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Reprinted from WOOD AND FIBER

Vol. 1, No. 1, Spring 1969

pp. 64-74

THE STATE OF MOISTURE TRANSPORT RATE  
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CEP67-68-84

# THE STATE OF MOISTURE TRANSPORT RATE CALCULATIONS IN WOOD DRYING<sup>1</sup>

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## ABSTRACT

The drying theories developed over the past fifty years have originated from the point of view of either the internal mechanisms of drying, which treats the flow of moisture within a porous material, or from the view of the external mechanisms of drying, which considers the movement of moisture away from the material. This paper considers the success the drying scientist has had in analytically predicting the moisture transport rates, suggests means to realize overall drying rates, and recommends areas of specific research required to obtain a technology which will result in faster, more economical, and more uniform drying of lumber.

## INTRODUCTION

Interest in the mechanisms occurring during wood drying has increased rapidly over the last fifty years. Most efforts have been directed toward shortening the overall drying time which is one of the most important factors in the economics of lumber production. To avoid undesirable shrinkage and stresses, it is necessary to dry lumber to a moisture content approximately equal to that present under service conditions. To procure suitable lumber in an economically convenient time, it is necessary to dry it artificially in kilns or drying chambers. As a result, seasoning is the most time-consuming operation in lumber manufacture. Conventionally, lumber is stacked in courses or layers separated by narrow strips of wood called stickers. In the kiln, the stacked lumber is subjected to a sequence of temperature, humidity, and air flow conditions. The drying rate is thus a complex function of the stacking geometry, the dry bulb temperature, the wet bulb depression, the diffusion characteristics within the wood, and any factor which controls the effectiveness of the air circulation in heating and removing the moisture from the lumber surface. In any given situation, it is to be expected that there exists some optimum combination of these states which provides the fastest drying rate compatible with low lumber de-grade.

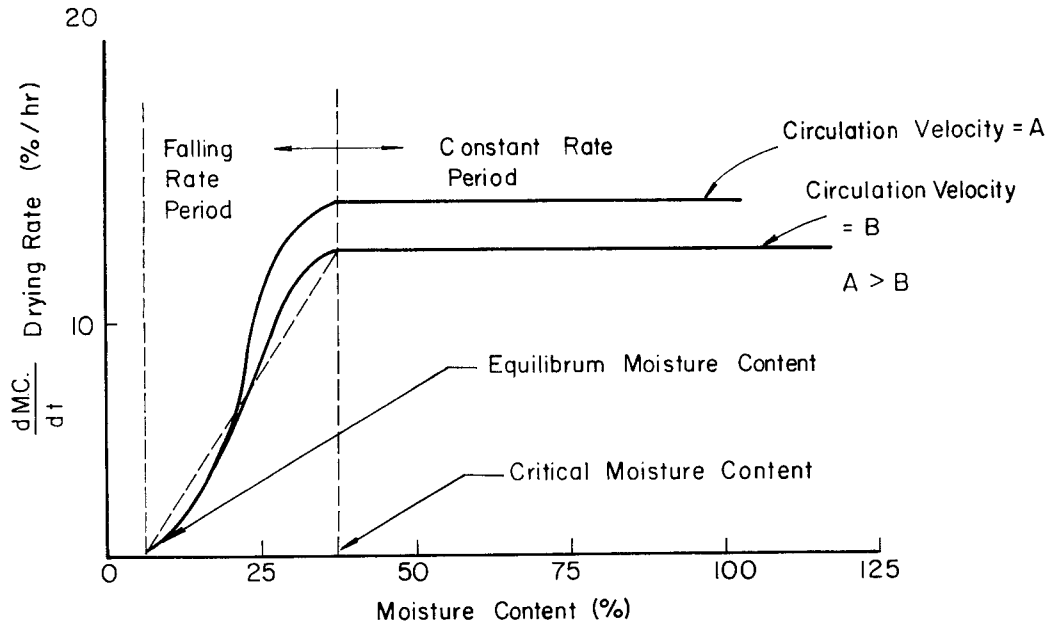
<sup>1</sup> The author would like to acknowledge the support of the U.S. Department of Agriculture, Forest Service under Grant 16-81 (5-10-66). See end of article for explanation of symbols and subscripts.

Historically, the magnitudes and sequence of these states (i.e., the so-called schedule development) have been determined by tedious empirical trial and error studies which involved changing those variables the operator believed were pertinent. Although qualitatively significant and specifically useful, this technique has resulted in a large amount of uncorrelatable data which cannot be extrapolated to new conditions or species.

