Numerical study of high-temperature treatment of wood including mass and heat transfers at the wood-fluid interface

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Abstract: Wood is an important building material but unfortunately it needs treatments to improve its poor performances concerning both durability and dimensional stability. Heat treatment at high temperature is an environment-friendly alternative to the chemical use. The heat treatment processes often need optimisations, in particular when some prototype furnaces are developed. Modelling processes occurring during the high-temperature treatment would be safer and cheaper than experimental optimisations. In this respect, a high-temperature treatment of wood in a prototype furnace was modelled by coupling heat and moisture transfers. These simultaneous unsteady transfers between a fluid (gas phase) and a wood (solid phase), including the two-way heat and mass transfers at the wood-fluid interface, were described by a three-dimensional mathematical model. The model coupled diffusion equation with variable diffusion coefficients for wood sample with the 3-dimensional incompressible Reynolds averaged Navier–Stokes equations for the fluid flow field. The model predicted well the experimental wood temperatures although realistic industrial conditions were applied. In this study, the numerical tool was used to assess the effect of a few parameters such as the input fluid flow velocity and the distance between the pieces of wood in a prototype furnace.

Keywords: 3D-modelling, heat and mass transfers, interface, thermal treatment, wood.

1. Introduction

People often experience various problems when they work with wood. Most of them are associated with its hygroscopic properties in combination with anisotropic swelling and shrinkage due to the changes in moisture content [1]. In addition to this problematic dimensional instability, there are other moisture related problems such as biological degradation [2]. The heat treatment of wood at high temperature aims to reduce the hygroscopic consequences, to improve dimensional stability and face biological attacks without using toxic chemicals products [3, 4].

At the early stage of the method, some undesired side effects, in particular loss of strength and increased brittleness, prevented commercial utilisation of heat-treated wood. Since 1990’s, the research on thermal modification techniques therefore focussed on optimisation of the process parameters to improve the wood dimensional stability and durability while minimising the decrease of strength [5]. Some high-temperature thermal treatment processes were developed in Europe (France, Finland, Germany, and Netherlands) to improve dimensional stability and biological durability of wood [6]. The main difference among the diverse thermal processes was due to the variations in the operating conditions such as process steps, gas (oxygen or nitrogen), streaming, wet or dry processes, use of oils, steering schedules etc. [6]. The common range of temperature varied among treatment processes; for example, from 160 °C to 190 °C for PLATO-process [7], from 185°C to 215 °C for thermowood process [8], from 180°C to 220 °C for Oli-heat treatment [9] and from 200°C to 240°C for Bois Perdure process [1]. In conventional heat treatment processes (120°C) there was no chemical change in wood structure. But the high-temperature treatment of wood resulted in several changes of the main components of wood (cellulose, hemicelluloses and lignin); thereby improving important properties like dimensional stability, strength/stiffness and resistance to biological degradation [2]. Furthermore, the targeted durability of the heat treated wood may vary significantly depending on exposure [10]. In order to control modifications and reactions occurring in the wood and resulting in environmental and performance advantages, the high-temperature treatment process must be both understood and optimised.

The modelling of the heat transport and mass transfer phenomena in wood has become today an important tool for predicting and understanding the behaviour of wood during its heat treatment at high temperature. The high-temperature heat treatment was numerically considered as simultaneous combination of heat transfer and mass transfer in porous media [11-13]. In this respect, the outstanding works of Luikov [14, 15] and Whitaker [16] on the development of the transport theory in porous materials were worth mentioning. Luikov [14] described heat transport and mass transfer in capillary porous media, assuming that moisture transfer was similar to heat transport and that the transport of water in the capillary was proportional to the gradients of both temperature and moisture. Several studies were based on this approach.
[17-19]. In addition, several works had also addressed numerically the heat treatment problem by solving transport equations for each component (the gas, liquid and solid phases separately). This complicated the task because it required extensive study and mathematical relationships of a large number of thermo-physical properties for each phase. That was why the diffusion model was used to solve the problem of heat and mass transfers in wood materials [20, 21].

Most of the studies had addressed the problem within either conventional (drying) or high-temperature heat treatments. They considered the equations for wood only, regardless of the gas flowing into the furnace. Then, Younsi et al. [22-26] coupled the flow of fluid (gas) with simultaneous diffusion of both heat and mass in the wood. However, the mass and heat transfers in the wood were solved using the mass and temperature continuity and their fluxes at the wood-fluid interface just as boundary conditions [22, 23]. Recently, some authors have used the similar assumption to model and study the high thermal treatment of wood [27, 28].

This work provides several new developments to aim a realistic 3D-modelling of mass and heat transfers during the high-temperature heat process in a prototype furnace. More particularly, turbulent fluid flow (gas heating) and equations related to both heat and mass transports in wood were coupled through the wood-fluid interface; in order to model the possess of the wood high-temperature treatment. The transfers from fluid to wood were described as well as the transfers from wood to fluid. Moreover, they influenced each other throughout the heat treatment. At each time step, the energy consumed by the wood was calculated and injected as a negative heat source in the gas energy computation. Thus the gas flow was continuously impacted by the phenomena occurring into the wood (e.g. increase of temperature, decrease of moisture, transfers of heat and mass to the fluid, etc.). To give an overview of the model, temperature and moisture contents had been estimated. Also, the effects of some parameters such as the input fluid flow velocity and the distance between different wood columns in the furnace had been studied.

2. Calculations

2.1. Balance equation of the model

The numerical tool was adapted from Younsi et al. [21] to solve the diffusion model of heat and moisture in the wood. In this study, a subroutine took accurately into account the heat and mass exchanges that occurred at the wood-fluid interface. The 3D-approach was to solve the hydrodynamic equations for the fluid, followed by solving the equations of heat and mass transfers in the wood and then use the fields of heat and moisture to determine the mass and heat fluxes exchanged at the wood-fluid interface. Thus, heat was transferred from gas to wood surface by convection and from surface to inside of the wood by conduction. The moisture is transferred to the surface from the inside by diffusion and from the wood surface to the gas by convection. In order to make the problem easier, some further assumptions were made: the fluid was assumed as turbulent, the wood system was a three-dimensional porous medium, and the effects of shrinkage and gravity were neglected and no degradation occurred in the wood during the heat treatment.

2.1.1. Balance equations for solid wood

The mass diffusion in the hygroscopic wood material was one of the complex transfer processes characterizing the migration of bound water. Usually, two types of diffusion occurred in the wood during heat treatment at high temperature [29]. The gaseous diffusion was considered as the diffusion of the water vapor through the air in the lumen of cells and the bound water diffusion was the migration of bound water in the cell walls. At the microscopic level, these two phenomena occurred simultaneously. Both of these diffusion modes were considered in the numerical study. The three dimensional equations [12, 30 and 31] describing heat and mass transfers in the wood high thermal treatment were:

Heat transfer equation

$$\rho \frac{\partial T}{\partial t} - \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right)$$

Moisture transfer equation

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D_x \frac{\partial M}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_y \frac{\partial M}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_z \frac{\partial M}{\partial z} \right)$$

2.1.2. Balance equations for the gaseous fluid flow

The flow regime was assumed to be turbulent with respect to the average gas velocity measured in the furnace. The three-dimensional Navier-Stokes energy and concentration equations as well as the turbulent kinetic energy conservation and its dissipation rate were expressed as follows [12, 13 and 31]:

Continuity
\[ \frac{\partial (\rho U)}{\partial x} + \frac{\partial (\rho U)}{\partial y} + \frac{\partial (\rho U)}{\partial z} = 0 \]  
\hspace{1cm} (3)

Momentum energy
\[ \rho_t \frac{\partial U}{\partial t} + U \nabla (\rho U) = -V . P + \nabla \left( \mu_{\nu} \nabla U \right) \]  
\hspace{1cm} (4)

Concentration equation
\[ \rho_t \frac{\partial C}{\partial t} + U \nabla (\rho C) = \nabla \left( D_{\nu} \nabla C \right) \]  
\hspace{1cm} (5)

Energy equation
\[ \rho_t C_r \frac{\partial \theta}{\partial t} + U \nabla (\rho \theta) = \nabla \left( k_{\nu} \nabla \theta \right) \]  
\hspace{1cm} (6)

