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Solving a two-scale model for vacuum drying of wood

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DRYING

Drying of porous media is characterized by the invasion of a gaseous phase replacing the evaporating liquid.

Simultaneous heat and mass transfer.

Then, in order to optimize this operation is important a description of drying physics.

VACUUM DRYING

Vacuum drying is an alternative method to alleviate collapse and discoloration for wood.

The reduction of the boiling point of water at low pressure facilitates an important overpressure to enhance moisture migration.

Reduced drying times, recovery of water vapor, and a higher end-product quality

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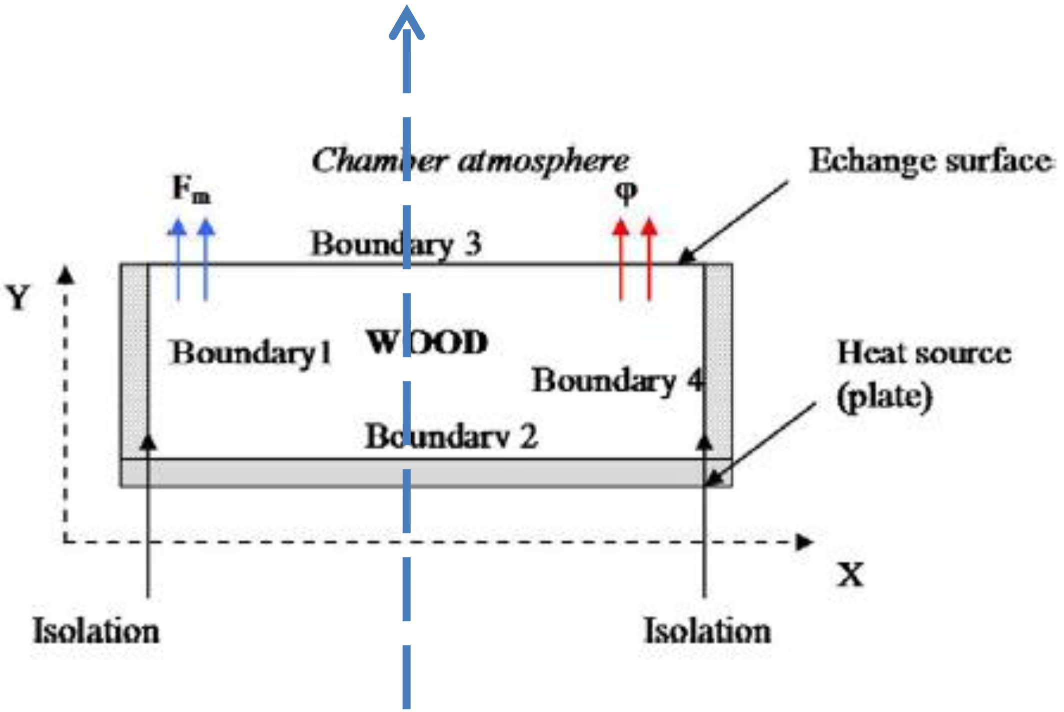
OUR APPROACH

We need to capture the physics of vacuum drying at 1D.



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MATHEMATICAL FORMULATION

Two Scales:

1) Material scale (heat and mass transport in porous media) :primary variables: W, T, rhoair

The porous media (wood sample): solid phase + liquid phase (free water)+ bound water.

2) Dryer scale (heat and mass balance in the chamber)

dry air and water vapor in the chamber

Gas phase = Perfect mixture of vapor and dry air.

Dry air and water vapor are considered as ideal gases.