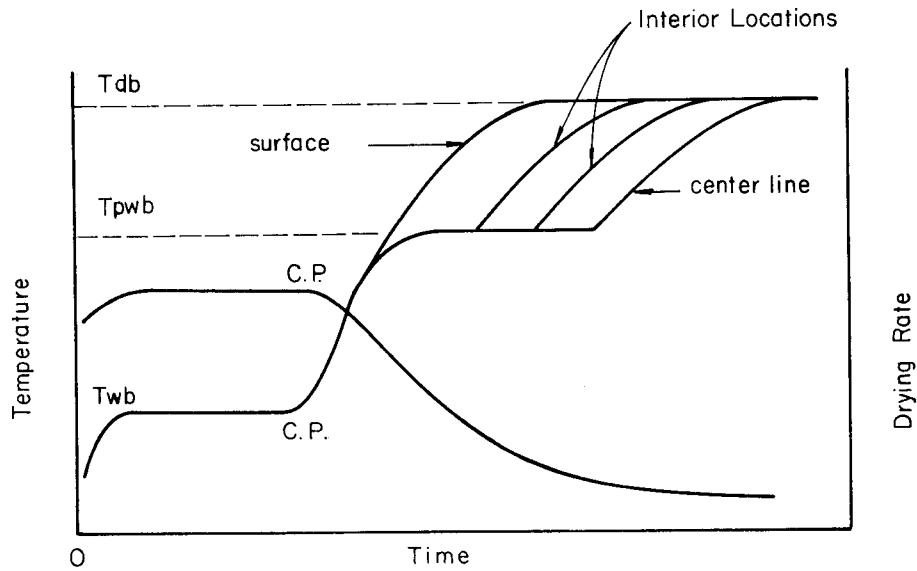
Within recent years, great advancements have been made in an understanding of the diffusion processes within wood substances. Studies by such researchers as Stamm, Tiemann, and Comstock have resulted in a thorough yet concise literature on the subject. (ANC Bulletin 1946; Baker 1956; Brown 1965; Burr and Stamm 1956; Choong and Fogg 1968; Comstock 1963; Panshin, Brown and Forsaith 1964; Stamm 1964 and 1967; Tiemann 1938). On the other hand, the regime of aerodynamically dominated drying has received considerably less investigation. New information and many new techniques of measurements are available in the field of fluid mechanics as developed by other disciplines. It is the intention of this paper to review that literature related to the latter mechanism.

## CLASSIFICATION OF DRYING MECHANISMS

W. K. Lewis and T. K. Sherwood were among the first to recognize that the drying process might be divided into a number of specific periods in which different drying mechanisms were dominant (Lewis 1921;



a) General drying rate curve



b) Generalized Time-Temperature Record

FIG. 1. Drying Rate Curves.

Sherwood 1929a; 1929b). They identified two basic regimes which were designated the "constant rate" and the "falling rate" periods. The rate of moisture loss during

the constant rate period was limited by the ability of the circulating air to remove the water from the lumber surface. Generalized time-temperature records from various ex-

periments indicate the presence of a constant rate regime for lumber (Nissan and Hansen 1961; Torgeson 1959). At low moisture contents (below 30%), the rate of moisture transport is limited by the ability of the water to diffuse through the wood to its surface and the energy available for sorption—hence the falling rate period.

Fig. 1a and 1b are generalized graphs of the drying rate and temperature distributions during a typical drying process. At a particular "critical moisture content," the rate of drying begins to decrease. The period from the moment when the critical moisture content is reached until the moment when the solid is "dry" is the "falling rate period." Some authors divide the falling rate region into further sections (McCready and McCabe 1933; Nissan and Hansen 1961; Sherwood 1929a, 1929b). It is also postulated by some authors that the initial drop in the falling rate period results because of a decrease in the total wetting surface as some areas dry out (Sherwood 1929a; Treybal 1955). This drop in drying rate would not necessarily be directly proportional to the areas involved because the dry areas might absorb more heat and raise the surface temperature (pseudo wet-bulb temperature) (Nissan and Hansen 1961; Sherwood 1929a). Other authors suggest that the initial part of the falling rate regime involves a retreat of the vaporization zone into the solid before the free water has been entirely removed from the center portion of the solid (McCready and McCabe 1933). It is at least evident that this portion of the falling rate regime responds to the behavior of the circulation about the lumber in a manner similar to the constant rate drying region.

#### FALLING RATE PERIOD OF DRYING

Early investigators recognized the effect of fluid motion on the moisture transfer rates but appeared reluctant to consider the problem in detail because of its difficulty. The first analytic approach to drying rates concentrated on the mathematical analogy between the conduction of heat in solids and the diffusion of moisture in a porous

medium (ANC Bulletin 1946; Carrier 1921; Lewis 1921; McCready and McCabe 1933; Newman 1932; Sherwood 1929a; 1929b; Tuttle 1925; Vick 1965). These solutions are dependent on the assumption that the surface of the wood is at its final equilibrium moisture content immediately after drying begins. This assumption is good for air-dried lumber near or below the fiber-saturation point at low or medium dry-bulb temperatures; however it has doubtful validity for many species whose original moisture content is high (Keer 1956). In addition, the conduction-analogy model buries in a pseudo-integral diffusion coefficient the effects of variation in the circulation and tends to disguise the specific effects of the fluid motion.

The mathematical analogy theory of drying initially required the following assumptions:

- a) the validity of Ficks' second law of diffusion in a solid (the rate of change of concentration,  $\partial c/\partial t$ , at any point into the diffusion medium in the  $x$  direction is proportional to the rate at which the rate of variation of concentration with distance changes,  $\partial^2 c/\partial x^2$ );
- b) the constancy of the diffusion factor  $D$  (proportionality constant in Ficks' second law);
- c) a uniform moisture distribution when drying starts (this assumption later removed by Newman [1932]);
- d) that the effective moisture movement is normal to the surface planes;
- e) that the surface fibers attain the equilibrium moisture content as soon as drying starts;
- f) that the thickness of the lumber does not change during drying; and
- g) that the equilibrium moisture content remains constant for the drying process

These criteria are met only roughly by drying wood. The dimensions of the wood vary from lamina to lamina because of the moisture content gradient and because wood naturally shrinks below the fiber-saturation point. The diffusion constant  $D$  has been found to vary with moisture content. Conditions e) and f) may not be met

over the entire drying period. Finally, cases have been recorded in which water vapor and bound water movement are in opposite directions (Burr and Stamm 1956). In such cases, the drying rate may be proportional to the vapor-pressure gradient rather than the moisture-content gradient.

