in the *eddy* or *turbulent* region the major fraction of the transfer occurs by eddy mixing.

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 produced by sources external to the heat transfer region, as for example by a pump, the described solid to fluid heat transfer is termed *forced convection.* In contrast, if the fluid currents are generated internally, 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, the transfer of heat is associated with matter. For *radiant heat transfer*, however, a change in

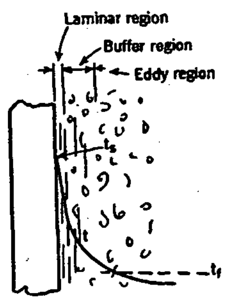

FIG. 1. THERMAL CONVECTION CONDITIONS

energy form takes place, from internal energy at the source to electromagnetic energy for transmission, then back to internal energy at the receiver.

The 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. The convection and radiation flow rate expressions may be approximated by a potential (temperature difference) and a resistance in order that heat transfer calculations may be effected more conveniently and rapidly.

Thermal Conduction Equation

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

$$\frac{q}{A} = -k\,\frac{dt}{dL} \tag{1}$$

The minus sign on the right side of the equation is introduced to indicate positive transfer in the direction of decreasing temperature. Fig. 2 shows the physical significance of the 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, where curved or spherical walls are concerned, 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 2 of Chapter 9, becomes 0.42 when used in the calculations of this chapter.

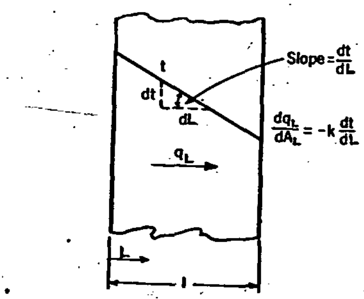

FIG. 2. THERMAL CONDUCTION IN A FLAT SLAB

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

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

This rate equation states that the thermal convection per unit transfer area (q/A), Btu per (hour) (square foot) is proportional to the tem-

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.