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 Luikov'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:

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

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

$$\vec{q}_m = -\underset{\sim}{K}(M, T)\cdot\vec{\nabla}\psi \qquad (2)$$

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

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

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

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

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

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

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

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:

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

with

$$\vec{q}_h = -\underset{\sim}{k}(M)\cdot\vec{\nabla}T \qquad (6)$$

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

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

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

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

$$q_{hn} = h_h(T_s - T_\infty) + (1 - \varepsilon)(\Delta h_o + \beta \Delta h_s)h_\psi(\psi_s - \psi_\infty) = -k_x(M)\frac{\partial T}{\partial x} \qquad (8)$$

where q_{hn} = net heat flux (J $m^{-2}{}_{\text{drying surface}}$ s^{-1}); h_h = convective heat transfer coefficient (W $m^{-2}{}_{\text{drying surface}}$ K^{-1}); T_s = surface temperature (K); T_∞ = ambient air temperature (K); h_ψ = convective mass transfer coefficient ($kg^2{}_{\text{water}}$ $m^{-2}{}_{\text{drying surface}}$ s^{-1} J^{-1}); ψ_s = surface water potential (J $kg^{-1}{}_{\text{water}}$); ψ_∞ = water potential of the air-water vapor mixture (J $kg^{-1}{}_{\text{water}}$). 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 2.5×10^6 J $kg^{-1}{}_{\text{water}}$. 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 > 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 ≤ 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 Luikov'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: $\varepsilon \simeq 0.10$, 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:

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

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

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

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

From Eqs. (9) and (10),

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

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

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

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

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

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:

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

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:

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

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:

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

finally

$$\varepsilon = \frac{\left.\dfrac{\partial}{\partial t}\displaystyle\int_{x_{q=0}}^{x} H\,dx - k_x(M)\frac{\partial T}{\partial x}\right|_{x}}{(\Delta h_o + \beta\Delta h_s)\dfrac{\partial}{\partial t}\displaystyle\int_{x_{q=0}}^{x} C\,dx} \qquad (17)$$

where the first term of the numerator is the resulting total heat flux ($\mathrm{J\ m^{-2}_{moist\ wood}\ s^{-1}}$), the second term of the numerator is the heat flux by conduction ($\mathrm{J\ m^{-2}_{moist\ wood}\ s^{-1}}$), and the term at the denominator is the energy required for the vaporization of the entire mass flux ($\mathrm{J\ m^{-2}_{moist\ wood}\ s^{-1}}$). 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:

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

with

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

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

= water vapor; l = liquid water; b = bound water. Each term of Eqs. (18) and (19) is described below.

Density $\rho_i(kg_i\, m^{-3}{}_i)$ *of each component of the system*

Density of cell-wall substance ρ_s

The density of the cell-wall substance was determined to be about 1,450 $kg_{cell\ wall}\ m^{-3}{}_{cell\ wall}$ in the oven-dry state (Kellogg and Wangaard 1969).

Density of air ρ_a

Considering air as a perfect gas, we can write:

$$p_a = \rho_a \frac{RT}{M_a} \tag{20}$$

then

$$\rho_a = \frac{p_a M_a}{RT} \tag{21}$$

where M_a = molar mass of air (0.028947 kg_{air} $mole^{-1}{}_{air}$); R = perfect gas constant (8.3143 J $mole^{-1}{}_{gas}$ K^{-1}); p_a = air partial pressure = P − p_v (Pa); P = ambient total pressure (101,300 Pa); p_v = water vapor pressure (Pa); ρ_a = density of air (kg_{air} $m^{-3}{}_{air}$).

Density of water vapor ρ_v

As for air, water vapor can be considered as a perfect gas in the conditions encountered during the kiln drying of wood at atmospheric pressure:

$$\rho_v = \frac{p_v M_w}{RT} \tag{22}$$

For M ≥ FSP, the water vapor pressure p_v is calculated from the moisture content-water potential ($M - \psi_m$) relationship (Tremblay et al. 1996) and the following equation:

$$\psi_{m+o} = \frac{RT}{M_w} \ln\left(\frac{p_v}{p_{v_s}}\right) \tag{23}$$

The partial pressure of water vapor can be obtained from Eq. (23) as follows:

$$p_v = p_{v_s} e^{[(\psi_{m+o} M_w)/RT]} \tag{24}$$

where p_{v_s} = saturated water vapor pressure at T (Pa); ψ_{m+o} = sum of the matric and osmotic potentials (equal to ψ_m above the FSP) (J $kg^{-1}{}_{water}$); M_w = molar mass of water (0.018 kg_{water} $mol^{-1}{}_{water}$). The value of ψ_{m+o} at a given moisture content is inferred from the $M - \psi_m$ relationship determined experimentally (Tremblay et al. 1996).