Although obviously not rigorously valid, the theory based on the above assumptions provides an estimation technique for moisture loss rates for wood below the fiber-saturation moisture content. The technique was originally suggested by Tuttle and Loughborough (Tuttle 1925). Subsequently, it was developed in greater detail, and convenient tables were produced by Newman (1932).

In essence, Tuttle recognized that Ficks' second law of diffusion,

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}, \quad (1)$$

and the pertinent boundary conditions were equivalent to a heat transport problem in conduction heat transfer. The solution for the moisture distribution, as developed by Newman for the general case where the effect of the evaporation resistance at the surface is not neglected, requires the boundary conditions:

$$\begin{aligned} -\partial c / \partial x &= h(c - c_1) \quad \text{at } x = a \\ \partial c / \partial x &= h(c - c_1) \quad \text{at } x = -a. \end{aligned} \quad (2)$$

The original moisture distribution may also be parabolic:

$$c - c_1 = (c_m - c_1) - \frac{c_m - c_a}{a^2} x^2 \quad \text{at } t = 0. \quad (3)$$

A solution which satisfies all these conditions is

$$\begin{aligned} c - c_1 &= (c_m - c_1) \\ &\times \sum_{n=1}^{\infty} 2 \exp\left(-\frac{Dt}{a^2} \beta_n^2\right) A_n \cos \frac{\beta_n x}{a} \\ &- (c_m - c_a) \\ &\times \sum_{n=1}^{\infty} 2 \exp\left(-\frac{Dt}{a^2} \beta_n^2\right) B_n \cos \frac{\beta_n x}{a}, \end{aligned} \quad (4)$$

in which the recursion expression for the coefficients is

$$\begin{aligned} A_n &= \frac{ha}{[(ha)^2 + \beta_n^2 + ha] \cos \beta_n}, \\ B_n &= \frac{2\beta_n^2 + ha\beta_n^2 - 2ha}{[(ha)^2 + \beta_n^2 + ha] \cos \beta_n}, \end{aligned} \quad (5)$$

and  $\beta_n$  is defined by  $\cos \beta_n = \beta_n / (ha)$ . (Tabulated in Tables by Jahnke and Emde and Newman [1932]).

The above solution of the problem gives the concentration in terms of time and location. An equation giving the average free liquid concentration at any time is useful and can be obtained by integration. Hence,

$$w - c_1 = \frac{1}{2a} \int_{-a}^a (c - c_1) dx \quad (6)$$

results in expressions which may be abbreviated as

$$\frac{w - c_1}{c_0 - c_1} = E \left( \frac{Dt}{a^2} \right) \quad (7)$$

for an initially uniform distribution, and as

$$\begin{aligned} \frac{w - c_1}{c_0 - c_1} &= \left( \frac{3c_m - 3c_1}{2c_m - 3c_1 + c_a} \right) E \\ &- \left( \frac{3c_m - 3c_a}{2c_m - 3c_1 + c_a} \right) E' \end{aligned} \quad (8)$$

for an initial parabolic distribution. The solution for an initially uniform moisture distribution results in Fig. 2. Tables for the functions  $E$  and  $E'$  in terms of  $(Dt/a^2)$  and  $(ha)$  are included in Newman (1932).

The empirical coefficients  $D$  (the average diffusion constant) and  $h$  (the surface evaporation rate coefficient) must be determined separately. The coefficient  $h$  is directly related to the flow configuration of the drying air passing over the wood surface. It will be a complex function of stacking geometry, surface roughness, air velocity, and turbulence level. This factor will be discussed in detail in a subsequent section.

The diffusion process is of great importance in general wood technology, since the treatment of wood with preservatives, fire retardants, anti-shrink and seasoning

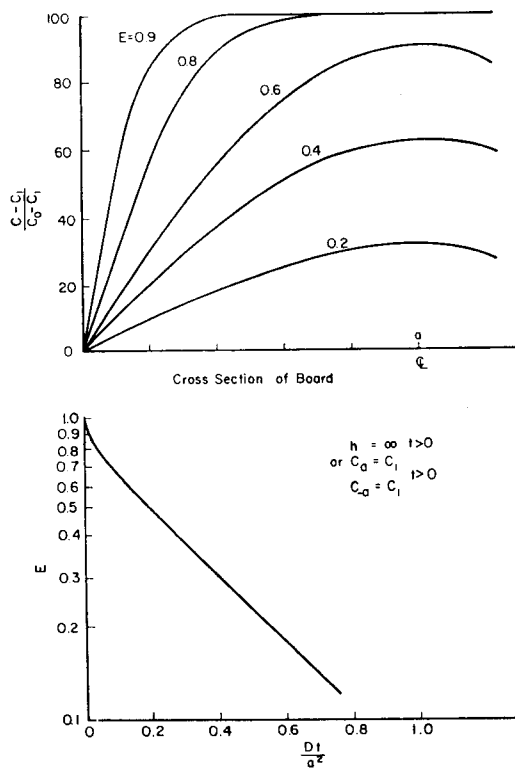


FIG. 2. Moisture gradients for zero surface resistance and uniform initial moisture distribution.

chemicals, and the penetration of chips with reagents prior to pulping all involve diffusion. Hence, the value of the diffusion coefficient,  $D$ , for various woods has been examined in great detail both empirically and analytically, (Burr and Stamm 1956; Comstock 1963; Marshall 1958; Stamm 1964; Yao 1966). Drying diffusion coefficients for wood have been obtained from three different types of data involving measurements of:

- moisture gradients set up under transient conditions;
- rate of water movement in wood under steady-state conditions; and
- rate of drying of wood.

