RELATIONSHIP BETWEEN A DIFFUSION MODEL AND A TRANSPORT MODEL FOR SOFTWOOD DRYING

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ABSTRACT

Transfer equations in a transport model for wood drying are rearranged to give equations that have similar form to those of Luikov's drying model. In this way the transport coefficients in these equations are derived from the transport model and are functions of moisture content, temperature, wood properties (density, permeability, and bound water diffusivity), and properties of moisture (liquid density and viscosity, vapor density, and viscosity).

The above-derived equations are used to examine the relationship between the transport model and the simple diffusion model. It is shown that the diffusion model can be regarded as a simplified form of the transport model when the effect of temperature gradient is neglected. The diffusion model is applicable to cases where the temperature gradient is flat or the coefficient for the temperature gradient is small compared to that for the moisture content gradient. In other cases, or where the wood temperature is of concern, the transport drying model should be employed.

Keywords: Lumber drying, transport model, diffusion model, moisture content, temperature.

NOTATION

A, B constants in Eq. (8)

b_1, b_2, b_3, b_4 coefficients in Eq. (14)

C_P specific heat of wood, J/kg·K

C_{PV} specific heat of vapor, J/kg·K

D diffusion coefficient, m²/s moisture transfer coefficient for moisture content gradient, m²/s

D_b bound water diffusion coefficient, kg s/m²

D_1, D_2, D_3 transfer coefficients for moisture content gradient in the first, second and third period of drying, m²/s

D_h heat transfer coefficient for moisture content gradient, K·m²/s

D_{h1}, D_{h2}, D_{h3} transfer coefficients for moisture content gradient in the first, second and third period of drying, K·m²/s

E moisture transfer coefficient for temperature gradient, m²/s·K

E_1, E_2, E_3 transfer coefficients for temperature gradient in the first, second and third period of drying, m²/s·K

E_h heat transfer coefficient for temperature gradient, m²/s

E_{h1}, E_{h2}, E_{h3} transfer coefficients for temperature gradient in the first, second and third period of drying, m²/s

$f(T)$ function of temperature defined by Eq. (16)

H_{WV} heat of vaporization of water, J/kg

j total moisture fluxes, kg/m²·s

j_b bound water flux, kg/m²·s

j_f liquid water flux, kg/m²·s

j_v water vapor flux, kg/m²·s

K_V wood permeability to vapor flow, m²

K_l wood permeability to liquid flow, m²

m_v molar weight of vapor, 0.018 kg/mol

M local moisture content, kg/kg

M_{FSP} fiber saturation point, kg/kg

M_{max} maximum moisture content of wood, kg/kg

M_{min} minimum moisture content for liquid continuity, kg/kg

p_c capillary pressure, Pa

p_l liquid pressure, Pa

p_v partial vapor pressure, Pa

p_v^s vapor pressure at saturation condition, Pa

S saturation of wood

S_{min} minimum saturation for liquid continuity in wood

t drying time, s

T temperature, K

u function of temperature and moisture content defined in Eq. (21)

v function of temperature and moisture content defined by Eq. (22)

w function of moisture content defined by Eq. (18)

X coordinate in drying direction, m

Greek

ϵ voidage of wood, m^3/m^3

λ thermal conductivity of moist wood, $J/m \cdot K$

μ_b chemical potential of bound water, J/kg

μ_l water viscosity, $N \cdot s/m^2$

μ_v vapor viscosity, $N \cdot s/m^2$

ρ_l density of water, kg/m^3

ρ_v density of water vapor, kg/m^3

ρ_w basic density of wood, kg/m^3

ψ relative humidity

η function of moisture content and temperature defined in Eq. (25)

ζ function of moisture content and temperature defined in Eq. (26)

INTRODUCTION

In the area of wood drying modeling, the diffusion model represents the earliest attempt to describe and quantify the drying of wood (Rosen 1987). However, it has been realized that using the diffusion equation to describe overall moisture movement in wood is inadequate under some circumstances. The diffusion model assumes that the moisture movement is driven by total moisture concentration differences (Treybal 1968). However, the moisture in wood normally exists in three phases—liquid water, bound water, and water vapor—and these phases are subject to different driving forces. For example, liquid water may be driven by capillary action (Spolek and Plumb 1981) or water potential (Cloutier and Fortin 1993); bound water by chemical potential (Stanish 1986); and water vapor by vapor pressure difference. The diffusion model is usually employed for impermeable species of wood where the drying is very slow. In softwood drying, owing to its simple form, the diffusion model is often used when describing stress development (Morén 1989; Salin 1989; Puiggali et al. 1993).