For M < FSP, the water vapor pressure p_v is inferred from Bradley's sorption model (Simpson 1973):

$$p_v = p_{v_s} e^{(K_1 K_2^{0.92M})} \tag{25}$$

with

$$K_1 = 17.883943 - (0.1422998T) + (0.0002363T^2)$$

$$K_2 = 1.032702 - (0.000674T)$$

Density of liquid water ρ_l

The density of liquid water can be calculated from the following linear regression equation (Incropera and De Witt 1990):

$$\rho_l = 1122.2 - 0.4259T \tag{26}$$

Density of bound water ρ_b

For M > FSP, ρ_b is supposed to be equal to ρi. For M ≤ FSP, the following relation is used (Siau 1984):

$$\rho_b = 1300.64 - 12.93M + 0.3162M^2 - 0.003111M^3 \tag{27}$$

Fractional volume $\chi_i\ (m^3{}_i\, m^{-3}{}_{moist\ wood})$ *of each component of the system*

Fractional volume of cell wall χ_s

$$\chi_s = \frac{G_m \rho_l}{\rho_s} \tag{28}$$

Fractional volume of bound water χ_b

$$\chi_b = \frac{G_m \rho_l}{\rho_b} \frac{M_b}{100} \tag{29}$$

Fractional volume of gas χ_g

$$\chi_g = \pi - \left(G_m \frac{M_l}{100}\right) \tag{30}$$

Fractional volume of liquid water χ_l

$$\chi_l = G_m \frac{M_l}{100} \tag{31}$$

where G_m = specific gravity of wood ($kg_{\text{oven-dry wood}}\ m^{-3}_{\text{moist wood}}\ kg^{-1}_{\text{water}}\ m^3_{\text{water}}$); M_b = bound water moisture content ($kg_{\text{bound water}}\ kg^{-1}_{\text{oven-dry wood}} \times 100$); M_l = liquid water moisture content ($kg_{\text{liquid water}}\ kg^{-1}_{\text{oven-dry wood}} \times 100$); π = porosity = $1 - (\chi_s + \chi_b)(m^3_{\text{pores}}\ m^{-3}_{\text{moist wood}})$.

Specific enthalpy h_i (J $kg^{-1}{}_i$) of each component of the system

The enthalpy is defined as a function of a reference state. In this work, we define the reference state as the specific enthalpy at T = 0 K.

Specific enthalpy of air h_a

The specific enthalpy of air is given by the following equation:

$$h_a = C_{p_a}(T - T_0) \tag{32}$$

where C_{p_a} = specific heat of air (1,003.5 J kg^{-1} K^{-1}); T_0 = reference temperature (0 K).

Specific enthalpy of the cell wall h_s

No information was available about the specific heat of the cell wall (C_{p_s}). Therefore, we considered the specific heat of oven-dry wood. C_{p_s} increases linearly with T from about 1,130 J kg^{-1} K^{-1} at 273.15 K to about 1548 J kg^{-1} K^{-1} at 373.15 K (Skaar 1988). C_{p_s} corresponds to the specific heat of graphite, which increases linearly from T = 0 to 350 K. Therefore, C_{p_s} was taken approximately as the following equation:

$$C_{p_s} = 4.18T \tag{33}$$

The specific enthalpy of the cell wall h_s is then given by the following equation:

$$h_s = \int_0^T 4.18T\ dT = 2.09T^2. \tag{34}$$

Specific enthalpy of liquid water h_l

From the reference state which is ice at T = 0 K, the specific enthalpy of liquid water between T = 273.15 and 373.15 K is given by:

$$h_l = h_o + (h_i)_m + \Delta h_m + C_{p_l}(T - T_m) \tag{35}$$

where h_o = enthalpy of ice at 0 K; $(h_i)_m$ = enthalpy of ice at the melting point (T_m = 273.15 K); Δh_m = heat of melting of ice at 273.15 K; $C_{p_l}(T - T_m)$ = heat required to increase the temperature of liquid water from T_m = 273.15 K to T. From Skaar (1988), the enthalpy of ice at the melting point is 3.045×10^5 J $kg^{-1}{}_{\text{water}}$ and the heat of melting is 3.347×10^5 J $kg^{-1}{}_{\text{water}}$. The specific heat of water (C_{p_l}) is 4.183×10^3 J $kg^{-1}{}_{\text{water}}$ K^{-1}. Therefore, the last equation becomes:

$$h_l = h_o + 6.392 \times 10^5 + 4.183 \times 10^3 (T - 273.15) \tag{36}$$

with h_l (J $kg^{-1}{}_{\text{water}}$) and h_o = 0.

