HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

COMPARISON OF THE 1D AND 3D MODELS FOR THE SIMULATION OF WOOD HEAT TREATMENT PROCESS

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ABSTRACT

Wood heat treatment at high temperatures (in the range of 180–240°C) is an ecological alternative to the chemical treatment of wood for its preservation. Thermal treatment provides dimensional stability and biological durability to wood due its structural changes. The dark color attained also gives the wood an aesthetic appearance. Various mathematical models have been developed for wood heat-treatment furnaces.

In this article, two models, 1D and 3D, will be described. They have been used to simulate the furnace behaviour for a number of wood species, and parametric studies have been carried out to determine the impact of various factors. Some of the results of the calculations with the two models will be presented. They will be compared and the applicability and limitations of the 1D approach will be discussed.

NOMENCLATURE

Symbols:

C	concentration (kg m^{-3})
C_p	heat capacity (J kg^{-1} K^{-1})
D	diffusion coefficient of water vapor in the fluid (m^{2}s^{-1})
D_S	diffusion coefficient in the wood material (m^2 s^{-1})
G_m	specific gravity
k	turbulent kinetic energy (m^2 s^{-2})
h_q	convective heat transfer coefficient (W m^{-2} K^{-1})
k_f	thermal conductivity of the fluid (W m^{-1} K^{-1})
k_q	thermal conductivity of the wood (W m^{-1} K^{-1})
M	moisture content, kg H2O (kg solid)$^{-1}$
P	pressure (Pa)
P_k	shear production of turbulent kinetic energy (m^2 s^{-3})
T	temperature
(x,y,z)	spatial coordinates (m, m, m)
(u,v,w)	velocity components in 3 directions (m s^{-1})

Greek letters

ρ	density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ε	viscous turbulent dissipation
$\sigma_{k,\varepsilon,T,C}$	turbulent Prandtl numbers of k, ε, T, and C
τ_w	wall shear stress (N m^{-2})
ΔH_{lv}	latent heat of vaporization (J kg^{-1})

Subscripts:

0	initial
D	dry porous solid
eff	effective value
bt	bound
f	fluid
T	turbulent

INTRODUCTION

High temperature heat treatment of wood (in the range of 180–240°C) is a process by which the dimensional stability and the biological durability of wood are increased. At these temperatures, the wood structure changes and its capacity to absorb water diminishes drastically. It also attains a dark color which gives the wood an aesthetic appearance. The heat-treated wood is an ecologically sound product and a good alternative to the chemically treated wood which is harmful for the environment due to chemicals used. Thus, the high temperature heat treatment adds value to this product. However, the structural changes result in the loss of mechanical properties such as elasticity. Therefore, it is important to optimize the heat treatment process [1-8].

Wood is a heterogeneous material. Its behaviour and structure vary from one species to another and even from one region to another for the same species. Therefore, a recipe has to be developed for each wood species for its thermal treatment at high temperatures. Of course, it is not economical to do a large number of testing under industrial conditions for recipe development. Mathematical modelling is a highly useful tool to reduce the industrial trials and, consequently, the cost. Mathematical models can also be used for the modifications in the design of furnaces.

During heat treatment, wood is heated slowly from the room temperature to the desired treatment temperature using hot gases, and it undergoes various structural changes. The simultaneous heat and mass transfer takes place in the wood.

The heat from the hot gases is transferred to the wood boards and the moisture diffuses out of these boards and vaporizes. Thus, hot gases act as the heating medium as well as the carrier gas for vapour. A schematic diagram of a heat treatment furnace is given in Figure 1. The thermal treatment is a dynamic process. Depending on the level of information required, different types of models can be used to simulate the process. Models in 3D as well as in 1D have been built.

