

# DEVELOPMENT OF A CONVECTIVE MASS TRANSFER COEFFICIENT CONVERSION METHOD

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## ABSTRACT

Because of the difficulty of determining wood surface moisture concentration nondestructively and continuously in unsteady-state drying conditions, theoretically calculated convective mass transfer coefficients have not been well proved by experimental results. The convective mass transfer coefficient conversion method developed using surface moisture data in this study has proven that boundary layer theory is useful for evaluating external resistance during wood drying. Because of this proof, the external resistance for wooden surfaces can be theoretically described in dynamic drying situations.

*Keywords:* Mass transfer coefficient, surface emission coefficient, surface moisture content, water vapor pressure, boundary layer theory.

## INTRODUCTION

Evaluation of moisture movement during wood drying requires determination of external moisture transfer resistance from wood surfaces, as well as internal resistance. External moisture transfer resistance is described as a reciprocal of the convective mass transfer coefficient. Convective mass transfer coefficients can be expressed several ways, depending on the potential gradient (driving force). Water vapor pressure in air, concentration of moisture in air, and concentration of moisture in wood can all be used as po-

tentials in the equation to estimate mass transfer coefficient (Siau 1995). Several theoretical and experimental approaches have been applied to determine convective mass transfer coefficients. However, a fully reliable method to determine this external moisture transfer resistance for a hygroscopic material over the entire moisture content range has not yet been developed. A primary reason is the difficulty in determining wood surface moisture concentration nondestructively and continuously in unsteady-state drying conditions. Because of this difficulty, theoretically calculated convective mass transfer coefficients have not been proven by experimental results.

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In this study, surface emission coefficients based on the driving potential of moisture concentration in wood were determined using a colorimetric technique for measuring surface moisture content nondestructively and continuously during unsteady-state desorption conditions (Yeo et al. 2002a). Convective mass transfer coefficients based on the potential of water vapor pressure were determined according to Hart's method (1977). Convective mass transfer coefficients based on the potential of concentration of moisture in air were determined by boundary layer theory (Geankoplis 1993). Subsequently, the convective mass transfer coefficient conversion method presented in this paper has been developed to facilitate making comparison between convective mass transfer coefficients obtained by other methods. To validate the efficiency of this newly developed conversion method, surface emission coefficients measured by Choong and Skaar (1969 and 1972) were compared with the values converted from convective mass transfer coefficients calculated by boundary layer theory.

#### MATERIALS AND MEASUREMENTS

Water-soaked cubes of hard maple (*Acer saccharum* Marsh), red oak (*Quercus rubra* L.), and southern pine (*Pinus* spp.), with 20-mm longitudinal, radial, and tangential dimensions were manufactured. Four side walls of each cubic specimen were wrapped with rubber tape (Magic Wrap, Glasgow Mfg. Ltd.), leaving open the two opposite surfaces of interest, to provide one-dimensional moisture flow for drying. Six replicates, to determine the surface emission coefficient in each orientation, longitudinal, radial, and tangential, were prepared. Using the recently developed colorimetric technique (Yeo et al. 2002b) and oven-drying, surface moisture content (SMC) and average moisture content (AMC) changes in wood were determined during drying at 25%RH and both 30° and 50°C in humidity- and temperature-controlled environmental chambers. Air velocity in these chambers was 1m/s, measured with a hot wire anemometer, and air-flow was parallel to exposed wood surfaces.

#### Measurement of surface emission coefficient

$$\begin{aligned}
 & (h_{H_2O,wood} = S) \\
 & h_{H_2O,wood} = S = \frac{J}{(C_{s,wood} - C_{e,wood})} = \\
 & \frac{\Delta W / (A \cdot \Delta t)}{G_{SMC} \cdot \rho_w \cdot SMC / 100 - G_{EMC} \cdot \rho_w \cdot EMC / 100} \quad (1)
 \end{aligned}$$

where,  $h_{H_2O,wood} = S$  = surface emission coefficient, m/s;  $J$  = moisture flux from surface to air, kg/m<sup>2</sup> s;  $C_{s,wood}$  = moisture concentration in wood at surface, kg/m<sup>3</sup>;  $C_{e,wood}$  = moisture concentration in wood in equilibrium with air, kg/m<sup>3</sup>;  $W$  = weight of evaporated moisture, kg;  $A$  = surface area of specimen, m<sup>2</sup>;  $t$  = time, s;  $\rho_w$  = density of water, kg/m<sup>3</sup>; SMC and EMC = % surface and equilibrium moisture content;  $G_{SMC}$  and  $G_{EMC}$  = specific gravities of wood based on oven-dry weight and volumes at SMC and EMC.

#### Mass transfer coefficient determined with water vapor pressure ( $h_p$ )

Convective mass transfer coefficients based on the potential of water vapor pressure were determined by the Hart method (1977) as

$$h_p = \frac{J}{(p_s - p_e)} \quad (2)$$

where,  $h_p$  = convective mass transfer coefficient based on the potential of water vapor pressure, kg/m<sup>2</sup>sPa;  $J$  = moisture flux from surface to air, kg/m<sup>2</sup>s, maximum moisture flux from a wet wood surface at an initial drying stage is used;  $p_s$  = water vapor pressure in air adjacent to the wood surface, Pa, this vapor pressure is assumed to be the saturated water vapor pressure at the wet bulb temperature;  $p_e$  = water vapor pressure in ambient air at the dry bulb temperature, Pa.

