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Computational and experimental analysis of high temperature thermal treatment of wood based on ThermoWood technology☆

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ABSTRACT

Heat treatment of wood at relatively high temperatures (in the range of 180–240 °C) is an effective method to improve the dimensional stability and increase biological durability of wood. In this article, a coupling method is presented for high thermal treatment of a wood based on ThermoWood technology. A three-dimensional mathematical model describing simultaneous unsteady heat and moisture transfer between a gas phase and a solid phase during heat treatment has been developed. The conservation equations for the wood sample are obtained using diffusion equation with variable diffusion coefficients and the 3-dimensional incompressible Reynolds averaged Navier–Stokes equations have been solved for the flow field. The experimental results and model predictions were found to be in good agreement.

1. Introduction

Wood, a composite of cellulose, hemicelluloses, lignin, and extractives, is commonly used as engineering and structural material. Unprotected wood exposed to outdoor conditions undergoes a variety of degradation reactions induced by diverse factors such as light, moisture, heat, oxygen, and pollutants [1,2]. The weathering process of wood is primarily a surface phenomenon, although the cracks and checks developing during weathering can be sensitive to fungal attack and lead to more severe destruction of wood. Heat treatment is one of the processes used to modify the properties of wood. Heat-treated wood is considered an eco-friendly alternative to chemically impregnated wood materials. The chemical modifications that occur in wood at high temperatures are accompanied by several favourable changes in its physical properties, including reduced shrinkage and swelling, improved biological durability, low equilibrium moisture content, enhanced weather resistance, a decorative dark colour, improved thermal insulation properties and better decay resistance [3–7].

Different methods for the thermal modification of wood have been developed in France, Finland, the Netherlands and Germany since the middle of the last century. All the heat processes have in common the treatment of wood at elevated temperatures in the range between 160 °C and 260 °C. The main differences between the processes are in the process conditions (process steps, oxygen or nitrogen, steaming, wet or dry process, use of oils, steering schedules etc.) [8]. The main targets for industrial heat treatment are improved dimensional stability, increased biological durability, enhanced weather resistance and decreased shrinking and swelling of wood. An industrial scale wood heat treatment process of wood, ThermoWood, has been developed at the Finnish Research Centre VTT together with the Finnish industry [9]. The ThermoWood process is based on heating the wood material at high temperatures above 180 °C under normal pressure while protecting it with water vapour [9]. Water vapour protects the wood from burning and cracking, and it also affects the chemical changes taking place in wood. This is the method used for all work done in this article.

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 [10–14]. Leading edge heats up faster when compared to other surfaces. Therefore, this thermal treatment has to be studied along with the flow field as a conjugate problem. Hence, it is necessary to solve Navier–Stokes equations in the surroundings of the wood sample in order to get information about the boundary conditions for the transport equations in the medium and solve the complete thermal problem [15,16]. The suggested model, which uses the three-dimensional diffusion model, is an attempt to improve the description of the coupled heat and mass transfer process during thermal treatment of wood, which is the originality of this study.

In the present work, the turbulent three-dimensional Navier–Stokes equations along with the energy and concentration equations for the flow domain coupled with the energy and mass conservation equations for wood sample are solved to study the conjugate high temperature thermal treatment of wood treated by ThermoWood technology. A comparison of the model predictions with experimental results was performed for different schedules to test the model.

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Nomenclature

C	concentration, kg m^{-3}
c_p	heat capacity, J kg^{-1} K^{-1}
D	diffusion coefficient of water vapour in the fluid, m^2 s^{-1}
D_s	diffusion in the wood sample, m^2 s^{-1}
G_m	specific gravity
k	turbulent kinetic energy, m^2 s^{-2}
k_q	thermal conductivity, W m^{-1} K^{-1}
M	moisture content, kg H_2O (kg solid)$^{-1}$
P	pressure, Pa
P_k	shear production of turbulent kinetic energy, m^2 s^{-3}
Re	Reynolds number based on the length of the wood sample, $\rho_f U_f L/\mu_f$
T	temperature, K
(x,y,z)	spatial coordinates, m
(u,v,w)	average velocities, m s^{-1}
Greek letters	
ρ	mass density, kg m^{-3}
μ	dynamic viscosity, kg m^{-3} s^{-1}
ε	viscous dissipation in turbulent flows
$\sigma_{k,\varepsilon,T,C}$	turbulent Prandtl numbers of k, ε, T, and C
τ_w	wall shear stress, N m^{-2}
ΔH_{lv}	latent heat of vapourization, J kg^{-1}
Subscripts	
0	initial
d	dry porous solid
eff	effective value
bt	bound
Y*	dimensionless distance from wall in turbulent flows

