

# THE SURFACE EMISSION COEFFICIENT OF WOOD

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## ABSTRACT

Considerable research has been undertaken to measure and characterize the mass convective surface resistance of wood, with particular emphasis on conditions below the fiber saturation point. While the effects of air velocity and wood moisture content have been demonstrated, the influence of other critical factors such as wood specific gravity, surface condition, and specimen size have not been evaluated. Results obtained by several investigators indicate little agreement between them with a wide range of coefficients whose values are a small fraction of those calculated from the classical equations that have been successfully applied to drying from moist surfaces. The low coefficients in the hygroscopic range indicate that surface resistance can add significantly to the energy consumption during drying. Therefore, a better understanding of the convection losses of dry hygroscopic materials such as wood may offer the opportunity of more effective optimization of drying conditions.

**Keywords:** Diffusion, drying, heat convection, laminar boundary layer, Lewis relation, mass convection, Newman's solution, non-Fickian diffusion, surface resistance, turbulent boundary layer.

## INTRODUCTION

Mass transfer of moisture or other fluids through wood is involved in many processes in the wood industry, the most important of which is the drying of lumber, veneer, and wood chips. Similar but slower mass transfer also takes place in wood products in service as members of buildings, bridges, or other structures and in furniture due to changing ambient conditions of temperature and relative humidity.

The rate of mass exchange between wood and its environment is controlled by two main

resistances: (a) the internal resistance, measured by the diffusion coefficient, which is related to the internal geometry of the wood and is affected by both temperature and moisture content; and (b) the external resistance, measured by the surface emission coefficient, which is a function of the fluid characteristics such as temperature, velocity, and viscosity, and of the wood specific gravity, moisture content, and surface condition.

During the initial stages of drying, when the moisture content of the surface is well above the fiber saturation point with free water in the voids, there is capillary flow from the interior to the surface. This occurs during the "constant drying period" in which the rate of mois-

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ture loss is constant, with the surface temperature approaching the wet-bulb temperature. The rate of drying is limited by the external resistance, which is relatively low under these conditions where the coefficient is predicted from classical drying theory applicable to moist surfaces. As drying proceeds toward the “decreasing rate period,” both the rate of diffusion and surface emission decrease, with the drying rate being limited by both internal and external resistances. It is during this period that the classical theory does not apply and that there is an apparent lack of knowledge of the basic principles of surface convection losses from dry hygroscopic materials.

In order to optimize energy consumption and minimize drying times and defects by reducing our dependence on “engineering judgment,” mathematical models that accurately describe the process of wood drying are required. These models usually involve separate highly-coupled and nonlinear equations that describe the simultaneous transfer of heat, liquid water, water vapor, and air. The solutions of these equations become more complicated when they take into account convection coefficients for both heat and moisture. Therefore, a clear understanding of the factors influencing the external resistance is necessary for the determination of mass surface emission coefficients for use in drying models.

#### SCIENTIFIC BACKGROUND

Surface emission coefficients of wood have been measured by many investigators with results that are difficult to correlate because there is so much disparity in reported values. Not only are there many significant variables involved, but efforts to correlate results with values calculated from the classical equations have been unsuccessful. As a background, it may be helpful to discuss the various ways in which the surface emission coefficient may be expressed.

Mass surface emission coefficients may be expressed in terms of various potentials as listed in Table 1. These are based on the general relationship whereby the coefficient is equal to

TABLE 1. Mass convection coefficients based on different potentials.

Coefficient	Potential	Units
$h_c$ or $S$	$C_{\text{wood}}$ , $\text{kg}/\text{m}_w^3$	$\text{m}_w/\text{s}$
$h_v$	$C_{\text{air}}$ , $\text{kg}/\text{m}_a^3$	$\text{m}_a/\text{s}$
$h_M$	$M$ in wood, %	$\text{kg}/\text{m}^2\text{s}\%$
$h_m$	$m$ in wood	$\text{kg}/\text{m}^2\text{s}$
$h_p$	$p$ in air	$\text{kg}/\text{m}_2\text{s Pa}$

The subscripts  $w$  and  $a$  signify concentration in wood and air, respectively.

the flux of moisture leaving the surface of the wood in  $\text{kg}/\text{m}^2\text{K}$  divided by the potential between the concentration, moisture content, or partial vapor pressure on the surface of the wood and that of the ambient air that passes over the wood.

