This is an author-deposited version published in: https://sam.ensam.eu
Handle ID: .http://hdl.handle.net/10985/8611

To cite this version :

Sadoth SANDOVAL-TORRES, Jean-Pierre NADEAU, Emilio HERNANDEZ-BAUTISTA, Juan RODRÍGUEZ-RAMÍREZ, Lilia Leticia MÉNDEZ-LAGUNAS - Numerical simulation of drying of Pinus pseudostrobus wood with Comsol Multiphysics - In: European Drying Conference - EuroDrying'2011, Spain, 2011-10-26 - EuroDrying'2011: III European drying conference : Palma de Mallorca (Spain), October 26-28, 2011 / Universitat de les Illes Balears - 2011

European Drying Conference - EuroDrying'2011
Palma. Balearic Island, Spain, 26-28 October 2011

Numerical simulation of drying of *Pinus pseudostrobus* wood with Comsol Multiphysics

S Sandoval-Torres[1], Jean-Pierre Nadeau[2], E Hernandez-Bautista[1], J Rodríguez-Ramírez[1], L Méndez-Lagunas[1]

[2]TREFLE – Ensam, Esplanade des Arts et Métiers,
Talence cedex 33405, France
Fax: +33 5 56 84 54 36
[1] Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional, Unidad Oaxaca
Hornos No. 1003, Col. Noche Buena, Santa Cruz Xoxocotlan, Oaxaca., 71230, México
Tel.:+52 951 51 706 10, ssandovalt@ipn.mx

Abstract:
In this work, we present the second part of our investigation. In the first part, we have published a semi-empirical model for drying. In this second part, we present the numerical solution of a drying model for *Pinus pseudostrobu*s (Mexican softwood). The model take into account a multiphysics approach. The model describes the moisture mobilities and profiles. The system of partial differential equations were solved in COMSOL 3.4 with the UMFPACK solver. Three primary variables are solved; the moisture content; the temperature; and the density of dry air. The model is validated by comparison. We have compared the phenomenological model versus experimental data and versus a semi-empirical model.

Keywords:

Numerical simulation, drying of Mexican pinewood, phenomenological model. Comsol Multiphisic 3.4.

INTRODUCTION

The description of the drying process and the mathematical formulation has become an effective technical that facilitates the understanding of transport phenomena occurring during drying (Truscott y Turner, 2005). The study of heat and mass in porous media explain the variations of constitutive properties in the material.

Because of the complexity of wood structure, the moisture transport occurs in different ways during drying. At the beginning, the drying removes mostly free water from the capillaries (Perré, 2006). Free water disappears gradually until the fiber saturation point (FSP). After that, the cavities or lumens in wood contain mostly air and water vapor. This gaseous mix is removed by a combination of convection-diffusion mechanisms up to the point of equilibrium where the forces of sorption and desorption are equal (Skaar, 1988).

Although there are many works oriented to drying simulation of wood, the majority of these works are primarily focuses on European wood. In Mexico the the Pinus pseudostrobus is one of the most important woods for the forest industry. It represents 80% of the volume of national production total (SEMARNAT, 2006), but models are not available for this wood. Then, it is necessary to propose models to enhance this operation.

The aim of this work is to develop a one-dimensional mathematical model to understand the mechanisms of heat and mass transport during drying. We have solved the set of equations by using COMSOL Multiphysics 3.4 and the UMFPACK solver.

METHODOLOGY

To validate the proposed model, several drying experiments were carried out in a dryer- tunnel. We have established four temperatures (50, 60, 70 y 80 °C), the air velocity constant and the relative humidity was not controlled. Two boards of fresh wood were used for each experiment. The edges of each board were isolated with silicon to ensure a one-direction moisture transport. 2 Thermocouples were placed into the board: The first one in the centre and the second one near from the surface. Each experiments with one replicate.

MODEL OF DRYING CHARACTERISTIC CURVE.

From experimental data, we have obtained a model based on the method of drying characteristic curve (DCC), to simulate the drying kinetics. The model was developed from the analysis of the reduced drying rate and the identification of phases, by considering a drying rate of reference. This model establishes that moisture transport mechanisms depend primarily on the reduced moisture content. This model was the first part of our work (Hernandez-Bautista et al., 2010).

THE PHENOMENOLOGICAL MODEL.

Our model takes into account the fundamentals proposed by Whitaker (1977) and subsequently by Turner and Perré (2001). Due to the setup configuration, it can be assumed that the moisture transport occurs mostly in the material thickness direction (Turner 1996). The model geometry is the thickness of the wood, which was represented by a straight line in COMSOL.

The transport equations are written in COMSOL Multiphysics 3.4. In the model navigator, three primary variables were declared: the moisture content (W), the temperature (T) and the intrinsic density of air (ρa). In the PDE module, the general form was used for the mass balance and the coefficient form for the heat balance.