Recently, numerous models based on detailed transport phenomena have been developed to simulate the wood drying process, as reviewed by Kamke and Vanek (1994). These models are based on transport processes alone (Plumb et al. 1985; Stanish et al. 1986; Nasrallah and Perré 1988; Chen and Pei 1989; Sutherland et al. 1994; Ferguson and Turner 1994) or based on both transport processes and physiological properties of wood related to drying (Pang 1994, 1996; Pang et al. 1992, 1994).

Because the transport drying models consider both heat and moisture transfer and identify the liquid water, bound water, and water vapor, they are able to cover a wider range of wood properties and drying conditions than does the diffusion drying model. However, the transport models are generally complex and contain numbers of mathematical formulae, which may limit their practical application.

The objectives of this work were to compare the diffusion model with a more rigorous transport model: (1) to determine under what conditions the simple diffusion model could adequately describe the drying process, and (2) to find a way to express the transfer coefficients so that they could be calculated from known wood properties and drying conditions. For the purpose of this comparison, the transport-based drying model of Pang (1996) and Pang et al. (1994) was used. In this model the drying process is divided into three periods, depending on moisture content level; and in the different stages of drying, each phase of moisture plays a different role.

DIFFUSION MODEL FOR LUMBER DRYING

This model assumes that moisture migrates in a material by diffusion due to a moisture concentration gradient. By using Fick's second law, an equation can be derived to express the moisture movement within the material being dried. The general form of the diffusion model is given as follows for one-dimensional drying:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial X}\left(D\frac{\partial M}{\partial X}\right) \tag{1}$$

To overcome the shortcomings of the diffusion model mentioned earlier, the diffusion coefficient (D) is usually determined from experiments. The coefficient has been found to vary with drying temperature, moisture content, and wood density (Collignan et al. 1993; Adesanya et al. 1988; Tang et al. 1994). In the work of Collignan et al. (1993), three different correlations were fitted for different stages of drying.

By using the experimentally determined coefficient, a diffusion model can predict moisture content in wood during drying. However, extrapolations of the coefficient to conditions outside the experimental range may result in significant errors in the model predictions (Rosen 1987). Therefore, extensive trials are needed in order for the model to cover a wide range of drying conditions and wood variables (wood permeability, density, sapwood, and heartwood, etc.).

TRANSPORT-BASED MODEL

The process of wood drying can be interpreted as simultaneous heat and moisture transfer with local thermodynamic equilibrium at each point within the wood. In the transport-based model of Pang (1996) and Pang et al. (1994), the movement of each phase of moisture as well as the physical properties of wood were considered.

In green sapwood of coniferous species such as radiata pine (*Pinus radiata* D. Don), most of the bordered pits and other channels for fluid flow are not closed because they are required for the transport of liquid nutrient in a living tree. During drying, liquid water flows through these channels towards the drying surfaces until the moisture content decreases to a minimum value for liquid continuity. Below this value, liquid is no longer continuous, and the liquid flow becomes impossible. Within wood cell lumens, liquid water evaporates to remain in equilibrium with water vapor At the same time, water vapor in wood moves outwards towards the wood surface due to vapor pressure difference. When the cells are below fiber saturation, bound water diffusion and water vapor movement control the drying.

In the model of Pang (1996) and Pang et al. (1994), heat transfer and moisture mass balance equations have been derived within wood. These equations are respectively:

$$C_P \cdot \rho_w \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\left[\lambda \cdot \frac{\partial T}{\partial X}\right] - H_{wv} \cdot \frac{\partial j_v}{\partial X} - \tag{2}$$

$$-\rho_w \cdot \frac{\partial M}{\partial t} = \frac{\partial j}{\partial X} \tag{3}$$

In order to solve the above equations, each term of the moisture fluxes (liquid water, bound water, and water vapor) must be evaluated.