The Standard \( k-\varepsilon \) Model, k-Eddy kinetic energy
\[ \rho_t \frac{\partial k}{\partial t} + U \nabla (\rho k) = \nabla \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k + P_k - \rho_t \varepsilon \]  
\hspace{1cm} (7)

c-Rate of dissipation of turbulence energy
\[ \rho_t \frac{\partial \varepsilon}{\partial t} + U \nabla (\rho \varepsilon) = \nabla \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon + \frac{\varepsilon}{k} \left[ (C_p \varepsilon - C_\varepsilon \rho_t \varepsilon) \right] \]  
\hspace{1cm} (8)

\[ P_k = \mu_t \left[ 2 (\nabla^2 U) + (\nabla U)^2 \right] \]  
\[ \mu_{\nu} = \mu + \mu_t, \quad k_{\nu} = k_f + \mu_t \varepsilon_{\nu} / \sigma_{\nu} \]  
\[ D_{\nu} = D + \mu / \sigma_{\nu}, \quad \mu = C_{\nu} \mu_t \]  
\[ \nu = \nu_{\nu} \]

In the above equations \( \mu \) was the turbulent dynamic viscosity of the gaseous fluid, \( P_k \) the production of turbulent kinetic energy due to shear, \( \sigma_k, \sigma_\varepsilon, \sigma_{\nu} \) and \( \sigma_{\nu} \) were the turbulent Prandtl numbers defined for the relevant variable. The values of the model constants for all the calculations were considered as \( \sigma_k = 1.0, \sigma_\varepsilon = 1.4, \sigma_{\nu} = 1.0, \sigma_{\nu} = 1.0, C_1 = 1.44, C_2 = 1.92, C_6 = 0.09. \) The turbulence model presented above was valid only in the fully turbulent region. In the regions close to the wall, it was assumed that viscous effects predominated over turbulence effects, due to the small local Reynolds number of turbulence. The classical wall function method [21] was retained for these regions to compute turbulent flow patterns. The wall functions were used to bridge the near-solid wall region in the case of the standard \( k-\varepsilon \) model.

2.2. Boundary conditions

Initially, the wood material undergoing heat treatment was supposed to have uniform temperature and moisture content throughout. Thus the initial conditions were expressed as:

Temperature uniformity:
\[ T(x, y, z, 0) = T_0 \]  
\hspace{1cm} (9)

Moisture content uniformity:
\[ M(x, y, z, 0) = M_0 \]  
\hspace{1cm} (10)

In all the steps, the boundary conditions were expressed in terms of the continuity of state variables and their respective fluxes at the interface [32]. The equations were:

Température Continuity :
\[ T_r = T_s \]  
\hspace{1cm} (11)

Concentration Continuity :
\[ C_r = C(T, M) \]  
\hspace{1cm} (12)

Energy Transfer at the wood-fluid interface :
\[ \frac{k_{\nu} \frac{dT}{dn}}{} = \Delta H_{iv} \frac{\partial C}{\partial n} + k_f \frac{dT}{dn} \]  
\hspace{1cm} (13)

Mass Transfer at the wood-fluid interface :
\[ \frac{\partial M}{\partial n} = D \frac{\partial C_f}{\partial n} \]  
\hspace{1cm} (14)

The boundary conditions (inflow and outflow) for the flow field were considered as:

Inflow : \( u = 0, v = U_x, w = 0, T = T_s, C = C_s, k = k_{\nu}, \varepsilon = \varepsilon_m \)

Outflow : \( P = 0, \frac{\partial T}{\partial y} = 0, \frac{\partial C}{\partial y} = 0, \frac{\partial k}{\partial y} = 0, \frac{\partial \varepsilon}{\partial y} = 0 \)
2.3. Wood thermo-physical properties

The realistic modelling of heat and mass transfers in wood is a complex phenomenon that takes into account not only the heat conduction, the moisture diffusion in the wood, the chemical decomposition of wood, but also variations in the specific gravity, density, moisture content, thermal conductivity and heat capacity. The thermodynamic and transport properties of gas-water system and the physical properties of the wood used in the simulation were summarized in Table 1. The density (ρ), specific gravity (G_m), thermal conductivity (k_{qx}, k_{qz}, k_{qy}) and heat capacity (C_p) of wood were calculated using expressions proposed by Simpson and Tenwolde [33] and Siau [29].

\[ \rho = 1000G_m \left(1 + M/100\right) \]  \hspace{1cm} (15)

The heat capacity of wood depends on the temperature and moisture content in the wood, but does not depend on the density of wood species [33]. The heat capacity of dry wood \( C_{p0} \) (kJ/kg /K) was estimated using temperature:

\[ C_{p0} = 0.1031 + 0.003867T \]  \hspace{1cm} (16)

The heat capacity of wood containing water (green wood) is higher than that of dry wood. Below the point of fibre saturation, it was the sum of heat capacity of dry wood, that of water and the factor B_C which defined the additional energy in the wood.