Equation (36) is valid for free liquid water. The specific enthalpy of capillary water (h_{wcap}) in the cell cavities is slightly lower than that of free liquid water for the following reasons (Skaar 1988): First, the vapor pressure of capillary water is lower than that of free liquid water because of the curvature of the air-water meniscus in a capillary; Second, the presence of water-soluble extractives in capillary water reduces the vapor pressure. The reduction of h_l can be considered using the following equation:

$$h_{wcap} = h_l - \Delta h_c \tag{37}$$

where Δh_c = enthalpy reduction due to capillary effects (J $kg^{-1}{}_{\text{water}}$).

According to Skaar (1988), the Clausius-Clapeyron equation applied to the Kelvin equation leads to the following equation describing Δh_c:

$$\Delta h_c = (3.1019 \times 10^{-4} - 5.1171 \times 10^{-7}T + 9.4301 \times 10^{-10}T^2)/r \qquad (38)$$

where r = radius of the capillary (m). For a given M value, the corresponding capillary radius was calculated using the following relation:

$$r = -\frac{\bar{V}_w 2\gamma}{\psi_m}\cos\theta \qquad (39)$$

where $\bar{V}_w$ = specific volume of water ($m^3{}_{water}$ $kg^{-1}{}_{water}$) (function of T); γ = surface tension of water ($N\ m^{-1}$) (function of T); θ = contact angle between the liquid and the surface of the capillary; and ψ_m = matric potential (J $kg^{-1}{}_{water}$) inferred from the M − ψ_m relationship established in a previous paper (Tremblay et al. 1996).

Δh_c increases as M decreases from 170% to 30%. Nevertheless, Δh_c stays relatively small compared to h_l. The maximum value of Δh_c represents about 0.5% of h_l at 18°C.

Specific enthalpy of water vapor h_v

For a phase change taking place between T = 273.15 and 373.15 K, the specific enthalpy of water vapor h_v is obtained by adding the latent heat of vaporization from the liquid to the vapor phase ($\Delta h_o = 2.5 \times 10^6$ J $kg^{-1}{}_{water}$) to the specific enthalpy of liquid water h_l at T:

$$h_v = h_l + \Delta h_o \qquad (40)$$

Specific enthalpy of bound water h_b

At a given temperature, the specific enthalpy of bound water h_b is lower than the specific enthalpy of liquid water h_l by the differential heat of sorption Δh_s:

$$h_b = h_l - \Delta h_s \qquad (41)$$

where Δh_s = energy released when one unit mass of liquid water is sorbed by wood at constant moisture content (J $kg^{-1}{}_{water}$). The value of Δh_s is a strong function of moisture content in the hygroscopic range. The differential heat of sorption Δh_s can also be defined as the energy to supply over the latent heat of vaporization Δh_o for the vaporization of one unit mass of sorbed water. It can be defined by the following equation (Skaar 1988):

$$\Delta h_s = 1.1715 \times 10^6\, e^{-0.14M} \qquad (42)$$

In the previous equations, the variation of the FSP with T was considered (Siau 1995). At a given temperature, the FSP was calculated from the following linear regression equation:

$$FSP = 59.315 - 0.1T \qquad (43)$$

MATERIAL AND METHODS

Material

The material used in the present study was of the same origin as that used previously for the determination of the moisture content-water potential relationship (Tremblay et al. 1996) and the effective water conductivity (Tremblay et al. 1999). The tests specimens were cut from red pine sapwood obtained from three trees and were free of visual defects. The specific gravity (O.D. weight/green volume) of the material varied from 0.360 to 0.460. The specimens were cut to 45 × 45 × 45 mm. Seven matched groups of three specimens (one from each tree) were prepared for the determination of ε at each temperature. After selection and classification, the specimens were kept in sealed polyethylene bags and stored at −15°C.

Methods

Specimens preparation and drying

The material intended for the determination of ϵ was saturated with distilled water using cycles of one-hour vacuum and one-hour atmospheric pressure until the water uptake became negligible. In order to realize a one-dimensional moisture flow along the radial direction only, the specimens were edge-coated with two layers of silicone sealant and aluminum foil. The bottom side of each specimen was covered with a two-mm-thick neoprene gasket and aluminum foil in order to allow pressure equalization through a pinhole made at the center of the foil. In order to realize a