Each of the coefficients may be expressed in terms of any other by converting the potentials,

$$h_v = h_c \frac{\Delta C_{\text{wood}}}{\Delta C_{\text{air}}} = \frac{h_c G \rho_w R T \Delta M}{0.018 p_0 \Delta H}, \quad (1)$$

where

$$\Delta H = H_s - H_a,$$

$$\Delta M = M_s - M_a,$$

$H_s$  = relative humidity in equilibrium with the wood, surface, %,

$H_a$  = relative humidity of the ambient air relatively far from the surface, %,

$M_s$  = surface moisture content, %,

$M_a$  = moisture content in equilibrium with  $H_a$ , %,

$p_0$  = saturated vapor pressure, Pa,

$G$  = specific gravity of wood,

$\rho_w$  = density of water,

$C_{\text{wood}}$  = concentration of moisture in wood,  $\text{kg}/\text{m}_w^3$ ,

$C_{\text{air}}$  = concentration of moisture in air,  $\text{kg}/\text{m}_a^3$ .

Similarly,  $h_v$  may be converted to  $h_c$  by the equation,

$$h_c = \frac{0.018 h_v p_0 \Delta H}{G \rho_w R T \Delta M} \quad (2)$$

The coefficient based on a potential of partial vapor pressure ( $h_p$ ) is a convenient one for

comparing data of different investigators because it is a weak function of temperature. To convert  $h_c$  or  $S$  to  $h_p$ ,

$$h_p = h_c \frac{\Delta C_{\text{wood}}}{\Delta p} = \frac{h_c G \rho_w}{p_0} \frac{\Delta M}{\Delta H}, \quad (3)$$

To convert from  $h_v$  to  $h_p$ ,

$$h_p = h_v \frac{\partial C_{\text{air}}}{\partial p} = \frac{0.018 h_v}{RT} \quad (4)$$

There is a close analogy between thermal and mass convection coefficients that results from the near equality of the respective diffusivities in air and therefore the Prandtl (Pr) and Schmidt (Sc) numbers. The coefficients are defined as

$$h_T = \frac{J_q}{T_s - T_a} \quad (5)$$

(Heat)

$$h_c = \frac{J_m}{C_s - C_a} \quad (6)$$

(Mass)

where

$h_T$  = thermal convection coefficient,  
W/m<sup>2</sup>K,

$J_q$  = heat flux, W/m<sup>2</sup>,

$T_s$  = surface temperature,

$T_a$  = ambient temperature of air relatively far from the surface,

$C_a$  = concentration of moisture in wood in equilibrium with ambient air, kg/m<sup>3</sup>,

$C_s$  = concentration of moisture on the wood surface, kg/m<sup>3</sup>.

The corresponding Prandtl (Pr) and Schmidt (Sc) numbers in air at 30°C and at a pressure of 101.3 kPa may be calculated and compared.

$$\text{Pr} = \frac{c_{pa} \mu}{K_{qa}} = \frac{\mu}{\rho_a D_{qa}} \quad (7)$$

(Heat)

$$\text{Sc} = \frac{\mu}{\rho_a D_a} \quad (8)$$

(Mass)

where

$c_{pa}$  = specific heat of air = 1,003 J/kg K,

$\mu$  = viscosity of air =  $1.90 \times 10^{-5}$  Ns/m<sup>2</sup>,

$\rho_a$  = density of air = 1.165 kg/m<sup>3</sup>,

$D_{qa}$  = thermal diffusivity of air, m<sup>2</sup>/s,

$K_{qa}$  = thermal conductivity of air  
= 0.024 W/mK,

$D_a$  = diffusivity of water vapor in air  
=  $2.6 \times 10^{-5}$  m<sup>2</sup>/s.

Then  $D_{qa} = K_{qa}/c_{pa} \rho_a = 0.024/1,003 (1.165) = 2.1 \times 10^{-5}$  m<sup>2</sup>/s, which is reasonably close to  $D_a$ . Therefore, the Prandtl and Schmidt numbers are in reasonable agreement with values of 0.78 and 0.63, respectively. This leads to the Lewis relation, which will be discussed later.

The convection coefficients are related to the dimensionless Nusselt (Nu) and Sherwood (Sh) numbers as

$$\text{Nu} = \frac{h_T L}{K_{qa}} \quad (9)$$

(Heat)

$$\text{Sh} = \frac{h_v L}{D_v} \quad (10)$$

(Mass)

where  $L$  = length of surface along which convection occurs, m.