Compressibility effects in the liquid phase are neglected.

$$\rho_l^l = \rho_l = cste.$$

Gas phase is considered as an air/water vapor ideal mixture, then:

$$\bar{\rho}_i^g = \frac{m_i \overline{P}_i^g}{R\overline{T}} \quad \text{Pour } i = a(\text{air}) \text{ or } v(\text{vapor})$$

$$\overline{P}_g^g = \overline{P}_a^g + \overline{P}_v^g,$$

$$\bar{\rho}_g^g = \bar{\rho}_a^g + \bar{\rho}_v^g.$$

Scalars in COMSOL

Thermodynamics equilibrium:

$$\overline{T}_v = \overline{T}_f = \overline{T} \quad \text{Thermodynamic equilibrium,}$$

$$P_v = a_w \cdot P_v^{sat} \quad \text{Vapor pressure,}$$

← isotherm

TRANSPORT OF THE LIQUID PHASE IN WOOD

Darcy's law

$$\overline{V}_l = -\frac{\underline{\underline{k}}\cdot \underline{\underline{k_{rl}}}}{\mu_l}\cdot \left(\nabla \overline{P}_l^l\right) \qquad \overline{V}_g = -\frac{\underline{\underline{k}}\cdot \underline{\underline{k_{rg}}}}{\mu_g}\cdot \left(\nabla \overline{P}_g^g\right)$$

In COMSOL:
Subdomains equations

Capillary pressure is defined as:

$$\overline{P}_l^l = \overline{P}_g^g - \boxed{Pc,}$$

$$P_c = 56.75 \times 10^3 (1 - S) \exp\left(\frac{1.062}{S}\right) \quad (\mathrm{Pa})$$

In COMSOL:
They are Scalars

$$\rho_l V_l = \rho_l \frac{\underline{\underline{k}}\cdot \underline{\underline{k_{rl}}}}{\mu_1}\cdot \boxed{\nabla P_c} - \rho_l \frac{\underline{\underline{k}}\cdot \underline{\underline{k_{rl}}}}{\mu_l} \boxed{\left(\nabla \overline{P}_g^g\right)}$$

In COMSOL:
Subdomains equations

TRANSPORT OF THE VAPOR PHASE IN WOOD

$$\bar{\rho}_v^g \overline{V}_v = \bar{\rho}_v^g \frac{\underline{\underline{k}}_{eq} \cdot \underline{\underline{k}}_{rg}}{\mu_g} \cdot \nabla \overline{P}_g^g - \bar{\rho}_g^g \underline{\underline{D}}_{eq} \cdot \nabla C,$$

Water vapor mobility

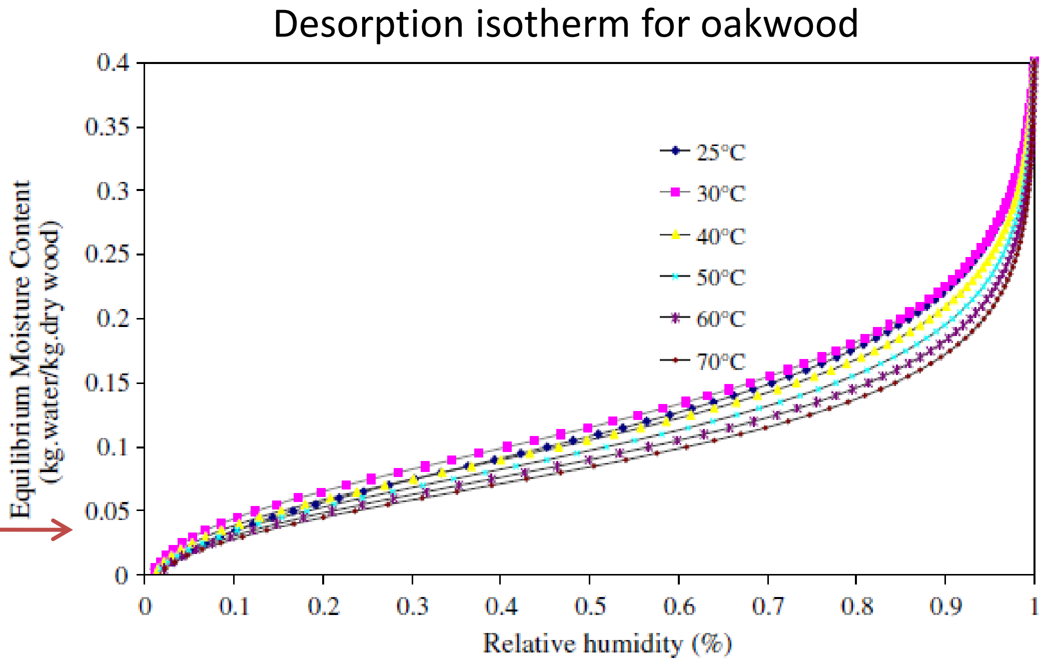
$$\bar{\rho}_a^g \overline{V}_a = \bar{\rho}_a^g \frac{\underline{\underline{k}}_{eq} \cdot \underline{\underline{k}}_{rg}}{\mu_g} \cdot \nabla \overline{P}_g^g - \bar{\rho}_g^g \underline{\underline{D}}_{eq} \cdot \nabla C,$$