The empirical diffusion coefficients are determined by fitting the experimental data to theoretical curves, assuming that Fick's diffusion laws hold, (Comstock 1963; Newman 1932; Sherwood 1929a; Stamm 1964; Tuttle 1925). Diffusion coefficients cal-

culated in this manner for a swollen-volume specific gravity of 0.4 plotted versus reciprocal temperature are summarized by Stamm in Fig. 23-1 of his text (1964).

The diffusion of water through a complex network of capillaries (actually a complex network of solids, liquids, and gases) in wood is analogous to electrical conduction in some equivalent resistance circuit. If the hindrance of the various structural components of the wood to diffusion is expressed in terms of a resistance, a diffusion coefficient may be predicted on the basis of a simple electrical conduction analog. This idea has been developed in detail by Stamm, et al., and the agreement between the theoretical and experimental values appears good, (Burr and Stamm 1956; Stamm 1964). Stamm has summarized the theoretical prediction for the diffusion coefficient between the fiber saturation point and the oven-dry condition in Fig. 23-3 of his text (1964).

Used properly, the conduction analogy technique is a very powerful tool to predict moisture loss rates. A recent paper by Vick claims very good agreement for predicting drying rate curves for yellow-poplar lumber; however, he does not indicate how he determined the diffusion coefficient or the surface transfer coefficient (1965).

Unfortunately, it would appear that the conduction-analogy technique has also been utilized for situations in which the initial moisture contents are much above the fiber-saturation point. Under such conditions, it is probable that the pseudo-integral diffusion coefficient deduced only masks variations in circulation and disguises the specific effects of the fluid motion.

A number of approximate drying relations have also been derived, (Lewis 1921; McCready and McCabe 1933; Sherwood 1929b). These are all essentially simplified versions of the previous analogy. A typical assumption would be that the drying rate is a linear function of the moisture content. This results in the expression

$$\ln E = \frac{S_c t}{(M.C._c - M.C._e) A e a} = -N \frac{t}{a}, \quad (9)$$

where

$$E = \frac{M.C. - M.C._e}{M.C._c - M.C._e}$$

A = surface area

$\rho$  = density of dry solid

$S_c$  = rate of drying in constant rate region

a = one-half thickness of wood slab

where N is an empirical constant. This constant is related to the pseudointegral diffusion coefficient mentioned above and has the same deficiencies.

#### CONSTANT RATE OF DRYING

Most very wet solids being dried under constant drying conditions exhibit a period during which the rate of drying is constant. The rate does not continue constant until the solid is dry, but at one definite liquid content "critical point," the rate of drying starts to decrease. Obviously, if the initial liquid content is less than critical, no constant rate period appears.

Most wood drying literature reports that the actual length of time the constant rate period exists is very short. In addition, the literature asserts that the equilibrium moisture content is attained at the surface almost immediately. The author has observed a constant rate period for drying Engleman spruce which was at least one-sixth of the total drying time for a dry-bulb temperature of 130 F and a wet-bulb depression of 20 F (Meroney and Ostrowski 1967). Even if the constant rate period itself is very short, it is evident that for lumber initially very wet (green), the factors which control the constant rate period drying rate also dominate an appreciable section of the falling rate region (Killmann 1961).

A constant rate drying region is generally concerned with the evaporation of liquid from the solid lateral surfaces of a porous material where resistance to internal diffusion is small as compared to the removal of vapor from the surface. Hence, the drying rate is generally independent of the material being dried (unless the material is water soluble and so affects the vapor pressure). During the constant rate period,

the evaporation takes place at the surface of the wet solid, the rate of drying being limited by the rate of diffusion of water vapor through the surface air film (boundary layer) out into the main body of the air. The drying, in this period, is similar to the evaporation of water from a free liquid surface, and for a sufficiently long constant rate period the solid may assume a constant equilibrium temperature, just as a free liquid surface is maintained by evaporation at the wet-bulb temperature of the air. The resistance of the surface film to moisture transport is a complex function of the stacking geometry (board spacing), dry-bulb temperature, wet-bulb depression, turbulent intensity level, uniformity of the circulation, surface roughness, and any other factor which controls the effectiveness of the fluid motion to heat and remove the moisture from the lumber surface.

Early investigators recognized the effect of the fluid motion on the moisture transfer rates, but appeared reluctant to consider the problem in any analytical detail because of its difficulty; thus, almost all schedule development has been empirical. At the beginning of the century, natural draught (free circulation) kilns were popular, and in the first forced circulation kilns which were used, air speeds over the lumber surface were less than 100 ft/min (Torgeson 1960). Subsequently, research by such organizations as the Forest Product Laboratory in Wisconsin encouraged the use of speeds up to 600 ft/min. More recently, some studies have utilized speeds as high as 2,700 ft/min (Kollmann 1961). Some investigators have examined the effect of fluid motion on a specific configuration and material (Lewis 1921; McCready and McCabe 1933; Sherwood 1929b; Stevens and Pratt 1958). Samples of such substances as asbestos, heel board, clay, whiting, paper pulp, cord-twine, and even wood were examined under a variety of conditions of velocity and humidity. These studies were not comprehensive in the sense that measurements were made at only one position and for a specific configura-

tion. Effects of free turbulence intensity, velocity, pulsation, stack geometry variation, and roughness variations were not considered at all.