#### Mass transfer coefficient calculated by boundary layer theory ( $h_{H_2O,air}$ )

$$h_{H_2O,air} = \frac{0.66 D_{H_2O,air} \text{Re}^{0.5} \text{Sc}^{1/3}}{L_s} \quad (3)$$

for laminar flow,

where,  $h_{H_2O,air}$  = convective mass transfer coefficient averaged over the length  $L_s$ ;  $D_{H_2O,air}$  = diffusion coefficient of water vapor in air,  $m^2/s$ ;

$$D_{H_2O,air} = 2.2 \cdot 10^{-5} \left( \frac{1.013 \cdot 10^5}{P} \right) \cdot \left( \frac{T}{273} \right)^{1.75}$$

(Dushmans equation, cited by Siau (1995))

Re = Reynolds number =  $\frac{L_s \cdot v \cdot \rho_a}{\mu}$ ; Sc = Schmidt number =  $\frac{\mu}{\rho_a D_{H_2O,air}}$ ;  $L_s$  = length of surface along which convection occurs, m;  $v$  = air velocity, m/s;  $\rho_a$  = density of air,  $kg/m^3$ ;  $\mu$  = dynamic viscosity of air, Pa s.

### Convective mass transfer coefficient conversion

Figure 1a illustrates non-equilibrium conditions on the surface of wood while drying above the FSP. When the surface of wood is wet, water vapor pressure in air adjacent to the surface remains as the saturated vapor pressure at the wet bulb ( $p_{o,wet}$ ) temperature. When above the FSP range, the moisture concentration in air adjacent to wood surfaces ( $C_{s,air}$ ) can thus be determined with surface temperature ( $T_s$ ), and the saturated water vapor pressure at wet bulb temperature ( $p_{o,wet}$ ).

$$C_{s,air} = \frac{W}{V} = \frac{M_{H_2O} \cdot P_s}{R \cdot T_s} = \frac{M_{H_2O} \cdot P_{o,wet}}{R \cdot T_s} \quad (4)$$

where,  $W$  = weight of water vapor, kg;  $V$  = volume of air including water vapor,  $m^3$ ;  $M_{H_2O}$  =

water molecular weight,  $18kg/kgmol$ ;  $p_s$  = water vapor pressure in air adjacent to surface of wood, Pa;  $T_s$  = surface temperature, K;  $R$  = universal gas constant,  $8314 m^3 Pa / kgmol K$ ;  $p_{o,wet}$  = saturated water vapor pressure at wet bulb temperature, Pa. However, when surface MC decreases from FSP to EMC (Fig. 1b), water vapor pressure in air adjacent to a surface ( $p_s$ ) decreases from saturated vapor pressure at wet bulb ( $p_{o,wet}$ ) to vapor pressure equilibrated to chamber condition ( $p_e$ ).

Using the following relationship of relative humidity and water vapor pressure,

$$\frac{P_{o,wet} - P_e}{100 - RH_e} = \frac{P_{o,wet} - P_s}{100 - RH_s} \quad (5)$$

where, as shown in Fig. 2,  $p_s$  = water vapor pressure in air adjacent to surface of wood, Pa;  $p_e$  = water vapor pressure in ambient air (=  $p_{o,dry}$  times  $RH_e/100$ );  $p_{o,dry}$  = saturated water vapor pressure at dry bulb temperature, Pa;  $RH_e$  = % relative humidity of ambient air; and  $RH_s$  = % relative humidity of air adjacent to surface of wood, the  $p_s$  and moisture concentration in air adjacent to wood surfaces ( $C_{s,air}$ ) could be determined as follows;

$$P_s = P_{o,wet} - \left( \frac{P_{o,wet} - P_e}{100 - RH_e} \right) \cdot (100 - RH_s) = P_{o,wet} - \left( \frac{P_{o,wet} - P_{o,dry} \cdot \left( \frac{RH_e}{100} \right)}{100 - RH_e} \right) \cdot (100 - RH_s) \quad (6)$$

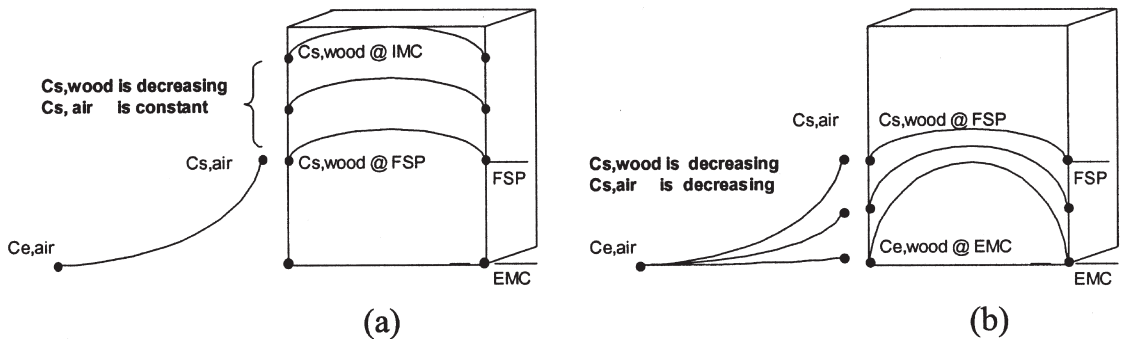


FIG. 1. Non-equilibrium condition on the surface of wood above FSP (a) and moisture concentrations below FSP (b).