Dry-air mobility

The Equilibrium moisture content is expressed by

$$W_{eq} = W(T, aw),$$
$$aw = HR.$$

In COMSOL: Insert Table →



Desorption isotherm for oakwood

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EQUATIONS FOR HEAT AND MASS CONSERVATION – material scale

$$\frac{\partial W}{\partial t} + \nabla \cdot \left\{ \frac{1}{\rho_s} \left(\rho_l \overline{V}_l + \bar{\rho}_v^g \overline{V}_l + Jb \right) \right\} = 0.$$

Moisture

$$\overline{\rho Cp} \frac{\partial \overline{T}}{\partial t} + \left[\left(\rho_l \overline{V}_l Cp_l + J_b Cp_l + \bar{\rho}_a^g \overline{V}_a Cp_a + \bar{\rho}_v^g \overline{V}_v Cp_v \right) \right] \nabla \overline{T} - \left(\overline{\rho_b V_b} \cdot \nabla h_b \right) +$$

$$(h_v K) + (h_v + h_b) K_b - \nabla \cdot (\underline{\underline{\lambda}} \cdot \nabla \overline{T}) = 0.$$

Energy

$$\overline{\rho Cp} = \bar{\rho}_s Cp_s + (\bar{\rho}_l + \bar{\rho}_b) Cp_l + \bar{\rho}_v Cp_v + \bar{\rho}_a Cp_a.$$

$$\frac{\partial \bar{\rho}_a}{\partial t} + \nabla \cdot \left(\bar{\rho}_a^g \overline{V}_a \right) = 0$$

Dry-air

In COMSOL: Velocity expressions are written as subdomain equations

DRYER SCALE

The air, vapor, and water mass balance equations are derived by assuming that the pressure and temperature fields within the chamber are homogeneous.

We considers the real pump aspiration and the mass flux evacuated from wood sample.

$$\frac{d\rho_a^{ch}}{dt} = -\rho_a^{ch}\frac{\boxed{q_{pump}}}{V_{ch}} + \rho_a^{atm}\frac{q_{leak}}{V_{ch}}$$

$$\frac{d\rho_v^{ch}}{dt} = -\rho_v^{ch}\frac{\boxed{q_{pump}} + q_{cond}}{V_{ch}} + \rho_v^{atm}\frac{q_{leak}}{V_{ch}} + \enclose{circle}{F_m}\frac{A}{V_{ch}}$$