Moisture vapor movement

In the transport drying model of Pang (1996) and Pang et al. (1994), the movement of water vapor is driven by vapor pressure gradient, so the vapor flux can be expressed by Darcy's law:

$$j_v = -\frac{K_v \cdot \rho_v}{\mu_v} \cdot \frac{\partial p_v}{\partial X} \qquad (4)$$

Bound water movement

Bound water diffusion occurs only when the wood cells are below the fiber saturation. Chemical potential is used as the driving force for bound water movement. Its flux can be expressed in a form given by Stanish et al. (1986):

$$j_b = -D_b \cdot (1 - \epsilon) \cdot \frac{\partial \mu_b}{\partial X} \qquad (5)$$

For local thermodynamic equilibrium, the chemical potential of bound water is the same as that of the water vapor. When the vapor obeys the ideal gas laws, the chemical potential gradient of bound water can be related to local temperature and vapor pressure (Stanish 1986; Stanish et al. 1986):

$$\frac{\partial \mu_b}{\partial X} = \frac{1}{m_v} \cdot \left\{ -\left[187 + C_{PV} \cdot \ln\left(\frac{T}{298.15}\right) - 8.314 \ln\left(\frac{p_v}{101,325}\right) \right] \cdot \frac{\partial T}{\partial X} + 8.314 \frac{T}{p_v} \cdot \frac{\partial p_v}{\partial X} \right\} \qquad (6)$$

Liquid water movement in sapwood

The pressure gradient in the liquid is a consequence of capillary action between liquid and gas phases within the cell lumens of the wood (Spolek and Plumb 1981). Thus, the liquid flux within wood is obtained from Darcy's law as:

$$j_f = \frac{-K_l \cdot \rho_l}{\mu_l} \cdot \frac{\partial p_l}{\partial X} = \frac{K_l \cdot \rho_l}{\mu_l} \cdot \frac{\partial p_c}{\partial X} \qquad (7)$$

The liquid permeability of wood (K_l) decreases with a reduction of the wood saturation and can be related to the permeability at saturation (Stanish et al. 1986).

For softwoods, the equation of Spolek and Plumb (1981) has been employed to calculate the capillary pressure, which is a simple algebraic function of saturation:

$$p_c = A \cdot S^{-B} \qquad (8)$$

in which A and B are constants with va.ues of 12,400 (Pa) and 0.61 for pine species (Spolek and Plumb 1981). The saturation of wood is calculated by:

$$S = \frac{\text{Liquid volume}}{\text{Void volume}} = \frac{M - M_{FSP}}{M_{max} - M_{FS}} \qquad (9)$$

The moisture content at the fiber saturation point is M_{FSP}, while M_{max} is the moisture content of wood when the entire void structure is filled with liquid. The minimum saturation for liquid flow is S_{min} with corresponding moisture content being M_{min}.

DESCRIPTION OF THE TRANSPORT MODEL BY MOISTURE-CONTENT AND TEMPERATURE GRADIENTS

For the purpose of comparison with the diffusion model, the transfer equations of the transport-based drying model (Pang 199€; Pang et al. 1994) will be rearranged and the moisture and heat transfer will be described by moisture content and temperature gradients. In the model, the whole process of drying can be divided into three periods according to the moisture content level. (1) The moisture content is greater than the minimum value for liquid continuity. During this period liquid movement and vapor flow occur. Liquid water initially moves outwards and evaporates in a thin layer (0.5 to 2 mm) close to the drying surface (Pang 1994). When the moisture content close to the wood surface decreases to the minimum value for liquid continuity, an evaporative front forms that divides the wood into a dry outskirt zone and a wet core zone. (2) The moisture content is less than the minimum value but greater than fiber saturation, in which period only vapor movement is possible. (3) The moisture content falls below the fiber saturation when vapor movement and bound water diffusion control the drying.