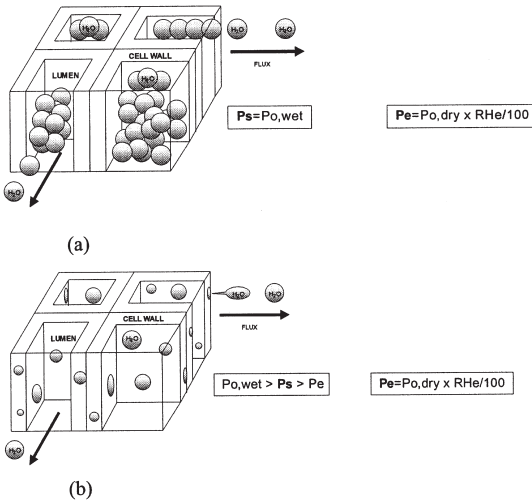


FIG. 2. Illustration of water vapor pressure in ambient air and in air adjacent to surface of wood above FSP (a) and below FSP (b).

$$C_{s,air} = \frac{M_{H_2O} \cdot P_s}{R \cdot T_s} = \frac{M_{H_2O}}{R \cdot T_s} \cdot \left( p_{o,wet} - \left( \frac{p_{o,wet} - p_{o,dry} \cdot \left( \frac{RH_e}{100} \right)}{100 - RH_e} \right) \cdot (100 - RH_s) \right) \quad (7)$$

Each of the mass transfer coefficients may be expressed in terms of any other by converting the potential as follows;

$$h_{H_2O,wood} = h_p \cdot \frac{(p_s - p_e)}{\left( C_{s,wood} - C_{e,wood} \right)} = h_p \cdot \frac{p_s - p_e}{G_{SMC} \cdot \rho_w \cdot \frac{SMC}{100} - G_{EMC} \cdot \rho_w \cdot \frac{EMC}{100}} \quad (8)$$

$$h_{H_2O,wood} = h_{H_2O,air} \cdot \frac{(C_{s,air} - C_{e,air})}{(C_{s,wood} - C_{e,wood})} = h_{H_2O,air} \cdot \frac{\frac{M_{H_2O} \cdot P_s}{R \cdot T_s} - \frac{M_{H_2O} \cdot P_e}{R \cdot T_{dry}}}{G_{SMC} \cdot \rho_w \cdot \frac{SMC}{100} - G_{EMC} \cdot \rho_w \cdot \frac{EMC}{100}} \quad (9)$$

Using this new conversion method,  $h_p$  and  $h_{H_2O,air}$  were converted to surface emission coefficients and their values were compared with the surface emission coefficients ( $h_{H_2O,wood}$ ) measured in this study and by Choong and Skaar (1969, 1972).

RESULTS AND DISCUSSION

The data plotted in Fig. 3 shows the relationship between the surface emission coefficients, which were measured and converted from  $h_p$  and  $h_{H_2O,air}$ , and surface moisture content of hard maple, red oak, and southern pine.

Measured surface emission coefficient ( $h_{H_2O,wood}$ )

The measured surface emission coefficients at 50°C were greater than those at 30°C. As surface MC decreased with progression of the drying process, the coefficients increased only slightly while above the FSP range, and then rapidly increased from FSP to the equilibrated MC at the surrounding conditions. These data mean that the surface emission coefficient is strongly dependent on the surface MC of wood and air temperature, as well as air velocity.

Mass transfer coefficient determined with water vapor pressure ( $h_p$ )

According to Hart's study (1977), moisture flux leaving from the surface to ambient air could be controlled by water vapor pressure difference on the surface of wood and in ambient air. When there is maximum moisture flux at an initial drying stage, water vapor pressure is assumed as saturated water vapor pressure at wet bulb temperature. With Kirchoff's equation, cited by Siau (1995),  $p_o = \exp(53.421 - 6516.3/T - 4.125 \cdot \ln T)$ , where,  $p_o$  = saturated vapor pressure, Pa; T = Kelvin temperature, K, saturated vapor pressures at dry bulb 30°C(303.15K) and 50°C(323.15K) were calculated to 4249Pa and 12349Pa, respectively. Partial vapor pressures of water in ambient air ( $p_e$ ) at 30°C and 50°C and 25%RH were calculated to 1062Pa and 3087Pa,

respectively. The wet bulb temperatures used in these experiments at 30°C and 50°C with 25%RH were 16.83°C and 30.42°C, respectively. Saturated vapor pressures calculated by Kirchoff's equation at wet bulb 16.83°C (289.98K) and 30.42°C(303.57K) were 1923Pa and 4353Pa, respectively.

When calculating  $h_p$ , these saturated vapor pressures at wet bulb ( $p_{o,wet}$ ) were used as water vapor pressure in air adjacent to the wood surface ( $p_s$ ). At 30°C, the average initial moisture fluxes leaving from the surface of hard maple, red oak and southern pine were  $1.18 \times 10^{-4}$ ,  $1.18 \times 10^{-4}$ , and  $1.16 \times 10^{-4}$  kg/s·m<sup>2</sup>, respectively. At 50°C, the average initial moisture fluxes leaving from the surface of hard maple, red oak and southern pine were  $3.10 \times 10^{-4}$ ,  $3.36 \times 10^{-4}$ , and  $3.30 \times 10^{-4}$  kg/s·m<sup>2</sup>, respectively. As shown in the initial drying stage, moisture fluxes leaving from the surfaces of the wet specimens for each species were similar to each other. Using the initial moisture flux (J), the saturated vapor pressures at wet bulb ( $p_{o,wet}$ ), and partial vapor pressure of water in ambient air ( $p_e$ ) at 30°C and 50°C at 25%RH,  $h_p$  were calculated (Eq. 2.).