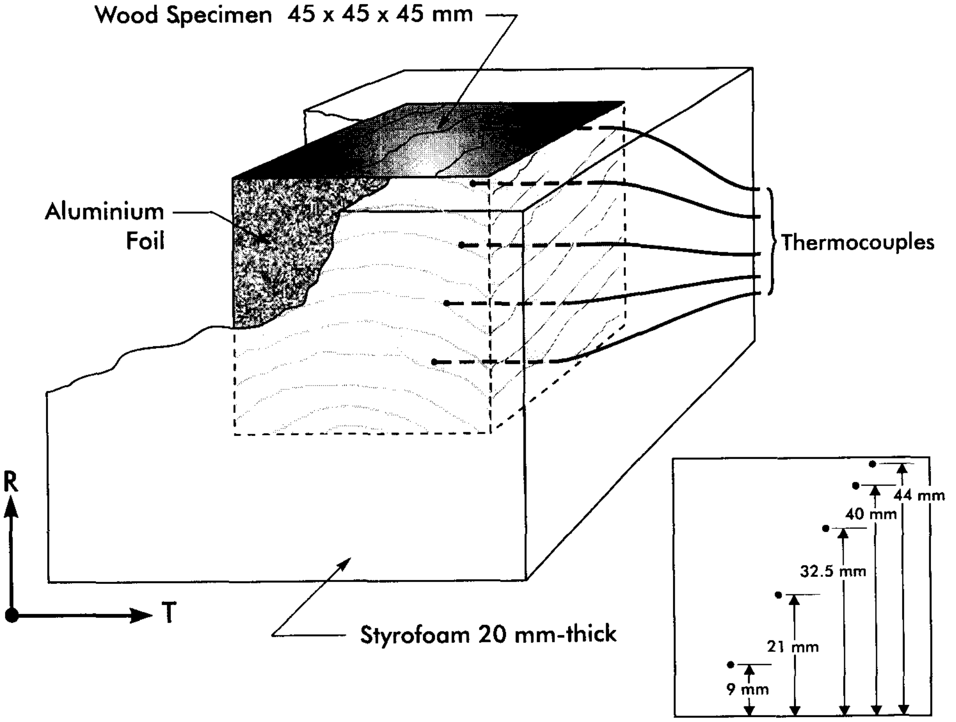

FIG. 1. Specimen with styrofoam insulation and thermocouples.

one-dimensional energy flux, the edge-coated specimens were put in styrofoam boxes made of 20-mm-thick walls leaving only the top side of the specimens open to the drying air stream (Fig. 1).

In order to determine ε, the specimens were allowed to dry in a conditioning cabinet at constant temperature, relative humidity, and air velocity. The dry and wet-bulb temperatures considered for the three drying experiments were 18 and 12.5°C; 56 and 46.5°C; 85 and 77.5°C. The resulting equilibrium moisture content (EMC) was 9% for each experiment. When introduced in the conditioning cabinet, the specimens were in equilibrium with the environment at 24°C. The specimens were exposed to a horizontal air stream of about 1.0 m s^{-1}.

For the determination of ε from the drying experiments, moisture content (M) and temperature (T) profiles were measured in the direction of moisture and energy fluxes (radial) at regular M changes. The measurements of M and T profiles were done at the following average M values of a sample board: full saturation, 150%, 120%, 90%, 60%, 30%, and 15%. Considering the numerous manipulations required to perform these experiments, special care was taken to minimize experimental errors. The maximum error related to the determination of M by the slicing technique was estimated to be ±1% M. The accuracy of the thermocouples was estimated to be ±0.5°C.

Mass flux determination

The instantaneous profile method was used for the determination of the mass flux q_{mx}. The technique is described in detail in Tremblay et al. (1999) and Cloutier and Fortin (1993). When a target M value was reached, one group of three specimens was taken out of the conditioning chamber for determination of the

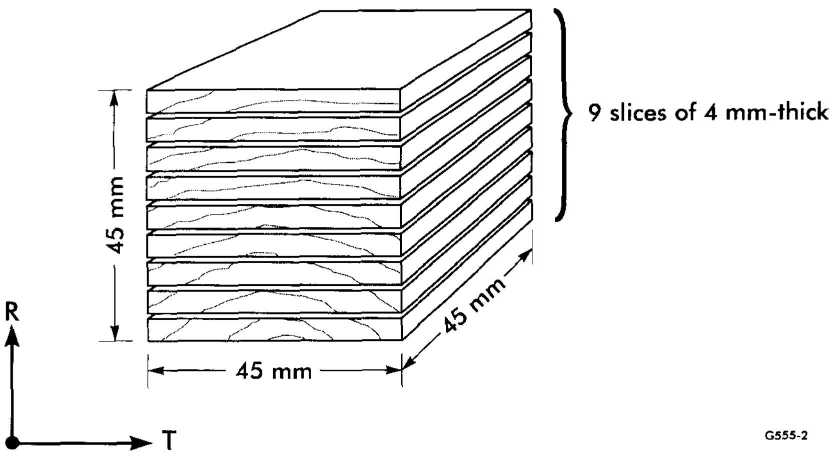

FIG. 2. Slicing diagram.