Based on the above classification, the moisture fluxes in each period are calculated as follows:

(1) $M \geq M_{min}$,

$$j = j_f + j_v =$$

$$= K_l \cdot \frac{\rho_l}{\mu_l} \cdot \frac{\partial p_c}{\partial X} - K_v \cdot \frac{\rho_v}{\mu_v} \cdot \frac{\partial p_v}{\partial X} \qquad (10)$$

(2) $M_{min} > M \geq M_{FSP}$,

$$j = j_v = -K_v \cdot \frac{\rho_v}{\mu_v} \cdot \frac{\partial p_v}{\partial X} \qquad (11)$$

(3) $M < M_{FSP}$,

$$j = j_v + j_b$$

$$= -K_v \cdot \frac{\rho_v}{\mu_v} \cdot \frac{\partial p_v}{\partial X} - D_b \cdot (1 - \epsilon) \cdot \frac{\partial \mu_b}{\partial X} \qquad (12)$$

In the transport model of Pang (1996) and Pang et al. (1994), three variables are considered: moisture content, temperature, and vapor pressure. However, when the moisture vapor is in equilibrium with water, only two of them are independent. For example, the vapor pressure can be related to moisture content and temperature using the sorption isotherm. Due to its simplicity, the correlation of Avramidis (1989) is chosen to calculate relative humidity from temperature and moisture content. The saturated vapor pressure as a function of temperature is determined using an equation of Kayihan (1982). Then the partial vapor pressure can be estimated using the following relationships:

$$p_v = \psi \cdot p_v^s \qquad (13)$$

$$\psi = 1 - \exp[b_1 \cdot T^{b_2} \cdot (100M)^{b_3 \cdot T^{b_4}}] \qquad (14)$$

$$p_v^s = \frac{101,330}{760} \cdot 10^{f(T)} \qquad (15)$$

$$f(T) = 16.3737 - \frac{2818.6}{T} - 1.6908 \log(T) -$$

$$- 5.7546 \times 10^{-3}T +$$

$$+ 4.0073 \times 10^{-6}T^2 \qquad (16)$$

In Eq. (14), b_1, b_2, b_3 and b_4 are constants with values of -3.4×10^{-17}, 5.98, 300, and -0.93, respectively. When the local moisture content is above M_{FSP}, the gas phase at that point is saturated at the local temperature and the vapor pressure is a function of temperature only.

Derivative of capillary pressure with respect to distance

Because the liquid capillary pressure is a function of saturation of moisture, its derivative with respect to distance can be expressed as a derivative of moisture content:

$$\frac{\partial p_c}{\partial X} = -w \cdot \frac{\partial M}{\partial X} \qquad (17)$$

where w is a function of moisture content:

$$w = \frac{A \cdot B \cdot (M_{max} - M_{FSP})^B}{(M - M_{FSP})^{(1+B)}} \qquad (18)$$

Derivative of partial vapor pressure with respect to distance

The gradient of vapor pressure is generally a function of temperature and moisture content and therefore can be derived using the chain rule:

$$\frac{\partial p_v}{\partial X} = \frac{\partial p_v}{\partial M} \cdot \frac{\partial M}{\partial X} + \frac{\partial p_v}{\partial T} \cdot \frac{\partial T}{\partial X} \qquad (19)$$

When the moisture content is above M_{FSP}, then,

$$\frac{\partial p_v}{\partial X} = \frac{\partial p_v}{\partial T} \cdot \frac{\partial T}{\partial X}$$

$$= \frac{101,330}{760} \cdot$$

$$\ln 10 \times 10^{f(T)} \cdot f'(T) \cdot \frac{\partial T}{\partial X}$$

$$= 307 \times 10^{f(T)} \cdot f'(T) \cdot \frac{\partial T}{\partial X} \qquad (20)$$

If the moisture content is below M_{FSP}, the derivative of the vapor pressure with respect to moisture content and temperature can be calculated from Eqs. (13) to (16):

$$\frac{\partial p_v}{\partial M} = p_v^s \cdot \frac{\partial \psi}{\partial M} = u(T, M) \qquad (21)$$

$$\frac{\partial p_v}{\partial T} = p_v^s \frac{\partial \psi}{\partial T} + \psi \frac{\partial p_v^s}{\partial T} = v(T, M) \quad (22)$$

