In most commercial equipment the main body of the fluid is in turbulent flow, and the laminar film exists at the solid walls only, as shown in Fig. 1. But in cases of low-velocity flow in small tubes, or with viscous liquids such as heavy oil (low Reynolds numbers), the entire flow may be laminar. In these latter cases there is no transition or eddy region.

When the fluid currents are induced by sources external to the heat transfer region, as for example a pump, the described solid to fluid heat transfer is termed *forced convection*. In contrast, if the fluid currents are internally generated, as a result of non-homogeneous densities arising from the temperature variations, the heat transfer is termed *free convection*.

In the conduction and convection mechanisms heat is transferred as internal energy, *i.e.*, the random molecular kinetic energy associated with the material temperature. For *radiant heat transfer*, however, a change in energy form takes place from internal energy at the source to electromagnetic energy for transmission, then back to internal energy at the receiver. Since radiant energy exhibits characteristic wave lengths, the

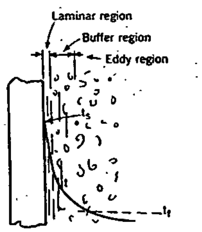

FIG. 1. THERMAL CONVECTION CONDITIONS

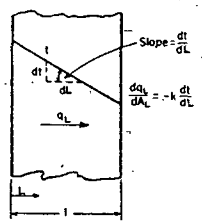

FIG. 2. THERMAL CONDUCTION IN A FLAT SLAB

solution of thermal radiation problems is in many respects similar to the solution of problems in the field of illumination.

The rate of thermal current flow (*i.e.*, rate of heat transfer), corresponding to the three transfer mechanisms previously described, may be expressed by three rate equations. These are similar to Ohm's Law for electrical flow, the current flow through a resistance being proportional to the potential difference.

Thermal Conduction Equation

Equation 1 states symbolically that the thermal conduction current per unit transfer area normal to the flow, $(dq)/(dA)$, Btu per (hour) (square foot), is proportional to the temperature gradient $(dt)/(dL)$, degrees Fahrenheit per foot. The proportionality factor is termed the *thermal conductivity*, k, Btu per (hour) (square foot) (degrees Fahrenheit per foot of thickness).

$$\frac{dq}{dA} = -k\frac{dt}{dL} \tag{1}$$

The minus sign on the right side of the equation is introduced to indicate positive current flow in the direction of decreasing temperature. Fig. 2 shows the physical significance of indicated quantities.

It should be emphasized that the thermal conductivity used should be expressed in consistent units; either using the inch or foot throughout.

Expressions of conductivity used in the heating field are usually inconsistent in this sense, in that it is customary to refer to the conductivity *per square foot* but for one inch of thickness. This custom has been adopted for the reason that wall thicknesses are usually expressed in inches, whereas if expressed in feet, decimal or fractional thicknesses would result. When dealing with flat walls no complication is involved in using the inconsistent expression of conductivity. However, when curved or spherical walls are considered, considerable complication is involved. Therefore, in this discussion the consistent units of conductivity expressed in *Btu per (hour) (square foot) (degrees Fahrenheit per one foot thickness)* are used throughout. *Conductivity values obtained from Chapter 6 or Table 1 in this chapter, which are expressed in inconsistent units, must therefore be converted for use in the calculations of this chapter by dividing by 12.* As an example, the conductivity of brick, expressed in inconsistent units as 5.0 in Table 2 of Chapter 6, becomes 0.42 when

TABLE 1. APPROXIMATE UNIT THERMAL CONDUCTIVITIES.[a]
Conductivity, k = Btu per (hr) (sq ft) (deg F 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 Heat Transmission, by W. H. McAdams (McGraw-Hill Co., 1942) for additional values.

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.*

Thermal Convection Equation

$$\frac{dq}{dA} = h_c\,(t_s - t_f) \tag{2}$$

This rate equation states that the thermal convection current per unit transfer area $(dq)/(dA)$, 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 convection conductance* (sometimes called the film coefficient for convection), h_c, Btu per (hour) (square foot) (degree Fahrenheit). These convection conditions are illustrated in Fig. 1.

The heat transmission by free or natural convection for objects surrounded by air can be conveniently expressed as in Equation 2a:

$$q_c = C\left(\frac{1}{D}\right)^{0.2}\left(\frac{1}{T_{av}}\right)^{0.181}(t_s - t_f)^{1.27} \tag{2a}$$

where

q_c = heat transmission by convection, Btu per (square foot) (hour).
C = a constant depending upon the surface shape.