Additional work of a qualitative nature has been done on the advantages of flow reversal (Keer 1956; Stevens and Pratt 1958). An article on pulsation on drying rate has been published, but has not resulted in any further attention in the drying literature (Fessel 1956). A large amount of work has been done on impingement drying, but the studies have not been based on fundamentals of heat and mass transfer in wood drying (Reitz 1967). One investigator, Lymann, used a wetted felt mat material to evaluate the circulation effects in impingement drying in an effort to avoid the variation of wood (1965).

Qualitative experiments such as those listed above and long empirical experience have produced various fundamental characteristics for wood drying. Among these are the following:

- a) sapwood dries more rapidly than heartwood of a species;
- b) drying rates from the end grain are from 10 to 15 times as fast as from the tangential surface;
- c) the drying rate, everything else being equal, is affected by velocity of air movement; and
- d) the drying rate is a direct function of temperature and an inverse function of the relative humidity.

These concepts are too fundamental, however, to be of much assistance in calculating the drying time for a specific piece of lumber. One might examine the data collected by such an organization as the Forest Product Laboratory; however, such an analysis would be affected by many confusing factors such as the wide range in initial moisture content conditions, variations from standard procedures, and the fact that scientific information regarding the interactions of some of the important variables is missing.

Hence, most calculations have been based on simple transport analogies to relations available from heat transport

equations under similar conditions. Much new information is available in this field, and the transport problem will be discussed in the next sections.

#### MOISTURE TRANSPORT FROM WETTED SURFACES

Although mathematical solutions are not available for all possible boundary conditions, dimensional analysis may be applied to group significant variables, thereby establishing, hopefully, a law of similarity for evaporation. A given set of conditions all uniquely determine the distribution of the vapor and the velocity in the flow and, hence, the evaporation rate from the surface. Consequently, one may expect a functional relationship to exist between the local rate of evaporation and properties or parameters which are descriptive of the specified conditions. Using the conventional dimensional analysis techniques as summarized by Bridgman (1931), one can obtain for momentum, heat, and mass transport the functional equations

$$f_1(R_d, C_f, T, Gr, x/d, d/a, k_s/d) = 0, \quad (10)$$

$$f_2(R_d, Nu_d, T, Gr, Pr, x/d, d/a, k_s/d) = 0, \quad (11)$$

and

$$f_3(R_d, Sh_d, T, Gr_m, Sc, x/d, d/a, k_s/d) = 0, \quad (12)$$

where the individual terms are identified in the list of symbols. It is experimentally evident that not all of the parameters are equally important or effective. For instance, the magnitude of the forced convection velocity in a modern industrial kiln is such that the dimensionless free convection modulus,  $Gr$ , the Grashoff number, can be neglected. These groups are often further combined or altered as experience indicates, hence, such moduli as the Pecklet number,  $Pe$ , and the Stanton number,  $St$ . In addition, the microscopic transport coefficients may often be simply replaced by their turbulent counterpart for turbulent flow; therefore,

$$Pr = \frac{\mu c_p}{k} \text{ may become } Pr_t = \frac{\epsilon}{\epsilon_k}.$$



where  $\epsilon$  represents the eddy diffusion coefficients due to turbulent fluctuations.

The large number of governing parameters which exist during drying require a carefully constructed series of experiments to isolate correctly their individual effects. The interpretation of data from experiments not controlling these variables is not possible.

Extensive solutions are available for heat or mass transport through a laminar boundary layer for a wide variety of boundary conditions including plates, pipes, ducts, and channels (Bird, Stewart, and Lightfoot 1960; Jakob 1949; Spalding 1963). Variations have been obtained for entrance regions, high mass transport rates, and variable wall temperatures or mass flux rates (Terrill 1965; Yih and Cermak 1951). Unfortunately, except for the flat plate solutions discussed below, the turbulent transport case is by no means as well treated or understood. The reason for this lack of success is the extreme complexity of turbulent motion. In turbulent flow, irregular velocity fluctuations are always superimposed upon the motion of the main stream, and the fluctuating components cannot be described by simple equations. Yet it is precisely these fluctuations which are primarily responsible for the transfer of heat, momentum, or mass in turbulent flow.

Exact solutions of the general equation for two-dimensional evaporation in the absence of a pressure gradient from a flat surface have been obtained, assuming that the exchange coefficient for momentum is the same as for vapor transport. Sutton, Pasquill, Kohler, and Yih determined solutions very similar in format, as compared by Cermak and Lin (1955). Yih's solution of wall evaporation is

$$\frac{c_s - c}{c_\infty - c_s} = \frac{\Gamma \left[ \frac{m}{1 + 2m}, \frac{\eta^{1+2m}}{(1 + 2m)^2} \right]}{\Gamma \left( \frac{m}{1 + 2m} \right)}, \quad (13)$$

where

$$\eta = z \left[ \frac{U_\infty (z_1)^{1-2m}}{K_m x} \right]^{\frac{1}{1+2m}}$$

and  $m$  is the exponent if one assumes  $U/U_\infty = (z/z_1)^m$ . The total rate of evaporation is found by writing

$$E_{tx} = \int_0^\infty [U(c - c_\infty)]_{at\ x} dz. \quad (14)$$

These expressions appear to correlate evaporation data for the flat wall case quite well.

Most relations utilized for industrial mass transport calculations are based on the assumption of an equivalent transport mechanism for heat, momentum, and mass transport. The basic concepts of this analogy were introduced by Osborn Reynolds in 1874. The analogy was later improved by Prandtl, Von Karman, Boelter, et al., Martenelli, and most recently by Deissler (Bird, Stewart, and Lightfoot 1960).