For example, the  $h_p$  for hard maple at 30°C and 25%RH was  $1.37 \times 10^{-7}$  kg/m<sup>2</sup>sPa.

$$h_p = \frac{J}{(p_s - p_e)} = \frac{1.18 \times 10^{-4} \text{ kg / s} \cdot \text{m}^2}{1923 \text{ Pa} - 1062 \text{ Pa}} = 1.37 \times 10^{-7} \text{ kg / m}^2 \text{ sPa}$$

At 30°C, the  $h_p$  for hard maple, red oak, and southern pine were  $1.37 \times 10^{-7}$ ,  $1.37 \times 10^{-7}$ , and  $1.35 \times 10^{-7}$  kg/m<sup>2</sup>sPa, respectively. At 50°C, the  $h_p$  for hard maple, red oak and southern pine were  $2.45 \times 10^{-7}$ ,  $2.65 \times 10^{-7}$ , and  $2.61 \times 10^{-7}$  kg/m<sup>2</sup>sPa, respectively.

*Mass transfer coefficient calculated by boundary layer theory ( $h_{H_2O, air}$ )*

After the physical properties of air such as velocity, density, and viscosity were measured and surveyed,  $h_{H_2O, air}$  values were calculated by boundary layer theory. Air velocities in the environmental chambers were 1m/s. The surface

length of specimens along which convection occurs was 0.02m. Air densities at 30°C and 50°C were 1.167 and 1.096 kg/m<sup>3</sup>, respectively. Air viscosities at 30°C and 50°C were  $1.87 \times 10^{-5}$  and  $1.96 \times 10^{-5}$  Pa·s, respectively. Based on those data, diffusion coefficients of water vapor in air ( $D_{H_2O,air}$ ,  $2.64 \times 10^{-5}$  m<sup>2</sup>/s at 30°C and  $2.95 \times 10^{-5}$  m<sup>2</sup>/s at 50°C), Reynolds numbers (Re, 1248 at 30°C and 1118 at 50°C) and Schmidt numbers (Sc, 0.6069 at 30°C and 0.6062 at 50°C) were determined. The Re is a dimensionless number that indicates degree of turbulence. Because Re of 1248 and 1118 at 30°C and 50°C, respectively, meet the requirement of  $Re < 500,000$  (Holman 1989; Geankoplis 1993) for which the laminar flow equation defines flow as laminar, the airflows used in this experiment were determined to be laminar. The Schmidt number is the dimensionless ratio of the molecular momentum diffusivity to the molecular mass diffusivity (Geankoplis 1993). Schmidt number values for gases range from about 0.5 to 2, while for liquids they can be from about 100 to over 10,000 if particularly viscous. The Sc numbers obtained in this work met the requirement of  $0.5 < Sc < 2$  for using boundary layer theory equation for gases. Using the above determined values,  $h_{H_2O, air}$  were calculated to be 0.026m/s and 0.028m/s at 30°C and 50°C, respectively.

*Conversion of  $h_p$*

Using the newly developed conversion method (Eq. 8), the  $h_p$  values were converted to surface emission coefficients ( $h_{H_2O, wood}$ ). For example, using the physical properties of hard maple at 30°C and 50°C, values for  $h_p$  were converted to  $h_{H_2O, wood}$  as follows;  $h_p$  for hard maple was  $1.37 \times 10^{-7}$  kg/m<sup>2</sup>sPa at 30°C and  $2.45 \times 10^{-7}$  kg/m<sup>2</sup>sPa at 50°C.

140%MC was used for initial SMC and 29%MC and 26%MC were used for FSP at 30°C and 50°C, respectively. 6.2%MC and 5.1%MC were used for EMC at 25%RH and 30°C and 50°C, respectively. 0.47 and 0.52 were used for green specific gravity ( $G_{IMC}$ ) and specific gravity at EMC ( $G_{EMC}$ ), respectively.

1923Pa ( $p_{o,wet}$ ) and 4249Pa ( $p_{o,dry}$ ) were used for the saturated vapor pressure of water in air at

wet bulb temperature 16.83°C and dry bulb temperature 30°C, respectively. Since the relative humidity was 25%RH, at 30°C water vapor pressure in ambient air ( $p_e$ ) was 1062Pa = 4249Pa × (25/100). 4353Pa ( $p_{o,wet}$ ) and 12349Pa ( $p_{o,dry}$ ) were used for the saturated vapor pressure of water in air at wet bulb temperature 30.42°C and dry bulb temperature 50°C, respectively. Since the relative humidity was 25%RH, at 50°C water vapor pressure in ambient air ( $p_e$ ) was 3087Pa = 12349Pa × (25/100).

When hard maple SMC = initial MC (140%MC), at dry-bulb 30°C and wet bulb 16.83°C,  $h_{H_2O,wood}$  converted from  $h_p$  is  $1.9 \times 10^{-7}$  m/s.

$$h_{H_2O,wood} = 1.37 \times 10^{-7} \text{ kg / sm}^2 \text{ Pa} \cdot \frac{1923 \text{ Pa} - 1062 \text{ Pa}}{0.47 \cdot 1000 \cdot \frac{140\% \text{ MC}}{100} - 0.52 \cdot 1000 \cdot \frac{6.2\% \text{ MC}}{100}} = 1.9 \times 10^{-7} \text{ m / s}$$

When SMC = FSP (29%MC), the  $h_{H_2O,wood}$  value is  $11 \times 10^{-7}$  m/s.