Therefore, for moisture contents below the fiber saturation, the derivative of partial vapor pressure with respect to distance can be calculated by:

$$\frac{\partial p_v}{\partial X} = u(T, M) \cdot \frac{\partial M}{\partial X} + v(T, M) \cdot \frac{\partial T}{\partial X} \quad (23)$$

Derivative of partial vapor pressure with respect to distance

The chemical potential gradient for the calculation of bound water movement is determined from Eq. (6). By substituting the vapor pressure and its derivative (Eqs. 13 and 23) into Eq. (6), one gets

$$\frac{\partial \mu_b}{\partial X} = \eta \cdot \frac{\partial T}{\partial X} + \zeta \cdot \frac{\partial M}{\partial X} \quad (24)$$

in which

$$\eta = \frac{1}{m_v} \left[-187 - C_{PV} \cdot \ln\left(\frac{T}{298.15}\right) + \quad (25) \right.$$

$$+ 8.314 \cdot \ln\left(\frac{p_v}{101,325}\right) +$$

$$\left. + \frac{8.314T}{p_v} \cdot v \right]$$

$$\zeta = \frac{8.314T}{m_v \cdot p_v} \cdot u \quad (26)$$

Rearrangement of transfer equations for the transport model

In the transport drying model, fluxes of each phase of moisture can be calculated using Eqs. (10) through (26). By substituting these fluxes into Eqs. (2) and (3), the heat and mass transfer equations can be rearranged as follows:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial X}\left[D_h \cdot \frac{\partial M}{\partial X} + E_h \cdot \frac{\partial T}{\partial X}\right] \quad (27)$$

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial X}\left[D \cdot \frac{\partial M}{\partial X} + E \cdot \frac{\partial T}{\partial X}\right] \quad (28)$$

The coefficients in the above equations have been obtained from the substitution procedure and are listed in Table 1 (Eqs. 29 to 37). Equations (27) and (28) have similar form to Luikov's equations (Luikov 1966); however, in the above equations, separate coefficients are defined for each of the three periods of drying and can be calculated from properties of the wood being dried and from the physical properties of moisture. From Eq. (28), it is apparent that the changes in moisture content can be described by a general equation as a function of moisture content and temperature gradients. In the following sections, only the coefficients involved in this equation (Eq. 28) will be discussed in comparison with the diffusion drying model.

DETERMINATION OF COEFFICIENTS FOR MOISTURE TRANSPORT

Transfer coefficient for liquid water in initial period of drying

From the above discussion, when moisture movement in wood during drying is described by an equation with a form similar to Luikov's equation, the coefficients need to be determined for each period of drying. In the first period of drying, the diffusion coefficient for liquid movement (moisture content coefficient) can be calculated from the transport model by using Eq. (33). From this equation, it can be seen that the coefficient varies with moisture content and wood density, and that temperature has an influence through changes in liquid viscosity and density. For radiata pine (*Pinus radiata* D. Don) with a wood density of 450 kg/m³ and saturation liquid permeability of 4×10^{-15} m² (Booker 1991; Pang 1994) in transverse direction, the diffusion coefficient is calculated as given in Fig. 1.

The calculated values for the transport coefficient are comparable with early experimental data of Cunningham et al. (1989) for the same species of wood at temperatures of 5°C and 30°C, respectively. The calculated coefficient increases with temperature and moisture content.

TABLE 1. *Transfer coefficients in Eqs. (27) and (28).*

	Moisture content	
$>M_{min}$	$M_{min} \sim M_{FSP}$	$\leq M_{FSP}$

$$D_h = D_{h1} = D_{h2} = 0 \qquad (29)$$

$$D_h = D_{h3} = \frac{H_{WV} \cdot K_V \cdot \rho_V}{C_P \cdot \rho_W \cdot \mu_V} \cdot u \qquad (30)$$

