Technical Report

PRELIMINARY EXAMINATION OF HEAT AND MASS TRANSFER TO STACKED GREEN LUMBER IN DRYING KILNS

by

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LIST OF SYMBOLS

Symbol	Definition
a	One-half slab thickness
d	Slab separation
h	Surface heat transfer coefficient
k_s	Effective roughness height
m	Exponent
t	Time
u	Local instantaneous velocity in the direction of x
w	Local instantaneous velocity in the vertical direction perpendicular to u
u'	Fluctuation of local instantaneous velocity from the mean in the direction of u
w'	Fluctuation of local instantaneous velocity
x	Distance downstream from the beginning of evaporation boundary
y	Distance measured cross-wind from the center of evaporation surface
z	Distance measured vertically from the surface of evaporation boundary
z_1	Reference elevation
C	Water vapor concentration
C_f	Drag coefficient -- $\frac{\tau}{\rho U_\infty^2/2}$

List of Symbols - continued:

Symbol

S_T	Heat transfer coefficient -- $\frac{q}{\rho U_\infty c_p \Delta T}$
C_o	Initial moisture concentration
C_s	Saturation water vapor concentration at temperature T_m
C_1	Final moisture concentration
C_∞	Water vapor concentration of ambient air
ΔC	$C_s - C_\infty$
D	Diffusion coefficient
E_t	Evaporation weight per unit area and unit time
E	See Equation (2.7)
K_m	Exchange coefficient of vapor
L	Length of evaporation boundary
M.C.	Moisture content
Nu	Nusselt Number -- $\frac{hx}{k}$
Pe	Pecklet Number -- ReSc
Pr	Prandtl Number - - - - $\frac{\mu c_p}{k}$
R_x	Reynolds Number -- $\frac{U_o x'}{\nu}$
R_*	Reynolds Number -- $\frac{U_* x}{\nu e}$
Sc	Schmidt Number - - - $\frac{\rho D}{\mu}$
S_c	Drying rate at critical moisture content -- $(\frac{d.M.C.}{dt})_c$
T_{db}	Dry bulb temperature

List of Symbols - continued:

<u>Symbol</u>

T_m	Mean temperature of evaporation surface over a length x
T	Turbulent intensity--$\overline{v'}/U_\infty$
T_∞	Mean temperature of ambient air
T_{wb}	Wet bulb temperature
U	x-component of the velocity of mean motion
U_∞	Ambient velocity of the mean motion
U_*	Mean apparent shear velocity at the downstream end of the surface under consideration
W	Weight of water evaporated
ν	Kinematic viscosity of air (molecular diffusivity coefficient for momentum transfer in air)
ν_e	Molecular diffusivity coefficient for water vapor into air
ρ_m	Average density of air on the surface under consideration
ρ_∞	Density of ambient air
τ	Shearing stress in a horizontal plane in the direction of x
Γ	Gamma function

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1.0 INTRODUCTION

Interest in the mechanisms occuring during wood drying has increased rapidly over the last fifty years. Most efforts have been directed toward shortening the overall drying time -- it is still one of the predominant factors in the economics of lumber production. During the last ten years, many authors have stressed the importance of flow structure in the slots and uniform flow control in the kiln. In spite of the large number of tests and analyses made the lack of a proper description is strikingly evident. The flow properties have not been correctly described, and the majority of measurements made are not quantitatively correlatable or comparable.

To avoid undesirable shrinkage and stresses, it has generally been necessary that lumber be dried 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. 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 to heat and remove 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 degrade.

Yet, it is still apparent that seasoning of "dimension" lumber is the most time consuming operation in lumber manufacture.

Historically, the magnitudes and sequence of these states (i. e. the so-called schedule development) have been determined by t e dious empirical trial and error studies, which involved changing those variables the operator believed were pertinent. Unfortunately, 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.

For conventional industrial drying kilns, the dry bulb temperature range from approximately 100 to 180^{o} F. In these kilns, for certain species of sapwood the former period may amount to 1/4 to 1/3 of the total drying time. Recently, however, certain species of lumber have been successfully dried at temperatures above the boiling point up to 250^{o} F. At higher temperatures moisture diffuses faster within the wood substance, and as a result, the regime of total to partially circulation-controlled drying has been extended even to the final moisture content. Obviously, air flow efficiency is currently an important factor in drying economics.

Within the last ten years great advancements have been made in an understanding of the diffusion processes within wood substances. Studies by such researchers as Stamm [45], Tiemann [49], and Comstock [12], have resulted in a thorough and concise literature on the subject. On the other hand, the regime of aerodynamically dominated drying has received considerably less investigation. Much new information and techniques of measurements are available in the field of fluid mechanics as developed by other disciplines.

2.0 DRYING OF WOOD

2.1 Structure and Movement of Moisture

Wood inherently has a strong affinity for moisture. Large moisture contents in green lumber result from the normal life processes of the living tree. Left to itself, cut lumber will come to equilibrium with its environment; however, such air drying is slow, and the final moisture content is often not at a low value. Kilns accelerate and improve the natural process of seasoning.

The rate at which wood will dry under a given set of conditions varies widely even for the same species. This results because wood at its simplest is still a complex organic material whose properties may vary with the silviculture environment or the position taken from the tree (i.e. heartwood or sapwood, base or top). Some species contain localized wet pockets which affect properties and drying rates (hemlock, noble fir, sweetgum). Green wood may vary from 30 to 200% or more in initial moisture content.

There is a wealth of information on wood structure to identify wood or to obtain certain structural, chemical, or artistic properties [6, 45]. For drying, one is only interested in how the wood structure affects moisture passage. The structure determines where the moisture is held, how it comes out, and how shrinkage may degrade the lumber.

Physically, wood is a combination of tube-like hollow cells made of cellulose, and bound together by a chemical substance called lignin. Other organic substances and minerals also exist in the sap, between the cells, or in the cells, and they affect seasoning. The diameter to length ratio of these cells run from about 1/55 to 1/100. Softwoods contain fiberous cells 1/4 inch in length, uniform in width, and arranged in rows, randomly including resin ducts, pores, and ray cells. Hardwoods have smaller fibers, 1/25 inch in length, with larger pores and rays. In hardwoods the pores rather than the fibers carry most of the water.

The cells themselves are penetrated by 50 to 300 minute pores or pit chambers with pit membranes which are most numerous at the ends of the fibers. Moisture moving through these openings often moves fairly easily longitudinally. Ray cells also are distributed along radial sections of the tree. These are believed to transport moisture across the tree diameter. Their effect on wood drying does not appear to be clear. Water is retained in the tree as sap which contains dissolved organic and mineral substances (sugars, tannins, coloring mater, etc.) For drying purposes, sap may be assumed to have exactly the same characteristics as pure water. In general, sapwood (the wood nearer the bark) is wetter than the heartwood section of a tree; however, the heartwood may dry slower because of ducts and pores plugged with various resins.

Moisture appears to be retained in the wood in several different modes. These may be generally classed as

a) free water

b) bound water (hygroscopic), and

c) constituitive water.

Free water exists in the small tubular cell cavities or in the pores of the lumber. These cells are rarely full, but on the average could contain up to 25% more water. The rest of the cavity space is filled with air and water vapor. Free water will exist for any moisture content greater than 30%. Bound water is that moisture hygroscopically attached to the cell walls. For a moisture content from 6 to 30%, the water molecules are bound to the wood in poly-molecular layers in the capillaries and cells. Below 6% moisture conduct, all molecules exist in a monolayer over the wood. This first layer is attracted to the wood by a force about twice as great as the cohesive force of water for itself. Layers of molecules progressively further from the first layers are more mobile and free to exert their normal pressures. In green lumber, most sapwood contains free water while the moisture in the heartwood is usually in the bound state. Water is also present in chemical composition with the cell walls themselves as constituitive moisture. This water is not normally lost in good seasoning because its loss results in loss of strength.

Since the water in the cell cavities has the highest vapor pressure, it is normally removed first during drying. Most properties of wood remain constant until the free water is removed; however, when only bound water remains, these properties (strength, conductivity, etc.) vary with moisture content. The point where all free moisture is removed is called the "fiber-saturation point." Below this point, the wood begins to shrink and most wood defects appear (splitting, checking, case hardening, etc.). On an oven-dry weight basis, the fiber-saturation point exists approximately at a 30% moisture content for most woods. Another point often specificed is the "equilibrium moisture content." This is the moisture content at which the vapor pressures within the capillary structure of the wood are in equilibrium with the pressures exerted by the environment at a specified relative humidity and temperature.

The average softwood cavity diameter is approximately 0.0125 mm, and this reduces vapor pressure at the most by 0.01%. Hence, free water movement for moisture contents greater than 30% is not restricted by negatively-acting capillary forces as long as air exists in the individual cavities. Below the fiber saturation point, however, the equilibrium moisture content appears to be a direct function of the capillary structure. Thus, one can expect moisture to diffuse faster for a given moisture gradient at a high moisture content than for the same moisture gradient at a lower moisture content.

The structure of wood allows five basic passageways for moisture movement. They are fiber and vessel cavities, ray cells, pit chambers and pit membrane openings, resin ducts, and transitory cell-wall passages. The passageways available for moisture travel constitute 25 to 85% of the total wood volume. Most of the moisture loss moves through the cavities, pit chambers, and transitory cell-wall passageways in a devious path to the lateral surfaces.

Moisture may be moved to the drying surface by one of a combination of mechanisms. At high moisture contents, capillary action causes the free water to flow through the cell cavities and pit chambers. This is because free evaporation in the sheared surface cells occurs until concave depressions occur in the pit membrane openings. Surface tension exerts a pressure on columns of interior water greater than 31, 000 psi, and moves it to the surface. This continues until the column of liquid is broken for some reason, and the surface fibers fall below the fiber-saturation moisture content.

When the surface moisture content falls too low, the capillary effects retreat into the wood interior. Water vapor and bound water are driven by gradients in vapor pressure or moisture content to the wood surface. When this occurs, internal diffusion rates control the total drying rate of the lumber. Wood variables that control the rate of drying are the size and relative dimensions of the wood in the three different structural directions; the permeability of the wood, including species, structural variations, and sapwood versus heartwood; the specific gravity of the wood; its original moisture content and distribution; the refractiveness of the wood, and its tendency to develop fungus and chemical stains[45]. A detailed discussion of the structure of wood and the probable mechanisms of moisture movement through the lumber may be found in References, 1, 2, 6, 8, 38, and 45.

2.2 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 where different drying mechanisms were dominant [24, 42, 43]. 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 experiments indicate the presence of a constant rate regime for lumber, [37, 55]. At lower moisture contents the rate of moisture transport is limited by the ability of the water to diffuse through the wood to its surface -- hence the falling rate period.

Figure 1 is a generalized graph 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 the critical moisture content is reached until the solid is "dry" is the "falling rate period." Some authors divide the falling rate region into further sections,[32, 37, 42, 43]. It is 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[42, 57]. 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)[37, 42]. 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[32]. 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 similar manner to the constant rate drying region.