The wood is not a good conductor of heat. Also, the wood boards usually have one dimension that is much smaller than the other two dimensions (for example, 25×100×2400 mm). Thus, the heat transfer through a wood board can be simulated by solving for the heat conduction and the moisture transfer through the shortest dimension in 1D, neglecting the gradients in other directions (see Figure 2). In the heat treatment, the wood boards are placed side by side forming a layer and many wood layers are piled on top of each other by leaving some spacing between them for the passage of hot gases (see Figure 1). The 1D model cannot solve for the hot gas flow through the wood pile unless the flow can be simplified and assumed uniformly distributed between layers. In general, though, the flow is not uniform; however, this assumption can be used as an approximation. A heat balance then can be written for the gas to determine the gas temperature profile.

In the case of 3D model, the flow, heat, and mass transfer equations in the gas and the heat and moisture transfer equations in the wood are solved. Similar to the 1D model, the two parts interact via heat and mass transfer at the wood surface. This model gives the 3D temperature and moisture profiles in the wood as well as in the gas. The 3D model gives detailed information; however it requires much longer computations times (in many hours). The 1D model is much faster (a few minutes), but cannot provide the details the 3D model can give.

The descriptions of the models are given in the following sections followed by the presentation of some of the results.

3D MATHEMATICAL MODEL

Earlier models developed for the conventional heat treatment (drying) or heat treatment at high temperature solved the equations for wood only without considering the impact of the hot gas medium in the furnace. More recently, mathematical models have been developed that included the flow with heat and mass transfer in the gas [9]. In the current model, this was modified to include the heat exchange at the wood-fluid interface more realistically. The momentum, heat and mass (moisture) transfer in the gas are solved using the commercial code CFX10 (ANSYS). The heat and moisture transfer in the wood was solved using the finite difference method. The two sub-models for the gas and the wood have been coupled at the gas/wood interface located at the wood surface. Thus, heat is 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 of the wood from the inside by diffusion and from the wood surface to the gas by convection. The coupling takes into account all these exchanges. In order simplify the problem, the effects of wood shrinkage, any degradation, and gravity were neglected.

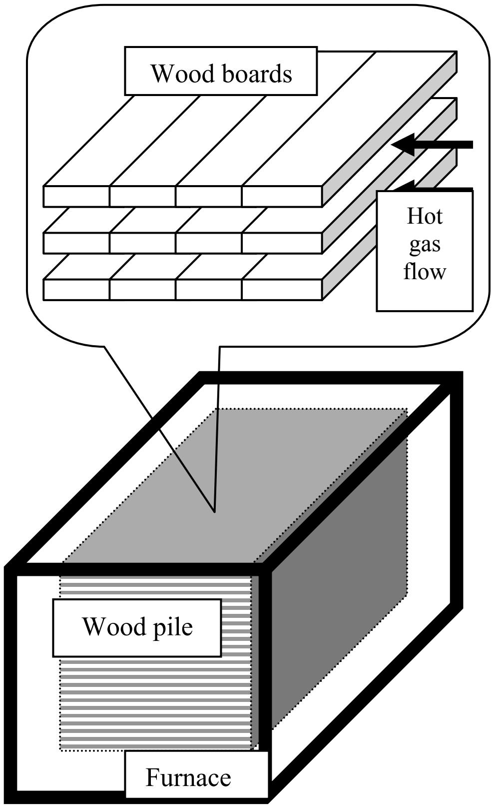

Figure 1 A schematic diagram of a heat treatment furnace

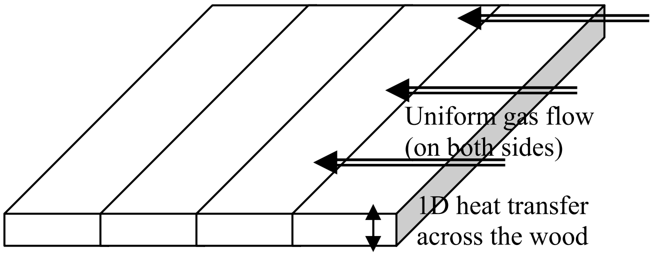

Figure 2 One-dimensional heat transfer for wood

WOOD:

