h_t = total heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
A = area of heat transfer and evaporation, square feet.
λ = latent heat of evaporation at t_s, Btu per pound.
k_g = mass transfer coefficient, pounds per (hour) (square foot) (atmosphere).
Δt = $(t_a - t_s)$ = temperature difference between air and surface of evaporation, Fahrenheit degrees.
t_a = air temperature, Fahrenheit.
t_s = temperature of surface of evaporation, Fahrenheit.
Δp = $(p_s - p_a)$ = vapor pressure difference, atmospheres.
p_s = vapor pressure of water at t_s, atmospheres.
p_a = partial pressure of water vapor in air, atmospheres.

When $h_t = h_c$, the coefficient of heat transfer by convection only, then t_s under equilibrium conditions becomes t_w, the wet-bulb temperature of the air, and p_s is the vapor pressure at this temperature. If heat is also supplied by radiation, then h_t is the sum $(h_c + h_r)$ where h_r is the radiation coefficient and h_c is the convection coefficient, and t_s becomes higher than the wet-bulb temperature. A similar result occurs when heat reaches the surface of evaporation by convection and conduction. When the surface is at the wet-bulb temperature, the value of Δp in millimeters of mercury, is almost exactly one-half the wet-bulb depression $(t_a - t_w)$, in *Centigrade* degrees.

Effect of Air Velocity. The principal effect of air velocity is on h_c and k_g, since the rate of transfer of heat and mass in the constant-rate period depends mainly on the rate of diffusion of heat and vapor through the air film at the surface of the solid, and air velocity is the chief factor affecting the thickness of this film. The influence of air velocity may be expressed by the following relationship:[3]

$$h_c = 0.0128\,G^{0.8} \tag{2}$$

where

h_c = convection heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
G = mass velocity of dry air, pounds per (hour) (square foot).

For estimating the constant rate in drying from plane surfaces with air flow parallel to the surface of evaporation and with no radiation or conduction effects, the following heat transfer expression can be used:

$$\frac{dw}{d\theta} = \frac{0.0128G^{0.8}A}{\lambda}(t_a - t_w) \tag{3}$$

where

t_w = wet-bulb temperature of the drying air, Fahrenheit degrees.

Heat transfer coefficients, rather than mass transfer coefficients, should be used to estimate drying rates, because heat transfer coefficients are generally more reliable, and, unless the temperature of the drying surface is measured, it must be calculated from heat transfer considerations before mass transfer coefficients can be applied for drying-rate predictions. The assumption that the surface of drying is at the wet-bulb temperature of the air, introduces a more serious error in the computation of mass transfer than of heat transfer.

Determination of True Surface Temperature. Frequently, radiation and conduction are of sufficient magnitude to cause the temperature of evaporation to exceed the wet-bulb temperature of the air. When this occurs, it is necessary to estimate the true surface temperature in order to calculate

the constant rate. This may be done by means of a heat balance equating the total heat transferred by convection, conduction, and radiation to the latent heat of evaporation.

Constant-Rate Period in Through-Circulation Drying. The equation for estimating the rate of evaporation when air flows *across* a free water surface must be modified for the case of air-flow *through* a permeable bed of solids. The constant rate in through-circulation drying depends on the air rate, air temperature, air humidity, size of the particles making up the permeable bed, and physical characteristics of these particles.[4]

The following general expression for the constant rate in through-circulation drying for the system water and air, was developed[5] from experiments on the rate of evaporation of water from the surface of wet spheres and cylindrical particles with through-circulation of air:

$$\frac{dW}{d\theta} = \frac{0.42aG^{0.59}(\Delta H)_m}{D_p^{0.41}} = \frac{0.37c_s aG^{0.59}\Delta t_m}{\lambda\rho_s D_p^{0.41}} \tag{4}$$

where

$\frac{dW}{d\theta}$ = constant rate, pounds of water per (hour) (pound of dry stock).
a = drying area, square feet per cubic foot of bed volume.
G = superficial mass velocity, pounds of dry air per (hour) (square foot).
ΔH_m = logarithmic mean of inlet and outlet humidity driving force across the air film adjacent to the particle through which the water vapor diffuses, pounds per pound (the surface humidity is taken as the humidity corresponding to the wet-bulb temperature of the drying air).
ρ_s = bulk density of dry granular bed, pounds per cubic foot.
D_p = average diameter of particle, feet.
Δt_m = logarithmic mean difference between temperature entering and leaving the bed and the wet-bulb temperature, Fahrenheit degree).
c_s = humid heat, Btu per (pound of dry air) (Fahrenheit degree).
λ = latent heat of evaporation, Btu per pound.

Equation 4 applies when the Reynolds number D_pG/μ is greater than 300, where μ is the viscosity of the air stream. For values less than 300, a modification of Equation 4 has been presented.[6]

Evaporation from Liquid Drops. For the important problem of spray drying, evaporation rates of liquid drops must be estimated. Below a value of Reynolds number (D_pG/μ) of 10 for spherical particles, the heat transfer coefficient across the gas film surrounding the drop is given by

$$h = \frac{2k_f}{D_p} \tag{5}$$

where

h = film heat transfer coefficient, Btu per (hour) (square foot) (Fahrenheit degree).
k_f = thermal conductivity of gas film, Btu per (hour) (square foot) (Fahrenheit degree per foot).

Equation 5 is applicable when the Reynolds number for liquid drops is less than 10. Drop diameters are almost always less than 500 microns, and usually in the range of 20 to 150 microns.

The rate of evaporation of drops may be expressed in terms of heat transfer or mass transfer. In terms of heat transfer, the evaporation rate is given by the equation: