-linear drying systems.

Murugesan et al. [14] 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 [15] 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. [16] 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.

In the majority of the models, described earlier, the heat and mass transfer coefficient values at the interface of the solid are specified from standard correlations. Also, these coefficients were assumed to be constant throughout the wood surfaces. But in reality, high thermal treatment of wood is a conjugate problem and transient. Leading edge heats up faster when compared to other surfaces. So, this thermal treatment has to be studied along with the flow field as a conjugate problem.

In this study, a three-dimensional mathematical model for high temperature thermal treatment of wood model has been developed to describe heat and mass transfer during the process. Three moisture phases were accounted for: free (liquid) water, bound water and water vapour, which is the advantage of this model. The three-dimensional Navier–Stokes equations have been solved for the flow field, which will enable to study the conjugate drying (heat treatment) process for any three-dimensional shape. A comparison with experimental results was performed under different operating conditions to test the model.

2. Mathematical formulation

The process of high thermal treatment of wood involves simultaneous transport of heat, and mass through a three-phase porous medium. In the formulation of the mathematical mode, the main transport mechanisms have been identified and numerically expressed. The problem considers a sample of wood exposed to convective heating in an inert atmosphere. The temperature, the specific humidity and the velocity of the incident external flow are denoted by T_g, C_g and U_g. Fig. 1 shows the geometry of the sample. The experimental part of this work and experimental apparatus details are described elsewhere [16].

The governing equations for wood were derived at a macroscopic level. Variables used in this study are averaged values over a control volume. This approach was first proposed by Whitaker [7] and has been widely used in heat and mass transfer studies related to drying of porous media [17]. Three dimensional Navier–Stokes equations, energy