The mass diffusion in the hygroscopic wood material is one of the complex transfer processes characterising the migration of bound water. Generally, two types of diffusion processes occur in the wood [10] during heat treatment at high temperature. The gaseous diffusion is considered as the diffusion of water vapor through air in the lumen of cells and the bound water diffusion is the migration of bound water in cell walls. At the microscopic level, these two phenomena occur simultaneously. Both of these diffusion modes were considered in this numerical study via the diffusion coefficient. The three-dimensional equations describing heat and mass transfers in wood during heat treatment at high temperature are given by [11-13]:

Heat transfer equation:

$$\rho_m \frac{\partial h_m}{\partial t} = \frac{\partial}{\partial x}\left(k_{qx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{qy}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{qz}\frac{\partial T}{\partial z}\right) \qquad (1)$$

Moisture transfer equation:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_x\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial M}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial M}{\partial z}\right) \qquad (2)$$

GAS:

The flow regime is 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 are expressed as follows [11, 14, 15]:

Continuity equation

$$\frac{\partial(\rho_f U)}{\partial x} + \frac{\partial(\rho_f U)}{\partial y} + \frac{\partial(\rho_f U)}{\partial z} = 0 \qquad (3)$$

Momentum equation

$$\rho_f \frac{\partial U}{\partial t} + U\nabla.(\rho_f U) = -\nabla.P + \nabla.\left(\mu_{e_{ff}}\nabla.U\right) \qquad (4)$$

Concentration equation

$$\rho_f \frac{\partial C}{\partial t} + U\nabla.(\rho_f C) = \nabla.\left(D_{e_{ff}}\nabla.C\right) \qquad (5)$$

Energy equation

$$\rho_f C_{p_f} \frac{\partial T}{\partial t} + U\nabla.\left(\rho_f C_{p_f} T\right) = \nabla.\left(k_{e_{ff}}\nabla.T\right) \qquad (6)$$

k–ε model
k - Eddy kinetic energy

$$\rho_f \frac{\partial k}{\partial t} + U\nabla.(\rho_f k) = \nabla.\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla.k + P_k - \rho_f\varepsilon \qquad (7)$$

e - Rate of dissipation of turbulent energy

$$\rho_f \frac{\partial \varepsilon}{\partial t} + U\nabla.(\rho_f \varepsilon) = \nabla.\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla.\varepsilon + \frac{\varepsilon}{k}\left(C_1 P_k - C_2\rho_f\varepsilon\right) \qquad (8)$$

$P_k = \mu_t\left[2\left(\nabla^2.U\right) + (\nabla U)^2\right]$, $\mu_{eff} = \mu + \mu_t$, $k_{eff} = k_f + \mu_t c_{pf}/\sigma_T$,

$D_{eff} = D + \mu_t/\sigma_C$, $\mu_t = C_\mu \rho_f k^2/\varepsilon$

In the above equations μ_t is turbulent dynamic viscosity of the gaseous fluid, P_k is the production of turbulent kinetic energy due to shear, σ_k, σ_ε, σ_T and σ_C are turbulent Prandtl numbers defined for the relevant variable. The values of the model constants for all the calculations are $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.4$, $\sigma_T = 1.0$, $\sigma_C = 1.0$, $C_1 = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$. The turbulence model presented above is valid only in the fully turbulent region. In 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 [9] was retained for these regions.

Boundary Conditions:

Initially, the wood has a uniform temperature and moisture content throughout. Thus the initial conditions are expressed as,

Temperature uniformity:

$$T(x,y,z,0) = T_0 \qquad (9)$$

Moisture content uniformity:

$$M(x,y,z,0) = M_0 \qquad (10)$$

During the simulation, the boundary conditions are expressed in terms of the continuity of state variables and their respective fluxes at the interface [16]. These are represented as follows:

Temperature continuity :

$$T_f = T_S \qquad (11)$$

Concentration continuity :

$$C_f = C(T,M)_S \qquad (12)$$

Energy transfer at the wood-fluid interface :

$$\left[k_q \frac{\partial T}{\partial n}\right] = \Delta H_{lV} D \frac{\partial C_f}{\partial n} + k_f \frac{\partial T}{\partial n} \qquad (13)$$