C profile. The specimens were sawn in 9 slices in the direction of flow (Fig. 2) using a thin kerf band saw. The water loss due to sawing was determined as being negligible (Cloutier and Fortin 1993). M was determined for each slice by the gravimetric method. The corresponding C value was then calculated from the following equation:

$$C = G_m \rho_l \frac{M}{100} \tag{44}$$

The average C profiles were hand-fitted to the data points, each data point representing the average C at a given position for the three slices of a group. The integral $\int_{x_{q_{mx}-0}}^{x}$ C dx at a specific time t_j was determined by graphical integration of the area defined by the C profile at t_i and the planes $x = x_i$ and $x_{q_{mx}-0}$. From the bottom of a specimen defined as $x = 0$ mm, three positions were considered in the calculation of ε: $x = 15$, 20, and 25 mm. The lower limit of the integral, $x_{q_{mx}=0}$, is defined as the bottom of the specimen at $x = 0$ mm. The term $\partial/\partial t \int_{x_{q_{mx}-0}}^{x}$ C dx corresponding to the mass flux was determined by plotting $\int_{x_{q_{mx}=0}}^{x}$ C dx against t and measuring the slope graphically at different drying times t_j.

Energy flux determination

When a target M value was attained during a drying experiment, the temperature profile was recorded just before a group of three specimens was removed for the determination of the C profile. The T profile was measured using thermocouples inserted at half-thickness of the specimens (22.5 mm). Ten thermocouples were positioned inside two specimens (five each) to measure the T profile in the direction of moisture flow. From the bottom of the specimen defined as $x = 0$ mm, the positions of the thermocouples were 9, 21, 32.5, 40, and 44 mm (Fig. 1). Therefore, from the C and T profiles at t_j, it was possible to calculate the total enthalpy (H) profile from the equations described above. The term of energy flux $\partial/\partial t \int_{x_{q_{hx}-0}}^{x}$ H dx is determined in the same way as the moisture flux $\partial/\partial t \int_{x_{q_{mx}-0}}^{x}$ C dx.

The determination of the heat conduction term of Eq. (17), $k_x(M)\partial T/\partial x$, was done by multiplying the temperature gradient at the position considered in the specimen by the transverse thermal conductivity as given by Siau (1995) for M ≥ 40%:

$$k_{RT'}(M, G_m) = G_m(0.200 + 0.0052M) + 0.024 \tag{45}$$

where $k_{RT}(M, G_m)$ = transverse thermal conductivity (W m^{-1} K^{-1}).

RESULTS AND DISCUSSION

Moisture content profiles and the corresponding C profiles inferred from Eq. (44) ob-

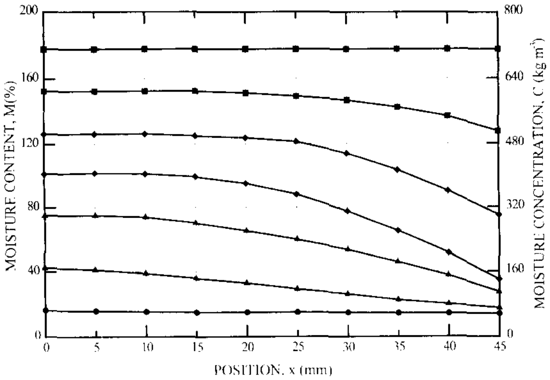

FIG. 3. Moisture content and moisture concentration profiles measured at 85°C after 0.0 (■), 1.5 (□), 5.0 (♦), 11.0 (◇), 22.0 (▲), 40.0 (△), and 67.5 (●) hours of drying.

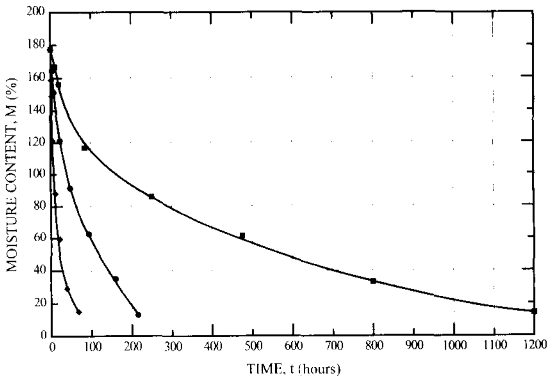

FIG. 4. Moisture content at x = 25 mm vs. time for drying at 18 (■), 56 (●), and 85°C (♦).

