

EXPERIMENTAL DETERMINATION OF THE RATIO OF VAPOR DIFFUSION TO THE TOTAL WATER MOVEMENT IN WOOD DURING DRYING

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ABSTRACT

The knowledge of the ratio ε of vapor diffusion to the total water movement in wood during drying is necessary when phase change is considered in the heat transfer equation of a wood-drying model based on water potential. An original experimental method was developed to determine the ratio ε . The method is based on the measurement of temperature and moisture content profiles in wood during drying and the calculation of total enthalpy profiles.

ε was determined from drying experiments of red pine sapwood (*Pinus resinosa* Ait.) in the radial direction at 18, 56, and 85°C. The experimental results show that ε increases from 0.15 to 0.5 as moisture content decreases from values close to saturation (160%) to about 15%. ε reaches a plateau at about 0.33 for intermediate moisture contents (35 to 120%).

Keywords: Wood drying, model, heat transfer, vapor diffusion

INTRODUCTION

The drying of wood is a complex mechanism involving simultaneous heat and mass transfer phenomena. The drying process produces uneven moisture content distributions in wood, leading to the development of stresses that can result in degradation if they are not

properly controlled. In order to optimize this process, models of moisture, temperature, and stress evolution in wood during drying have to be developed.

From the recent literature, two main approaches have been identified to represent heat and mass transfer phenomena. Following Lui-kov's (1966) approach, Thomas et al. (1980), Liu and Cheng (1989, 1991), Irudayaraj et al. (1990) and Gui et al. (1994) presented equa-

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tions of heat and mass transfer in wood based on the concept of moisture potential. Water in wood in the three phases is characterized by the moisture potential. On the basis of Luikov's approach, Fortin (1979) used the water potential concept to characterize water in wood in terms of free energy. Siau (1984) mentioned that the gradient in water potential can be regarded as the driving force for the transport of water in wood in both the liquid and vapor phases, including bound water. The second approach was proposed by Whitaker (1977). It can be qualified as a multi-component approach since conservation equations (energy and mass) are written for liquid water, water vapor, and the gaseous mixture (water vapor + air). The multi-component approach provides a comprehensive description of the mechanisms involved during drying, but it results in large sets of equations requiring the knowledge of transport properties or other physical parameters which are not easily obtainable.

MATHEMATICAL MODEL

Following Luikov's approach, Cloutier et al. (1992) presented a two-dimensional finite element model (FEM) of isothermal wood drying based on the water potential concept. The equation of mass transfer in wood is given by:

$$\frac{\partial C}{\partial t} + \vec{\nabla} \cdot \vec{q}_m = 0 \quad (1)$$

where C = moisture concentration ($\text{kg}_{\text{water}} \text{m}^{-3}_{\text{moist wood}}$); \vec{q}_m = moisture flux vector (liquid water + water vapor + bound water) ($\text{kg}_{\text{water}} \text{m}^{-2}_{\text{moist wood}} \text{s}^{-1}$); t = time (sec). The moisture flux vector, \vec{q}_m , is given by:

$$\vec{q}_m = -\underline{\mathbf{K}}(\mathbf{M}, \mathbf{T}) \cdot \vec{\nabla} \psi \quad (2)$$

where $\underline{\mathbf{K}}(\mathbf{M}, \mathbf{T})$ = effective water conductivity tensor ($\text{kg}^2_{\text{water}} \text{m}^{-1}_{\text{moist wood}} \text{s}^{-1} \text{J}^{-1}$) (function of moisture content \mathbf{M} ($\text{kg}_{\text{water}} \text{kg}^{-1}_{\text{oven-dry wood}} \times 100$) and temperature \mathbf{T} (K)); and $\vec{\nabla} \psi$ = gradient in water potential ($\text{J kg}^{-1}_{\text{water}} \text{m}^{-1}_{\text{moist wood}}$).

For a one-dimensional problem, the initial condition for Eq. (1) is given by:

$$\psi(x, t = 0) = \psi_0 \quad (3)$$

where ψ = water potential ($\text{J kg}^{-1}_{\text{water}}$).

The convective mass transfer boundary condition at wood surface is given by:

$$q_{mc} = h_{\psi}(\psi_s - \psi_{\infty}) = -K_x(\mathbf{M}, \mathbf{T}) \frac{\partial \psi}{\partial x} \quad (4)$$

where q_{mc} = convective moisture flux normal to the wood surface ($\text{kg}_{\text{water}} \text{m}^{-2}_{\text{moist wood}} \text{s}^{-1}$); h_{ψ} = convective mass transfer coefficient ($\text{kg}^2_{\text{water}} \text{m}^{-2}_{\text{drying surface}} \text{s}^{-1} \text{J}^{-1}$); ψ_s = surface water potential ($\text{J kg}^{-1}_{\text{water}}$); ψ_{∞} = water potential of the air-water vapor mixture ($\text{J kg}^{-1}_{\text{water}}$).

In order to broaden the range of application of the previous model, the heat transfer phenomena occurring in wood during drying have to be considered. Using an enthalpic formulation for the wood-air-water system, the equation of heat transfer in wood during convective drying at atmospheric pressure can be written as follows:

$$\frac{\partial H}{\partial t} + \vec{\nabla} \cdot \vec{q}_h = \varepsilon(\Delta h_o + \beta \Delta h_s) \frac{\partial C}{\partial t} \quad (5)$$

with

$$\vec{q}_h = -\underline{\mathbf{k}}(\mathbf{M}) \cdot \vec{\nabla} T \quad (6)$$

where \vec{q}_h = conductive heat flux vector ($\text{J m}^{-2}_{\text{moist wood}} \text{s}^{-1}$); H = total enthalpy of the wood-air-water system ($\text{J m}^{-3}_{\text{moist wood}}$); $\underline{\mathbf{k}}(\mathbf{M})$ = thermal conductivity tensor ($\text{W m}^{-1}_{\text{moist wood}} \text{K}^{-1}$); ε = ratio of vapor diffusion to the total water movement; Δh_o = latent heat of vaporization ($\text{J kg}^{-1}_{\text{water}}$); Δh_s = differential heat of sorption ($\text{J kg}^{-1}_{\text{water}}$); C = moisture concentration ($\text{kg}_{\text{water}} \text{m}^{-3}_{\text{moist wood}}$); t = time (sec); $\beta = 0$ for $\mathbf{M} >$ fiber saturation point (FSP) and $\beta = 1$ for $\mathbf{M} \leq$ FSP.

For a one-dimensional problem, the initial condition for Eq. (5) is given by:

$$T(x, t = 0) = T_0 \quad (7)$$

The convective heat transfer boundary condition at the wood surface is given by:

$$\begin{aligned}
q_{hn} &= h_h(T_s - T_z) \\
&+ (1 - \varepsilon)(\Delta h_o + \beta \Delta h_s)h_\psi(\psi_s - \psi_z) \\
&= -k_x(M)\frac{\partial T}{\partial x} \quad (8)
\end{aligned}$$

where q_{hn} = net heat flux (J m^{-2} drying surface s^{-1}); h_h = convective heat transfer coefficient (W m^{-2} drying surface K^{-1}); T_s = surface temperature (K); T_z = ambient air temperature (K); h_ψ = convective mass transfer coefficient (kg^2 water m^{-2} drying surface $\text{s}^{-1} \text{J}^{-1}$); ψ_s = surface water potential (J kg^{-1} water); ψ_z = water potential of the air-water vapor mixture (J kg^{-1} water). The proportion of q_{hn} used for vaporization of water at the wood surface is considered in Eq. (8).

The latent heat of vaporization Δh_o required for the vaporization of liquid water can be considered constant at $2.5 \times 10^6 \text{ J kg}^{-1}$ water. The differential heat of sorption Δh_s is required to consider the phase change from the bound to the liquid phase. On one hand, for $M > \text{FSP}$, $\beta = 0$ because the hypothesis is made that phase change occurs only from the liquid to the vapor phase. On the other hand, for $M \leq \text{FSP}$, $\beta = 1$ and Δh_s increases with the reduction of M under the FSP. The second term on the left-hand side of Eq. (5) stands for heat transfer by conduction. The term on the right-hand side of Eq. (5) stands for the heat transfer due to phase change in wood during drying. Heat transfer by advection is neglected. This assumption is reasonable for wood drying taking place below 100°C (Sutherland et al. 1992). The ratio of vapor diffusion to the total water movement ε must be known to consider phase change in the heat transfer model. ε varies between zero and one. It is equal to one if the total water movement occurs in the vapor phase only. Conversely, ε is equal to zero for water movement occurring in the liquid phase only. Different values of ε have been considered in the literature. Thomas et al. (1980) and Liu and Cheng (1989, 1991) used a constant value of 0.3. In order to get better results from the FEM solution of Luitkov's equations, Irudayaraj et al. (1990) considered a constant value of 0.1 for M higher

than 30% and a linear increment from 0.1 to 1.0 for M varying respectively from 30% to 0%. Finally, Viktorin (1991) considered ε to vary as follows: $\varepsilon \approx 0.10, 0.40,$ and 1.0 for M varying respectively from 100% to 65%; 65% to 30%; and 30% to 0%. In the literature mentioned above, no information is given on the method used to determine ε . It seems that ε is usually determined on the basis of the results obtained with numerical models. No experimental procedure designed to determine ε was found in the literature.

In this study, an original method is presented for the determination of ε as a function of moisture content from nearly saturated to dry conditions. The coefficient ε was determined from drying experiments on red pine (*Pinus resinosa* Ait.) sapwood at 18, 56 and 85°C in the radial direction.

THE NATURE OF THE ε COEFFICIENT

Equation (1) can be written in one dimension as follows:

$$\frac{\partial C}{\partial t} = -\frac{\partial q_{mx}}{\partial x} \quad (9)$$

where q_{mx} is the total water flux which can be divided in three phases:

$$q_{mx} = q_{lx} + q_{bx} + q_{vx} \quad (10)$$

where l = liquid water; b = bound water; v = water vapor.