When SMC = 20 %MC, RHs = 85%, and  $G_{SMC}=0.49$ , the  $h_{H_2O,wood}$  value is  $14 \times 10^{-7}$  m/s.

When SMC = 15 %MC, RHs = 73%, and  $G_{SMC}=0.50$ , the  $h_{H_2O,wood}$  value is  $18 \times 10^{-7}$  m/s.

When SMC = 10 %MC, RHs = 51%, and  $G_{SMC}=0.51$ , the  $h_{H_2O,wood}$  value is  $22 \times 10^{-7}$  m/s.

When hard maple SMC = initial MC (140%MC), at dry-bulb 50°C and wet bulb 30.42°C,  $h_{H_2O,wood}$  converted from  $h_p$  is  $4.9 \times 10^{-7}$  m/s.

When SMC = FSP (26%MC), the  $h_{H_2O,wood}$  value is  $32 \times 10^{-7}$  m/s.

When SMC = 20 %MC, RHs = 91%, and  $G_{SMC}=0.48$ , the  $h_{H_2O,wood}$  value is  $38 \times 10^{-7}$  m/s.

When SMC = 15 %MC, RHs = 80%, and  $G_{SMC}=0.50$ , the  $h_{H_2O,wood}$  value is  $47 \times 10^{-7}$  m/s.

When SMC = 10 %MC, RHs = 63%, and  $G_{SMC}=0.51$ , the  $h_{H_2O,wood}$  value is  $63 \times 10^{-7}$  m/s.

Figure 3 shows that the  $h_{H_2O,wood}$  values converted from  $h_p$  are close to the measured surface emission coefficients. These results validate the assumption that water vapor pressure in air adjacent to a wood surface is equal to the saturated

vapor pressure at wet-bulb temperature, used in the convective mass transfer coefficient conversion method.

### Conversion of $h_{H_2O,air}$

By the newly developed conversion method (Eq. 9),  $h_{H_2O,air}$  values were converted to surface emission coefficients ( $h_{H_2O,wood}$ ). For example, using the physical properties of hard maple at 30°C and 50°C,  $h_{H_2O,air}$  was converted to  $h_{H_2O,wood}$  as follows;

When hard maple SMC = initial MC (140%MC), at dry-bulb 30°C and wet bulb 16.83°C,  $h_{H_2O,wood}$  converted from  $h_{H_2O,air}$  is  $2.6 \times 10^{-7}$  m/s.

$$h_{H_2O,wood} = 0.25 \text{ m / s} \cdot \frac{\frac{18 \cdot 1923 \text{ Pa}}{8314 \cdot 303.15} - \frac{18 \cdot 1062 \text{ Pa}}{8314 \cdot 303.15}}{0.47 \cdot 1000 \cdot \frac{140\% \text{ MC}}{100} - 0.52 \cdot 1000 \cdot \frac{6.2\% \text{ MC}}{100}} = 2.6 \times 10^{-7} \text{ m / s}$$

When SMC = FSP (29%MC), the  $h_{H_2O,wood}$  value is  $15 \times 10^{-7}$  m/s.

When SMC = 20 %MC, RHs = 85%, and  $G_{SMC}=0.49$ , the  $h_{H_2O,wood}$  value is  $20 \times 10^{-7}$  m/s.

When SMC = 15 %MC, RHs = 73%, and  $G_{SMC}=0.50$ , the  $h_{H_2O,wood}$  value is  $24 \times 10^{-7}$  m/s.

When SMC = 10 %MC, RHs = 51%, and  $G_{SMC}=0.51$ , the  $h_{H_2O,wood}$  value is  $30 \times 10^{-7}$  m/s.

When hard maple SMC = initial MC (140%MC), at dry-bulb 50°C, and wet bulb 30.42°C,  $h_{H_2O,wood}$  converted from  $h_{H_2O,air}$  is  $3.8 \times 10^{-7}$  m/s.

When SMC = FSP (26%MC), the  $h_{H_2O,wood}$  value is  $24 \times 10^{-7}$  m/s.

When SMC = 20 %MC, RHs = 91%, and  $G_{SMC}=0.48$ , the  $h_{H_2O,wood}$  value is  $29 \times 10^{-7}$  m/s.

When SMC = 15 %MC, RHs = 80%, and  $G_{SMC}=0.50$ , the  $h_{H_2O,wood}$  value is  $36 \times 10^{-7}$  m/s.

When SMC = 10 %MC, RHs = 63%, and  $G_{SMC}=0.51$ , the  $h_{H_2O,wood}$  value is  $48 \times 10^{-7}$  m/s.

These converted surface emission coefficients were close to the experimentally measured values (Fig. 3 a-f). This means that boundary layer theory is useful for evaluating the external moisture movement resistance during wood drying. The re-

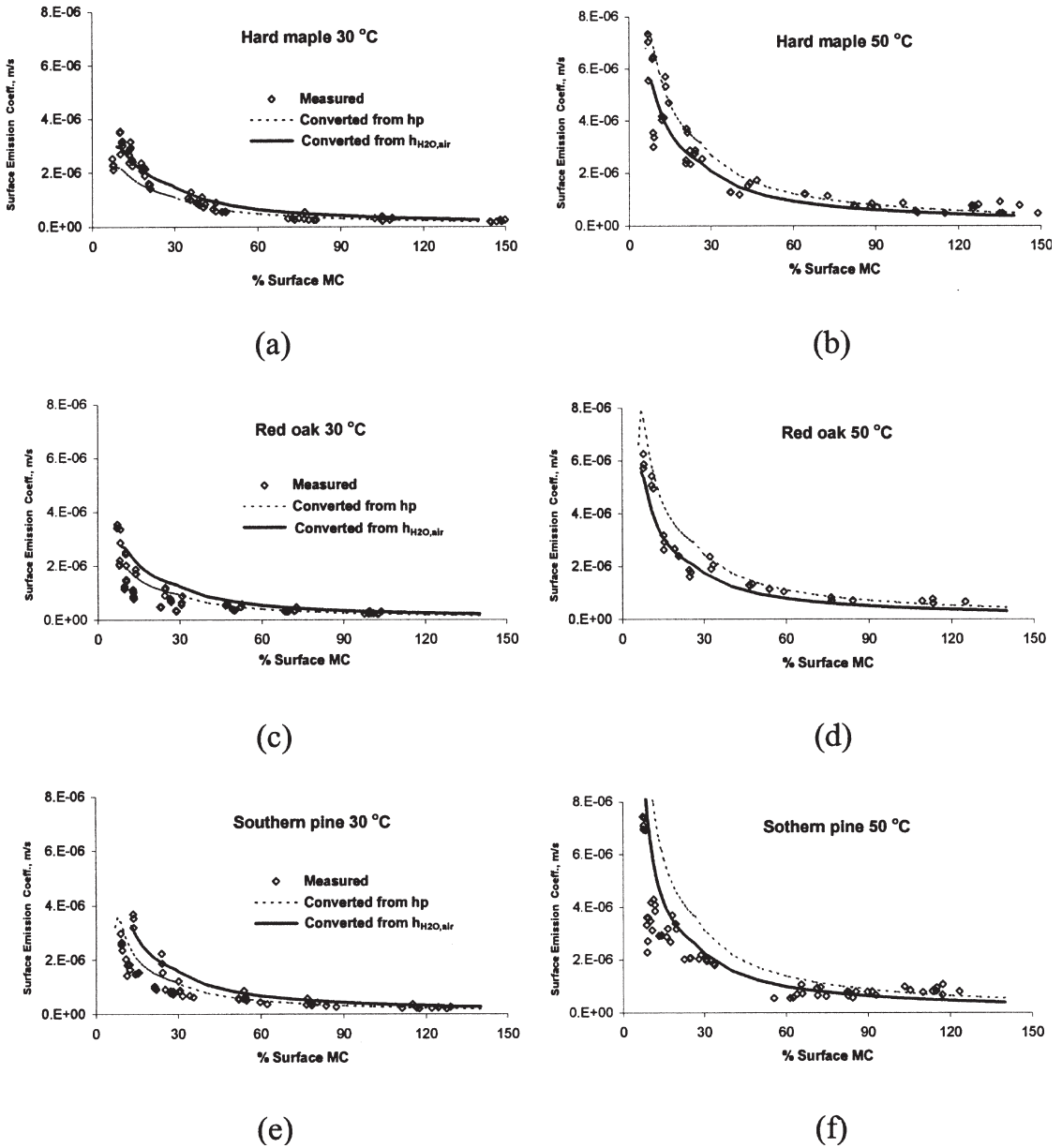


FIG. 3. Comparison of the measured surface emission coefficients for hard maple, red oak, and southern pine at 30 and 50°C with the values converted from mass transfer coefficient determined by water vapor pressure and boundary layer theory.

sults also show clearly that the surface emission coefficients depend on the surface physical properties of each species, especially specific gravity and sorption properties. Surface emission coefficients of maple are greater than that of oak and less than that of southern pine. Use of the nonde-

structive and continuous colorimetric measurement technique for determining surface moisture content of wood in unsteady-state drying conditions can thus increase the credibility of methods for determining the external resistance for surface evaporation from wood.

In these experiments, surface temperature was not measured. The surface temperature ( $T_s$ ) was assumed to be the dry bulb temperature ( $T_{dry}$ ). Of course, instead of using this assumption, the surface temperature could be approximated by Hart's (1977) results that showed sorption rate and the temperature difference between the ambient air and the wood surface were directly proportional. However, because the maximum error that could be caused by this assumption is very small, the dry bulb assumption was satisfactorily used in this study. For example, the maximum error which could be caused by this assumption is when the surface temperature of the wet-bulb temperature is overestimated as the dry-bulb temperature. At 30°C and 50°C, the maximum such error would be just 4.3% and 6.1% of true moisture concentration in air adjacent to the surface, respectively. When  $T_s = T_{wet} = 16.83^\circ\text{C} = 289.98\text{K}$ ,  $p_{o,wet} = 1923\text{Pa}$ ,  $M_{H_2O} = 18\text{kg/kgmol}$ ,  $R = 8314\text{ m}^3\text{ Pa / kgmol K}$ ,

$$C_{s,air} = \frac{W}{V} = \frac{M_{H_2O} \cdot P_s}{R \cdot T_s} = \frac{M_{H_2O} \cdot P_{o,wet}}{R \cdot T_s} = \frac{18 \cdot 1923}{8314 \cdot 289.98} = 0.0144\text{kg / m}^3$$

And when  $T_s = 30^\circ\text{C} = 303.15\text{K}$ ,  $C_{s,air}$  is  $0.0137\text{kg/m}^3$ .