The Nusselt and Sherwood numbers averaged over  $L$  may be calculated from the dimensionless Reynolds', Prandtl, and Schmidt numbers (Kreith 1962; Geankoplis 1978) as

$$\bar{\text{Nu}} = 0.66 \text{Re}^{0.5} \text{Pr}^{0.33} \quad (11)$$

(Heat)

$$\bar{\text{Sh}} = 0.66 \text{Re}^{0.5} \text{Sc}^{0.33} \quad (12)$$

(Mass)

(Laminar flow,  $\text{Re} < 16,000$ )

$$\bar{\text{Nu}} = 0.036 \text{Re}^{0.8} \text{Pr}^{0.33} \quad (13)$$

(Heat)

$$\bar{\text{Sh}} = 0.036 \text{Re}^{0.8} \text{Sc}^{0.33} \quad (14)$$

(Mass)

(Turbulent flow,  $\text{Re} > 16,000$ )

and,

where  $Re = Lv\rho_a/\mu_a$  for a plane surface,

$v$  = linear velocity, m/s.

It is evident that the Nusselt and Sherwood numbers will be equal if the Prandtl and Schmidt numbers, and therefore the diffusivities, are equal. This near equality leads to the Lewis relation obtained from Eqs. (9) and (10).

$$\frac{h_T}{K_{qa}} \text{ or } \frac{h_T}{c_{pa}\rho_a D_{qa}} \approx \frac{h_v}{D_v}$$

Solving for  $h_v$ ,

$$h_v \approx h_T/c_{pa} \rho_a \quad (15)$$

Therefore, a mass convection coefficient may be estimated from a thermal coefficient under the same conditions of temperature and air velocity.

By substitution of Eqs. (9) and (10) into Eqs. (11) through (14), the averaged thermal and mass coefficients may be calculated from the classical equations as

$$\bar{h}_T = \frac{0.66K_{qa}Re^{0.5}Pr^{0.33}}{L} \quad (16)$$

(Heat)

$$\bar{h}_v = \frac{0.66D_aRe^{0.5}Sc^{0.33}}{L} \quad (17)$$

(Mass)  
(Laminar flow)

$$\bar{h}_T = \frac{0.036K_{qa}Re^{0.8}Pr^{0.33}}{L} \quad (18)$$

(Heat)

$$\bar{h}_v = \frac{0.036D_aRe^{0.8}Sc^{0.33}}{L} \quad (19)$$

(Mass)  
(Turbulent flow)

Equations (17) and (19) may be simplified for calculations involving drying from a moist, smooth surface by the substitution of numerical values for air at 30°C and by conversion to a vapor pressure gradient using Eq. (4).

$$\bar{h}_p = 27 \times 10^{-9}(v/L)^{0.5} \quad (20)$$

(Laminar flow)

$$\bar{h}_p = \frac{40 \times 10^{-9}v^{0.8}}{L^{0.2}} \quad (21)$$

(Turbulent flow)

where  $\bar{h}_p$  = coefficient calculated from Eqs. (20) and (21) to distinguish it from experimental values designated as  $h_p$ .

Surface roughness has not been quantified in the studies with wood. In viscous flow, it would not be a factor, but in turbulent flow one would expect an increase in the convective coefficient with roughness. Kreith (1962) cited research that established this but stated that the increase in the coefficient is small compared with the increase in the friction coefficient and it is usually neglected in calculations. Although Eq. (21) is based on a smooth surface, the effect of greater roughness is probably negligible, although energy requirements to maintain a given air velocity would be expected to increase significantly.

#### NEWMAN'S SOLUTION

Newman (1931) presented an equation for the diffusion process that accounts for the surface resistance due to convection. Although constant coefficients and initial concentrations are assumed, this equation offers an analytical method by which average values of the diffusion and surface emission coefficients may be measured. Skaar (1954) indicated that there is a linear relationship between the logarithm of the dimensionless potential of moisture content ( $\bar{E}$ ) and the dimensionless time ( $T$ ) for values of  $\bar{E}$  greater than 0.5 as revealed in Fig. 1. The line corresponding to  $Ha$  or  $Sa/D$  equal to infinity represents no convection losses, for which the dimensionless half time is 0.2. At the value of  $\bar{E} = 0.5$ , there is a linear relationship between the half time and  $Sa/D$ , which may be stated as

$$T_{0.5} = 0.2 + 0.7 D/Sa, \quad (22)$$

where

$$\begin{aligned} T_{0.5} &= \text{dimensionless half time} \\ 0.2 &= \text{dimensionless half time for no convective losses,} \end{aligned}$$