Material scale

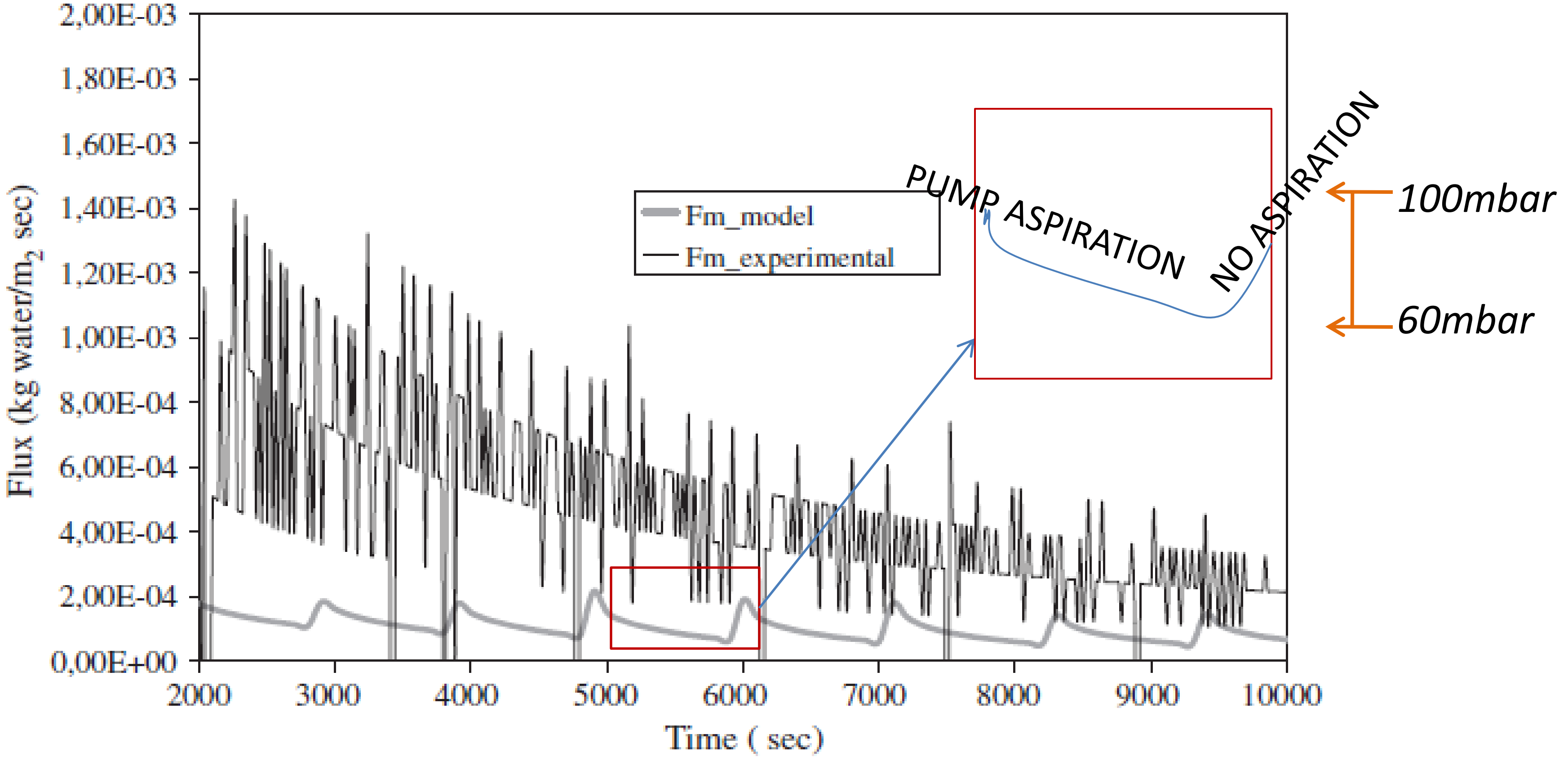
Integration of evacuated moisture

In COMSOL:
Global equations
ODE's

Pini=Patm

REGIMES OF VACUUM DRYING

Vacuum pressure is controlled between 2 values (Pmax , Pmin): when the dryer pressure reach the Pmax Then, vacuum aspiration works until reach the Pmin (60mbar)



Masse flux. Vacuum drying at 70 C and 60-100 mbar.

BOUNDARY CONDITIONS

The pressure at the external drying surfaces is fixed at the atmospheric pressure Pch (Pressure of the chamber). we impose the Dirichlet boundary condition for the air-flux.