2.3 Falling Rate Period of Drying

Early investigators recognized the effect of the 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 the drying rates concentrated on the mathematical analogy between the coinduction of heat in solids and the diffusion of moisture in a porous media [1, 9, 24, 32, 36, 42, 43, 58, 59]. 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 [19]. In addition, the conduction-analogy model buries in a pseudo-integral diffusion coefficient the effects of variations in the circulation and tends to disguise the specific effects of the fluid motion.

The mathematical analogy theory of drying requires the following assumptions:

a) the validity of Ficks' second law of diffusion in a solid (the rate of change of concentration, dc/dt, 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, d^2c/dx^2);

b) the constancy of the diffusion factor D (proportionality constant in Ficks' second law);

c) a uniform moisture distribution when drying starts;

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, due to the moisture content gradient, 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 where water vapor and boundary water movement are in opposite directions [8]. 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 these boundary conditions 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 [58]. Subsequently, it was developed in greater detail, and convenient tables were produced by Newman [36].

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

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \tag{2.1}$$

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:

$$-\frac{\partial c}{\partial x} = h\,(c - c_1) \quad \text{at} \quad x = a$$

$$\frac{\partial c}{\partial x} = h\,(c - c_1) \quad \text{at} \quad x = -a \tag{2.2}$$

The original moisture distribution may also be parabolic,

$$c - c_1 = (c_m - c_1) - \frac{c_m - c_a}{a^2}\, x^2 \quad \text{at} \quad t = 0 \tag{2.3}$$

A solution which satisfies all these conditions is

$$c - c_1 = (c_m - c_1) \sum_{n=1}^{\infty} 2 \exp\left(-\left(\frac{Dt}{a^2}\right)\beta_n^2\right) A_n \operatorname{Cos} \frac{\beta_n x}{a}$$

$$- (c_m - c_a) \sum_{n=1}^{\infty} 2 \exp\left(-\left(\frac{Dt}{a^2}\right)\beta_n^2\right) B_n \operatorname{Cos} \frac{\beta_n x}{a} \tag{2.4}$$

in which the recurrsion expression for the coefficients is

$$A_n = \frac{h\,a}{\left[(h\,a)^2 + \beta_n^{\,2} + h\,a\right] \cos \beta_n}$$

$$B_n = \frac{2\,\beta_n^{\,2} + h\,a\,\beta_n^{\,2} - 2\,h\,a}{\left[(h\,a)^2 + \beta_n^{\,2} + h\,a\right] \cos \beta_n} \tag{2.5}$$

and β_n is defined by $\cot \beta_n = \beta_n / h\,a$. (Tabulated in Tables by Jahnke & Emde and in Reference 36.)

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,

$$w - c_1 = \frac{1}{2\,a} \int_{-a}^{a} (c - c_1)\, d\,x \tag{2.6}$$

results in expressions which may be abbreviated as

$$\frac{w - c_1}{c_o - c_1} = E\left(\frac{D\,t}{a^2}\right) \tag{2.7}$$

for an initially uniform distribution and as

$$\frac{w - c_1}{c_o - c_1} = \left(\frac{3\,c_m - 3\,c_1}{2\,c_m - 3\,c_1 + c_a}\right) E - \left(\frac{3\,c_m - 3\,c_a}{2\,c_m - 3\,c_1 + c_a}\right) E' \qquad (2.8)$$

for an initial parabolic distribution. The solution for an initially uniform moisture distribution results in Figure (2). Tables for E and E' in terms of $\left(\frac{Dt}{a^2}\right)$ and (h a) are included by Newman in Reference 38.

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 shall 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 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,[8, 12, 45, 60]. Drying diffusion coefficients for wood have been obtained from three different types of data involving measurements of:

a) moisture gradients set up under transient conditions;

b) rate of water flow in wood under steady-state conditions; and

c) rate of drying of wood.

The empirical diffusion coefficients are determined by fitting the experimental data to theoretical curves assuming Ficks' diffusion laws hold,[12, 36, 42, 45, 58]. Diffusion coefficients calculated in this manner for a swollen-volume specific gravity of 0.4 plotted versus reciprocal temperature is summarized by Stamm in Figure 23-1 of his text [45].

The diffusion of water through a complex network of capillaries in wood is analagous 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 analogy. This idea has been developed in detail by Stamm, et al., and the agreement between the theoretical and experimental values appears good,[8, 45]. Stamm has summarized the theoretical prediction for the diffusion coefficient between the fiber saturation point and the oven dry condition in Figure 23-3 of his text,[45].

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 co-efficient, [59].

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

A number of approximate drying relations have also been derived, [24, 32, 43]. 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

$$\ln E = \frac{S_c t}{(M.C._c - M.C._E)\, A D a} = -K \frac{t}{a} \qquad (2.9)$$

where K is an empirical constant. This constant is related to the pseudo-integral diffusion coefficient mentioned above, and has the same deficiencies.

2.4 Constant Rate Period of Drying

All 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.

In the wood drying literature, it is often observed that the actual length of time the constant rate period exists is very short. In addition, it is asserted 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^{o} F and a wet bulb depression of 20^{o} F. In addition, 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, [21].

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 the solid assumes 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), the dry-bulb temperature, the wet-bulb depression, the turbulent intensity level, the uniformity of the circulation, the 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, [51]. 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 2700 ft/min., [20]. Some investigators have examined the effect of fluid motion on a specific configuration and material, [24, 32, 43, 37]. 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 configuration. 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, [19, 47]. An article on the effects of pulsation on drying rate has been published, but has not resulted in any further attention in the drying literature, [14]. 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, (Raymond Reitz). One investigaor, Lymann, used a wetted felt mat material to evaluate the circulation effects in impingement drying in an effort to avoid the variations of wood, [27].

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

a) sapwood dries more rapidly than heartwood of a species; b) drying rates from the end grain is from 10 to 15 times as fast as the tangential section; c) that the drying rate, everything else being equal, is affected by velocity of air movement; and d) that 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 are 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 chapter.

3.0 MOISTURE TRANSPORT IN AIR FROM WETTED SURFACES

3.1 Dimensional Analysis

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.

Through a priori reasoning and empirical experience, the evaporation from a saturated surface may be influenced by the following general criteria:

a) the physical properties, both static and dynamic of the evaporating fluid;

b) the physical properties, the current state, and the dynamical description of the ambient stream; and

c) the characteristics of the evaporating surface and its environment, including geometry, temperature, and position.

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.

For many transport problems, it is possible to uncouple the inter-effects of momentum, heat, and mass transfer. Hence, the governing functional relation for momentum transport might appear as

$$f_1\left(U_{\infty}, x, d, a, k_s, \rho_m, \rho_{\infty}, \mu_o, \tau, \sqrt{\overline{-w-'^2}} \right) = 0 \tag{3.1}$$

Using the conventional dimensional analysis techniques as summarized by Bridgman, one obtains,[64]

$$f_2\left(\frac{\rho_o U_{\infty} x}{\mu_o}, \frac{x}{d}, \frac{d}{a}, \frac{k_s}{d}, \frac{\sqrt{\overline{-w-'^2}}}{U_m}, \frac{\tau}{\rho_o U_m^2}, \frac{\rho_{\infty} - \rho_m}{\rho_{\infty}} \right) = 0 \tag{3.2}$$

Several groups may be identified by separate symbols or regrouped such that,

$$f_3\left(Re_d, C_f, T, Gr, \frac{x}{d}, \frac{d}{a}, \frac{k_s}{d} \right) = 0 \tag{3.3}$$

where the individual terms are identified in the list of symbols.

In a similar manner, one may obtain for heat and mass transport the functional equations,

$$f_4\left(Re_d, Nu_d, T, Gr, Pr, \frac{x}{d}, \frac{d}{a}, \frac{k_s}{d} \right) = 0 \tag{3.4}$$

and

$$f_5\left(Re_d, Sh_d, T, Gr_m, Sc, \frac{x}{d}, \frac{d}{a}, \frac{k_s}{d} \right) = 0 \tag{3.5}$$

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, indicated in Table 1. In addition, the microscopic transport coefficients may often be simply replaced by their turbulent counterpart for turbulent flow; hence,

$$Pr = \frac{\mu\, cp}{k} \quad \text{may become} \quad Pr_t = \frac{\epsilon}{\epsilon_k},$$

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

3.2 General Equations of Turbulent Exchange

By a mass balance over an arbitrary differential fluid element, one can establish the equations of continuity for the two species (water vapor and air) in a binary fluid mixture. The insertion of expressions for turbulent exchange coefficients and the elimination of higher order terms by order of magnitude arguments produces a final diffusion equation, [63, 65, 71, 80]. In rectangular coordinates this becomes

$$\frac{\partial c}{\partial t} + \left(u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z} \right) = \frac{\partial}{\partial x}\left(K_m \frac{\partial c}{\partial x} \right)$$

$$+ \frac{\partial}{\partial y}\left(K_m \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z}\left(K_m \frac{\partial c}{\partial z} \right) \quad (3.6)$$

For the case of a steady, two dimensional, turbulent flow, this is,

$$u \frac{\partial c}{\partial x} = \frac{\partial}{\partial z}\left(K_m \frac{\partial c}{\partial z} \right) \quad (3.7)$$

3.3 Mass Transport Solutions

Extensive solutions are available for mass transport through a laminar boundary layer for a wide variety of boundary conditions including plates, pipes, ducts, and channels, [63, 71, 80]. Variations have been obtained for entrance regions, high mass transport rates, and variable wall temperatures or mass flux rates, [82, 83]. 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 the exchange coefficient for momentum is the same as for vapor transport. Stutton, Pasquill, Kohler, and Yih determined solutions very similar in format [65]. Yih's solution of wall evaporation is

$$\frac{c_s - c}{c_\infty - c_s} = \Gamma\left[\frac{m}{1 + 2m}, \frac{\eta^{1+2m}}{(1 + 2m)^2}\right]\left[\Gamma\left(\frac{m}{1 + 2m}\right)\right]^{-1} \qquad (3.8)$$

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

$$E_t x = \int_0^\infty \left[U(c - c_\infty)\right]_{\text{at } x} dz \qquad (3.9)$$

These expressions appear to correlate evaporation data for the flat wall case quite well. (See Figure 3).

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 [63].

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 in Section 3.1. Hence, if a solution is obtained for one transport process in a given situation and is expressed functionally as suggested by Equations 3.3, 3.4, or 3.5, 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 temperature, flux rates, and pressure gradients [72, 75, 76]. 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 [66, 70]. Since 1961 flow between parallel plates has specifically received concerted attention; recent papers by Hatton, et al., [67, 68, 69], Mori and Ochida [74], Barrow [61, 62], and Seban [77], are available. In most cases, scant experimental evidence exists to confirm the results which are displayed by the various authors graphically. None have considered the specific case of parallel plates with constant temperature walls in detail. 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 [9], Stevens [46], Torgeson [52], and Gaby [15], suggest a linear variation of drying rate with velocity; yet experiments by Sherwood [43] Lewis [24], and recent practice in fluid mechanics would suggest that drying rates should vary as a power of one-half to eight-tenths velocity.