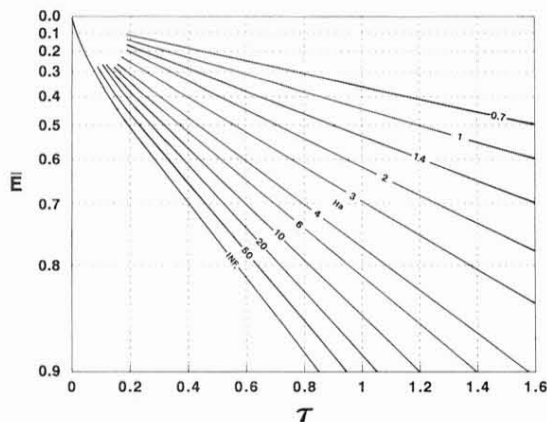


FIG. 1. Graphical solution of Newman's equation (Skaar 1954) with a plot of  $\bar{E}$  vs.  $\tau$  for various values of  $Ha$ .

$D$  = true diffusion coefficient,  $m_w^2/s$ ,  
 $S$  =  $h_c$ ,  $m_w/s$   
 $a$  = half thickness,  $m$ .

The dimensionless half time may be defined in terms of the true diffusion coefficient and the real half time as

$$T_{0.5} = t_{0.5} D/a^2 \quad (23)$$

where  $t_{0.5}$  = real half time,  $s$ .

An apparent diffusion coefficient, neglecting surface resistance, may be calculated from the real half time as

$$D^a = 0.2 a^2/t_{0.5} \quad (24)$$

where  $D^a$  = apparent diffusion coefficient,  $m_w^2/s$ .

By substituting Eqs. (23) and (24) into (22),

$$\frac{1}{D^a} = \frac{1}{D} + \frac{3.5}{Sa} \quad (25)$$

where

$1/D^a$  = total resistance,

$1/D$  = internal resistance,

$3.5/Sa$  = external resistance due to convection.

It is apparent from Eq. (25) that, if  $1/D = 3.5/Sa$ , the internal and external resistances are equal and twice the time will be required to reach a given  $\bar{E}$  than if surface resistance were

absent. The thickness ( $2a$ ) corresponding to this condition will then be

$$2a = 7D/S \quad (26)$$

As an aid to the determination of  $D$  and  $S$  from measurements on two or more specimens of different thicknesses, Eq. (25) may be transformed to

$$\frac{a}{D^a} = \frac{a}{D} + \frac{3.5}{S} \quad (27)$$

A plot of  $a/D^a$  vs. ( $a$ ) for two or more thicknesses should yield a straight line with a slope of  $1/D$  and an intercept of  $3.5/S$  permitting the determination of both  $D$  and  $S$ .

#### MEASUREMENTS OF MASS CONVECTION COEFFICIENTS AND COMPARISON WITH CLASSICAL VALUES

In order to compare values of  $S$  (or  $h_c$ ) determined by several investigators with classical values of  $\bar{h}_p$ , which are weak functions of temperature, reference to Eqs. (3), (20), and (21) indicates that it is necessary to know the temperature, the specific gravity, the air velocity, the dimension in the direction of air flow ( $L$ ), and finally the sorption data to determine the relationship between  $\Delta M$  and  $\Delta H$ .

Results of mass-convection coefficient measurements on wood are revealed in Table 2. All the studies except that of Teischinger (1987) employed multiple specimens to determine the coefficient by the Newman method. The only investigation extending over a range of temperatures (30°C to 70°C) was that of Avramidis and Siau (1987). In addition, moisture contents varied from 1.5% to 14% in this study. Rosen's (1978) investigation was the only one including a range of air velocities (0.4 to 12 m/s). In the latter case, the average moisture content was 17.5%.

The data of Avramidis and Siau (1987), measured in adsorption, indicate that  $S$  increases with temperature and decreases with moisture content. When the coefficients are converted to  $h_p$ , the temperature variation is essentially removed, but there is a moderate

TABLE 2. Results of mass convection coefficient measurements of wood.