This Dirichlet boundary condition has been modified to form an appropriate non-linear equation for this primary variable.

$$P_a^g = P_a^{chamber}$$

$$\rho_v^g = \rho_v^{chamber}$$

$$T_{chamber} \approx T_{surf}$$

RESULTS

In this work we use the UMFPACK. We have used the Arbitrary Lagrange–Eulerian (ALE) formulation. The sparse matrix A factorized by UMFPACK can be real or complex, square or rectangular, and singular or nonsingular (or any combination).

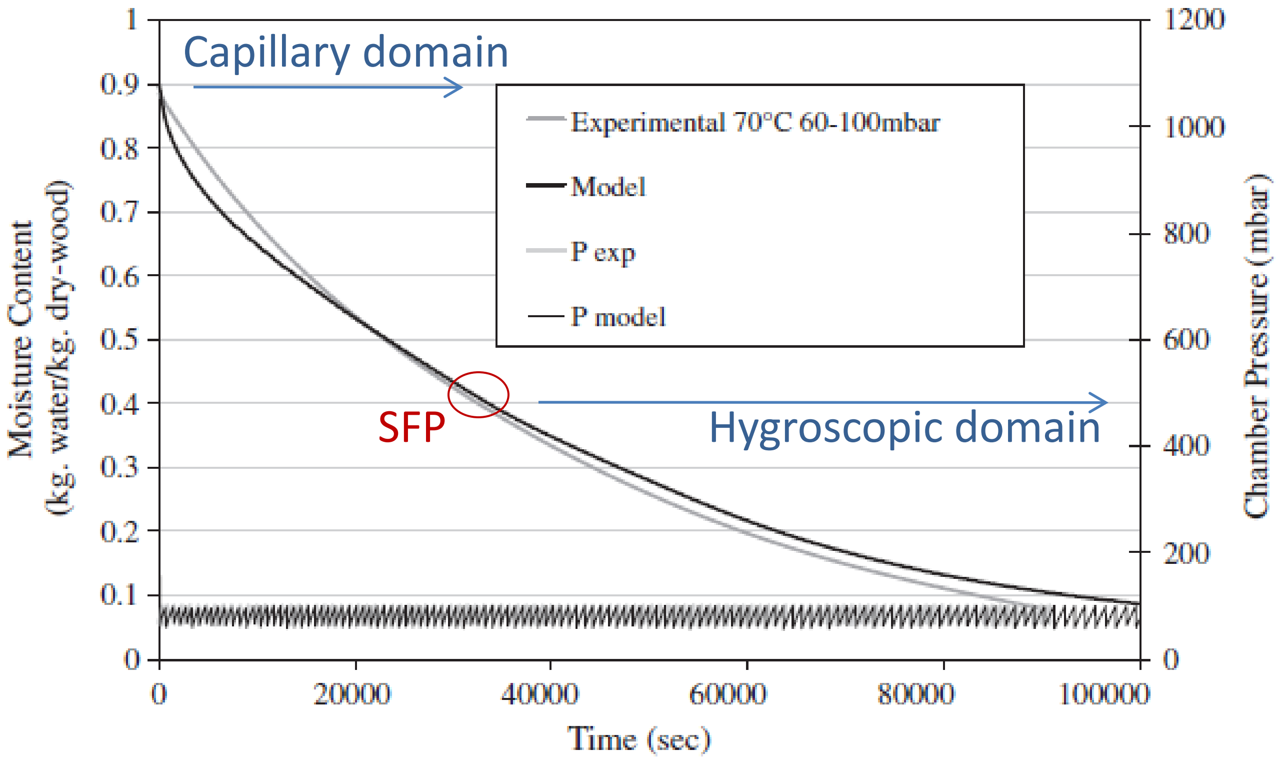
We have used COMSOL 3.5a

We could implement the model for COMSOL 4.3!

IMPLEMENTATION UN COMSOL

- We have written the partial differential equations (material scale) in the general form.
- The two ordinary differential equations (dryer scale) were introduced by considering a pump aspiration of 0.0027 m3/s (the real situation).
- To add a space-independent equation such as an ODE, we have chosen a global equation format. As the time derivative of a state variable (density of air and water vapor) appears, the state variable needs an initial condition; in this problem we consider chamber pressure begins at atmospheric pressure.