\[ C_p = \left(C_{p0} + 0.01MC_{pw}\right)\left(1 + 0.01M\right) + B_C \]  \hspace{1cm} (17)

M was the moisture content (%). The heat capacity of water was about 4.19 KJ.kg\(^{-1}\).K\(^{-1}\). The adjustment factor \( B_C \) was deducted from the following expression:

\[ B_C = M \left(B_1 + B_2T + B_3M\right) \]  \hspace{1cm} (18)

With \( B_1 = -0.06191 \), \( B_2 = 2.36 \times 10^{-4} \) and \( B_3 = -1.33 \times 10^{-4} \).

The thermal conductivity was a measure of the heat flow rate through unit area of a material subjected to a temperature gradient. The thermal conductivity of wood was affected by several factors such as density, moisture content, grain direction, structural irregularities and temperature [34, 35]. Thermal conductivity had approximately the same value in the radial and tangential directions while it was about twice greater along the grain [36]. For moisture levels below the saturation point of the fibre, the thermal conductivity in directions orthogonal to the grain (radial and tangential) was given by the linear equation:

\[ k_{qx} = k_{qz} = A_1 + G_m(A_2 + A_3M), \quad (k_{qy} = 2k_{qx} = 2k_{qz}) \]  \hspace{1cm} (19)

Where \( A_1 \), \( A_2 \) and \( A_3 \) were constants given by: \( A_1 = 0.01864 \), \( A_2 = 0.1941 \) and \( A_3 = 0.004064 \). The latent heat of vaporization was correlated with the temperature by a polynomial function [36].

\[ \Delta H_{nv} = 2.792 \times 10^8 - 160(T) - 3.43(T)^2 \]  \hspace{1cm} (20)

<table>
<thead>
<tr>
<th>Parameter expression</th>
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<tbody>
<tr>
<td>( G_m = 0.40 )</td>
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<tr>
<td>( \gamma = 1 - G_m(0.667 + M) )</td>
</tr>
<tr>
<td>( \rho_g (\text{kg.m}^{-3}) = 400 )</td>
</tr>
<tr>
<td>( D_r (\text{m}^2\text{s}^{-1}) = \sqrt{\gamma D_{bt}}/(1 - \gamma) \left( \sqrt{\gamma D_{bt}} + (1 - \sqrt{\gamma D_v}) \right) )</td>
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<tr>
<td>( D_v (\text{m}^2\text{s}^{-1}) = (1.29.10^{-13}(1.0 + 1.54M)P_T T_k^{2.5}/T_K + 245.18) d\phi/dM )</td>
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<tr>
<td>( D_{bt} (\text{m}^2\text{s}^{-1}) = \exp(-9.9 + 9.8M - 4300/T_K) )</td>
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<tr>
<td>( D (\text{m}^2\text{s}^{-1}) = 9.2.10^{-9}T_k^{2.5}/T_K + 245.18 )</td>
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<tr>
<td>( P_T (\text{Pa}) = 3390, \exp(-1.74 + 0.0759T - 0.000424T_k^2 - 2.44.10^6T_k^2) )</td>
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<tr>
<td>( C_{pw} (\text{kJ}^{-1}\text{K}) = 4190 )</td>
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<tr>
<td>( M_0(%) = 12 - 13% )</td>
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<tr>
<td>( T_0(K) = 288 - 298 )</td>
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<tr>
<td>( U_g (\text{ms}^{-1}) = 15 )</td>
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3. Materiel and methods

3.1. Numerical procedure

The mathematical equations of the coupling system were resolved in a two-stage procedure. First, the solutions of hydrodynamic equations for the flow of gas in the furnace were obtained using the commercial software ANSYS CFX-10 [37] to assess, for each time step, the temperature and mass gradients at wood-fluid interface. Secondly, these parameters were used as boundary conditions for solving heat and mass transfers within the wood with a FORTRAN© subroutine based on a finite difference method. The solution of the matrix was obtained using the method of Gauss-Seidel iterative at each time step. Exchanges of heat and mass at wood-fluid interface were calculated using the heat and the mass fluxes generated within the wood sample as a function of both temperature and humidity in the wood. The model of coupling thermo fluid described above was optimized for sensitivity to the number of iterations, the time steps and the refining mesh. All the calculations were made for the refining mesh. In this study, numerical model was usually illustrated by presenting results in the central plane x-y (at Lz/2) of a wood sample and having width, height and length of Lx, Ly and Lz respectively; except when the position of the broad within the wood column height (h) was considered (Fig. 1).

