considerable complication is involved. Therefore, in this discussion the consistent units of conductivity expressed in *Btu per (hour) (square foot) (Fahrenheit degrees per one foot thickness)* are used throughout. *Conductivity values obtained from Chapter 9 or Table 1 in this chapter, must therefore be converted for use in the calculations of this chapter by dividing by 12.* As an example, the conductivity of brick listed as 5.0 in Table 4 of Chapter 9, becomes 0.42 when used in the calculations of this chapter. Also, it should be emphasized that in order to make the calculations and applications consistent in this chapter, *all dimensions of thickness must be expressed in feet.*

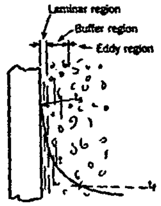


Fig. 1 . . . . Thermal Convection Conditions

Thermal Convection Equation

$$\frac{q}{A} = h_c(t_s - t_f) \qquad (2)$$

This rate equation states that the thermal convection per unit transfer area (q/A), Btu per (hour) (square foot) is proportional to the temperature difference ($t_s - t_f$) which is the temperature of the surface less that of the fluid. The particular fluid temperature to use for a given system will be noted under the discussion of that system. The proportionality factor is termed the *unit thermal convective conductance* (sometimes called the film coefficient for convection), h_c, Btu per (hour) (square foot) (Fahrenheit degree). Fig. 1 shows the conditions associated with convection.

The heat transmission by free or natural convection for objects surrounded by air can be conveniently expressed as in Equation 3:

$$\frac{q}{A} = B\left(\frac{1}{D}\right)^{0.2}\left(\frac{1}{T_{av}}\right)^{0.181}(t_s - t_f)^{1.27} \qquad (3)$$

where

$\frac{q}{A}$ = heat transmission by convection, Btu per (square foot) (hour).

B = a constant depending upon the shape of the surface.

D = diameter of pipe or circular duct or height of vertical wall, inches. (Effect of diameter or height becomes constant at 24 in.)

T_{av} = average of wall surface and surrounding air temperature, Fahrenheit degrees absolute.

$t_s - t_f$ = temperature excess between wall surface and surrounding air, Fahrenheit degrees.

For horizontal cylinders, the value of B = 1.02 has been well established by various investigations. For vertical plates, the value of B = 1.39 has been fairly well established. Suggested values[2] of B for horizontal plates warmer than the surrounding air are 1.79 when facing upward, and 0.89 when facing downward.

Problems in either forced convection or natural convection may be solved by the simple first-power equation if the convection coefficient is expressed as a unit conductance:

$$q = h_c A (t_1 - t_2) \qquad (4)$$

where

q = heat transmission by convection, Btu per hour.

A = surface area, square feet.

$t_1 - t_2$ = temperature difference between the surface and the fluid, Fahrenheit degrees.

h_c = unit convective conductance, from Table 2, Btu per (square foot) (hour) (Fahrenheit degree temperature difference).

Table 1 . . . . Approximate Unit Thermal Conductivities[a]

Conductivity, k = Btu per (hr) (sq ft) (F deg per in.)

Material	*k*	*Material*	*k*
Air	0.168	Lead	240.0
Aluminum	1416.0	Nickel	408.0
Brass (70 – 30)	720.0	Soil	2.4–12.0
Cast-Iron	336.0	Steel, mild	312.0
Copper	2640.0	Water, liquid	4.08
Glass	3.6–7.32		

[a] Thermal conductivities depend to some extent on temperature. The above magnitudes are approximate only. Refer to Chapter 9, and Reference 4 for additional data.

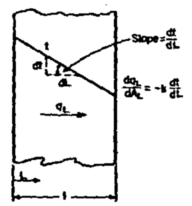


Fig. 2 . . . . Thermal Conduction in a Flat Slab

Thermal Radiation Equation

The relation given by Equation 5 is applicable to systems in which radiant exchange takes place between the surfaces of solids, as schematically shown in Fig. 3.