$$E_h = E_{h1} = E_{h2}$$
$$= \frac{\lambda}{C_P \cdot \rho_W} + 307 \times 10^{f(T)} \cdot f'(T) \cdot H_{WV} \cdot \frac{K_V \cdot \rho_V}{C_P \cdot \rho_W \cdot \mu_V} \qquad (31)$$

$$E_h = E_{h3}$$
$$= \frac{1}{C_P \cdot \rho_W} \cdot \left[\lambda + \frac{H_{WV} \cdot K_V \cdot \rho_V}{\mu_V} \cdot V \right] \qquad (32)$$

$$D = D_1 = K_1 \cdot \frac{\rho_1}{\rho_W} \cdot \frac{W}{\mu_1} \qquad (33) \qquad\qquad D = D_2 = 0 \qquad (34)$$

$$D = D_3 = K_V \cdot \frac{\rho_V \cdot u}{\rho_W \cdot \mu_V} + \frac{D_b \cdot (1 - \epsilon)}{\rho_W} \cdot \zeta \qquad (35)$$

$$E = E_1 = E_2 = 307 \times 10^{f(T)} \cdot f'(T) \cdot \frac{K_V \cdot \rho_V}{\mu_V \cdot \rho_W} \qquad (36)$$

$$E = E_3 = K_V \cdot \frac{\rho_V \cdot V}{\rho_W \cdot \mu_V} + \frac{D_b \cdot (1 - \epsilon)}{\rho_W} \cdot \eta \qquad (37)$$

Vapor transfer coefficient above the fiber saturation

If local moisture content is above the fiber saturation point, the transfer coefficients E_1 and E_2 reflect the transfer of moisture vapor and can be calculated using Eq. (36). Moisture content affects the transfer coefficient as well because vapor permeability of wet wood decreases with increasing water saturation. A linear relationship between the water saturation and vapor permeability is proposed by Stanish et al. (1986). In the calculation, the gas permeability for radiata pine (*Pinus radiata* D. Don) is taken as 1.2×10^{-15} m^2 (Booker 1991; Pang 1994). The calculated results for the vapor transfer coefficient above the fiber saturation point are shown in Fig. 2. From this figure, it is apparent that the coefficient increases with temperature but decreases with increasing moisture content. The values of the coefficient vary between 10^{-14} and 10^{-9} m^2/s·K in the investigated range of conditions (temperatures of 20°C to 100°C and moisture contents of 30% to 150%).

Transfer coefficients below the fiber saturation

When the moisture content is below the fiber saturation point, bound water movement and vapor flow occur simultaneously and the gradients of both moisture concentration and temperature influence drying. The transfer co-
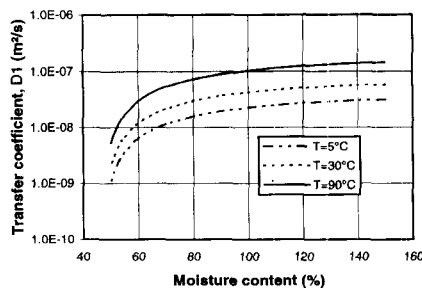

FIG. 1. The changes of liquid water transfer coefficient in transverse direction with moisture content and temperature.
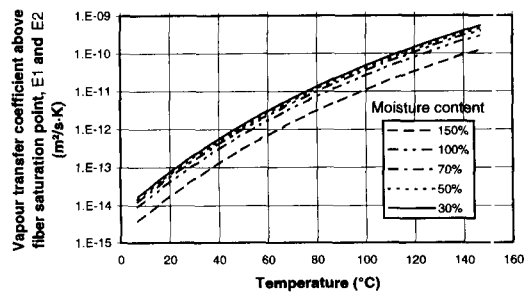

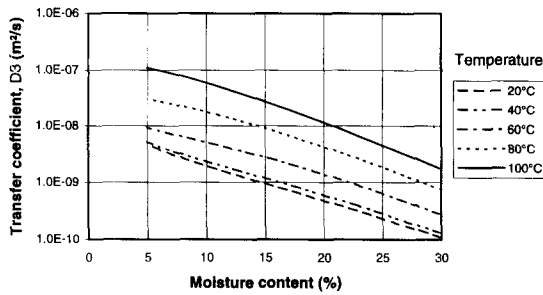FIG. 2. The vapor transfer coefficient above the fiber saturation.