tained from the drying experiment at 85°C are shown in Fig. 3. The small M gradients measured between 0 and 25 mm justify the assumption made that $\varepsilon(\Delta h_0 + \beta\Delta h_s)$ is constant over x as used to develop Eq. (16). The M values at x = 25 mm as a function of time obtained for each experiment are shown in Fig. 4. As could be expected, the time required to reach the dry condition varied with temperature. Therefore, 67.5 h were necessary to reach an average final M value of about 15% from nearly saturated conditions at 85°C. Corresponding drying times at 56°C and 18°C were 215 h and 1,200 h, respectively. The drying time decreases as T increases mainly because the effective water conductivity $K_x(M, T)$ of wood and the heat transfer at the surface increase with T.

Temperature profiles measured for the drying experiment at 85°C are shown in Fig. 5. The initial wood temperature was 24°C. The heat conduction term of Eq. (17) $(k_x(M)\partial T/\partial x)$ was considered only at t = 1 and 1.5 h for the calculation of ε at 85°C. At 56°C, it was considered only at t = 3.5 h. The temperature gradients were negligible at the other drying times. They were also negligible at the drying times considered for the calculation of ε during the drying experiment performed at 18°C.

The evolution of the wood temperature at x = 25 mm for the drying experiments at 18, 56, and 85°C is illustrated in Fig. 6. Without regard to the dry bulb temperature used, the evolution of the temperature in wood during the experiments at 56 and 85°C follows a similar pattern. From the initial temperature of 24°C at t = 0 h, the wet bulb temperature was reached within 2 h at 56°C and 6 h at 85°C. For the experiment at 18°C, the wet bulb temperature of 12.5°C wasn't attained, but the lowest temperature of 14°C was recorded after 8 h. For each drying experiment, the temperature gradients were dissipated by the time the wet bulb temperatures (or the lowest value at 18°C) were reached in the specimens. The maximum temperature gradient recorded at x = 25 mm was 0.81°C mm^{-1} after 19 min of

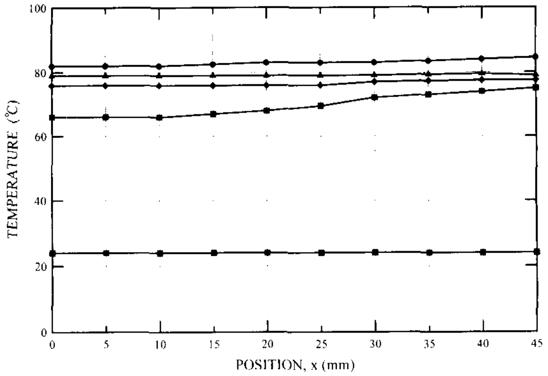

FIG. 5. Temperature profiles measured at 85°C after 0.0 (■), 1.5 (□), 5.0 (♦), 22.0 (▲), and 67.5 (●) hours of drying.

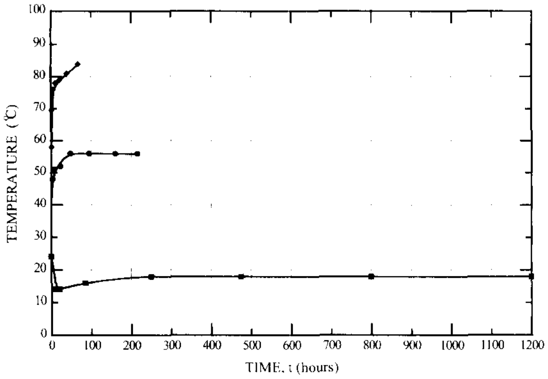

FIG. 6. Temperature at x = 25 mm vs. time for drying at 18 (■), 56 (●), and 85°C (♦).

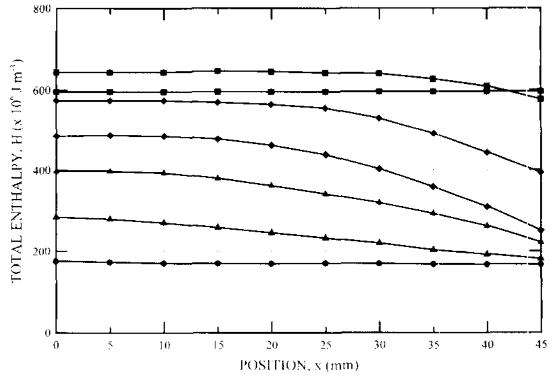

FIG. 7. Enthalpy profiles obtained at 85°C after 0.0 (■), 1.5 (□), 5.0 (♦), 11.0 (◇), 22.0 (▲), 40.0 (△), and 67.5 (●) hours of drying.

drying at 85°C, 0.55°C mm^{-1} after 15 min at 56°C, and −0.32°C mm^{-1} after 22 min at 18°C. For the drying experiments performed at 18 and 56°C, the dry bulb temperature was attained at slicing number 5 corresponding to an average M value of about 90% (Table 1). From that point on, the temperatures remained constant at their respective dry bulb value until the end of the experiment. On the other hand, for the experiment at 85°C, the dry bulb temperature was reached only at the end (slicing number 8, M value of 15%). A more intensive vaporization of water inside the specimens could explain the lower temperature reached inside the wood specimens during the drying process.

As previously mentioned, the H profile in wood can be determined from the C and T profiles and Eq. (18) at a specific drying time t_j. The resulting H profiles at 85°C are shown in Fig. 7. The increment of H values at the beginning of the drying process is explained by the elevation of the specimen temperature at high moisture contents. Then, the H values decrease with the reduction of M. Enthalpy values of each component H_i (J $\mathrm{m}^{-3}_{\text{moist wood}}$) at x = 25 mm are given in Table 2. Even though the specific enthalpy of water vapor h_v (J $\mathrm{kg}^{-1}_{\text{vapor}}$) is the highest, its contribution to the total enthalpy H of the moist wood system is negligible due to the low water vapor content. The enthalpy of air H_a (J $\mathrm{m}^{-3}_{\text{moist wood}}$) is also very low when compared to the total enthalpy H. The most important proportion of H is included in the capillary water term H_{wcap} at high moisture contents. This is true for M values varying from near saturation (177.5%) to 88%

TABLE 1. *Wood temperature and moisture content at x = 25 mm.*

	18°C			56°C			85°C		
Slicing no.	t (h)	Temp. (°C)	M (%)	t (h)	Temp. (°C)	M (%)	t (h)	Temp. (°C)	M (%)
1	0	24	177.5	0	24	177.5	0	24	177.5
2	10	14	166.9	3.5	48	164.4	1	58	158.8
3	20	14	156.3	6.75	51	151.3	1.5	69.5	149.3
4	85	16	116.8	23	52	121.3	5	76	121.3
5	250	18	85.8	48	56	91.3	11	78	88.0
6	475	18	61.3	94	56	62.5	22	79	59.5
7	800	18	33.0	160	56	35.0	40	81	29.3
8	1,200	18	14.0	215	56	13.0	67.5	84	15.0

Corresponding wet bulb temperatures at 18, 56, and 85°C are 12.5, 46.5, and 77.5°C.

TABLE 2. *Enthalpy values for each component of the total enthalpy H at 85°C and x = 25 mm.*

Time (h)	M (%)	T (°C)	H_s ($\times 10^6$J m^{-3})	H_a ($\times^6$J m^{-3})	H_v ($\times 10^6$J m^{-3})	H_{wcap} ($\times 10^6$J m^{-3})	H_b ($\times 10^6$J m^{-3})	H ($\times 10^6$J m^{-3})
0	177.5	24	73.8 (12.4%)	0.0 (0.0%)	0.0 (0.0%)	436.7 (73.3%)	85.4 (14.3%)	595.9 (100%)
1.5	149.3	69.5	98.2 (15.3%)	0.0 (0.0%)	0.1 (0.0%)	435.5 (67.9%)	107.9 (16.8%)	641.6 (100%)
5	121.3	76	101.9 (18.4%)	0.1 (0.0%)	0.2 (0.0%)	341.9 (61.6%)	111.1 (20.0%)	555.2 (100%)
11	88.0	78	103.9 (23.7%)	0.1 (0.0%)	0.3 (0.1%)	221.0 (50.4%)	113.0 (25.8%)	438.3 (100%)
22	59.5	79	107.5 (31.5%)	0.1 (0.0%)	0.4 (0.1%)	116.9 (34.2%)	116.7 (34.2%)	341.6 (100%)
40	29.3	81	111.8 (48.1%)	0.1 (0.1%)	0.6 (0.3%)	0.0 (0.0%)	119.8 (51.6%)	232.3 (100%)
67.5	15.0	84	114.4 (67.4%)	0.1 (0.1%)	0.6 (0.4%)	0.0 (0.0%)	54.6 (32.2%)	169.7 (100%)

where more than 50% of the total enthalpy H is explained by H_{wcap} (Table 2). As expected, H_{wcap} decreases with the reduction of M and becomes equal to zero at the FSP and below. The enthalpy of bound water H_b and cell wall H_s can be considered as significant proportions of the total enthalpy H over the entire M range considered. The proportion of H explained by H_b and H_s becomes more important as M decreases. More than 99% of the total enthalpy H is due to H_s and H_b close to the FSP (Table 2, 29.3% M). Below the FSP, the contribution of H_s to H increases as M decreases. As could be expected, H_b decreases below the FSP due to the decrease of moisture content.

