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3D-modelling of conjugate heat and mass transfers: Effects of storage conditions and species on wood high temperature treatment

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ABSTRACT

Wood is definitely advantageous for industry because it is a renewable resource environment-friendly produced. However, the biological origin of wood requires some treatments to preserve and stabilise it. Heat treatment of wood at high temperature is one of the new techniques that reduce the hygroscopicity, improve dimensional stability, and increase resistance to biological degradation of wood material without the use of chemical products.

In this work, transient heat and mass transfers during heat treatment of wood at high temperature were numerically studied. The averaged energy Reynolds Navier–Stokes equations and concentration equations for the fluid were coupled with the energy and mass conservation equations for the wood. The numerical conjugate problem considered also heat and mass exchange at the fluid-wood interface and was used to study the effects of specie-dependant (specific gravity) and storage-dependant (initial temperature and moisture content) parameters during the heat treatment. Both temperature and moisture content were affected by a low initial temperature during the first hours of the treatment, representing hypothetically a risk for wood quality. A high specific gravity or a high initial moisture content required supplemental heating time to reach the targeted final moisture content that potentially represent a supplemental energy and cost for industry.

1. Introduction

In the current battle against greenhouse gas emission, the wood material finds great importance in industrial applications because its production presents both low energy costs and benefits for carbon footprint. Wood is also a hygroscopic material with sophisticated multilayer cellular microstructure. Hence, it must be treated to build up dimensional stability and durability for industrial application. Heat treatment of wood has been considered as an effective method to modify wood without the use of any toxic chemicals.

Even though the effects of heat treatment for protection of wood were known for hundreds of years, industrial operations began quite recently. And only since last decades this issue has been scientifically studied and investigations on heat-treated wood at high temperature were subject of numerous publications [1–4]. Since 1990 different heat treatment processes for wood at high temperature were used in industries; including Finnish process (Thermo-Wood), Dutch process (Plato-Wood), French process (Bois-Rétifié, Bois-Perdure) and German process (Menz Holz or Oil-heat treatment) [5]. These technologies are developed using different heating medium like oil at high temperature, water vapour, nitrogen, etc. and aim to implement a gradual rise in temperature of the wood in absence of oxygen. In the conventional heat treatment processes (drying) where the maximum temperature reached was usually 100–120 °C, chemical changes in wood structure were limited. Furthermore, Trcala 2012 [6] showed that the Soret effect on the moisture distribution, which was important at the beginning of the drying process, decreased progressively (for the time between 20,000 s and 50,000 s) and then vanished.

The high-temperature thermal treatments usually reach 150–260 °C; that was an intermediate range of temperatures between the drying and the carbonization of the wood. The heat treatment at high temperature of wood is known to improve its physical properties by reducing its hygroscopicity and increasing its dimensional stability [3,7]. Also, Kamdem et al. [8] showed that the resistance of wood against decay by fungal attack was a friendly consequence of the heat treatment; and more broadly, thermal treatment of wood at high temperature is an effective method to improve its biological durability [9–13]. Chemical modifications

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Nomenclature

Symbols

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 coefficient in the wood material (m^2 s^{-1})
G_m	wood specific gravity
k	turbulent kinetic energy (m^2 s^{-2})
h_q	convective heat transfer coefficient (W m^{-2} K^{-1})
h_m (C_pT)	thermal energy per mass unit (J kg^{-1})
k_f	thermal conductivity of fluid (W m^{-1} K^{-1})
k_q	thermal conductivity of wood (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})
T	temperature (K)
(x, y, z)	spatial coordinates (m, m, m)
(v, u, w)	average velocity (m s^{-1})

Greek letters

ρ	mass density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} 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 vaporisation (J kg^{-1})

Subscripts

0	initial
d	dry porous solid
eff	effective value
bt	bound
f	fluid
m	wood
Y^*	dimensionless distance from wall in turbulent flow

of wood components occurring during high temperature heat treatment are mainly responsible for these new properties [8,14] and the decrease of hydroxyl groups, the increase of cellulose crystallinity and cross-linking occurring in lignin are both pointed out [15]. Turner et al. [16] showed that the wood component decomposition (wood gasification) was strongly affected by the heat reaction in the range of high temperature (greater than 210 °C). However, for the temperature approximately lower than 210 °C, the heat reaction did not affect the temperature evolution within the wood [16]. Furthermore, the targeted durability of the heat treated wood may vary significantly depending on the exposure conditions [17]. Thereby, heat-treated wood is usually not a suitable material for ground contact applications [18]. Beyond the targeted changes, heat treatment also causes adverse effects such as diminishing mechanical properties [19–22].

The high-temperature treatment is a complex process involving simultaneous heat, mass and momentum transfer phenomena. In consequence, effective models are helpful for process design, optimization, energy integration, and control [23–25]. Thus the problem can be numerically considered as a simultaneous heat and mass transfer through the porous medium [26,27]. Furthermore, the theory of transport phenomena in porous materials has been itemised and reported in the literature [28–32]. Numerous models use a standard correlation to compute the heat and mass transfer at the interface of wood *in silico*. But *in situ*, high temperature treatment of wood is a transient conjugate problem in which the coefficients cannot be assumed as a constant throughout the wood surface. Thus, it is necessary to adapt models solving Navier–Stokes equations in the surroundings of the wood sample to get more information about the boundary conditions for the transport equations in the medium [33–35]. In some investigations, the classical Luikov model is used for the numerical formulation of the problem in wood [36–37] in order to analyse only the conjugate problem of heat and moisture transport. Kocaefe et al. [38] compared the different models for the thermal treatment of wood at high temperature (Diffusion, Luikov and Multiphase). The authors showed that the diffusion model was very useful for industrial applications. Younsi and co-workers [39,40] modelled heat treatment of wood by solving diffusion equations for heat and mass transfers in wood and turbulent Navier–Stokes equations in the fluid field. However, the mass and heat transfers in the wood were solved just using the mass and temperature continuity and their fluxes at the wood-fluid interface as boundary conditions [40,41]. Now, the heat and mass transfers at the fluid-wood interface must be taken into account during the entire treatment in order to be close the real phenomena that are occurring during the heat process.

In this work, a three-dimensional model coupled the solved diffusion equations of heat and mass transfers for the wood sample with the turbulent averaged Navier–Stokes equations for the fluid flow field. The exchanges of heat and mass at fluid-wood interface were considered during the entire heating process by a subroutine which calculated the energy consumed by the wood and the moisture removed from wood, and then injected it as a negative heat source and positive moisture source in the gas computation. Our model was applied on some realistic industrial contexts. The final wood properties depend on both intrinsic such as the wood species and extrinsic parameters such as the wood storage conditions or the thermal process. Thus, industrial heat treatment of wood requires an efficient control of both the material and the process to obtain reproducibility and good quality. In this context, the model highlighted effects of one species-dependent parameter (specific gravity) as well as impact of some storage conditions resulting in several initial temperature and moisture content of wood.

2. Numerical method

High temperature treatment of wood is a complex problem where a conjugate simultaneous heat and mass transfer through porous medium occur. In this paper, the fluid flow field was coupled to the heat and mass transfers inside wood. The numerical considerations involved solution of the hydrodynamic equations for the fluid followed by solving the equations of heat and mass transfers in wood. Thus, heat was transferred from heating gas to wood surface by convection and from surface to inside of the wood by conduction. Similarly, the moisture was transferred to the surface from the inside by diffusion and from the wood surface to the gas by convection.

2.1. Numerical assumptions

It was assumed that the flow field was a turbulent and incompressible fluid, the fluid flow-porous system was three-dimensional, and the temperature and moisture content were