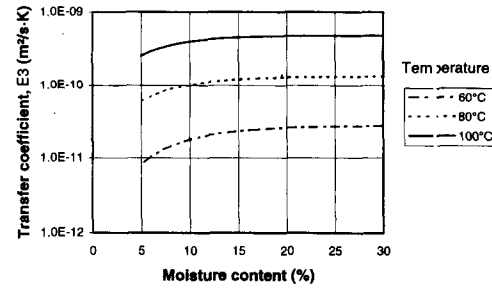FIG. 3. The transfer coefficient for moisture content gradient below the fiber saturation.

FIG. 4. The transfer coefficient for temperature gradient below the fiber saturation.

efficients (D_3 and E_3) are calculated by using Eqs. (35) and (37) and the results are illustrated in Figs. 3 and 4. By taking the bound water diffusion coefficient as 8×10^{-13} kg/s·m^2 (Pang 1994), the coefficient for moisture content gradient (D_3) is calculated to range from 10^{-10} to 10^{-7} (m^2/s), increasing with temperature but decreasing with moisture content. The coefficient for temperature gradient (E_3) varies in a similar way with temperature, but moisture content has only minor influence particularly for moisture content above 10%. At the same temperature and moisture content, the value of E_3 is much less than that of D_3. In Fig. 4, the coefficient for low temperature (below 40°C) cannot be given because the values at very low temperatures are negative.

DISCUSSION AND CONCLUSION

Moisture transfer equations in a transport model can be rearranged to give equations with similar form to Luikov's equations in which the moisture movement is driven by both moisture content and temperature gradients. The transfer coefficients in the rearranged equations for the transport drying model can be calculated using different equations depending on the moisture content level. These coefficients are normally functions of temperature, moisture content, wood properties (density, permeability, and bound water diffusivity) and properties of moisture (liquid density and viscosity, vapor density, and viscosity).

Comparing Eq. (28) with Eq. (1), it is apparent that the diffusion model can be regarded as a simplified form of the transport model when the effect of temperature gradient is neglected. This occurs where the temperature gradient is significantly small or the value of the transfer coefficient E is much less than that of D.

In the initial stages of drying of a softwood board when the moisture content is high (above the minimum value for liquid continuity), liquid water moves towards the drying surfaces or to an evaporative front within the material. In this period, water evaporation within the wet zone of wood is not significant and the effect of temperature gradient is small. Also the coefficient for temperature gradient (E) is much less than that for moisture content gradient (D). In this case, the diffusion model could predict similar moisture content profile to that obtained from the transport drying model if appropriate transfer coefficient is used in the diffusion model.

The above discussion relates to local moisture content and not to the average moisture content of the whole board. When the evaporative front recedes into the wood, the diffusion equation is valid only for the wet zone. In the dry zone, a significant amount of heat is conducted from the wood surface to the evaporative front where the liquid water evaporates. Therefore, temperature gradient in the dry zone can not be neglected and its effect on drying should be considered.

When the local moisture content is between the fiber saturation point and the minimum value for liquid continuity, the drying can only

be described by temperature gradient because the transfer coefficient D_2 is zero for this moisture content range.

In the last period of drying, there are uncertainties regarding whether the diffusion drying model could adequately describe the drying. With moderate drying schedules, the drying rate becomes very slow in this period and the wood temperatures approach the air temperature (Pang 1994); thus the diffusion drying model may be sufficiently accurate to calculate the moisture profile. However, in the case where the drying rate is relatively high and temperature gradient is significant, for example under severe drying condition for very permeable species of wood, temperature gradient is significant and the diffusion model is no longer suitable to describe the drying.

It is not possible to couple the diffusion model with the heat transfer equation to calculate the temperature profile in wood during drying because a term for the vapor evaporation is not included in the simple diffusion equation. When the temperature profile is of concern, the heat and moisture mass transfer equations (Eqs. 27 and 28) in the transport model can be solved together, while the transfer coefficients can be determined from Eqs. (29) to (37).

ACKNOWLEDGMENTS

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