Table 13. Nomenclature and Units

(The units are based on feet, pounds, hours, degrees Fahrenheit, and B.t.u. Any other consistent set may be used in the dimensionless relations given, but for the dimensional equations the units of this table must be used.)

A = area of heat-transfer surface, sq. ft.; A_i for inside, A_o for outside, A_m for average.
a = dimensionless constant in equations as specified.
b = empirical dimensional factor in Eq. (28c).
c_p = specific heat at constant pressure, B.t.u./(lb.)(°F.)
d = prefix, indicating differential.
D = diameter, ft.; D_c for helix; D_i for inside diameter; D_o for outside diameter; D_p for packing.
D' = diameter, in., D_i' for inside diameter; D_o' for outside diameter.
e = base of natural logarithms, 2.718.
f = friction factor, dimensionless (p. 381).
G = mass velocity, equals w/S, lb./(hr.)(sq. ft. of cross section occupied by fluid); G' = lb./(sec.)(sq. ft.).
G_{max} = mass velocity through minimum free area in a row of pipes normal to the fluid stream, lb./(hr.)(sq. ft.).
g_c = conversion factor 4.18×10^8, (lb. mass)(ft.)/(force lb.)(hr.)^2.
g_L = acceleration due to gravity, 4.18×10^8 ft./hr.^{2}
h = local individual coefficient of heat transfer, equals $dq/dA\,\Delta t$, B.t.u./(hr.)(sq. ft.)(°F. diff.).
$h_c + h_r$ = combined coefficient by conduction, convection, and radiation between surface and surroundings.
h_m = mean value of h for entire apparatus, based on Δt_m.
$h_{a.m.}$ = average h, arbitrarily based on arithmetic-mean temperature difference.
h_s = heat-transfer coefficient for deposit of dirt or scale on the surface.
j = dimensionless ordinate as specified in Fig. 8.
J = mechanical equivalent of heat, 778 ft.-lb./B.t.u.
k = thermal conductivity of fluid, B.t.u./(hr.)(sq. ft.)(unit temperature gradient, °F./ft.).

$$k_m = \frac{1}{(t_1 - t_2)} \int_2^1 k\,dt$$

k_f = k at the "film" temperature, $t_f = (t + t_w)/2$
L = length of heat-transfer surface, heated length, ft.; L' = length of horizontal tube, ft.
L_p = length of horizontal flat paddle; see page **474**.
ln = logarithm to base e; = 2.30 × logarithm to the base 10.
N = number of revolutions per hour.
n = number of rows in a vertical plane; exponent.
P = total pressure, atm.
Q = quantity of heat, B.t.u.
q = rate of heat flow, B.t.u./hr.
R = thermal resistance, $1/UA$.
r = radius, ft.
r_m = distance from surface to mid-plane, ft.
S = cross section, filled by fluid, in plane normal to direction of fluid flow, sq. ft.
T = temperature, °F. abs. = t + 460°.
T_1, T_2 = inlet and outlet bulk temperatures, respectively, of warmer fluid, °F.; t_1', t_2' in Fig. 7b–d.
t = bulk temperature (based on heat balance), °F.
t_v = saturation temperature of vapor.
t_w = wall temperature, °F.
t_1, t_2 = inlet and outlet bulk temperatures of colder fluid, °F.; t_1'', t_2'' in Fig. 7b–d.
t_∞ = temperature of stream of great depth, ambient temperature, °F.
t_i, t_o = temperatures of fluid inside and outside, °F.
t_f = $(t + t_w)/2$.
t_f' = $t_v - 0.75(\Delta t)_m$ for Eqs. (47) and (48).
U = over-all coefficient of heat transfer, B.t.u./(hr.)(sq. ft.)(°F.); U_o based on outside surface.
V = average velocity, ft./hr.
V_a = acoustic velocity, ft./hr.
V_s = average velocity, volumetric rate divided by cross section filled by fluid, ft./sec.
V_∞ = velocity of stream of great depth, ft./hr.
w = mass rate of flow from each tube, lb./(hr.)(tube).
x = length of conduction path, ft.
Y = dimensionless correction factor for Δt; see Figs. 7b and 7c; $Y = \Delta t_{om}/\Delta t_{o,lm}$.
y = dimensionless recovery factor, page **468**.
Z = $(T_1 - T_2)/(t_2 - t_1)$.
z_p = twice the perimeter over which fluid flows in passing fin, ft.
α = a constant.
β = volumetric coefficient of thermal expansion, having units of reciprocal of Fahrenheit absolute temperature.
Γ = mass rate of flow from tube, lb./(hr.)(ft. of wetted periphery measured on a plane normal to direction of fluid flow); $w/\pi D$ for a vertical and $w/2L'$ for a horizontal tube.
Δt = temperature difference, °F., Δt_o for over-all, and Δt for individual.
$\Delta t_{a.m.}$, $\Delta t_{l.m.}$ = arithmetic and logarithmic means of terminal temperature differences, respectively, °F.
Δt_m = true average (length-mean) value of the terminal temperature differences, °F.
Δt_s = temperature difference between surface and surroundings, °F.
θ = time, hr.
λ = latent heat (enthalpy) of vaporization, B.t.u./lb.
μ = absolute viscosity at bulk temperature, lb. mass/(hr.)(ft.); equals 2.42 × centipoises = 105,800 × (lb. force)(sec.)/sq. ft.
μ_f = viscosity, lb. mass/(hr.)(ft.), at arithmetic mean of wall and fluid temperatures.
μ_w = viscosity at wall temperature, lb. mass/(hr.)(ft.).
π = 3.1416.
ρ = density, lb. mass/cu. ft.
ρ_∞ = density of stream of great depth, lb. mass/cu. ft.