Mass transfer at the wood-fluid interface :

$$\left[\rho_d D_S \frac{\partial M}{\partial n}\right] = D \frac{\partial C_f}{\partial n} \qquad (14)$$

The boundary conditions (inlet to the furnace and outlet of the furnace) for the flow field were considered as:

In flow :

$$u = 0, v = U_g, w = 0, T = T_g, C = C_g, k = k_{in}, \varepsilon = \varepsilon_{in} \qquad (15)$$

Outflow:

$$P = 0, \partial T/\partial y = 0, \partial C/\partial y = 0, \partial k/\partial y = 0, \partial\varepsilon/\partial y = 0. \qquad (16)$$

1D MATHEMATICAL MODEL

In the 1D model, many simplifications are made. For wood, the heat and moisture transfers are solved in one direction only (along the shortest dimension of the wood board) by neglecting the transfer in the other two directions due to differences in the magnitude of the dimensions (see figure 2). Therefore the equations are similar to Equations 1 and 2, but only one-dimensional; that is, only one term is retained on the right-hand side.

For the gas side, the flow is simplified by assuming a uniform flow between the wood layers. Then, an overall balance for the energy is applied to the gas: the change in the gas temperature is due to heat loss to the wood boards and vaporization of the moisture coming from the wood. This allows the variation of wood temperature along the main flow direction. The moisture that enters the gas from the wood surface is uniformly distributed within the gas and is carried away.

RESULTS AND DISCUSSION

3D Model:

Some of the results of the 3D model are given in Figures 3 to 6 for one wood thermal treatment case of 16 hours. Figure 3 shows the evolution of temperature as a function of time inside the wood along the thickness. The temperature is uniform at the beginning at 17°C. Then, since the wood boards are heated from the surfaces, the surface temperature increases first. The temperatures inside the wood follow the increase in the surface temperature with a certain time lag depending on the wood properties.

There is significant vapor evolution between 80°C and120°C. When the wood reaches these temperatures, its temperature increases more slowly since the heat provided by the gas is mostly used for moisture vaporization. This allows the temperatures on the inside to approach the surface temperatures leading to reduction in the temperature gradient (see Figure 3, profile for 8 h). At the end of the process, there is a one hour plateau at the maximum treatment temperature to ensure the homogenization of the temperature in the wood. Again, the temperature gradient decreases as can be seen in Figure 3, profile at 16h.

Figure 4 shows the variation of the moisture content within the same board starting with an initial moisture content of 10%. As expected, first the moisture near the surface diffuses out; and the moisture at the center starts to decrease after 8 hours of treatment. The final moisture content is reduced to lower values depending on the diffusion rate.

Such profiles are important for the treatment since large temperature and moisture concentration gradients between the surface and the center could cause cracking due to mechanical stresses created by these gradients.

The 3D model also provides a detailed insight into the velocity profile in the gas. It is important to have a reasonable gas flow for en efficient heat transfer between the gas and the wood surface. As an example, the velocity field is given on a plane between two wood layers in Figure 5. This figure demonstrates a case where significant variation in the velocity field is observed. With the model, other cases can be simulated and the flow in different parts of a furnace can be visualized. The model will allow the assessment of the flow field for different furnace designs and, consequently, will help improve the design to have a better and more uniform flow field.

Figure 6 shows the increase in the average wood temperature as a function of time during the thermal treatment. The average wood temperatures were measured using a number of thermocouples. The figure compares the measured values with the model predictions. As it can be seen, the wood heat treatment process can be simulated reasonably well with the 3D model.