3.4 Novel Drying Techniques to Accelerate Mass Transport

It is frequently true that transport rates of the greatest magnitude may be found in transient, intermittent, and random phenomena not easily analyzed nor investigated. A specific example in the heat transport during nucleate boiling which has defied specific analysis and descriptions for over four decades. Hence, it is pertinent to inquire if there is some phenomena which might intensify mass transport in a conventional drying kiln.

It appears that there may be two techniques worthy of specific investigation. The first mass transport intensifier considered involves the insertion of an array of small turbulence generators between the lumber layers. A possible design might be a series of small sheet metal delta wings. Properly oriented these delta wings should produce strong tip vortices which would scour the parallel walls and increase transport. Vortex motion is extremely stable and once produced would maintain itself for considerable slot depth. In addition, it is expected that the pressure drop across such flow impedances for a given increase in mass transport should be less than the pressure drop required to obtain equivalent mass transport with an increase in velocity. Since fan power increases with the cube of circulation velocity the economy might be considerable. A preliminary investigation of the delta-wing vortex generator is contained in Section 4.0.

It is well known that conical vortices are created along the edges of delta wings as shown in Figure 4 a,[84, 85, 86]. These vortices are steady in character, and when they do decay, they can create pressure pulsations from three to six times the dynamic pressure of the mean velocity depending upon the density of wing units placed in the slot. These pulsations are transmitted into an intense turbulence field with strong vertical and horizontal components.

There are two possible mounting configurations for such vortex generators in a slot. If the wings are mounted as in Figure 4 b the rotational velocity components will become accentuated. This secondary flow should be strong enough to transport fluid from the wall to the central stream and back, which would greatly increase heat and mass transport. If the wings are positioned so that the vortices generated are in opposition, as in Figure 4 c, then the flow will decay quickly, creating intense turbulence.

Either configuration may be satisfactory. The vortex generators should maintain their optimum performance at the velocities currently utilized in wood drying schedules.

Another novel device that appears to have merit involves the deliberate pulsation of the circulating air. Although the mechanisms in such flow are not at all clear, flow visualization studies have indicated that heat appears to almost boil upward from a cooled surface when the convecting medium is periodically halted and then started again. It appears that most transport occurs across a developing boundary layer rather than a developed layer. The action might be visualized as similar to the agitation obtained in an automatic laundry machine. This concept has received attention in German and Russian literature; however, it has not been considered in any detail in the United States [14]. The concept may be incorporated in existing kilns through the implimentation of movable baffles in the circulating air streams. The quantitative value of this technique and its optimization should be determined empirically.

3.5 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 diversible 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, [24, 37, 43], or perhaps to a polynominal relation fitted to match the constant drying rate at the critical point.

The assumptions of a linear variation of drying rate in the falling rate region yields

$$\ln E_f = \frac{S_c t}{(M.C._c - M.C._e) A \rho a} \qquad (3.10)$$

where

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

A = surface area

ρ = density of dry solid

S_c = rate of drying in constant rate region

a = one-half thickness of wood slab.

Hence, 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 are probably available from existing drying theories discussed in Section 3.3, 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 [32]. 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.

4.0 EXPERIMENTAL EXAMINATION OF NOVEL DRYING TECHNIQUE: VORTEX GENERATION

To weigh the importance of different drying variables, it is considered necessary to perform a typical drying experiment. Measurements were made to evaluate the order of magnitude and importance of temperature, moisture content, drying rates, roughness, velocity, and the ability to maintain a drying control. In addition, it is expected to qualitatively evaluate the effectiveness of the delta-wing vortex generators discussed in Section 3.4.

4.1 Experimental Arrangement

The Army Meteorological Wind Tunnel in the Fluid Dynamics and Diffusion Laboratory at Colorado State University has the capability of producing temperature, humidity, and velocity conditions typically found in an industrial drying kiln. The Army Meteorological Wind Tunnel includes a 6 by 6 foot cross-section with an 80 foot test-section length. Velocity can be controlled from zero to 100 fps, and humidity and temperature are variable from 0 to 100%, and 32°F to 180°F respectively. The general tunnel configuration is shown in Figure 5. The tunnel was not designed for drying applications; hence, the kiln loading arrangement and operation schedule were not conventional.

The lumber stacks consisted of six layers of Engleman Spruce ten to twelve boards deep. Each board was rough cut lumber 1 inch thick by 8 inches wide and 6 feet long. The layers were separated by 5/8" by 3/4" stickers. The stacking configuration, including sheet metal entrance vanes and brick and fence baffles, is shown in Figure 6.

The separating stickers were so notched that a set of six test boards could be removed for weighing during drying. Two boards were positioned downstream from a set of delta-wing vortex generators. The delta-shaped generators were manufactured from 1/32" thick sheet metal and soldered at a uniform spacing to a small diameter positioning rod which was driven firmly into the board upstream of the test boards. These generators are shown in place in Figure 7. For each test board affected by vortex intensified flow, there was a second board cut from the same piece of lumber in a geometrically similar position in the stack to act as a control.

The flow velocity was measured by a pitot tube positioned directly behind the stack slots on a traversing mechanism. The dynamic pressure head was measured by a Transonic pressure transducer and recorded on an x-y recorder. Dry- and wet-bulb temperatures of the circulating air up- and downstream of the stacked lumber were indicated on psychrometers hung in the main air stream.

A copper-constantan thermocouple was also installed in one test board in a 1/16" diameter hole drilled parallel to the lateral surfaces.

All tests were initiated with an average flow velocity of 10 feet/sec in the slots. Dry bulb temperatures were maintained at 130° F and wet bulb depression was 17 to 20° F.

4.2 Discussion of Experimental Results

A total of nineteen sample boards were weighed and the surface moisture content measured during four separate lumber charges. A final dry weight was also measured for each board. The results were displayed as moisture content versus time, rate of change of moisture content versus time, and rate of change of moisture content versus moisture content.

The originial moisture content of the samples chosen from the first charge were all less than the fiber-saturated point. No constant rate region was indicated. Samples chosen for the other charges ranged in initial moisture content from 30 to 190% moisture content on a dry weight basis. All samples encountered constant rate region drying, and in most cases, this amounted to at least one-fifth the total drying time. Not all pieces of lumber were of equal thickness; samples up or downstream from thicker slabs appeared to deviate strongly from the mean drying rate. Due to wide sample variations, no statistical analysis of data was possible.

A wide variation was observed in the absolute magnitude of the drying rate in the constant rate region for the various samples. The curves for the widest deviations are shown in Figure 8. An examination of the lumber after each drying schedule revealed severe warping. In addition, velocity profiles measured behind the charge of lumber indicated a wide variation of the average velocity in any given slot as shown in Figure 9. It is hypothesized that the variations of drying rate result from variations in flow circulation due to warping in the stack.

It does not seem reasonable, however, that the large variation in drying rate noticed during the constant rate regime can be entirely due to non-uniformity in flow velocity. Other possible explanations are initial conditions near the fiber saturation point, variations in initial moisture distribution through the samples, and transition from laminar to turbulent mechanisms. A more probable hypothesis is that variations in porosity within the board itself yield only patches of fully wetted surface even during constant rate drying; hence, the effective drying area may vary from sample to sample. Thus, any decisive study of the constant rate region should be performed over a homogeneous fully wetted porous material, and an average actual wetted area factor be estimated or measured for various species.

It should be observed that flow non-uniformity was found in spite of uniform flow upstream of the lumber stack. The addition of disturbing agents such as the vortex generating delta-wings make the flow more uniform and improve drying quality.

The variations discussed above make it very difficult to reach any conclusion concerning the effectiveness of the delta-wing vortex generators. Comparison of the test samples and their controls were very poor. A comparison of wood samples with the same initial moisture content with and without vortex generators is displayed in Figure 8 (a). In addition, it was observed that two samples with vortex generation upstream and an average flow velocities of 7 ft/sec dried at about the same rate as two control samples without vortex generators and an average flow velocity of 12 ft/sec. The same test performed over evaporation surfaces maintained in the constant rate region without warping would be decisive.

Other characteristics of the drying process that were observed have been described by other authors. A typical rate of change of moisture content versus moisture content (Figure 8) reveals the constant rate, falling rate, and critical point configuration. The critical points all fell close to the supposed fiber-saturation value of 28% moisture content. The falling rate curves begin with a sudden break and reveal a parabolic slope. Temperature versus time curves(Figure 9) reveal the initial heating periods, the constant rate period, and the falling rate periods observed in Reference 37. In addition, the pseudo-wet bulb temperature during the falling rate period is obvious.

5.0 RECOMMENDATIONS FOR FUTURE RESEARCH

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 investigations in the following areas are urgently needed:

1. Measurement of flow dynamics between parallel surfaces should be made to determine,
   a) the influence of the geometrical parameters of slot thickness, board width, and length on the velocity distribution and turbulent intensity (longitudinal and vertical),
   b) the influence of roughness and the separation regions near the board edges on turbulence generation, and
   c) the effect of artificial vortex generation on the turbulent intensities, heat and mass transfer, and power input by circulating fans.
2. Measurement of actual mass and heat transfer data in the optimum flow configuration suggested by findings from studies under Section 3.3 to determine the influence of turbulence level, slot geometry, etc. when:

a) a homogeneous re-wettable medium is used to simulate the constant-rate drying regime, and

b) sample boards of various species of wood are utilized to determine the critical point and expected variances due to nonhomogeneous structure.

3. Development of the proper analytical formulations to generalize the conclusions of Sections 3 and 4.
4. A study of the effect of artificial vortex generation and/or flow pulsation on drying rates.
5. Optimization of kiln geometry to provide uniform flow through the stacked lumber, including development of flow control and estimation of turbulence levels, through flow visualization of the fluid motion in various kiln models.

BIBLIOGRAPHY

<u>Wood Drying Literature</u>

1. ANC Bulletin, "Kiln Certification," Army-Navy - Civil Committee ANC-21, March 1946.

2. Baker, W. J., "How Wood Dries," Forest Products Laboratory, Madison, Wisconsin, Rept. No. 1642, September 1956.

3. Bateson, R. B., "<u>Timber Drying</u>," London, 1946.

4. Biggerstaff, T., "Drying Diffusion Coefficients in Wood," <u>Forest Products Journal</u>, March 1965. pp. 127-133.

5. Brown, M. C., "High Temperature Kiln Drying of Lodgepole Pine Studs," M.S. Thesis in Forestry, Colorado State University, August 1965.

6. Brown, W. H., "<u>An Introduction to the Seasoning of Timber</u>," Pergamon Press, MacMillan Co., New York, 1965.

7. Bryant, R. C., "<u>Lumber, - Its Manufacture and Distribution</u>," John Wiley and Sons, Inc., 1922.

8. Burr, H. K. and A. J. Stamm, "Diffusion in Wood," Forest Products Laboratory, Madison, Wisconsin, Rept. No. 1674, March 1956.

9. Carrier, W. H., "The Theory of Atmospheric Evaporation - With Special Reference to Compartment Dryers," <u>I and E.C.</u>, Vol. 13, 1921, pp. 432-438.

10. Carrier, W. H. and A. C. Stacy, "The Compartment Dryer," <u>I and E.C.</u>, May 1921. Vol. 13, No. 5, pp. 438-447.

11. Cobler, W. E., "Accelerated Air-Drying Rate of Sugar Maple as Affected by Relative Humidity and Air Velocity," Forest Products Laboratory, Rept. No. 1264, April 1957.

12. Comstock, Gilbert L., "Moisture Diffusion Coefficients in Wood as Calculated from Adsorption, Desorption, and Steady State Data." <u>Forest Prod. Journal</u>. Mar. 1963, pp. 97-103.

13. Devine, John., Production Kiln Drying, May 1960.

14. Fessel, F., "A Turning Point in the Technique of Drying," Australian Timber Journal, 22, p. 125, 127-8, 131, 218, March 1956.

15. Gaby, L. I., "Forced Air-Drying of Southern Pine Lumber," Station Paper No. 121, USDA Southeastern Forest Experiment Station, May 1961.

16. Hann, R. A., "Theoretical Considerations in the Drying of Wood at Pressures Above Atmospheric," Forest Product Journal, Vol. 16, No. 4, (April 1966) pp. 25-32.

17. Haygreen, J. G., "Status of Drying Research and Practice," Forest Products Journal, Jan. 1965, pp. 1-7.

18. Henderson, H. L., The Air Seasoning and Kiln Drying of Wood, J. B. Lyan Comp., Pub., Albany, N. Y., 1939.

19. Keer, G. A., Air Circulation in the Drying Kiln, Wood, Vol. 21, pp. 314-316, (London) Aug. 1956.

20. Koehler A., and R. Thelen, The Kiln Drying of Lumber, McGraw Hill Book Co., New York, 1926.

21. Kollmann, F. F. P., "High Temperature Drying," Forest Products Journal, Nov. 1961, pp.

22. Kozlik, Charles J., "Developments in Wood Drying," Forest Products Journal, Jan. 1963.

23. Latvian Academy of Science, "Rational Methods of Utilizing and Drying Lumber," Book 26, Publication of Latvian Academy of Sciences.

24. Lewis, W. K., "The Rate of Drying of Solid Materials," I and E. C., Vol. 13, 1921, pp. 427-432.

25. Liversidge, R. M., and R. Finigan, "Low Speed Wind Tunnel to Aid Air-Seasoning Research," Southern Lumberman, Nov. 15, 1964, pp. 27-28.

26. Lowery, David P. "Developments in Wood Drying," Forest Products Journal, Jan. 1964, pp. 1-8.

27. Lyman, L. C. "Effect of Air Flow on Heat Transfer and Water Evaporation in Jet Drying Systems," Forest Products Journal, October 1965, pp. 453-458.

28. Krechetov, L. Wood Drying, Agriculture and Forestry State Publications, Warsaw, Poland, 1953.

29. MacLean, J. D. "Thermal Conductivity of Wood," Heating, Piping and Air Conditioning Journal, June 1964, pp. 380-391.

30. Malinquist, V. L. and H. Meischner, "On the Heat Transfer in Convective Drying of Wood in Superheated Steam," Holz als Roh-und Werkstoff, 22. Jg Heft 3, Marz 1964, pp. 95 - 106.

31. Mathewson, James S. "High-Temperature Drying: Its Application to the Drying of Lumber," Journal of FPRS, Oct. 1954, pp. 276-279.

32. McCready, P. W. and W. L. McCabe, "The Adiabatic Air Drying of Hygroscopic Solids," American Institute of Chemical Engineers, Trans. Vol. 29, pp. 131-160, 1933.

33. Millett, Ralph S. "New Tools Highlight Wood Drying," Forest Products Journal, Jan. 1962, pp. 1-6.

34. Modern Techniques for the Drying and Conditioning of Timber O. E. E. C., Paris, Project No. 241, July, 1957.

35. Nelson, Donald E. "The Role of Temperature in the Relief of Drying Stresses," Forest Products Journal, Mar. 1963, pp. 124-130.

36. Newman, A. B. "The Drying of Porous Solids," Cooper Union Bulletin, Engineering and Science Series, Vol. 5 No. 42, 1932.

37. Nissan, A. H. and D. Hansen, "Fundamentals of Drying Porous Materials," Tappi, Vol. 44, No. 8, Aug. 1961 pp. 529-534.

38. Panshin, A. J., H. P. Brown, and C. C. Forsaith, Textbook of Wood Technology, Vol. I and II, McGraw Hill, New York, 1964.

39. Preston, S. B. and D. E. Nelson "Wood Seasoning Bibliography, 1956-7," Forest Products Journal, Feb. 1959, pp. 81-84.

40. Rzadkawski, S. T., Lumber Drying in Kilns, Agricultural Forestry State Publications, Warsaw, Poland, 1962.

41. Rice, W. W., "Annual Review of Wood Drying," Forest Products Journal, Vol. 16, No. 1, Jan. 1966, pp. 19-23.

42. Sherwood, T. K., "The Drying of Solids-I," I and E. C., Vol. 21, No. 1, 1929, pp. 12-16.

43. Sherwood, T. K., "The Drying of Solids-II", I and E. C., Vol. 21, No. 10, October 1929, pp. 976-980.

44. Shovchkov, P. A., Processes of Wood Drying in Forestry Industry, Forest Industry, Moscow, 1965.

45. Stamm, A. J., Wood and Cellulose Science, Ronald Press Company, New York, 1964.

46. Stevens, W. C., D. D. Johnston, and G. H. Pratt, "An Investigation into the Effects of Air Speed on the Transference of Heat from Air to Water," Timber Technology, Vol. 64, No. 2208, Oct. 1956, pp. 537-9.

47. Stevens, W. C. and G. H. Pratt, "The Effect of Air Speed and Flow Direction on the Drying of a Pile of Timber," Timber Technology and Mach. Woodworking, Wood Preservation and Seasoning, Vol. 66, (2225) pp. 121-23, March, 1958.

48. Thelen, R., Kiln Drying Handbook, U. S. Dept. of Agriculture, Dept. Bulletin No. 1136, May 1929.

49. Tiemann, H. D., "Lessons in Kiln Drying," Southern Timberman, Nashville, Sept. 1938.

50. Tiemann, H. D., The Kiln Drying of Lumber, J. B. Lippincott Co., Philadelphia, 1917.

51. Torgeson, O. W. "Why the Drying Time of a Kiln Load of Lumber is Affected by Air Velocity," Forest Product Lab. Report No. 1269, Wisconsin, 1960.

52. Torgeson, O. W., "The Drying Rate of Sugar Maple as Affected by Relative Humidity and Air Velocity," Forest Products Laboratory, Report 126, April, 1957.

53. Torgeson, O. W., "Function and Calculation of Ventilation in Drying Compartments," Forest Products Lab. Report No. 1265, Oct. 1958.

54. Torgeson, O. W., "Techniques of Developing a Drying Process for Small Stock," Forest Products Lab. Report No. 1263, Feb. 1955.

55. Torgeson, O. W., "Circulation of Air in a Lumber Drying Kiln," Forest Products Laboratory, Report No. 1678, Jan. 1959.

56. Torgeson, O. W., "Simplifying the Calculation of the Quantity of Air Required in Kiln Drying Lumber," Forest Products Laboratory, Report No. 1266, 1960.

57. Treybal, R. E., Mass Transfer Operations, McGraw Hill, 1955.

58. Tuttle, F., "AMathematical Theory of the Drying of Wood," Franklin Inst. Journal, Vol. 200, pp. 609-614, 1925.

59. Vick, C. B., "Drying Rate Curves for One-Inch Yellow Poplar Lumber in Low Temperature Forced-Air Dryers," Forest Products Journal, Dec. 1965, pp. 500-504.

60. Yao, J., "A New Approach to the Study of Drying Diffusion Coefficients of Wood," Forest Products Journal, Vol. 16, June, 1966, pp. 61-69.

Heat and Mass Transfer Literature

61. Barrow, H., "An Analytical and Experimental Study of Turbulent Gas Flow Between Two Smooth Parallel Walls with Unequal Heat Fluxes," Int. J. Heat Mass Transfer, Vol. 5 pp. 469-487. Pergamon Press, 1962.

62. Barrow, H., "Convection Heat Transfer Coefficients for Turbulent Flow Between Parallel Plates with Unequal Heat Fluxes," In. J. Heat, Mass Trans., V.1, pp. 306-311, Pergamon Press, 1961.

63. Bird, R. B., W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, John Wiley and Sons, Inc., New York, 1960.

64. Bridgman, P. W., Dimensional Analysis, Yale University Press, London, 1931.

65. Cermak, J. E., and P. N. Lin, "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, Jan. 1955.

66. Deissler, R. G., "Analysis of Turbulent Heat Transfer and Flow in the Entrance Regions of Smooth Passages," NACA TN 3016, Oct. 1953.

67. Hatton, A. P., and A. Quarmby, "The Effect of Axially Varying and Unsymmetrical Boundary Conditions on Heat Transfer with Turbulent Flow Between Parallel Plates," Int. Journal of Heat and Mass Transfer, Vol. 6, No. 10, Oct. 1963, pp. 903-914.

68. Hatton, A. Quarmby, & I. Grundy, "Further Calculations on the Heat Transfer with Turbulent Flow Between Parallel Plates. Int. J. Heat, Mass Transfer, Vol. 7, pp. 817-823, Pergamon Press, 1964.

69. Hatton, A. P., and A. Quarmby, "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 Transfer, Vol. 7, pp. 1143-1144, Pergamon Press, 1964.

70. Hatton, A. P., "Heat Transfer in the Thermal Entrance Region with Turbulent Flow Between Parallel Plates at Unequal Temperatures, J. Applied Science, Rev. Sec. A. Vol. 12, 1963-64.

71. Jakob, M., Heat Transfer, Vols. I & II, John Wiley & Sons, Inc., New York, 1949.

72. Kestin, J., and P. O. Richardson, "Heat Transfer Across Turbulent Incompressible Boundary Layers," Int. J. of Heat, Mass Transfer, Vol. 6, No. 2, Feb. 1963, pp. 147ff.

73. Lighthill, M. J., "Contributions to the Theory of Heat Transfer Through a Laminar Boundary Layer," Proceedings of Royal Society of London, Vol. 202A, pp. 359-377, 1950.

74. Mori, Y., and Y. Uchida," Forced Convective Heat Transfer Between Horizontal Flat Plates," Int. Jour. of Heat, Mass Transfer, Vol. 9, No. 8, Aug. 1966, pp. 803-18.

75. Reynolds, W. K., et al., "A Summary of Experiments on Turbulent Heat Transfer from a Non-Insothermal Flat Plate," ASME, Jour. of Heat Transfer, Vol. 82, Series C., No. 3, Aug. 1960, pp. 341-46.

76. Rotta, J. C., "Recent Developments in Calculation Methods for Turbulent Boundary Layers with Pressure Gradients and Heat Transfer," J. of Applied Mech., March 1965, ASME Paper No. 66-APM-F.

77. Seban, R. A., "Heat Transfer to a Fluid Flowing Turbulently Between Parallel Walls with Asymmetric Wall Temperature," Trans, ASME, Vol. 72, 1950, pp. 789-795.

78. Sherwood, T. K., "Mass, Heat, and Momentum Transfer Between Phases," Chemical Engineering Progress Symposium, Series No. 25, Vol. 55, 1958, p. 71ff.

79. Sleicher, C. A.Jr., & M. Tribus, "Heat Transfer in a Pipe with Turbulent Flow and Arbitrary Wall Temperature Distribution," Trans. ASME, Vol. 79, 1957, pp. 789-797.

80. Spalding, D. B., Convective Mass Transfer, McGraw Hill Book Company, New York, 1963.

81. Sparrow, E. M., and R. Siegel, "Unsteady Turbulent Heat Transfer in Tubes," Trans. ASME, Aug. 1960, pp. 170-180.

82. Terrill, R. M., "Heat Transfer in Laminar Flow Between Parallel Porous Plates," Int. Jour. of Heat and Mass Transfer, Vol. 8, No. 12, December 1965, pp. 1991-6498.

83. Yih, C. S., and J. E. Cermak, "Laminar Heat Convection in Pipes and Ducts," Civil Engineering Department, Colorado State University, Report CER47-52CSU8, Sept. 1951.

Vortex Generation Literature

84. Kuchemann, D., "Types of Flow on Swept Wings," Journal of the Royal Aeronautical Society, Vol. , November, 1963, pp.

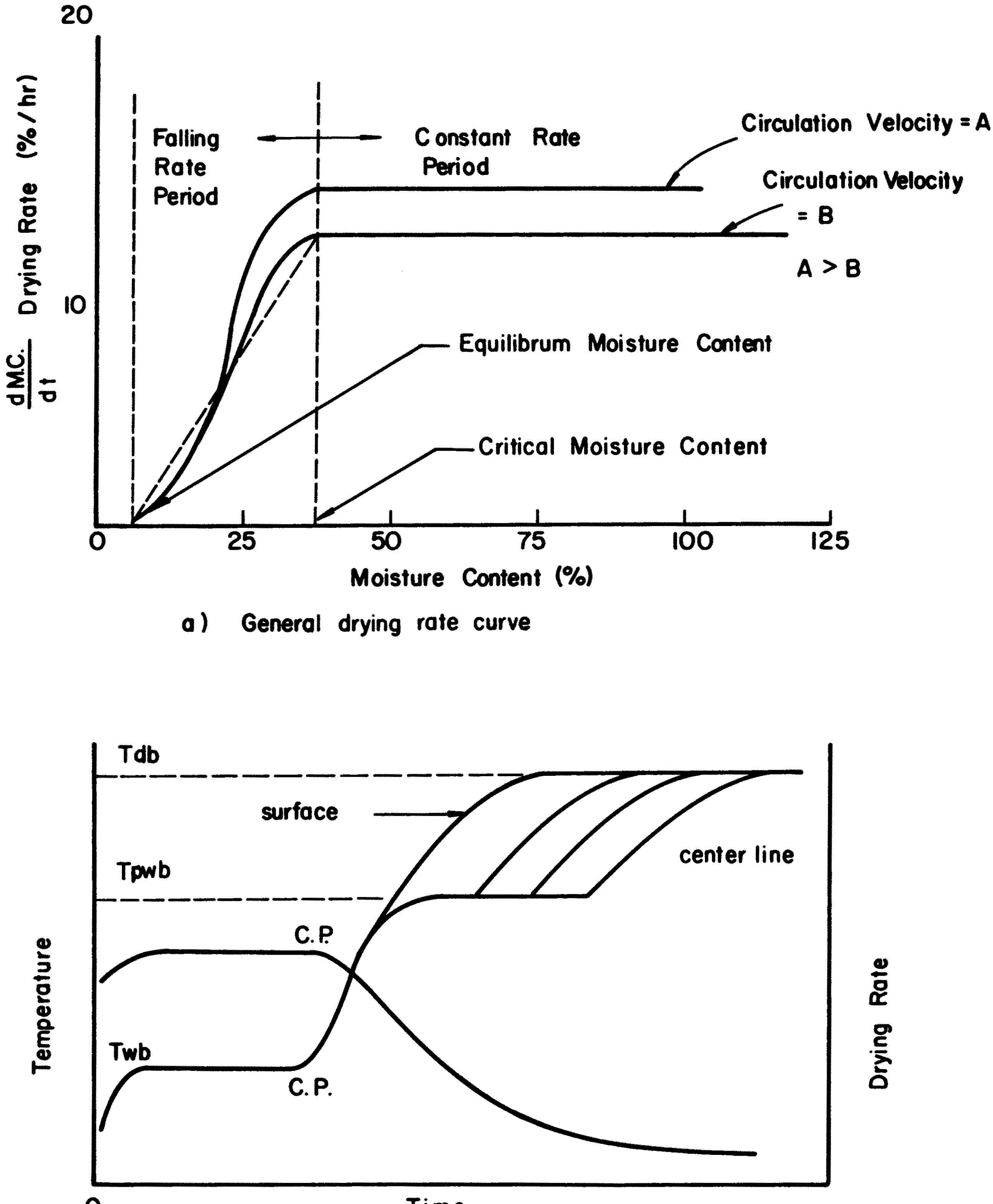
85. Ostrowski, J. S., "Flow Properties of Swept Back Wings at High Incidences," Archiv. of Machinary Building, Book VII, Warsaw, Poland, 1960.

86. Verle, M.," Visualization en Tunnel Hydrodynamics, La Recherche Aeronautique, No. 33, 1953.

TABLE 1

ANALOGIES BETWEEN HEAT AND MASS TRANSFER AT LOW MASS-TRANSFER RATES

	Heat-Transfer Quantities	Binary Mass-Transfer Quantities
Profiles	T	x_A
Diffusivity	$\alpha = \frac{k}{\rho C_\nu}$	AB
Effect of profiles on density	$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_{p, x_A}$	$\zeta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial x_A}\right)_{p,T}$
Flux	$q^{(c)}$	$J_A = N_A - x_A (N_A + N_B)$
Transfer rate	Q	$w_A^{(m)} - x_{A0}(w_A^{(m)} + w_B^{(m)})$
Transfer coefficient	$h = \frac{Q}{A \Delta T}$	$k_x = \frac{w_A^{(m)} - x_{A0}(w_A^{(m)} + w_B^{(m)})}{A \Delta x_A}$
Dimensionless groups which are the same in both correlations	$Re = \frac{DV\rho}{\mu} = \frac{DG}{\mu}$ $Fr = \frac{V^2}{gD}$ $\frac{L}{D}$	$Re = \frac{DV\rho}{\mu} = \frac{DG}{\mu}$ $Fr = \frac{V^2}{gD}$ $\frac{L}{D}$
Basic dimensionless groups which are different	$Nu = \frac{hD}{k}$ $Pr = \frac{C_p \mu}{k} = \frac{\nu}{\alpha}$ $Gr = \frac{D^3 \rho^2 g \beta \Delta T}{\mu^2}$ $St = \frac{Nu}{Re\,Pr} = \frac{h}{\rho C_p V}$	$Nu_{AB} = \frac{k_x D}{c \quad \mathrm{AB}}$ $Sc = \frac{\mu}{\rho \quad \mathrm{AB}} = \frac{\nu}{\mathrm{AB}}$ $Gr_{AB} = \frac{D^3 \rho^2 g \zeta \Delta x_A}{\mu^2}$ $St_{AB} = \frac{Nu_{AB}}{Re\,Sc} = \frac{k_x}{c V}$
Special combinations of dimensionless groups	$Pe = Re\,Pr = \frac{D V \rho C_p}{k}$ $jH = Nu\,Re^{-1} Pr^{-1/3}$ $= \frac{h}{\rho C_p V}\left(\frac{C_p \mu}{k}\right)^{2/3}$	$Pe_{AB} = Re\,Sc = \frac{DV}{\mathrm{AB}}$ $jD = Nu_{AB} Re^{-1} Sc^{-1/3}$ $= \frac{k_x}{c V}\left(\frac{\mu}{\rho \quad \mathrm{AB}}\right)^{2/3}$



a) General drying rate curve

b) Generalized Time-Temperature Record

FIGURE I: DRYING RATE CURVES

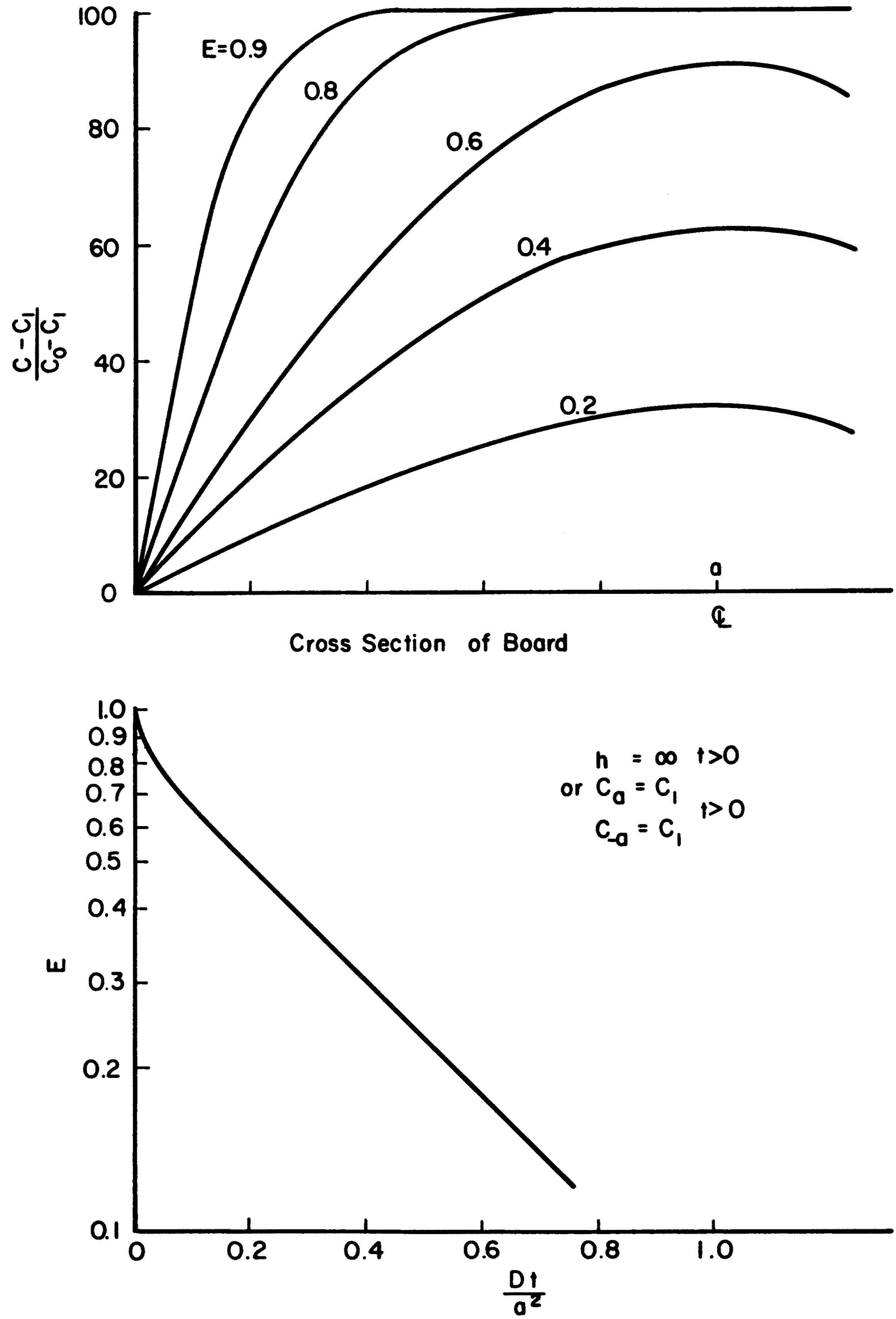


FIGURE 2: MOISTURE GRADIENTS FOR ZERO SURFACERRESISTANCE AND UNIFORM INITIAL MOISTURE DISTRIBUTION

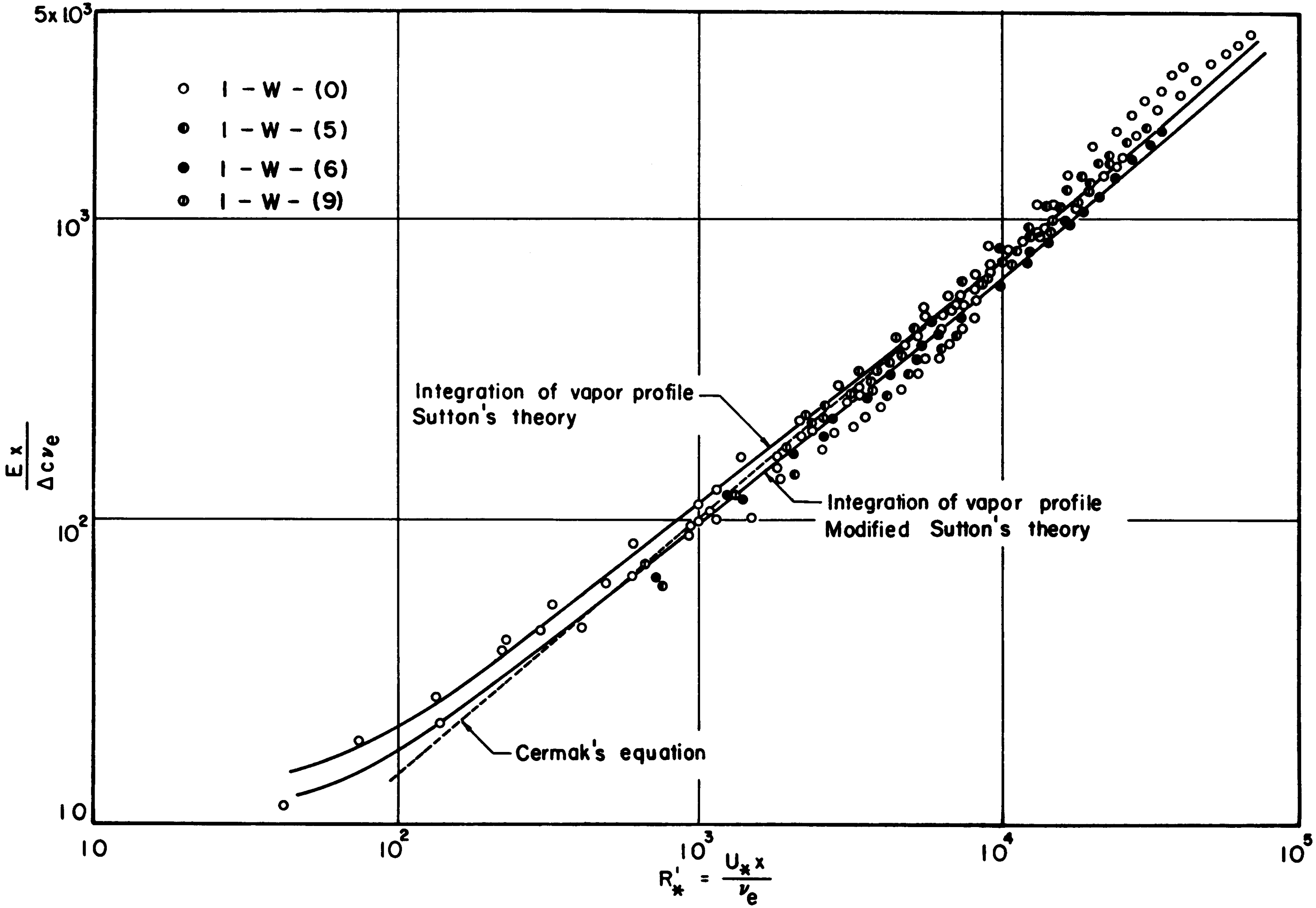


FIGURE 3 VARIATION OF N WITH R'_* FOR TURBULENT BOUNDARY LAYER (BUFFERS WET, ALL DATA)