Moisture conservation equation.

$$\frac{\partial W}{\partial t} = -\nabla \cdot \left\{ \frac{1}{\rho_s} \left(\overline{\rho}_l \overline{\mathbf{v}}_l^l + \overline{\rho}_v \overline{\mathbf{v}}_v^g + J_b \right) \right\} \tag{1}$$

Heat conservation equation.

$$\rho C_p \frac{\partial T}{\partial t} + \Delta h_{vap} \overline{m}_{lv} + \Delta h_{sorp} \overline{m}_{bv} + \left(C_{pl}\rho_l \mathbf{v}_l + C_{pb}\rho_b \mathbf{v}_b + C_{pv}\rho_v \mathbf{v}_v + C_{pa}\rho_a \mathbf{v}_a \right) \cdot \nabla T = \nabla(\boldsymbol{\lambda} \nabla T) \tag{2}$$

Equation for the conservation of dry air.

$$\frac{\partial}{\partial t}\left(\overline{\rho}_a\right) + \nabla \cdot \left(\overline{\rho}_a^g \overline{\mathbf{v}}_a\right) = 0 \tag{3}$$

The equation for the conservation of the dry air (3) allows an accurate description of the gradients of pressure inside the wood. The equation for the moisture transport (1) is an advanced version of the model diffusive, however, the major difference between the two approaches is the separation of phases as well as the relationship constituting which include the contribution of each of the stages (Krabbenhøft, 2003). The equation of conservation of heat (2) involves several mechanisms, heat conduction, heat transfer by convection, and the energy due to phase changes.

The velocities of phases (flow of moisture) are part of the subdomain settings. Free water flow is assumed to follow a generalized behavior described by the Darcy's law. Then, the mass average velocity is given by:

$$\rho_l \mathbf{v}_l = \rho_l \frac{\mathbf{K}_l \mathbf{k}_{rl}}{\mu_l} \nabla \cdot P_c - \rho_l \frac{\mathbf{K}_l \mathbf{k}_{rl}}{\mu_l} \nabla \cdot P_g^g \tag{4}$$

Furthermore, it has showed that gravity are very small compared with the capillary pressure and therefore it is negligible (Plumb y Prat, 1992 ;Turner, 2010).

The transfer of water vapor and air can be described by the combination of Fick's and Darcy's law. The transport of gaseous phase is explained by the following mathematical expression:

$$\overline{\rho}_v^g \overline{v}_v = -\overline{\rho}_v^g \frac{\mathbf{K}_g \mathbf{k}_{rg}}{\mu_g} \cdot \nabla \overline{P}_g^g - \overline{\rho}_g^g \mathbf{D}_{eff} \nabla \left(\frac{\overline{\rho}_v^g}{\overline{\rho}_g^g} \right) \tag{5}$$

$$\overline{\rho}_a^g \overline{v}_a = -\overline{\rho}_a^g \frac{\mathbf{K}_g \mathbf{k}_{rg}}{\mu_g} \cdot \nabla \overline{P}_g^g - \overline{\rho}_g^g \mathbf{D}_{eff} \nabla \left(\frac{\overline{\rho}_a^g}{\overline{\rho}_g^g} \right) \tag{6}$$

The dry-air flow has a similar behavior like the vapor but in the opposite way. Finally, the transport mechanism of bound water in the hygroscopic domain is described as follows.

$$J_b = -\rho_s D_b \cdot \nabla W_b - \rho_s D_{bt} \nabla T \tag{7}$$

Where the flow of water diffusion-sorption takes into account two mechanisms. The first one is the diffusion due to gradients of moisture content, and the second one due to the temperature gradients.

The boundary conditions are as follows.

$$\mathbf{J}_{\mathbf{w}} \cdot \hat{\mathbf{n}} = \overline{\mathbf{m}}_{\mathbf{lv}} = k_m c M_v \ln\left(\frac{1 - x_{v_\infty}}{1 - x_v} \right) \tag{8}$$

$$c = \frac{P_{atm}}{RT_\infty} \tag{9}$$

$$\mathbf{J}_{\mathbf{e}} \cdot \hat{\mathbf{n}} = \mathbf{q} + \Delta h_v \overline{\mathbf{m}}_{\mathbf{lv}} = h(T - T_\infty) + \Delta h_v k_m c M_v \ln\left(\frac{1 - x_{v_\infty}}{1 - x_v} \right) \tag{10}$$

The system of equations was resolved numerically using a computer with processor AMD Athlon(tm) X2 DualCore, 2100 Mhz, with a computation time of 20 s.

RESULTS.

To simplify our results, we presents the numerical simulation of trials at 60°C. The thickness of each board is 0.0254 m. with a transfer area of 0.075 m2, an initial temperature of 25°C and with an initial moisture content of 96% (dry basis).

The drying kinetics were simulated and compared with experimental data and with the characteristic drying curve (CDC) model. Figure 1 shows the numerical results at two temperatures. CDC model is developed from experimental data. The equations are derived and the parameters are estimated in excel with the solver tool.