In essence, Reynolds observed that under certain circumstances the simplified governing exchange equation and boundary conditions for mass, momentum, and heat transfer are formally equivalent, except for certain transport coefficients which combined into the various dimensionless parameters previously discussed. Hence, if a solution is obtained for one transport process in a given situation and is expressed functionally as suggested by Equations (10, 11, or 12), then the same functional formulation should exist for the remaining transport process when the appropriate dimensional parameters are inserted.

In view of the fact that most mass transport solutions are obtained by analogy, potential success of the prediction of the mass transport in a turbulent system is dependent on the equivalent state of the art for heat and momentum transport. Analytically, the basic solution of the constant rate drying region between flat plates looks very favorable. Heat transfer solutions for turbulent flow are available for the simple flat plate case for a wide variety of wall temperatures, flux rates, and pressure gradients (Keston and Richardson 1963; Reynolds et al. 1960; Rotta 1965). These solution techniques have been extended to the slot problem for a variety of boundary conditions. Deissler and Hatton have provided an analysis of turbulent heat transfer

and flow in the entrance regions of smooth passages (Deissler 1953; Hatton 1963-64). Since 1961, flow between parallel plates has specifically received concerted attention; recent papers by Hatton et al. (Hatton and Quarmby 1963; Hatton and Gundy 1964; Hatton and Quarmby 1964), Mori and Uchida (1966), Barrow (1961; 1962), and Seban (1950) are available. In most cases, scant experimental evidence exists to confirm the results which are displayed by the various authors graphically. No experimental evidence is available to confirm the adequacy of any of the solutions for their equivalent mass transport situation. Even for the qualitative effect of a simple change in air velocity on drying rates, there appears to be a large discrepancy in published results. Papers by Carrier (1921), Stevens (1956), Torgeson (1957), and Gaby (1961) suggest a linear variation of drying rate with velocity; yet experiments by Sherwood and Lewis (1929b; 1921) and recent practice in fluid mechanics would suggest that drying rates should vary as a power of one-half to eight-tenths velocity.

#### PREDICTION OF TOTAL DRYING TIME

The mechanism of drying in the falling rate period has been seen to be complicated, this period being, in general, divisible into two zones, involving at least two different drying mechanisms. However, for practical analysis of drying data and for computations involved in the design and operation of commercial drying equipment, it is important to have a simple formulation, which, even if only an approximation, is easily manipulated. Such an equation may be derived by the simplification that the drying rate is proportional to the moisture content (Lewis 1921; Nissan and Hansen 1961; Sherwood 1929b) or perhaps to a polynomial relation fitted to match the constant drying rate at the critical point. For example, the assumption of a linear variation of drying rate in the falling rate region yields Eq. (9). It is evident that knowledge of  $S_c$  and  $M.C._c$  provides a suitable method to construct analytical drying curves.

Although a knowledge of the variations of  $S_c$  is probably available from existing drying theories as discussed, there is very little systematic information available concerning the critical moisture content,  $M.C._c$ . From the studies of McCready and McCabe, the critical moisture content is related to the fiber-saturation moisture content, but it is not necessarily the same value (1933). The critical moisture content does not appear to vary significantly with relative humidity, air velocity, or slab thickness; however, it does vary with dry density or porosity.

#### CONCLUSION

The remarks contained in the previous sections summarize briefly the current status of the understanding of the lumber drying process as found in industrial kilns. The lack of a consistent set of experimental data and a conclusive analytical formulation is apparent. It is, therefore, concluded that future investigations should involve the measurement of actual mass and heat transfer data to determine, specifically, the influence of slab thickness, board width, turbulent intensity, surface roughness, and kiln geometry for presentation in terms of the specified dimensionless parameters. In addition, the mechanisms of the establishment of the constant-rate region, its duration, and the value of the critical moisture content warrant further investigation.

#### LIST OF SYMBOLS

| Symbol         | Definition   | Dimensions         |
|----------------|--|--------------------|
| A              | Surface area   | (L) <sup>2</sup>   |
| a              | One-half slab thickness  | L                  |
| c              | Water vapor concentration  | M/L <sup>3</sup>   |
| C.P.           | Critical point   | —                  |
| C <sub>f</sub> | Drag coefficient $\tau/(\rho U_\infty^2/2)$                        | —                  |
| c <sub>∞</sub> | Water vapor concentration of ambient air                           | M/L <sup>3</sup>   |
| c <sub>s</sub> | Saturation water vapor concentration at temperature T <sub>m</sub> | M/L <sup>3</sup>   |
| d              | Slab separation  | L                  |
| D              | Diffusion coefficient  | L <sup>2</sup> /T  |
| Δc             | c <sub>s</sub> - c <sub>∞</sub>                                    | M/L <sup>3</sup>   |
| E <sub>t</sub> | Evaporation weight per unit area and unit time                     | M/L <sup>2</sup> T |
| E              | See Eq. 9  | —                  |
| Gr             | Grashoff number $[\rho^2 g \beta (T - T_\infty) d^3] / \mu^2$      | —                  |