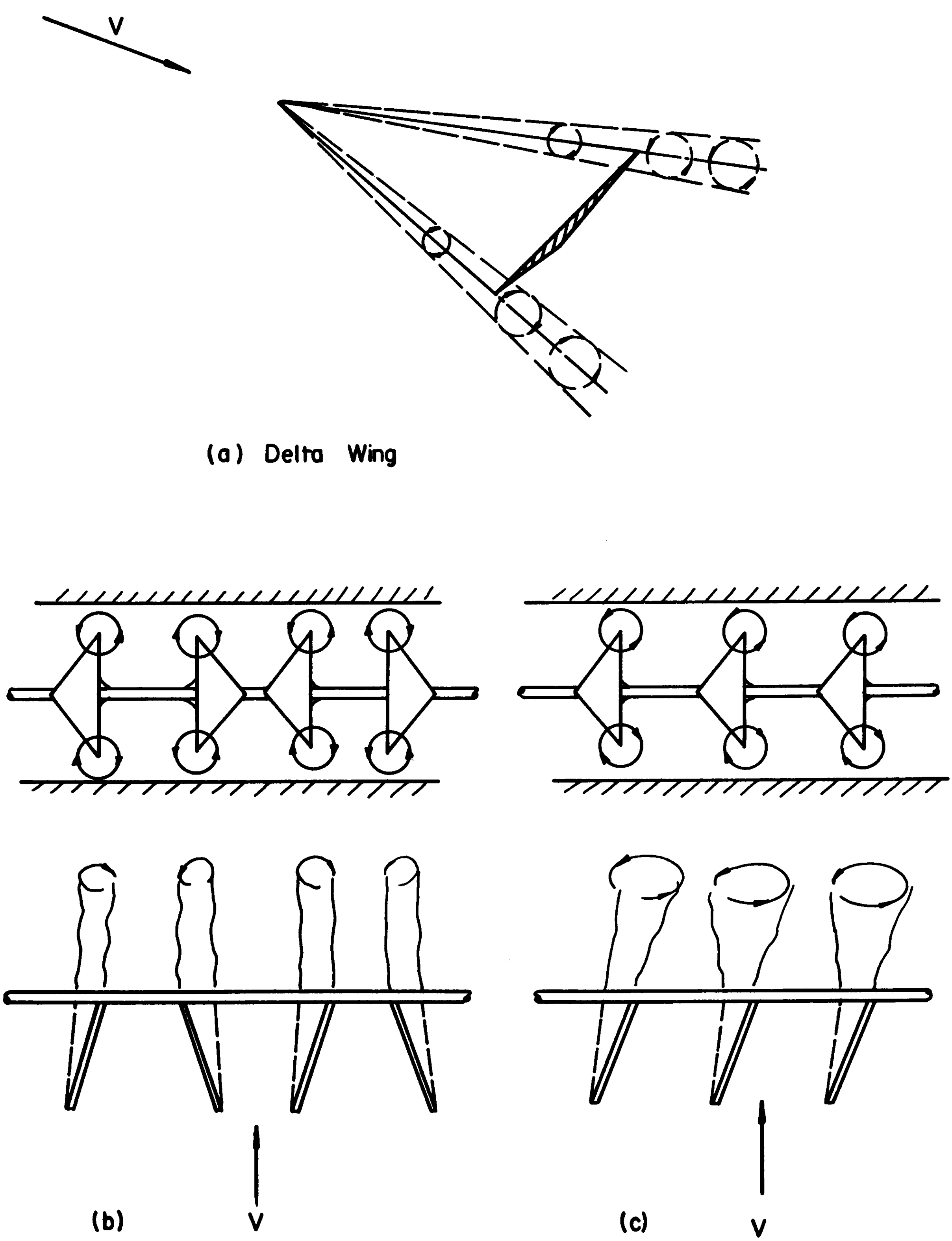


FIGURE 4 VORTEX GENERATORS

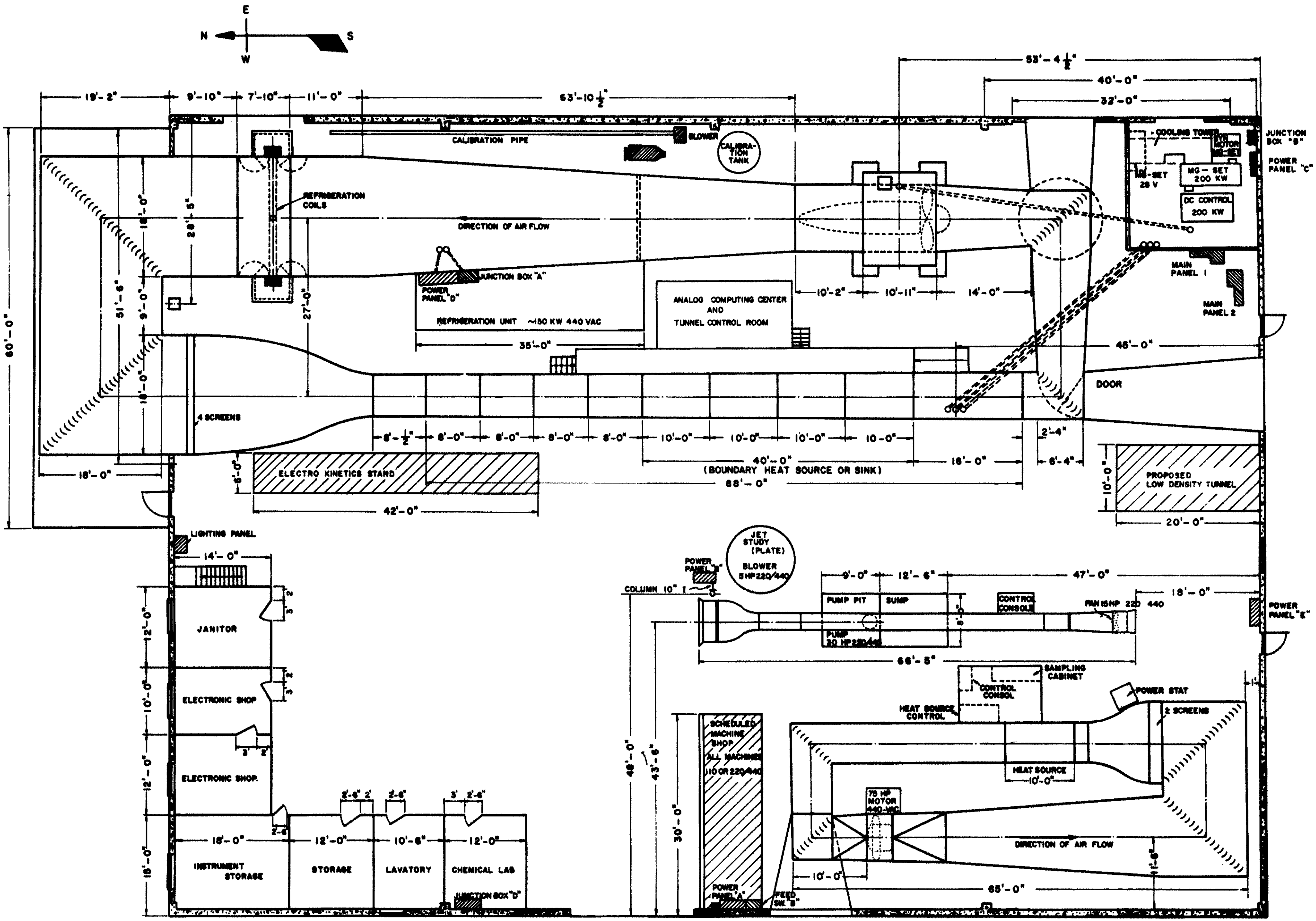
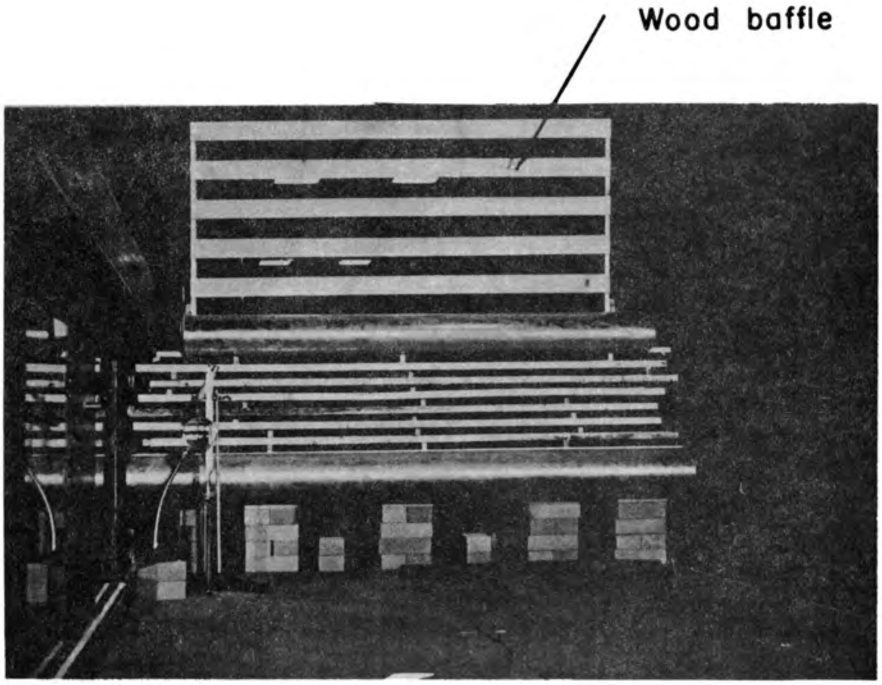