![Figure 1. Schematic representation of (a) the layout and geometry of wood board columns, (b) the geometry of one board and (c) the heat (red) and mass (green) exchanges at the fluid-wood interface.](image)

3.2. Experimental procedure

The experiments were carried out in a prototype furnace at the University of Quebec at Chicoutimi (Canada). Two wood species, Aspen (Populustremuloides) and birch (Betulapapyrifera) were tested. The wood samples boards had dimensions of 0.05m x 0.20m x 0.62m and from 60 to 80 wood boards were dried simultaneously in the furnace. The wood initial moisture content M0 ranged from 12 to 13%. The initial moisture content of wood samples was measured before each experiment using a wood moisture meter Delmhorst RDM-2S with accuracy of 0.1%. The samples were heat-treated up to a maximum temperature of 210°C (483 K). During experiments, the temperature gradient between the surface and the inner site of the boards was controlled such that it did not exceed 15–20°C during heating-up. This gently gradient reduced the possibility of mechanical degradation of wood in order to maintain a high quality. The temperatures at predetermined positions within the wood boards were measured every 60 s by mean of the readings of T-type thermocouples which were connected to the data acquisition system Keithley KE 2700-Omnitronix TC4000. The accuracy of the thermocouples was 3.8%.

4. Results and discussions

4.1. Experimental vs modelled wood temperatures

The validation of the model was performed by comparing modelled temperature to the experimental data. Aspen and birch woods were heat treated at high temperature using the experimental setup. The two samples were heated gradually up to maximal temperature (210°C), maintained two hours at this temperature and cooled down. The temperature predictions of the model were compared with the experimental data obtained for the various positions of thermocouples. The temperature evolution (predicted and measured) with heating time is presented in figures 2 a (aspen) and 2 b (birch). The both modelled and experimental temperatures were close showing that the model was in good agreement with experiment.
4.2. Evolution of temperature and moisture during the heat treatment

The temperature and the moisture distributions, along the wood width (x direction) and for several durations of heating, were modelled and plotted in figures 3 a and 3 b respectively. There were three ranges (time inferior to 8 hours, around 8 hours and time superior to 8 hours) of variations in this gradient with time (Fig. 3 a). The temperature gradient between the surface and the centre of the wood was high at the beginning of heating and decreased with time. This highlighted slow heat propagation from the wood surface – exposed to the heated fluid flow – to the wood centre. The temperature gradient decreased with time and reach a minimum value about 8 hours later (Fig. 3 a). The gradient of wood moisture content between the wood surface and the middle was high and decreased with respect to temperature increase. For example, at two hours of heat treatment, the moisture, close to the surface, evaporated quickly while the moisture content remained equal to its initial value at the centre (Fig. 3 b). The decrease in the temperature gradient could be attributed to an increase in the rate of moisture evaporation. Indeed, at around t = 8 hours, the rate of moisture evaporation was very high (Fig. 3 b) and the energy required for vaporization of the moisture was quasi-equal to the energy supplied by the fluid. Thus during intensive moisture evaporation, the temperature of wood surface changed slowly and it became similar to that of the fluid. After 8 hours of heat treatment the temperature gradient in the wood increased again due to the reduction in evaporation rate and the gradient nearly disappeared at the end of the heat treatment.

4.3. Effect of the position of the broad within the wood column

In our prototype oven, the gaseous fluid entered the furnace at the bottom and left the furnace at the top. Thus the heating fluid was in contact with columns of wood broads from bottom to top resulting in a variation in both temperature and moisture distributions along the height of the wood column. Therefore, the temperature and moisture
distributions (along the x direction) were modelled at three different height positions along the column (h1, h2 and h3; Fig. 4 a and 4 b). The temperature distribution at h1 was slightly higher than those for the two other positions (h2 and h3). This difference was more prominent near the wood surface (Fig. 4 a). Consequently, the temperature of the wood surface near the gas inlet was slightly higher than those obtained at the two other positions. Also, this slight difference decreased gradually with the heating time and faded completely at the end of treatment. Moreover, this difference was within the range of the thermocouple precision, hence it would be assumed as a negligible difference. Therefore, the change of moisture at different wood height positions was negligible for short-term heating (Fig. 4 b). The difference in moisture contents at the three positions along the column became important after the domain of intense moisture evaporation (about 8 hours) and vanished at the end of treatment (16 hours). The change in temperature and moisture from position h1 to the two other positions (h2 and h3) was low and disappeared completely at the end of the treatment. Thus the result of the numerical model highlighted possible uniform heat treatment of wood regardless of its position relative to the gas inlet.