Maximum error =  $(0.0144 - 0.0137) / 0.0144 \times 100 = 4.3\%$

When  $T_s = T_{wet} = 30.42^\circ\text{C} = 303.57\text{K}$ , and  $p_{o,wet} = 4353\text{Pa}$ ,

$$C_{s,air} = \frac{W}{V} = \frac{M_{H_2O} \cdot P_s}{R \cdot T_s} = \frac{M_{H_2O} \cdot P_{o,wet}}{R \cdot T_s} = \frac{18 \cdot 4353}{8314 \cdot 303.57} = 0.0310\text{kg / m}^3$$

And when  $T_s = 50^\circ\text{C} = 323.15\text{K}$ ,  $C_{s,air}$  is  $0.0292\text{kg/m}^3$

Maximum error =  $(0.0310 - 0.0292) / 0.0310 \times 100 = 6.1\%$

*Efficiency of the convective mass transfer coefficient conversion method*

To validate the efficiency of the newly developed conversion method, surface emission coef-

ficients determined by Choong and Skaar (1969 and 1972) were compared with the values converted from mass transfer coefficients calculated by boundary layer theory. They measured the surface emission coefficients in desorption of yellow poplar at 32°C at 40%RH, and sweetgum and redwood 38°C at 75%RH (Table 1.).

Using the reported drying chamber conditions and the surveyed air properties, convective mass transfer coefficients ( $h_{H_2O,air}$ ) were calculated by boundary layer theory.

The Reynolds number for yellow poplar was

$$Re = \frac{L_s \cdot v \cdot \rho_a}{\mu} = \frac{0.05\text{m} \cdot 3.3\text{m/s} \cdot 1.161\text{kg/m}^3}{1.88 \times 10^{-5}\text{ Pa}\cdot\text{s}} = 10190$$

, while

Re for sweetgum and redwood was 4484.

Where,  $L_s$  = length of surface along which convection occurs in m;  $v$  = air velocity, m/sec;  $\rho_a$  = density of air,  $\text{kg/m}^3$ ;  $\mu$  = dynamic viscosity of air,  $\text{Pa}\cdot\text{s}$ .

Since Re of 10,190 and 4,484 both met the laminar flow requirement of  $Re < 500,000$ , airflows used in their experiments were determined to have been laminar. Diffusion coefficients of water vapor in air ( $D_{H_2O,air}$ ) were calculated by Dushman's equation;

$D_{H_2O,air}$  for yellow poplar at 32°C was

$$D_{H_2O,air} = 2.2 \cdot 10^{-5} \left( \frac{1.013 \cdot 10^5}{1.013 \cdot 10^5} \right) \cdot \left( \frac{305.15}{273.15} \right)^{1.75} = 2.67 \times 10^{-5}\text{ m}^2 / \text{s}$$

$D_{H_2O,air}$  for sweetgum and redwood at 38°C was  $2.76 \times 10^{-5}\text{m}^2/\text{s}$ .

The Schmidt(Sc) number for yellow poplar at 32°C was

$$Sc_{@32C} = \frac{\mu}{\rho_a D_{H_2O,air}} = \frac{1.88 \times 10^{-5}\text{ Pa}\cdot\text{s}}{1.161\text{kg/m}^3 \cdot 2.67 \cdot 10^{-5}\text{ m}^2 / \text{s}} = 0.606$$

while Sc for sweetgum and redwood at 38°C was 0.606.

The  $h_{H_2O,air}$  for yellow poplar at 32°C was

$$h_{H_2O,air} = \frac{0.66 D_{H_2O,air} Re^{0.5} Sc^{1/3}}{L_s} = \frac{0.66 \cdot 2.67 \times 10^{-5} \cdot 10190^{1/2} \cdot 0.606^{1/3}}{0.05} = 0.030\text{m / s}$$

, while

$h_{H_2O,air}$  for sweetgum and redwood at 38°C was 0.021 m/s.



TABLE 1. *Drying chamber and wood specimen conditions used in Choong and Skaar experiments (1969 and 1972).*

	Choong/Skaar 1969		Choong/Skaar 1972
Species	Yellow poplar	Sweetgum	Redwood
Dry-bulb temperature	32°C	38°C	38°C
Wet-bulb temperature	21.6°C	33.7°C	33.7°C
%RH	40	75	75
Air velocity (m/s)	3.3	1.5	1.5
Air density ( $\rho_a$ ) (kg/m <sup>3</sup> )	1.161	1.136	1.136
Air viscosity ( $\mu$ ) (Pa s)	$1.88 \times 10^{-5}$	$1.90 \times 10^{-5}$	$1.90 \times 10^{-5}$
Initial MC (%)	25	30	30
EMC (%)	8	18	18
Specific gravity	0.4	0.52	0.4
Length of surface along which convection occurs (m)	0.05	0.05	0.05
Surface emission coefficient (m/s)	$\sim 9.4 \times 10^{-7}$ to $15.2 \times 10^{-7}$	$\sim 9 \times 10^{-7}$ to $12 \times 10^{-7}$	$\sim 13 \times 10^{-7}$ to $19 \times 10^{-7}$

Using the newly developed conversion method,  $h_{H_2O,air}$  values were converted to surface emission coefficients, and these values compared with the surface emission coefficients determined by Choong and Skaar (1969, 1972).

For yellow poplar at 32°C: saturated vapor pressure of water at the dry bulb temperature of 32°C ( $p_{o,dry}$ ) was 4761Pa. Saturated vapor pressure of water at the wet bulb temperature of 21.6°C ( $p_{o,wet}$ ) was 2583Pa. Since the relative humidity condition in the drying chamber ( $RH_e$ ) was 40%, the vapor pressure of water in ambient air of 32°C ( $p_e$ ) was determined as  $4761 \times 40 / 100 = 1905Pa$ .

For sweetgum and redwood at 38°C: saturated vapor pressure of water at the dry bulb temperature of 38°C ( $p_{o,dry}$ ) was 6632Pa. Saturated vapor pressure of water at the wet bulb temperature of

33.7°C ( $p_{o,wet}$ ) was 5247Pa. Since the relative humidity condition of the drying chamber ( $RH_e$ ) was 75%, the vapor pressure of water in ambient air of 38°C ( $p_e$ ) was determined as  $6632 \times 75 / 100 = 4974Pa$ .

Using Eq. (9) and data in Tables 1 and 2, the  $h_{H_2O,air}$  values in Table 2 were converted to surface emission coefficients. Figure 4 shows the converted surface emission coefficients and surface emission coefficients determined by Choong and Skaar (1969 and 1972). Sorption data for each species were required to determine the vapor pressure of water adjacent to the surface of wood. However, because Choong and Skaar did not report sorption data, the sorption data of maple measured at 30°C in this study was used for determining the vapor pressure of water adjacent to the surface of wood.

TABLE 2. *Diffusion coefficient of water vapor in bulk air ( $D_{H_2O,air}$ ), convective mass transfer coefficient calculated by boundary layer theory ( $h_{H_2O,air}$ ), and water vapor pressures determined using Choong and Skaar's experimental data (1969 and 1972).*

	Choong/Skaar 1969	Choong/Skaar 1972
	Yellow poplar	Sweetgum/Redwood
$D_{H_2O,air}$ (m <sup>2</sup> /s)	$2.67 \times 10^{-5}$	$2.76 \times 10^{-5}$
$h_{H_2O,air}$ (m/s)	0.030	0.021
Saturated water vapor pressure at dry bulb (Pa)	4761	6632
Saturated water vapor pressure at wet bulb (Pa)	2583	5247
Partial vapor pressure of water in ambient air(Pa)	1905	4974

Choong and Skaar could not specifically measure surface moisture content. This forced them to make the assumption that surface emission coefficients are constant during drying from initial moisture content to final moisture content or EMC, ~25% to 8%MC at 32°C, and ~30% to 18%MC at 38°C (Table 1). Their constant surface emission coefficients for yellow poplar,

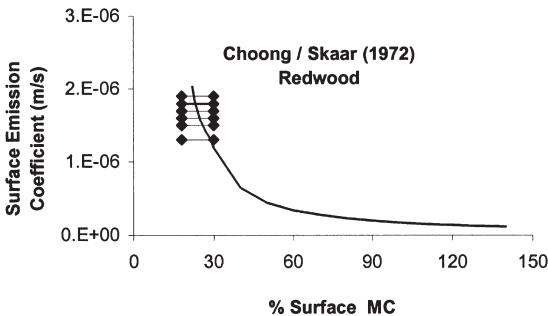
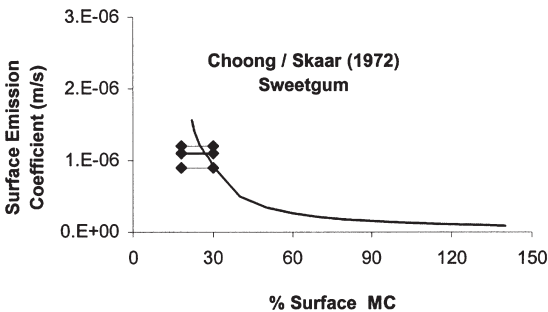
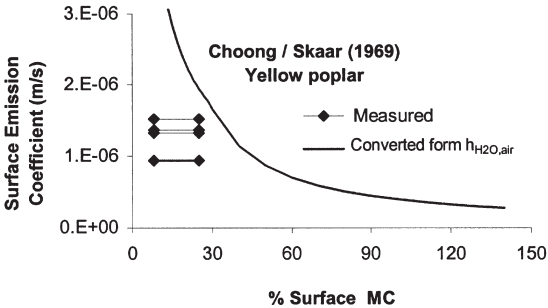


FIG. 4. Comparison of surface emission coefficients measured by Choong and Skaar (1969 and 1972) with the values converted from convective mass transfer coefficient calculated by boundary layer theory using the new conversion method.

sweetgum, and redwood were in the range of approximately  $9.4 \times 10^{-7}$  to  $15.2 \times 10^{-7}$ ,  $9 \times 10^{-7}$  to  $12 \times 10^{-7}$ , and  $13 \times 10^{-7}$  to  $19 \times 10^{-7}$  m/s, respectively (Fig. 4). Bars on the graphs of Figure 4 show Choong and Skaar's (1969 and 1972) constant surface emission coefficients during drying from initial moisture content to final moisture content. Figure 4 illustrates that the converted values were close to the surface emission coefficients measured by Choong and Skaar, especially the values published in 1972. If actual sorption data of each species used in Choong and Skaar's experiments had been available and were used in the conversion equation, it is expected that the measured surface emission coefficients might be even closer to the values converted from convective mass transfer coefficients calculated by boundary layer theory.

#### CONCLUSIONS

The convective mass transfer coefficient conversion method developed using surface moisture data in this study has proven that the boundary layer theory is useful for evaluating the external resistance during wood drying. Because of this proof, the external resistance for wooden surfaces can be theoretically described in dynamic drying situations. That can help scientists predict moisture profiles, and subsequent stress development, in wood during drying. Additional applications of the technique are expected in areas such as controlling biological attack by molds and fungi, and optimizing composite adhesive and finishing operations.

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