NUMERICAL SOLUTION
DRYING KINETIC AND PRESSURE



Comparison between vacuum drying kinetics: experimental and model. 70°C and 60–100 mbar.

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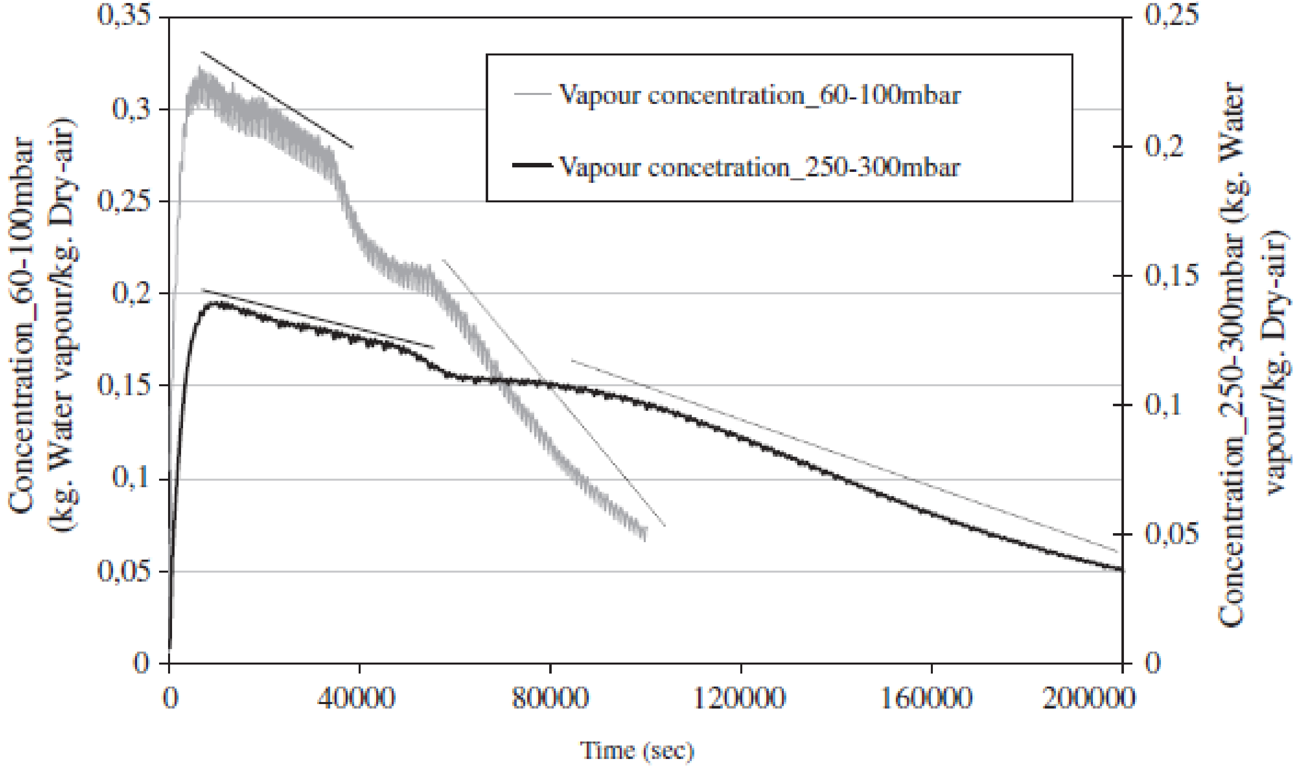
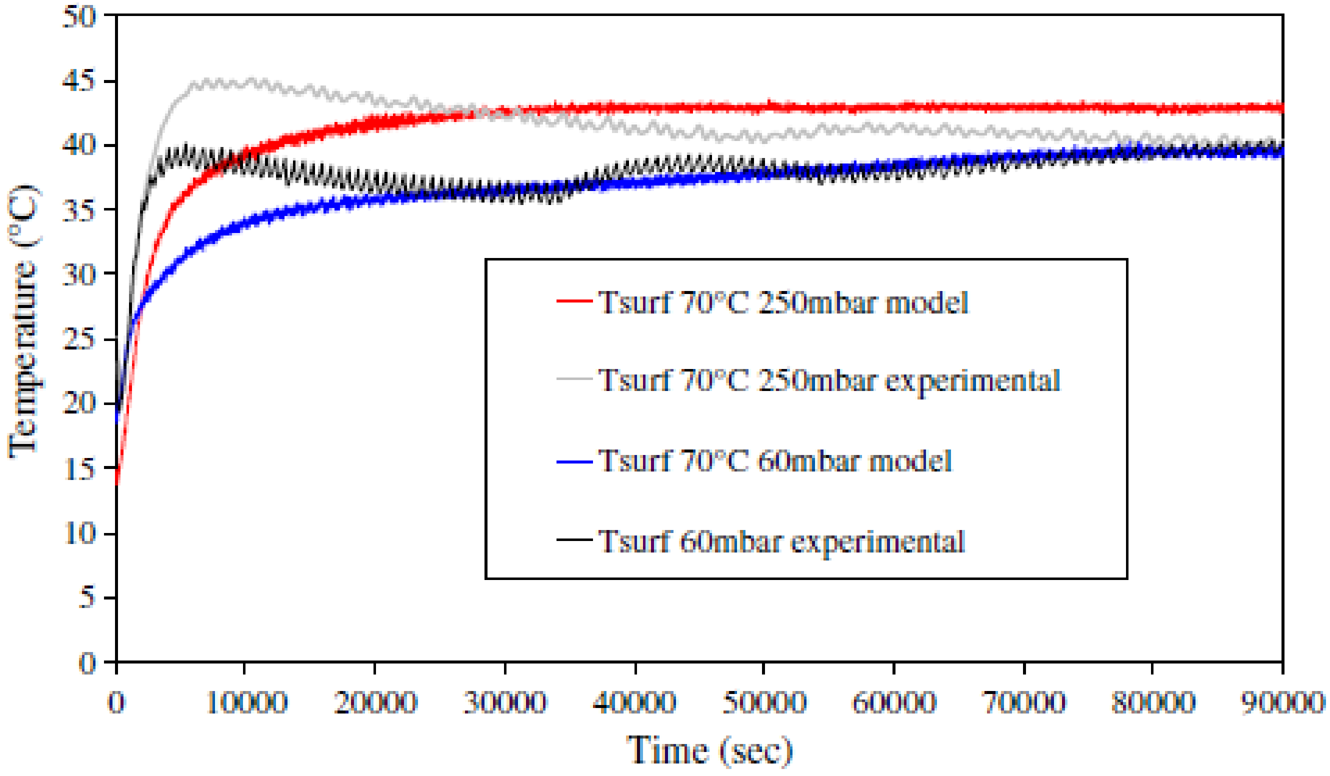
VAPOR EVOLUTION WITHIN THE CHAMBER