Figure 4. Distribution of (a) temperature gradient and (b) moisture content gradient along x direction at three wood positions (h1, black line; h2, red dotted line; and h3, blue square) during a heat treatment at high temperature (Vg = 15 m /s, Tf = 485 K, M0 = 12.2%, dx = 0.015 m, dx was the distance between the wood columns in the furnace).

4.4. Effect of the distance between the wood broads

Three configurations of distance between wood broads (0.010, 0.015 and 0.025 m) in the furnace were studied for the same physical fluid model, initial conditions and properties of the wood. These distances were selected because they would be realistic industrial conditions. The figures 5 a and 5 b show the temperature and the moisture distributions in the wood. At the scale of wood configuration used in our numerical study, higher was the distance between wood columns, greater was the temperature distribution in the wood broad.

Figure 5. Effect of the distance (0.010, blue square; 0.015, red dotted line and 0.025 m, black line) between the wood columns on (a) the temperature gradient and (b) the moisture content during a heat treatment of wood at high temperature (Vg =15m/s, Tf = 485 K, M0 = 12.2% ).
The volume occupied by the wood in the furnace increased by about 27% when separation between the wood columns changed from 0.010 m to 0.025 m. In consequence, more energy was needed to heat the wood. This explained probably the decrease in temperature linked to the decrease in distance between the wood columns, in the conditions of constant inlet heating gas flow and fixed furnace volume. Furthermore, wood broads after 8 hours - which corresponded to an equilibrium - as well as after 16 hours treatments - which corresponded to dried conditions - were the only ones which presented, similar and uniform temperatures whatever the configuration (0.010, 0.015 and 0.025 m). That suggested potential impact of moisture level. Indeed, the wood moisture content is higher during all heat treatment for short distance (0.01 m) separating the wood columns in the furnace. It means that more abundant were the wood broads in the furnace; lower was the rate of evaporation of moisture. Thus for short distance of separation between the wood columns, more energy or/and more heat duration were needed to reduce the amount of moisture to the desired level. Reducing distances between the wood broads is important for industries. For a constant furnace volume, that resulted in increasing the number of treated wood broads in one cycle. The results indicated that it was possible without compromising wood quality. However, during the modelled heat treatment, smaller is the distance between the wood broads, lower is the temperature and higher is the wood moisture content. Consequently more energy and/or more time were necessary to optimize the heat treatment results. For a definite input gas temperature, more energy can be supplied to the system by increasing flow velocity of the hot gas at the furnace input.

4.5. Effect of the input fluid flow velocity

To better understand the influence of velocity of gas on the heat treatment of wood, two input velocity values were selected: 5 and 15 m s⁻¹. The wood columns were spaced by a 0.015 m interval in the furnace. The physical fluid model, the initial conditions and the wood properties remained the same. The wood temperature and moisture distributions were presented in figures 6 a and 6 b. During the heat treatment operations, the wood temperature was lower for low velocity of the input gas than for the high one. In the same time and compared to the case of high input gas velocity; the moisture content remained high for low input gas velocity (Fig. 6 b). In brief, to improve thermal treatment, heat diffusion and therefore moisture removal, the input gas velocity must be relatively high or/and the total time of heat treatment should be long.

Figure 6. Effect of the input fluid flow velocity (5, black line and 15 m.s⁻¹, red dotted line) on (a) the temperature gradient and (b) the moisture content during a heat treatment of wood at high temperature (Tᵥ = 485 K, Mᵥ = 12.2%, dx= 0.015m, dx was the distance between the wood columns in the furnace).

Conclusions

A three-dimensional model which coupled a turbulent gas flow with heat and mass transfers in the wood was developed to study the wood heat treatment at high temperature in a prototype furnace. The modelled temperatures were in good agreement with the experimental data although realistic industrial conditions were applied. Thus that was mainly due to the supplementary subroutine added to the coupling model. It took into account more accurately the real heat and mass exchanges between the fluid gas and the wood solids. The model was an useful tool to understand and explain many phenomena occurring during the wood high thermal treatment.
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