FIG. 5 FLUID DYNAMICS AND DIFFUSION LABORATORY FLOOR PLAN



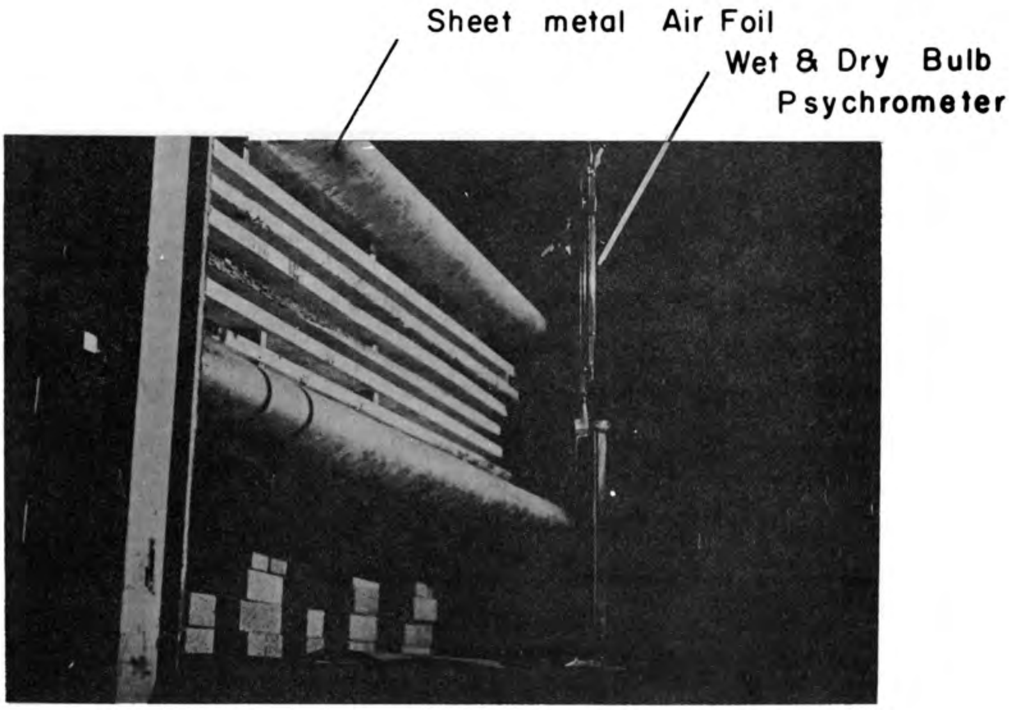


FIGURE 6: STACKING ARRANGEMENT

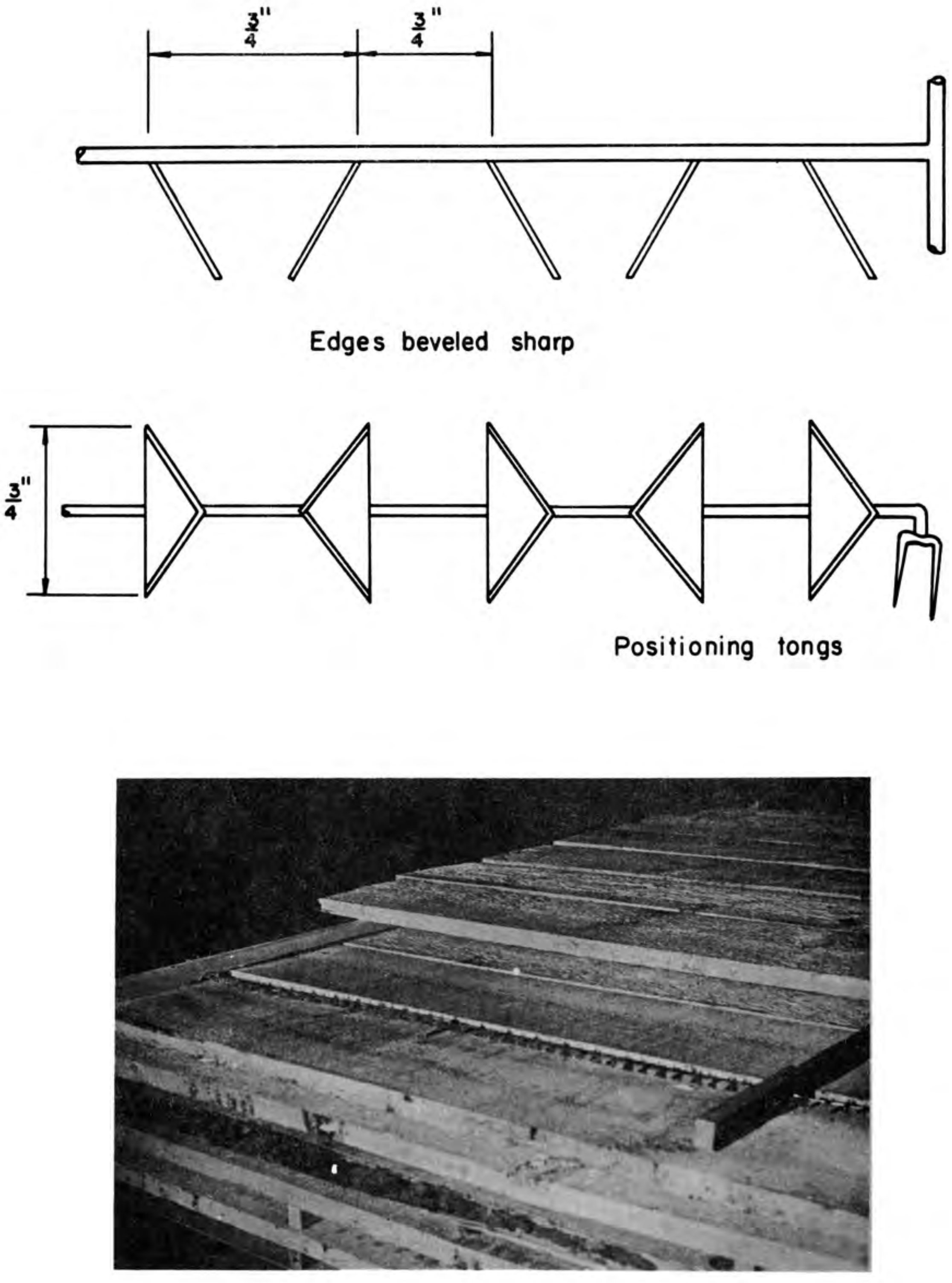
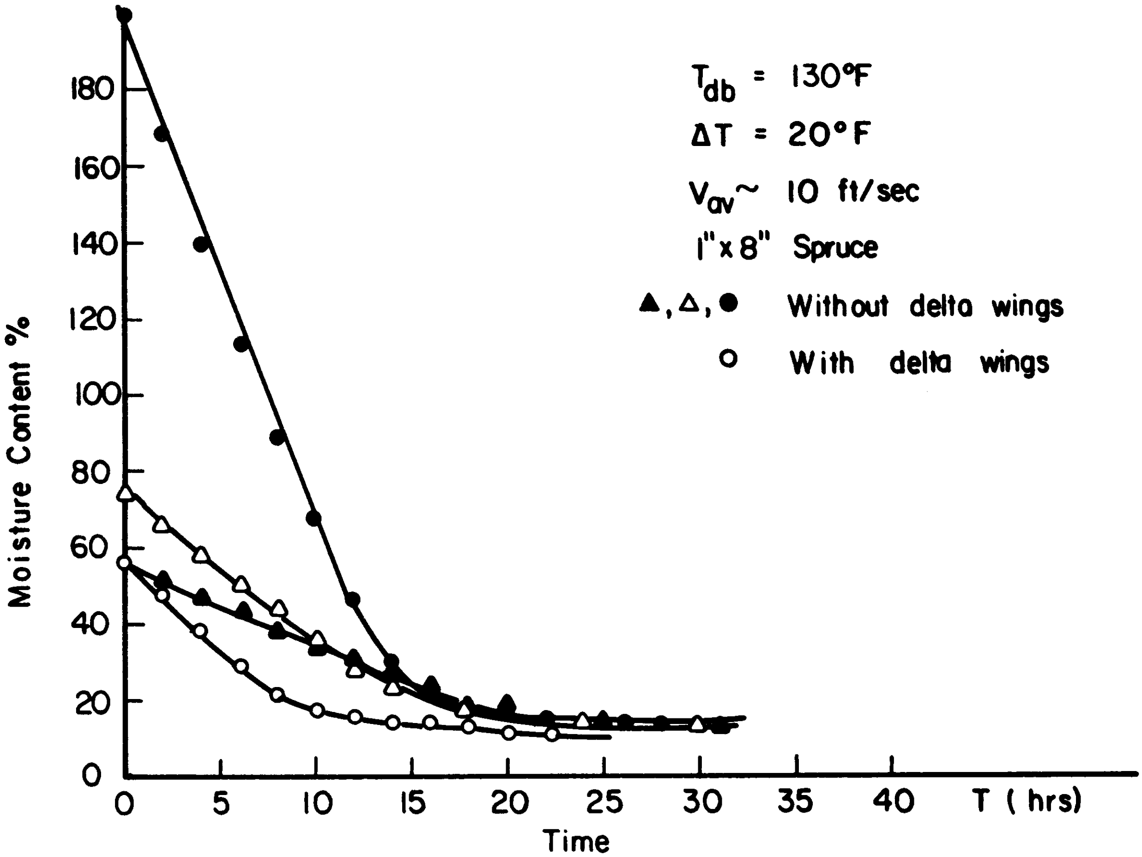
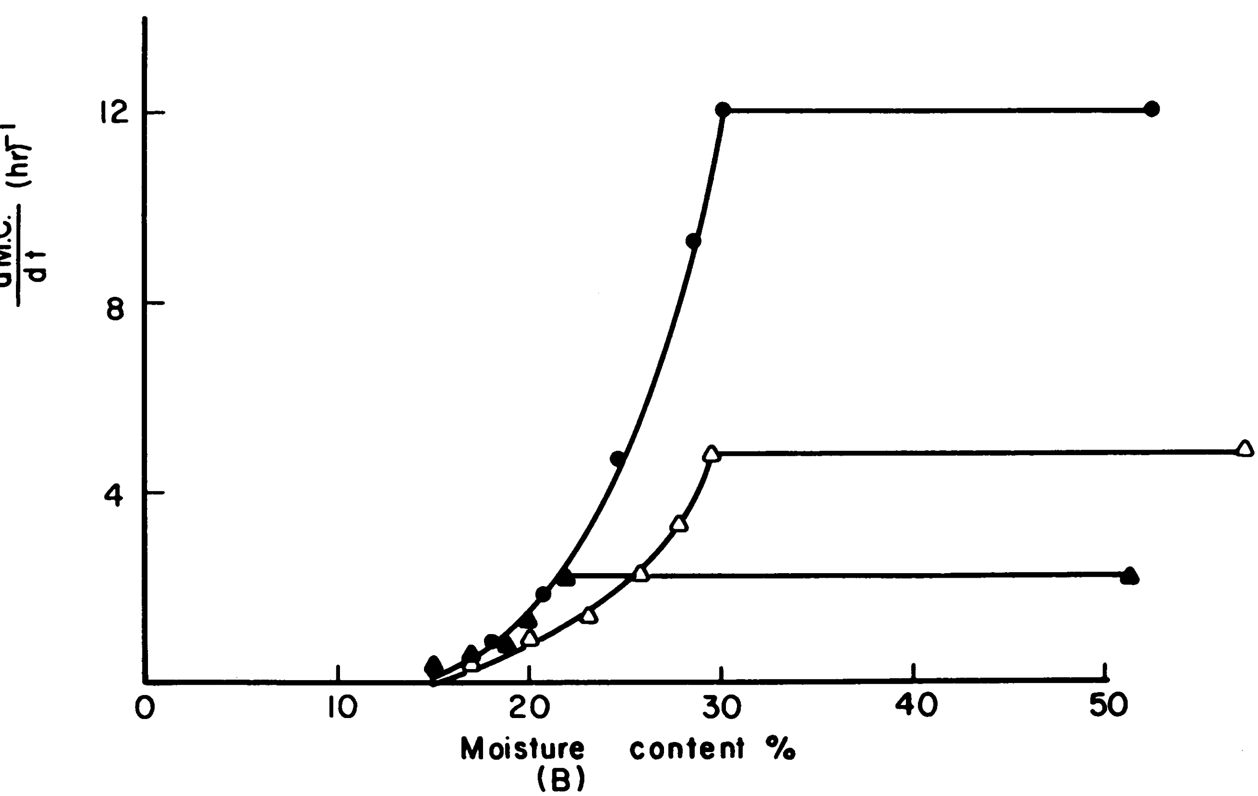


FIGURE 7 : DELTA WING VORTEX GENERATORS



(A)



(B)

FIGURE 8: TYPICAL DRYING CURVES

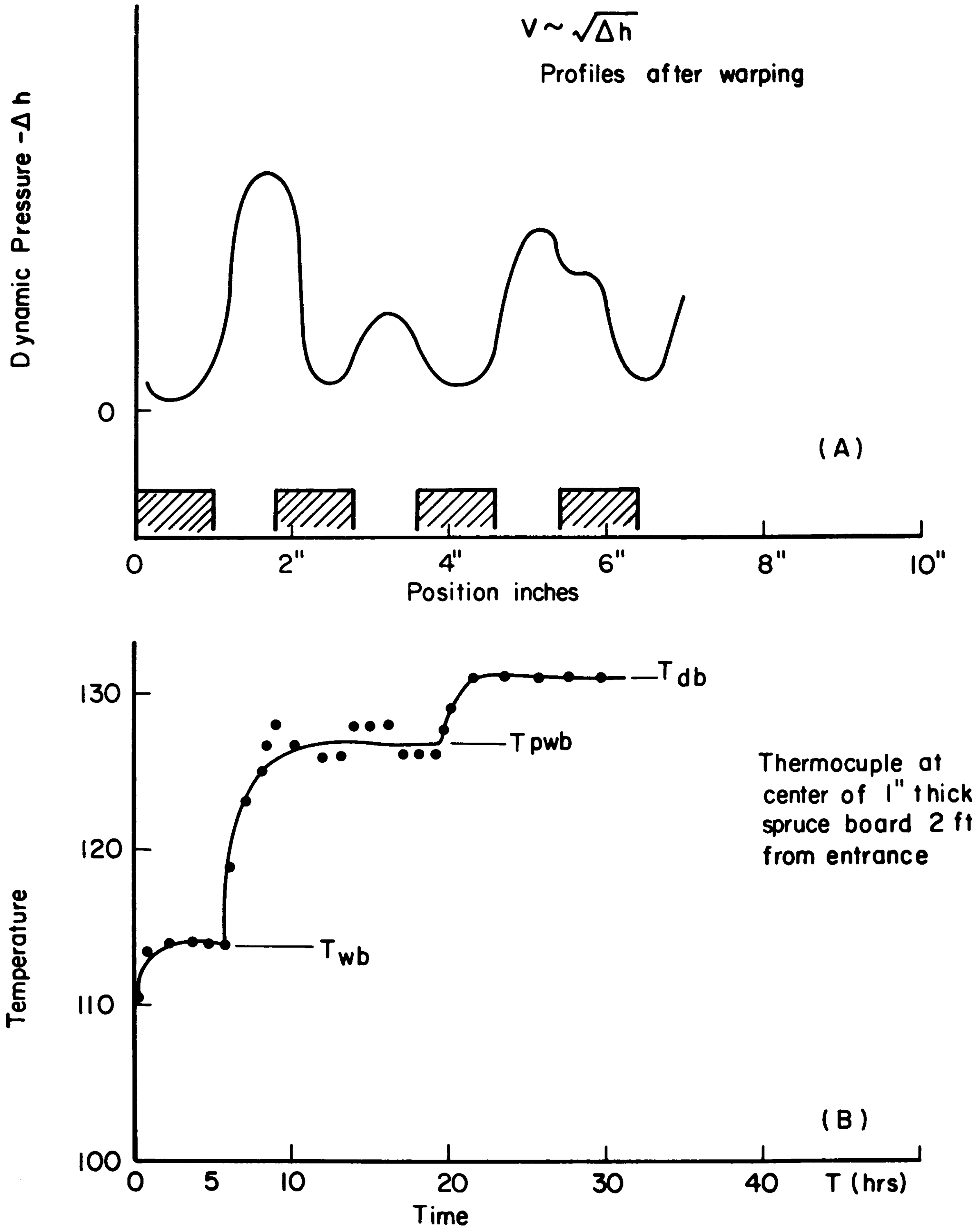


FIGURE 9 VELOCITY AND TEMPERATURE PROFILES