Heating and Cooling of Fluids (No Change in Phase)

Figure 8 shows correlations of film coefficients for warming or cooling by forced convection for a number of shapes. In the **dimensionless** relations any self-consistent units may be employed, but those given in Table 13 (p. 467) are generally used. For the **dimensional** equations the units of Table 13 must be employed. Viscosities are given on p. 372, thermal conductivities on p. 459, and specific heats on p. 225*ff*. For gases at ordinary pressures the following values of the dimensionless Prandtl group $c_p\mu/k$ may be used, independent of temperature: air, oxygen, nitrogen, hydrogen, carbon monoxide, 0.74; methane, 0.78; carbon dioxide, 0.79; ethylene 0.81; a value of 0.78 may be used for steam at low pressures. The values of h do not include heat transfer by radiation, which at high temperature becomes important with gases (p. 490).

Gases in Long Straight Tubes. For the turbulent flow of gases in straight tubes, the following **dimensional** equation for forced convection is recommended for general use:

$$h = \frac{16.6c_p(G')^{0.8}}{(D_i')^{0.2}} \tag{24}$$

where c_p is the specific heat of the gas at constant pressure, B.t.u./(lb.)(°F.) = g.-cal./(g.)(°C.) = p.c.u./(lb.)(°C.); G' is the mass velocity, expressed as lb. of gas/**sec.**/sq. ft. of cross section of the gas passage; and D_i' is the actual inside diameter in **inches**. Equation (24) is based on the data of Nusselt [*Z. Ver. deut. Ing.*, **53**, 1750, 1808 (1909)] who used air, carbon dioxide, and illuminating gas at temperatures around 120°F., and the data of a number of other investigators using air in tubes ranging from 0.17 to 3.77 in. diameter, and covers values of G' ranging from G_t' to 30. Below the transitional value G_t', free convection factors are important, and h should be predicted as shown on p. 472. Based on the data of Nusselt for air at approximately 120°F., flowing inside a horizontal tube having an inside diameter 0.868 in., and at temperature differences in the neighborhood of 100°F., A. P. Colburn (personal communication) finds that $G_t' = 0.46P^{0.645}$, where P ranges from 1 to 13 atm. abs. The effect of pressure up to 16 atm. for air is taken care of by the mass velocity term; at higher pressures, see Colburn, Drew, and Worthington, Heat Transfer in a 3:1 Hydrogen-nitrogen Mixture at High Pressure, *Ind. Eng. Chem.*, **39**, 958 (1947). Data on the flow of gases at high temperatures are rather inconclusive as to the effect of temperature on h; hence, at this time, it seems best not to introduce a temperature-correction term. For a similar reason, no term for the ratio of length to diameter is included, but the effect is probably small, except for ratios of length to diameter from 0 to 10. From the meager comparative data as to the effect of roughness or tube materials on h, one concludes that the effect is minor for metal tubes. The effect of a given scale deposit is far less serious for a gas than for water (see