flows laminarly with practically no cross flow (*i.e.*, in the direction of heat transfer). Finally, in fluid systems in which the fluid is moved only by gravity (free convection) and the hot fluid exists at the top, transfer of thermal energy will occur only by conduction (an example is the room with the hot air at the ceiling in the absence of forced circulation).

Contrasted to the thermal conduction mechanism, *thermal convection* involves energy transfer by eddy mixing and diffusion[2] in addition to conduction. This condition is pictured schematically in Fig. 1 which exhibits transfer from a pipe wall at surface temperature t_s to a colder fluid at a bulk temperature t_f. In the *laminar* sublayer, immediately adjacent to the wall, the heat transfer is by thermal conduction, in the *transition* region, which is called the buffer layer, eddy mixing as well as conduction effects are significant, while in the *eddy* or *turbulent* region the major fraction of the transfer is by eddy mixing.

In the case of laminar (also called streamlined) flow there is no transition or eddy region. However, in most commercial equipment, except that involving low velocity flows of viscous liquids, the flow is turbulent.

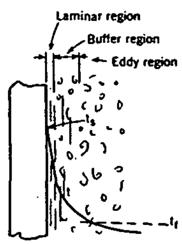

FIG. 1. THERMAL CONVECTION CONDITIONS

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 visible radiant energy exhibits characteristic wave lengths, the 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 transfer mechanisms previously described, may be expressed by the following rate equations. These are similar to Ohm's

[2]Absorption and Extraction, by T. K. Sherwood (McGraw-Hill Co., 1937).

Law for electrical flow, the current flow through a resistance being proportional to the potential difference.

Thermal Conduction Equation

$$\frac{dq}{dA} = -k\frac{dt}{dx} \quad (1)$$

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

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

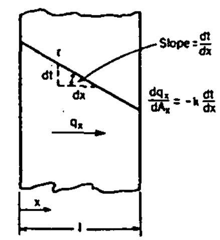

FIG. 2. THERMAL CONDUCTION IN A FLAT SLAB

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 per square foot per degree Fahrenheit for one foot of thickness is used throughout. Conductivity values obtained from Chapter 4 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 4, 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.

The minus sign on the right side of the equation is introduced to indicate positive current flow in the direction of decreasing temperature. The physical significance of indicated quantities are illustrated further by the schematic diagram Fig. 2.