Reference	A or D	T °C	M %	G	v m/s	L m	$D \times 10^{11}$ m <sup>2</sup> /s	$S \times 10^7$ m <sub>w</sub> /s	$h_p \times 10^9$ kg/m <sup>2</sup> s Pa	$\bar{h}_p \times 10^9$ kg/m <sup>2</sup> s Pa	$h_p/\bar{h}_p$	7D/S mm
Avramidis and Siau (1987)	A	30	3.2–13.7	0.38	3.0	0.05	8.4–17.9	1.1–0.4	0.7–2.3	175	0.004–0.013	5–32
	A	45	1.8–13.7	0.38	3.0	0.05	7.9–43	2.4–0.9	0.4–1.8	175	0.002–0.010	1.6–34
	A	60	1.5–10.2	0.38	3.0	0.05	27–40	8.2–3.2	0.5–3.4	175	0.003–0.019	2.3–6.2
	A	70	2.2–11	0.38	3.0	0.05	32–102	6.4–2.8	0.5–1.7	175	0.003–0.010	3.5–25
Rosen (1978)	A	25	17.5	0.55	0.43	0.05	7.3	0.12	0.8	79	0.011	35
	A	25	17.5	0.55	2.9	0.05	7.1	0.67	1.8	170	0.011	7.0
	A	25	17.5	0.55	11.7	0.05	7.0	0.87	5.9	521	0.011	5.4
Wadsö (1993)	A	23	12.6	0.5	3.0	0.05	10.2	0.48	2.0	175	0.011	15.0
Teischinger (1987)	A	20	21.0	0.45	0.1	0.13	27.4	0.51	6.4	24	0.26	3.6
Choong/Skaar (1969)	D	32	23	0.40	3.3	0.05	92	13	41	176	0.23	5.0
Choong/Skaar (1972)	D	37	26	0.46	1.5	0.05	101	16	30	100	0.30	7.9

increase with moisture content, which may be explained by the rapid increase in the slope of the sorption isotherm at higher moisture contents. Both of these effects are evident from the ranges of  $h_p$  in Table 2, with the entire range between 0.4 and  $3.4 \times 10^{-9}$  kg/m<sup>2</sup>s Pa. the classical value from Eq. (21) is constant at  $175 \times 10^{-9}$  kg/m<sup>2</sup>s Pa, with the ratio of  $h_p/\bar{h}_p$  extending from 0.002 to 0.019, and increasing with moisture content. These small ratios were corroborated by the results of Rosen (1978), whose values of  $h_p$  increased from 0.8 to  $5.9 \times 10^{-9}$  kg/m<sup>2</sup>s Pa when the air velocity was increased from 0.4 to 12 m/s. The flow was laminar below 5 m/s. The corresponding classical values ( $\bar{h}_p$ ) extended from 79 to  $520 \times 10^{-9}$  kg/m<sup>2</sup>s Pa with a constant ratio of  $h_p/\bar{h}_p$  of 0.011.

Wadsö (1993) conducted a thorough investigation of surface convection including a sorption experiment with specimens of different thicknesses. His ratio of  $h_p/\bar{h}_p$  was in close agreement with those of Avramidis and Siau (1987) and Rosen (1978). Wadsö interpreted the results in a different way, assuming the classical coefficient  $\bar{h}_p$  to be the correct one and attributing his low experimental values to a non-Fickian component of diffusion caused by a relatively slow rate of relaxation of the cell wall. This component was modeled by a time-

dependent function which, when added to a Fickian component, gave excellent agreement with his experimental sorption curve. This is a valid point that needs further investigation; however, it would be expected to be more important during adsorption than desorption.

Teischinger (1987) measured the surface-emission coefficient in adsorption from a single specimen by establishing a linear relationship between the rate of change of the average moisture content ( $d\bar{E}/dT$ ) and the difference in moisture content potential between the surface ( $M_s$ ) and the EMC corresponding to the relative humidity of the ambient air ( $M_a$ ). Since this was linear over a wide range of moisture contents, it was possible to calculate the apparent diffusion coefficient  $D^a$  and  $S$ , and finally the true diffusion coefficient from Eq. (25). The low air velocity reported in this investigation resulted in a low  $\bar{h}_p$  and consequently a high ratio of  $h_p/\bar{h}_p$ .

In regard to desorption, Choong and Skaar (1969, 1972) measured higher coefficients of 13 and  $16 \times 10^{-7}$  m<sub>w</sub>/s than those in adsorption. This could be due to two factors, namely higher moisture contents and less resistance due to compressive stresses in the cell wall than would be expected in adsorption.