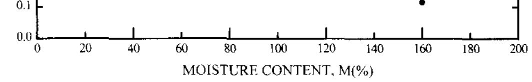

FIG. 8. Ratio of vapor diffusion to the total water movement vs. moisture content at 18 (■), 56 (▲), and 85°C (●).

Experimental values of ε obtained at 18, 56, and 85°C are presented in Fig. 8. The curve was hand-fitted to the data points. The coefficient ε is minimum at about 0.1 for M values close to saturation. This is understandable since water movement at high M values occurs mainly in the liquid phase. The coefficient ε increases as M decreases from nearly saturated conditions to about 120%. It reaches a plateau at an average value of 0.33 for intermediate M values (35 to 120%). Finally, ε increases rapidly from the FSP to about 15% M. This increment of ε was expected since the proportion of the water movement in the vapor phase increases with the reduction of M under the FSP. No significant variations of ε with T were noticed for the experimental conditions considered in this work. It seems that T impacts on the rate of change of moisture concentration with time, $\partial C/\partial t$, but not on the proportion ε of $\partial C/\partial t$ occurring in the vapor phase. No consistent results were obtained close to saturation for drying at 18°C. Therefore, no data points are presented.

Some similarities are found between the experimental values of ε presented in Fig. 8 and values used in the literature. The constant value of 0.3 used by Thomas et al. (1980) and Liu and Cheng (1989, 1991) corresponds to the plateau found at intermediate moisture contents in this study. Irudayaraj et al. (1990)

TABLE 3. *Calculation of ε from Eq.(17) at 85° C and x = 25 mm.*

Time (h)	Moisture content (%)	$\partial/\partial t \int_{x_q=0}^{x} H\,dx$ ($J\ m^{-2}\ s^{-1}$)	$k_x(M)\partial T/\partial x$ ($J\ m^{-2}\ s^{-1}$)	$(\Delta h_0 + \beta \Delta h_s)\partial/\partial t \int_{x_q=0}^{x} C\,dx$ ($J\ m^{-2}\ s^{-1}$)	ε
1	158.8	−203.7	−44.0	−1097.3	0.15
1.5	149.3	−151.9	−33.0	−694.5	0.17
5	121.3	−98.4	0.0	−361.0	0.27
11	88.0	−72.2	0.0	−218.3	0.33
22	59.5	−55.6	0.0	−151.5	0.37
40	29.3	−38.2	0.0	−115.9	0.33
67.5	15.0	−14.8	0.0	−31.2	0.48

considered a linear increment of ε from 0.1 at 30% M to 1.0 at 0% M. Experimental values of ε obtained in this study also increase as M decreases below the FSP.

Values related to each term of Eq. (17) as obtained for the drying experiment performed at 85°C are presented in Table 3. The second column of Table 3 shows the M values measured at x = 25 mm for different drying times. The third column shows the values of the total heat flux term ($\partial/\partial t \int_{x_{q_{hx}=0}}^{x} H\,dx$). The fourth column shows the values related to the heat flux by conduction $k_x(M)\partial T/\partial x$ only significant at t = 1 and 1.5 hours. The fifth column is the total energy flux required for the vaporization of the entire mass flux corresponding to the denominator of Eq. (17). The last column shows the resulting ε values. Column (3) decreases slower than column (5). This demonstrates that a higher proportion of the total water movement occurs in the vapor phase later in the process, explaining the increment of ε as shown in column (6).

CONCLUSIONS

A method of determination of the ratio of vapor diffusion to the total moisture movement, ε, is presented. The coefficient ε is calculated from the heat transfer equation considering heat transfer by conduction and phase change. The determination of ε is required when considering the heat of phase change in a wood-drying model based on water potential. Experimental results of ε obtained from the drying of red pine sapwood specimens at 18, 56, and 85°C 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%). The drying temperature had no significant effect on ε within the range considered in this study.

The calculation of H profiles inside the specimens at different drying times is required for the determination of ε. The results show that the most important proportion of the total enthalpy is included in the capillary water term (H_{wcap}) at high M values. As expected, H_{wcap} decreases with the reduction of M and becomes equal to zero for M values equal or lower than the fiber saturation point. The enthalpy of bound water (H_b) and cell-wall material (H_s) are significant over the entire M range considered.

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