| Symbol     | Definition  | Dimensions                       |
|------------|---|----------------------------------|
| $Gr_m$     | Grashoff number due to concentration variation rather than temperature                | —                                |
| $h$        | Surface transfer coefficient  | $\frac{M}{L^2T}, \frac{Q}{L^2T}$ |
| $k_s$      | Effective roughness height  | L                                |
| $k_m$      | Exchange coefficient of vapor   | —                                |
| M.C.       | Moisture content  | —                                |
| $Nu_d$     | Nusselt number $hd/k$   | —                                |
| Pe         | Pecklet number $RePr$   | —                                |
| Pr         | Prandtl number $\mu c_p/k$  | —                                |
| $Re_s$     | Reynolds number $U_s d/\nu_s$   | —                                |
| $Re_d$     | Reynolds number $U_\infty \lambda/\nu$  | —                                |
| Sc         | Schmidt number $\rho D/\mu$   | —                                |
| $S_c$      | Drying rate at critical moisture content $(d \text{ mass}/dt)_c$                      | M/T                              |
| $Sh_d$     | Sherwood number $k_m d/(cD)$  | —                                |
| $St$       | Stanton number = $NuRe/Pr$  | —                                |
| t          | Time  | T                                |
| T          | Temperature   | $\theta$                         |
| T          | Turbulent intensity $\bar{v}/U_\infty$  | —                                |
| U          | Local velocity in boundary layer  | L/T                              |
| $U_s$      | Mean apparent shear velocity at the downstream end of the surface under consideration | L/T                              |
| $U_\infty$ | Ambient velocity of the mean motion   | L/T                              |
| w          | Weight of water evaporated  | —                                |
| x          | Distance downstream from the beginning of evaporation boundary                        | L                                |
| z          | Distance measured vertically from the surface of evaporation boundary                 | L                                |
| $z_1$      | Reference elevation   | L                                |
| $\Gamma$   | Gamma function  | —                                |
| $\rho$     | Density   | M/L <sup>3</sup>                 |
| $\mu$      | Dynamic viscosity   | M/LT                             |
| $\nu$      | Kinematic viscosity   | L <sup>2</sup> /T                |
| $\epsilon$ | Eddy diffusivity  | L <sup>2</sup> /T                |

LIST OF SUBSCRIPTS

| Subscripts | Definition      |
|------------|-----------------|
| l          | Equilibrium     |
| a          | Surface         |
| c          | Critical point  |
| e          | Equilibrium     |
| m          | Center plane    |
| o          | Initial         |
| db         | Drybulb         |
| pwb        | Pseudo-wet bulb |
| wb         | Wet bulb        |

REFERENCES

Wood Drying Literature

ANC BULLETIN. 1946. Kiln certification. Army-Navy—Civil Committee ANC-21.  
 BAKER, W. J. 1956. How wood dries. Forest Products Laboratory, Madison, Wisconsin. Rept. No. 1642.

BROWN, W. H. 1965. An introduction to the seasoning of timber. Pergamon Press, MacMillan Co., New York.  
 BURR, H. K., AND A. J. STAMM. 1956. Diffusion in wood. Forest Products Laboratory, Madison, Wisconsin. Rept. No. 1674.  
 CARRIER, W. H. 1921. The theory of atmospheric evaporation—with special reference to compartment dryers. I and E.C., 13: 432-458.  
 ———, AND A. C. STACY. 1921. The compartment dryer. I and E.C., 13: 438-447.  
 CHOONG, E. T., AND P. J. FOGG. 1968. Moisture movement in six wood species. Forest Prod. J., 18 (15): 66-70.  
 COMSTOCK, GILBERT L. 1963. Moisture diffusion coefficients in wood as calculated from adsorption, desorption, and steady state data. Forest Prod. J., 13: 97-103.  
 FESSEL, F. 1956. A turning point in the technique of drying. Austr. Timber J., 22: 125, 127-8, 131, 218.  
 GABY, L. I. 1961. Forced air-drying of southern pine lumber, Station Paper No. 121. USDA Southeastern Forest Experiment Station.  
 KEER, G. A. 1956. Air circulation in the drying kiln. Wood, 21: 314-316.  
 KOEHLER, A., AND R. THELEN. 1926. The kiln drying of lumber. McGraw-Hill, New York.  
 KOLLMANN, F. F. P. 1961. High temperature drying. Forest Prod. J., 11: 508-515.  
 LEWIS, W. K. 1921. The rate of drying of solid materials. I and E.C., 13: 427-432.  
 LYMAN, L. C. 1965. Effect of air flow on heat transfer and water evaporation in jet drying systems. Forest Prod. J., 15: 453-458.  
 MARSHALL, W. R., JR. 1958. Drying—Its status in chemical engineering in 1958. Chem. Eng. Progress, 55: 213-227.  
 MCCREADY, P. W., AND W. L. MCCABE. 1933. The adiabatic air drying of hygroscopic solids. Amer. Inst. of Chem. Eng., Trans., 29: 131-160.  
 MERONEY, R. N., AND J. OSTROWSKI. 1967. Preliminary examination of heat and mass transfer to stacked green lumber in drying kilns. Colorado State University, Fluid Dynamics and Diffusion Laboratory Report, CER66-67-31.  
 NEWMAN, A. B. 1932. The drying of porous solids. Cooper Union Bulletin, Engineering and Science Series, Vol. 42.  
 NISSAN, A. H., AND D. HANSEN. 1961. Fundamentals of drying porous materials. TAPPI, 44: 529-534.  
 PANSHIN, A. J., H. P. BROWN, AND C. C. FORSAITH. 1964. Textbook of wood technology, Vol. I and II. McGraw-Hill, New York.  
 REITZ, R. 1967. Personal communication.  
 SHERWOOD, T. K. 1929a. The drying of solids—I. I and E.C., 21: 12-16.  
 ———. 1929b. The drying of solids—II. I and E.C., 21: 976-980.