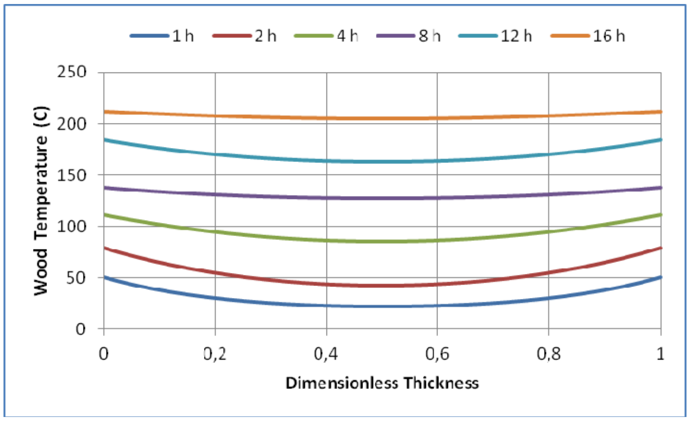

Figure 3 The evolution of the temperature profile as a function of time in the wood board along the shortest side (thickness)

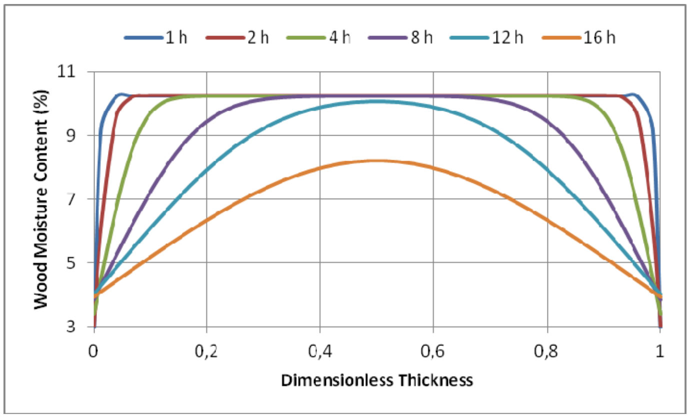

Figure 4 The evolution of the moisture profile as a function of time in the wood board along the shortest side (thickness)

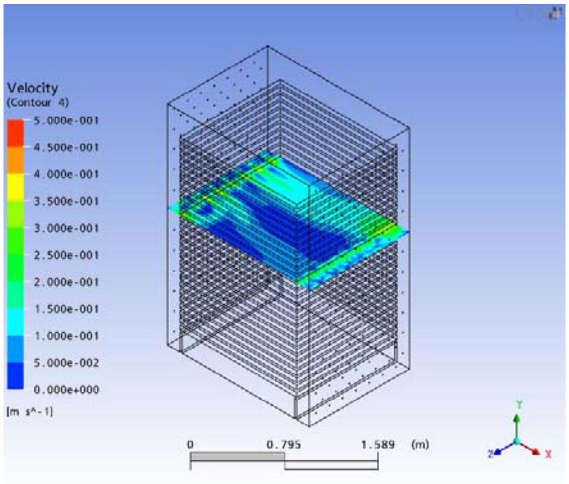

Figure 5 The velocity field between two layers of wood at a given plane.

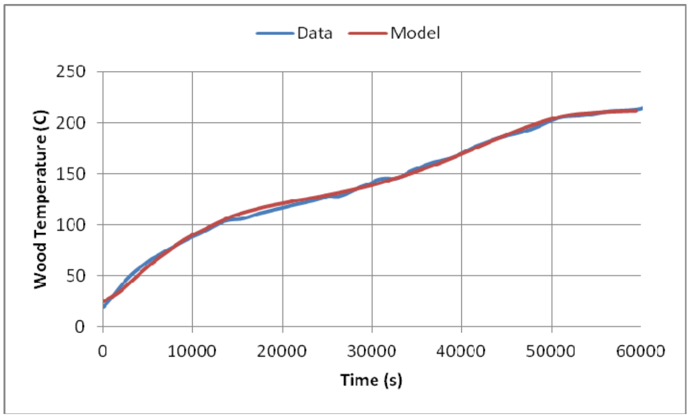

Figure 6 The comparison of the calculated and experimental wood temperature as a function of time

1D Model:

Figures 7 and 8 give some of the results obtained with the 1D model. Figure 7 shows the temperature profiles in a wood board along the thickness for the same case as given in Figure 3. The results indicate similar predictions as expected since the heat transfer in this direction is dominant due to the smaller length scale compared to other directions. The same tendencies are observed as the ones discussed above.