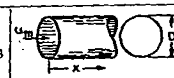
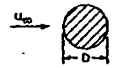
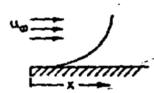
$$q_r = \sigma A_1 F_A F_E (T_1^4 - T_2^4) \qquad (5)$$

Gaseous and luminous radiation are not considered in this discussion. Equation 5 states that the net radiation per unit transfer area of surface 1, q_r/A Btu per (hour) (square foot), which sees surface 2 through a non-absorbing medium, is proportional to the difference of the fourth powers of the absolute surface temperatures ($T_1^4 - T_2^4$). The proportionality factor ($\sigma F_A F_E$) may be conveniently separated into three parts (excepting in some problems involving interreflections, where it is not possible to divide the product ($F_A F_E$) into separate terms):

σ = the Stefan-Boltzmann radiation constant = 1730×10^{-12} Btu per (hour) (square foot) (Fahrenheit degree absolute temperature to the fourth power).

Table 2 . . . . Approximate Unit Conductances for Thermal Convection for Several Flow Systems

Expressed in Convenient Empirical Form

Case	*System*	*Heat Transfer Equation[a] and Its Limits of Application*
		Forced Convection
1 Ref. 3	 Longitudinal flow in a circular cylinder.[b]	*General Equation* $\frac{h_c D}{k} = 0.0225\left(\frac{DG}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{0.33}$ *where* $x > 4.4D$ and $\left(\frac{DG}{\mu}\right) > 2200$
2 Ref. 3	Same as Case 1.[b]	*Equation for Air* $h_c = 5.4 \times 10^{-4}(T_f)^{0.3}\frac{G^{0.8}}{D^{0.2}}$ *where* $x > 4.4D$ and $\left(\frac{DG}{\mu}\right) > 2200$
3 Ref. 3	Same as Case 1.[b]	*Equation for Liquid Water* (32–400 F) $h_c = 13.5(t_f)^{0.54}\frac{u_m^{0.8}}{D^{0.2}}$ *where* $x > 4.4D$ and $\left(\frac{DG}{\mu}\right) > 2200$
4 Ref. 4	 Flow normal to a single cylinder.	*General Equation* $\frac{h_c D}{k} = 0.26\left(\frac{DG}{\mu}\right)^{0.6}\left(\frac{c_p\mu}{k}\right)^{0.3}$ *where* $1000 < \frac{DG}{\mu} < 50{,}000$
5 Ref. 4	Same as Case 4.	*Equation for Air* $h_{c(average)} = 0.211(T_f)^{0.43}\frac{(u_\infty\rho)^{0.6}}{D^{0.4}}$ *where* $1000 < \frac{DG}{\mu} < 50{,}000$
6 Ref. 4	Same as Case 4.	*Equation for Liquid Water* (32–400 F) $h_{c(average)} = 34.0(t_f)^{0.38}\left(\frac{(u_\infty)^{0.6}}{D^{0.4}}\right)$ *where* $1000 > \frac{DG}{\mu} > 50{,}000$
7 Ref. 3	 Flow along a flat plate.	*General Equation* (Turbulent Flow) $\frac{h_{cx}x}{k} = 0.0296\left(\frac{xG}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{k}\right)^{0.33}$ *where* $\left(\frac{xG}{\mu}\right) > 500{,}000$ and $h_c = 1.25h_{cx}$
8 Ref. 3	Same as Case 7.	*Equation for Air* (Turbulent Flow) $h_{cx} = 0.51(T_f)^{0.3}\frac{(u_\infty\rho)^{0.8}}{(x)^{0.2}}$ *where* $\left(\frac{xG}{\mu}\right) > 500{,}000$ and $h_{c(average)} = 1.25h_{cx}$
9 Ref. 3	Same as Case 7.	*General Equation* (Laminar Flow) $\frac{h_{cx}x}{k} = 0.332\left(\frac{xG}{\mu}\right)^{0.5}\left(\frac{c_p\mu}{k}\right)^{0.33}$ For $\left(\frac{xG}{\mu}\right) < 500{,}000$ and $h_{c(average)} = 2h_{cx}$
10 Ref. 3	Same as Case 7.	*Equation for Air* (Laminar Flow) $h_{cx} = 0.0562(T_f)^{0.5}\frac{(u_\infty\rho)^{0.5}}{x^{0.5}}$ For $\left(\frac{xG}{\mu}\right) < 500{,}000$