- STAMM, A. J. 1964. Wood and cellulose science. Ronald Press Company, New York.
- . 1967. Movement of fluids in wood—I—Liquids. II—Diffusion. Wood science and technology, Vol. 1, 122–141 and 205–230.
- STEVENS, W. C, D. D. JOHNSTON, AND G. H. PRATT. 1956. An investigation into the effects of air speed on the transference of heat from air to water. *Timber Technol.*, **64**: 537–539.
- , AND G. H. PRATT. 1958. The effect of air speed and flow direction on the drying of a pile of timber. *Timber Technol. and Mach. Woodworking, Wood Preservation, and Seasoning*, **66**: 121–23.
- TIEMANN, H. D. 1938. Lessons in kiln drying. Southern Timberman, Nashville.
- TORGESON, O. W. 1960. Why the drying time of a kiln load of lumber is affected by air velocity. Forest Product Lab., Report No. 1269, Madison, Wisconsin.
- . 1957. The drying rate of sugar maple as affected by relative humidity and air velocity. Forest Products Lab., Report No. 126, Madison, Wisconsin.
- . 1959. Circulation of air in a lumber drying kiln. Forest Products Lab., Report No. 1678, Madison, Wisconsin.
- TREYBAL, R. E. 1955. Mass transfer operations. McGraw-Hill, New York.
- TUTTLE, F. 1925. A mathematical theory of the drying of wood. *Franklin Inst. J.*, **200**: 609–614.
- VICK, C. B. 1965. Drying rate curves for one-inch yellow poplar lumber in low temperature forced-air dryers. *Forest Prod. J.*, **15**: 500–504.
- YAO, J. 1966. A new approach to the study of drying diffusion coefficients of wood. *Forest Prod. J.*, **16**: 61–69.
- Heat and Mass Transfer Literature*
- BARROW, H. 1962. An analytical and experimental study of turbulent gas flow between two smooth parallel walls with unequal heat fluxes. *Int. J. Heat Mass Trans.*, **5**: 469–487.
- . 1961. Convection heat transfer coefficients for turbulent flow between parallel plates with unequal heat fluxes. *Int. J. Heat Mass Trans.*, **1**: 306–311.
- BIRD, R. B., W. E. STEWART, AND E. N. LIGHTFOOT. 1960. Transport phenomena. John Wiley and Sons, Inc., New York.
- BRIDGMAN, P. W. 1931. Dimensional analysis. Yale University Press, London.
- CARSLAW, H. S., AND J. C. JAEGER. 1959. Conduction of heat in solids. Clarendon Press, Oxford. 510 p.
- CERMAK, J. E., AND P. N. LIN. 1955. Vapor transfer by forced convection from a smooth plane boundary. Report Prepared for the Office of Naval Research, Colorado State University, Fort Collins, Colorado, Report No. CER55JEC1.
- CRANK, J. 1956. The mathematics of diffusion. Clarendon Press, Oxford. 347 p.
- DEISSLER, R. G. 1953. Analysis of turbulent heat transfer and flow in the entrance regions of smooth passages, NACA TN 3016.
- HATTON, A. P., AND A. QUARMBY. 1963. The effect of axially varying and unsymmetrical boundary conditions on heat transfer with turbulent flow between parallel plates. *Int. J. Heat Mass Trans.*, **6**: 903–914.
- , AND I. GRUNDY. 1964. Further calculations on the heat transfer with turbulent flow between parallel plates. *Int. J. Heat, Mass Trans.*, **7**: 817–823.
- , AND ———. 1964. Shorter communications, comments on the effect of axially and unsymmetric boundary conditions on heat transfer with turbulent flow between parallel plates. *Int. J. Heat Mass Trans.*, **7**: 1143–1144.
- . 1963–64. Heat transfer in the thermal entrance region with turbulent flow between parallel plates at unequal temperatures. *J. Appl. Sci., Rev. Sec. A*, Vol. 12.
- JAKOB, M. 1949. Heat transfer, Vols. I and II. John Wiley and Sons, Inc., New York.
- KESTIN, J., AND P. O. RICHARDSON. 1963. Heat transfer across turbulent incompressible boundary layers. *Int. J. Heat, Mass Trans.*, **6**: 147ff.
- MAC ADAMS, W. H. 1954. Heat transmission. McGraw-Hill, New York. 532 p.
- MORI, Y., AND Y. UCHIDA. 1966. Forced convective heat transfer between horizontal flat plates. *Int. J. Heat, Mass Trans.*, **9**: 803–818.
- REYNOLDS, W. K., et al. 1960. A summary of experiments on turbulent heat transfer from a non-isothermal flat plate. *ASME, J. Heat Trans., Series C*, **82**: 341–346.
- ROTTA, J. C. 1965. Recent developments in calculation methods for turbulent boundary layers with pressure gradients and heat transfer. *J. Appl. Mech.* ASME Paper No. 66-APM-F.
- SEBAN, R. A. 1950. Heat transfer to a fluid flowing turbulently between parallel walls with asymmetric wall temperature, *Trans. ASME*, **72**: 789–795.
- SPALDING, D. B. 1963. Convective Mass Transfer. McGraw-Hill, New York.
- TERRILL, R. M. 1965. Heat transfer in laminar flow between parallel porous plates. *Int. J. Heat, Mass Trans.*, **8**: 1991–6498.
- YIH, C. S., AND J. E. CERMAK. 1951. Laminar heat convection in pipes and ducts. Civil Engineering Department, Colorado State University, Report No. CER47-52CSU8.