2. Mathematical formulation

The problem can be viewed as *a* batch of wood exposed to high convective heating in an inert atmosphere (Fig. 1). The approach adopted in this study consists of solving the hydrodynamics problem and then solving for the heat and mass transfer in wood. It is assumed that the flow field is turbulent, the flow-porous system is three-dimensional, the shrinkage and gravity effects are negligible and no degradation of the solid occurs, there is no heat generation inside the wood. Fig. 1 shows the geometry of the physical model.

2.1. Governing equations for the flow field

Based on the average velocities measured in the furnace, the flow regime is expected to be turbulent. The three-dimensional Navier–Stokes, energy and concentration equations are considered as follows [16]:

Continuity

$$\frac{\partial(\rho_f u)}{\partial x} + \frac{\partial(\rho_f v)}{\partial y} + \frac{\partial(\rho_f w)}{\partial z} = 0 \tag{1}$$

Momentum

X-momentum

$$\frac{\partial}{\partial t}(\rho_f u) + \frac{\partial}{\partial x}(\rho_f uu) + \frac{\partial}{\partial y}(\rho_f uv) + \frac{\partial}{\partial z}(\rho_f uw) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial u}{\partial y}\right] + \frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial u}{\partial z}\right] \tag{2}$$

Y-momentum

$$\frac{\partial}{\partial t}(\rho_f v) + \frac{\partial}{\partial x}(\rho_f uv) + \frac{\partial}{\partial y}(\rho_f vv) + \frac{\partial}{\partial z}(\rho_f vw) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial v}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial v}{\partial y}\right] + \frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial v}{\partial z}\right] \tag{3}$$

Z-momentum

$$\frac{\partial}{\partial t}(\rho_f w) + \frac{\partial}{\partial x}(\rho_f uw) + \frac{\partial}{\partial y}(\rho_f vw) + \frac{\partial}{\partial z}(\rho_f ww) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left[(\mu_{eff})\frac{\partial w}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\mu_{eff})\frac{\partial w}{\partial y}\right] + \frac{\partial}{\partial z}\left[(\mu_{eff})\frac{\partial w}{\partial z}\right] \tag{4}$$

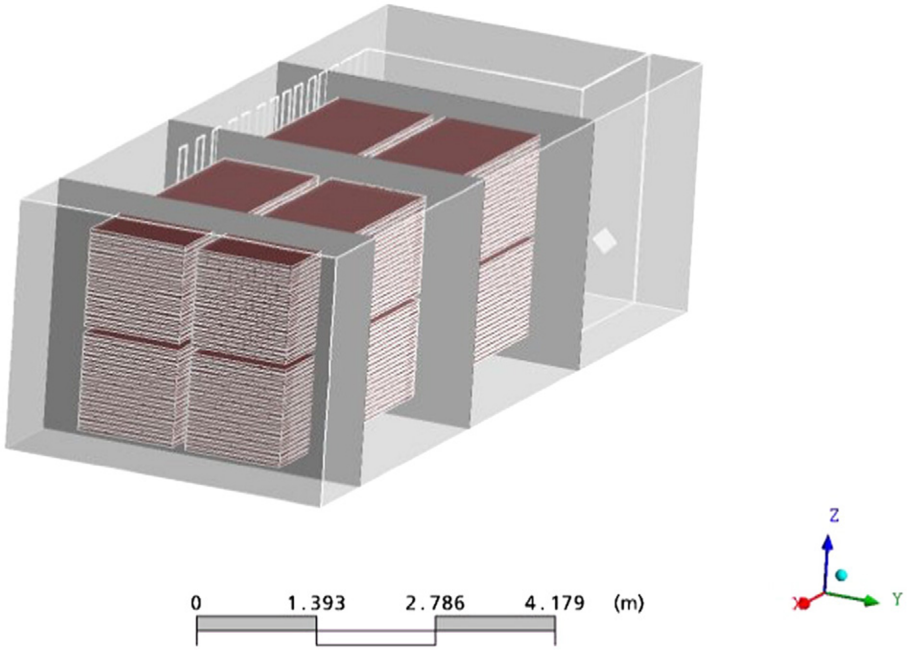

Fig. 1. Global schematic of the physical model.