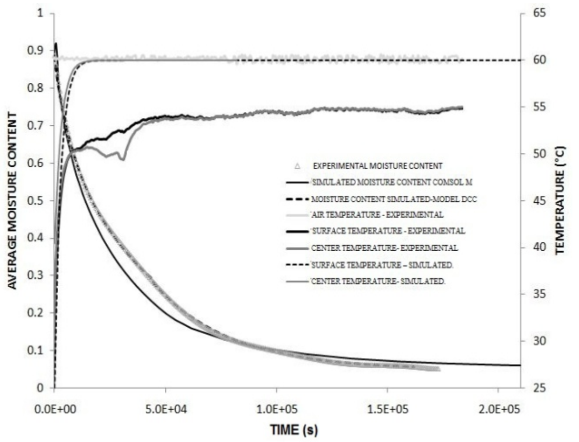

Fig. 1.Drying kinetics and temperature profiles, simulated and experimental at 60 °C.

The phenomenological model is compared in figure 1 too. Deviations can be due to thermo-physical properties, since several constitutive equations (properties) corresponds to similar pine specie, because of they are not available and is necessary to determine them experimentally. The temperature profiles are shown in Figure 1. These profiles presents a noticeable difference between the material surface temperature, due meanly to wood properties variations. Several properties, for example the heat conductivity expression used in this work corresponds to another coniferous species with a similar density. (Hernández y Puiggali, 1994).

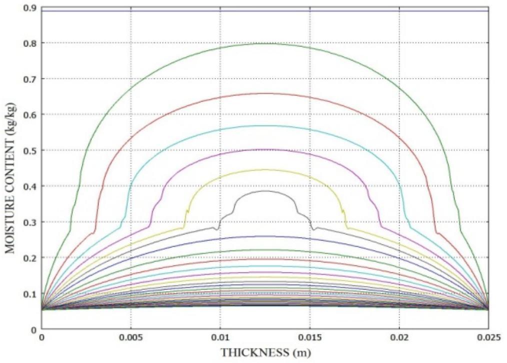

Fig. 2.Profil of moisture content.

Figure 2 shows the results of the phenomenological model. It depicted the moisture profile in wood and their evolution seems to be well described. Near the PSF (W = 0.30), there is a fluctuation in the parable. This is due to the transition from capillary phase to hygroscopic phase.

CONCLUSIONS

In this work, we present the results of numerical simulation of wood drying of *Pinus pseudostrobus* by using a semi-empirical and a phenomenological model. The numerical results and experimental measures provide some confidence in the proposed model. The moisture profiles and temperature evolution have some deviations probably due to changes in wood properties. COMSOL Multiphysics 3.4 is a very useful tool to simulate drying.

It is hopped that the information generated by these simulations can help to analyze the drying operation. The understanding of that is very important; because of the forest industry in Mexico needs a more realistic approach to enhance this very important industrial operation.

ACKNOWLEDGEMENTS

To the Instituto Politécnico Nacional and COFAA.

NOMENCLATURE

Cp	Specific heat	J kg^{-1} k^{-1}
c	Molar concentration	mol m^{-3}
D	liquid diffusivity	m^2 s^{-1}
J	Flux	m
km	Mass transfer coefficient	m s^{-1}
K	Relative permeability	m^2
kr	Relative permeability	m
M	Molar mass	kg mol^{-1}
n	Unit outward normal	m
P	Pressure	Pa
W	Moisture content	kg kg^{-1}
T	Temperature	K

Greek letters

Δ	Differential heat	J kg^{-1}
ρ	density [kg/m”]	kg m $^{-3}$
λ	thermal conductivity [W/m/K]	W m^{-1}K^{-1}
μ	Dynamic viscosity	kg m^{-1}s^{-1}

Subscripts

b	Bound
bt	termo-diffusivity
e	energy
eff	effective
g	gas
l	liquid
s	solid
v	vapor
w	free water.

REFERENCES

Hernández-Bautista E, Sandoval-Torres S., Rodríguez-Ramírez J, & Velasco-Cruz O. (2010), Modelización del secado de madera de Pinus pseudostrobus utilizando el método de la curva característica. Bois et forêts des tropiques, 306.

Hernández J & Puiggali J. (1994), Simulation of drying of coniferous wood using varius processes. International Chemical Engineering, 34, 339-350.

Krabbenhøft K. (2003), Moisture Transport in Wood. A Study of Physical Mathematical Models and their Numerical Implementation. Technical University of Denmark, Denmark.

Perré P (2006), Multiscale aspects of heat an mass transfer during drying. Transp Porous Med, 66, 59-76.

Plumb O & Prat M (1992), Microscopic model for the study of drying of capillary porous media. Drying '92, 397-406.

SEMARNAT (2006), Anuario Estadístico de la Producción Forestal 2006.

Truscott S and Turner I. (2005), A heterogeneous three-dimensional computational model for wood drying. Applied Mathematical Modelling 29(4), 381–410.