Figure 8 gives the predicted average wood temperature as a function of time during the treatment and compares the results with the experimental values. A good agreement is observed between the two lines. The success of the 1D model is due to two reasons:

- the wood thickness is much smaller compared to other dimensions which ensures the dominant heat transfer along the thickness, and
- the flow in the furnace is more or less uniform for the case chosen.

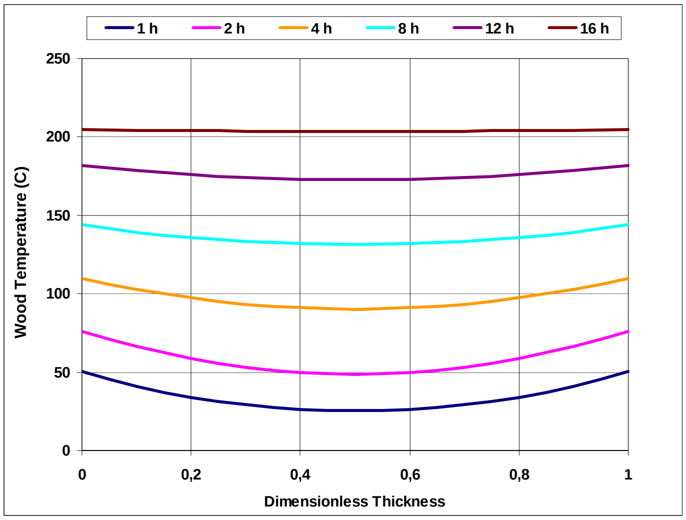

Figure 7 The evolution of the temperature profile as a function of time in the wood board along the shortest side (thickness)

The first condition is relatively common since much of the treatment is done for wood boards of relatively small thicknesses. Therefore, the solution of the heat and mass transfer in wood in one direction only is a reasonable assumption for the simulation of the thermal treatment of wood boards. However, if the wood thickness becomes comparable to its width, then heat and mass transfer in other directions should be considered as well.

The second condition, however, is not as simple. The flow in the furnace depends on the technology and the gas flow rates. In some cases, the flow may be uniform in certain section of the furnace, but not everywhere. The 3D model can handle any situation and thus more general and reliable. In cases where an approximate solution is sought, the 1D model with the uniform flow assumption can be used.

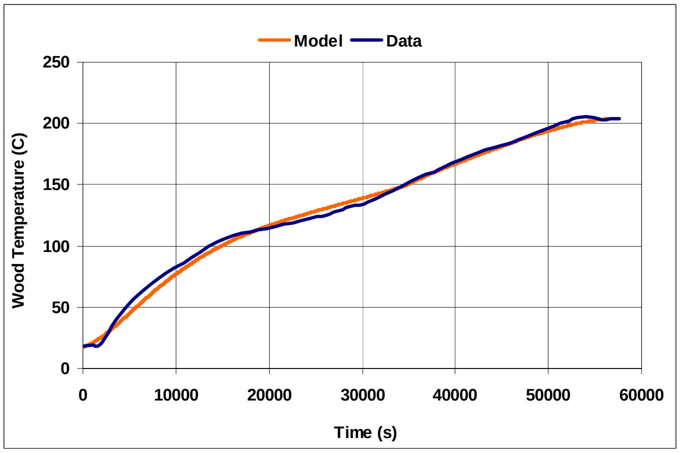

Figure 8 The comparison of the calculated and experimental wood temperature as a function of time

CONCLUSIONS

The thermal treatment of at high temperatures offers an environment-friendly option for wood preservation. The treatment is carried out in large furnaces where the wood is heated from room temperature to temperatures around 180-240°C. Models of varying complexity have been developed over the years. A 3D model and a 1D model have been presented in this article. The 3D model is general and can simulate heat treatment in any furnace taking into account all the important phenomena. The 1D model, on the other hand, can be used when the wood board thickness is much less than the other dimensions and the flow is uniform.

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