Christensen (1965) investigated adsorption in a vacuum of wood specimens ranging in



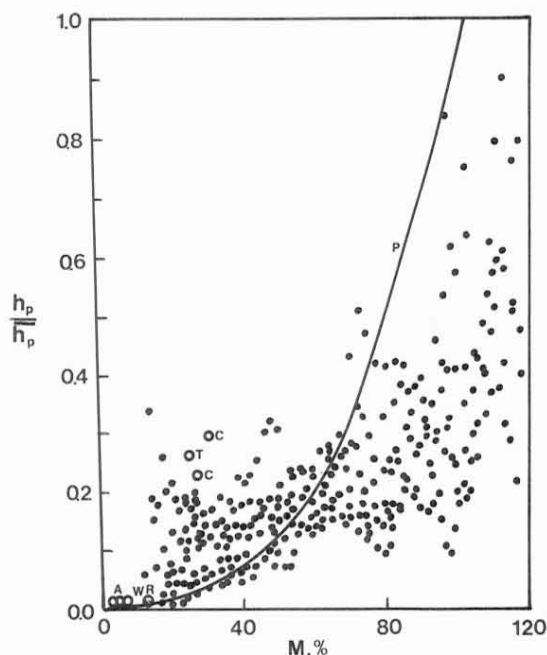


FIG. 2. Plot of  $h_p/\bar{h}_p$  for wood. The curved line is from Plumb et al. (1985) and the solid data points are from Laurilla's thesis (not seen) (adapted from Morén et al. (1992). Open circular data points are identified as follows: (A) Avramidis and Siau (1987), (C) Choong and Skaar (1969, 1972), (R) Rosen (1978), (T) Teischinger (1987), and (W) Wadsö (1994).

thickness from 1  $\mu\text{m}$  to 1 mm at low and high moisture contents. It was found that the rate of sorption was independent of thickness and that the flux was lower at the higher moisture contents. Although both of these results would be expected due to surface-convection resistance, convection cannot occur in the absence of air. Christensen explained these results as due to the necessity of molecular rearrangement, or cell-wall relaxation, similar to the interpretation of Wadsö (1993).

Another interesting result of the investigations listed in Table 2 is the ratio  $7D/S$ , which is the thickness corresponding to equal internal and external resistances. These range from 1.6 mm at low moisture contents and high air velocities to 35 mm at high temperatures and low velocities. At thicknesses significantly less than these values, the internal resistance becomes negligible and the flux is controlled by

the surface emission coefficient. Under these conditions the flux would be independent of the thickness.

#### CONCLUSIONS

Figure 2 reveals a graphical comparison of  $h_p/\bar{h}_p$  of the data in Table 2 with a large number of data points presented by Morén et al. (1992) taken from Laurilla's thesis (not seen) and a curve taken from Plumb et al. (1985). It is clear from this that the data in Table 2 are within the range of the others in the plot. The excessive scatter of these data is evidence of the lack of understanding of the mechanism of mass convection from dry hygroscopic materials such as wood. However, it can be concluded from Table 2 and Fig. 2 that the coefficient  $h_p$  generally increases with moisture content, approaching the classical value at moisture contents of 100% or more which would be typical of green wood having a moist surface such as wood during the constant drying period. This is apparently a condition upon which the classical equations are based. It may be speculated that the decreased coefficients that were measured at lower moisture contents in the hygroscopic range are due to a greatly decreased area fraction of moist surface. Even though the cell wall is exposed, only a portion of this will contain bound water.

Other factors that could explain the disparity of the results plotted in Fig. 2 include the large number of factors that affect the results such as air velocity, temperature, sorption history, specific gravity, size of the specimen, and condition of the surface. Many of the available results do not include all these important data. In addition, there are several assumptions in the use of the Newman equation to determine the coefficient which are discussed by Skaar (1954). The method used by Teischinger (1987) requires accurate determination of the moisture content on the surface. In addition, there is the possibility of non-Fickian behavior as discussed at length by Christensen (1965) and Wadsö (1993). It should be pointed out that, despite the divergent value of the surface emission coefficients measured by the different in-

investigators, the diffusion coefficients were typical of others in the literature when the effects of temperature and moisture content were taken into account.

The theory and factors affecting the drying of moist materials is fairly well understood, but clearly this is not applicable to dry hygroscopic materials such as wood at the lower moisture contents. This is an important area in which additional research is needed to elucidate the significant factors in this aspect of wood drying, and the transfer of moisture through wood walls, the equilibrium of wood with its environment, and the effect of surface roughness on the cost of operating blowers in dry kilns. There is clearly a significant gap in our understanding of the influence of surface convection losses on the diffusion process.

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