Concentration of water vapor in the chamber. Simulations at 60–100 mbar and 250–300 mbar.

TEMPERATURE



Perturbations due to on/off action of vacuum pump
Zig-zag behavior of chamber pressure

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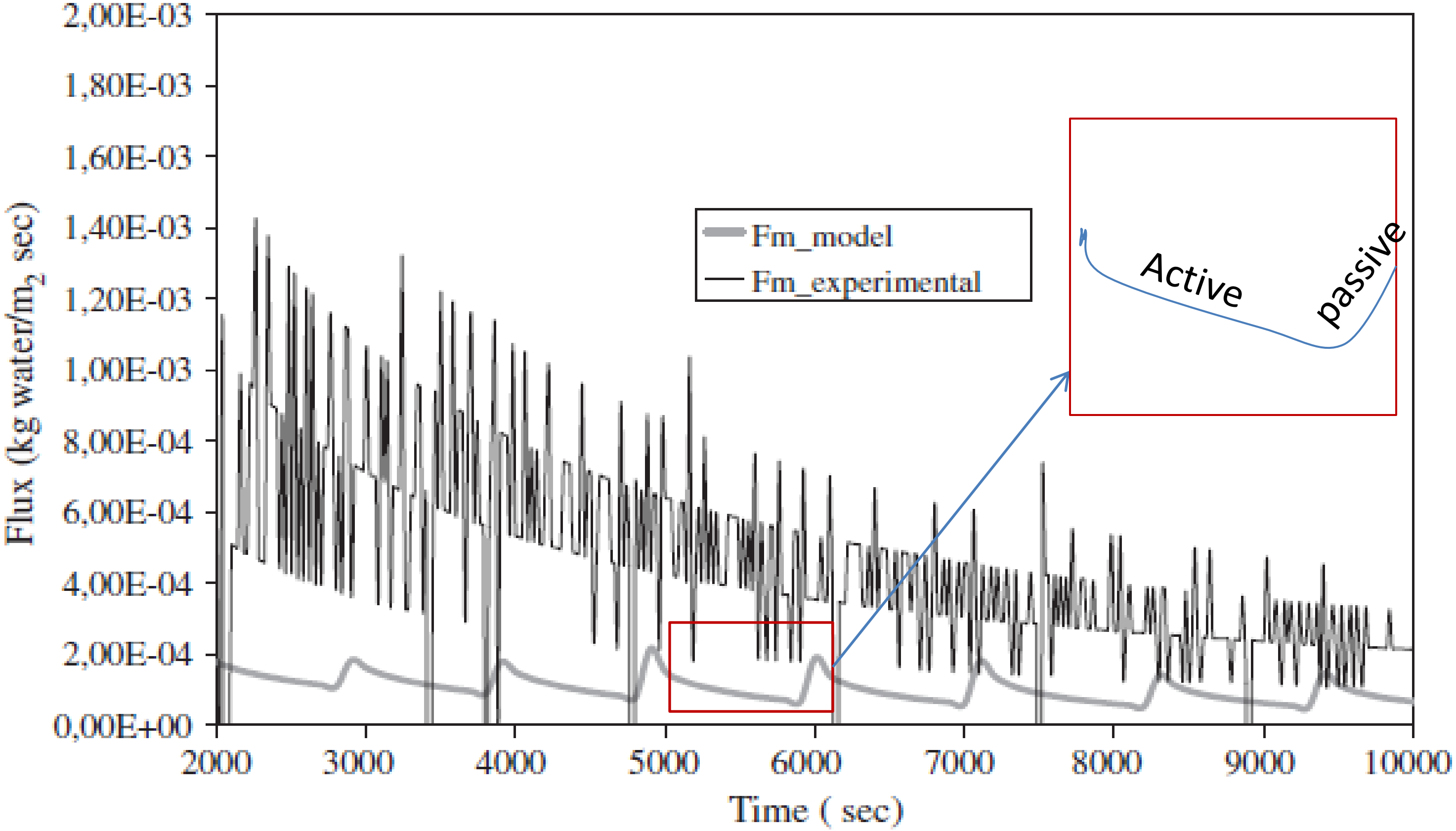
MASS FLUX



Mass flux. Vacuum drying at 70°C and 60-100 mbar.

PUBLICATIONS

Sandoval-Torres, S., Jomaa, W. and Puiggali, J-R. Avramidis. S. 2011. Multiphysics Modeling Vacuum Drying of Wood. *Applied Mathematical Modeling Journal*, 35(10) 5006–5016.

Sadoth Sandoval-Torres, J. Rodríguez-Ramírez, L.L. Méndez-Lagunas. 2011. Modeling Drying Kinetics and Mass Flux During Plain Vacuum Drying by Considering a Dynamic Capillary Pressure. *Chemical and Biochemical Eng. Quarterly.* 25(3) 327-334.

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