From Eqs. (9) and (10),

$$\frac{\partial C}{\partial t} = -\frac{\partial q_{lx}}{\partial x} - \frac{\partial q_{bx}}{\partial x} - \frac{\partial q_{vx}}{\partial x} \quad (11)$$

If we define q_{vx} as a given proportion of the total moisture flux q_{mx} as follows:

$$q_{vx} = \varepsilon q_{mx} \quad (12)$$

Then, from Eqs. (9), (11) and (12), we can write:

$$-\frac{\partial q_{vx}}{\partial x} = -\frac{\partial(\varepsilon q_{mx})}{\partial x} = -q_{mx}\frac{\partial \varepsilon}{\partial x} - \varepsilon\frac{\partial q_{mx}}{\partial x} \quad (13)$$

From our experimental results, it can be demonstrated that the term $-q_{mx}\partial\varepsilon/\partial x$ is about 10

to 100 times smaller than $\varepsilon \partial q_{mx} / \partial x$. Therefore, we considered $-q_{mx} \partial \varepsilon / \partial x$ as being negligible. Then, Eq. (13) can be rewritten as follows:

$$-\frac{\partial q_{vx}}{\partial x} = -\varepsilon \frac{\partial q_{mx}}{\partial x} = \varepsilon \frac{\partial C}{\partial t} \quad (14)$$

Equation (14) indicates that a proportion ε of the rate of change of the moisture concentration occurs in the vapor phase. The remaining proportion of the rate of change of the moisture concentration, $(1 - \varepsilon)$, represents the summation of the liquid and bound moisture components of the total water flux.

DETERMINATION OF ε

From the integration of Eq. (5) applied in the x -direction, the following equation is obtained:

$$\int_{x_{q=0}}^x \frac{\partial H}{\partial t} dx = \int_{x_{q=0}}^x \frac{\partial}{\partial x} \left(k_x(M) \frac{\partial T}{\partial x} \right) dx + \int_{x_{q=0}}^x \varepsilon (\Delta h_o + \beta \Delta h_s) \frac{\partial C}{\partial t} dx \quad (15)$$

The position corresponding to the lower limit of the integral, $x_{q=0}$, is defined as the bottom of the specimen, where $x = 0$ mm. Following Leibnitz property and considering $\varepsilon (\Delta h_o + \beta \Delta h_s)$ constant over the range $x_{q=0}$ and x , we can write:

$$\frac{\partial}{\partial t} \int_{x_{q=0}}^x H dx = \frac{\partial}{\partial x} \int_{x_{q=0}}^x \left(k_x(M) \frac{\partial T}{\partial x} \right) dx + \varepsilon (\Delta h_o + \beta \Delta h_s) \frac{\partial}{\partial t} \int_{x_{q=0}}^x C dx \quad (16)$$

finally

$$\varepsilon = \frac{\frac{\partial}{\partial t} \int_{x_{q=0}}^x H dx - k_x(M) \frac{\partial T}{\partial x} \Big|_x}{(\Delta h_o + \beta \Delta h_s) \frac{\partial}{\partial t} \int_{x_{q=0}}^x C dx} \quad (17)$$

where the first term of the numerator is the

resulting total heat flux ($J m^{-2} \text{moist wood } s^{-1}$), the second term of the numerator is the heat flux by conduction ($J m^{-2} \text{moist wood } s^{-1}$), and the term at the denominator is the energy required for the vaporization of the entire mass flux ($J m^{-2} \text{moist wood } s^{-1}$). Therefore, ε can be defined as the ratio of the actual energy used for vaporization in given conditions over the energy required for vaporization of the entire mass flux. To solve Eq. (17), fluxes of heat and moisture limited to one direction are required in the porous media with the flux known at one position. This last requirement can be fulfilled by closing one end of the flow system, $x_{q=0}$ at $x = 0$ mm.

From Eq. (17), ε is equal to zero if the resulting total heat flux within the specimen is equal to the heat flux by conduction, meaning that there is no heat transfer due to phase change. This situation could be met in a saturated wood specimen containing bound and liquid water only. On the opposite, ε is equal to one when the energy used for vaporization is equal to the energy required for the vaporization of the entire mass flux. Therefore, energy is available for vaporization of all the water in bound and liquid phases. As a result, ε gets closer to one as the bound and liquid water disappear.

CALCULATION OF THE TOTAL ENTHALPY H

The determination of ε from Eq. (17) requires the calculation of the total enthalpy H of the wood-air-water system. The enthalpy of each component of the system is considered in the calculation of H as follows:

$$H = \rho_s \chi_s h_s + \rho_g \chi_g h_g + \rho_l \chi_l h_l + \rho_b \chi_b h_b \quad (18)$$

with

$$\rho_g \chi_g h_g = \rho_a \chi_a h_a + \rho_v \chi_v h_v \quad (19)$$

where ρ_i = density of component i ($kg_i m^{-3}$); χ_i = fractional volume of component i ($m^3_i m^{-3} \text{moist wood}$); h_i = specific enthalpy of component i ($J kg^{-1}$); H = total enthalpy of the wood-air-water system ($J m^{-3} \text{moist wood}$); with subscripts: s = cell wall; g = gas; a = air; v

