CHAPTER 3

Fundamentals of Heat Transfer

Conduction, Convection, Radiation, Combined Convection and Radiation, Heat-Flow Resistance, Electrical Analogies, Practical Heat Transfer Problems, Unit Conductances for Convection Flow Systems, Radiation Factors or Emissivities, Solutions for Steady-State Conduction Problems

HEAT is that form of energy which is transferred from place to place by virtue of an existing temperature difference. The temperature difference is the potential which causes the transfer, the latter in turn being resisted by the thermal properties of the material combined in a simple term and known as the resistance. Energy exchange associated with mass transfer from place to place (evaporation, condensation, etc.) due to concentration differences will be treated elsewhere such as the section on *cooling tower design* in Chapter 26. The objectives of this chapter are to:

1. Describe the mechanisms and present the rate equations for the different modes of heat transfer.
2. Illustrate the application of the basic concepts to steady-state problems (temperature independent of time or a cyclic variable thereof) by means of several typical solutions of heat transfer systems.

Further applications to specific systems will be found throughout THE GUIDE.

CONDUCTION, CONVECTION AND RADIATION

Thermal conduction is the term applied to the mechanism of heat transfer whereby in fluids the molecules of higher random kinetic energies transmit by direct molecular collision part of their energy to adjacent molecules of lower random kinetic energy. Since the temperature is proportional to the random kinetic energy of the molecules, thermal transfer will occur in the direction of decreasing temperature. The molecules oscillate about a mean position at fairly high velocities and frequencies, but there is no net material flow associated with the conduction mechanism.

In solids the significant mechanism of heat transport is thermal conduction and is ascribed to a transfer mechanism associated with the free electrons[1]. Even in the case of fluids, thermal conduction is significant in the region very close to a solid boundary or wall, for in this region the flow is laminar, parallel with the wall surface, and there are practically no cross currents in the direction of the heat transfer.

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. (Bulk temperature is that which would be attained if the fluid stream were drawn off at a certain section and mixed. It is therefore slightly higher than the lowest temperature in the stream. In the *laminar* sublayer, immediately adjacent to the wall, the heat transfer occurs by thermal conduction; in the *transition* region, which is

[1]The Metallic State, by H. Hume-Rothery (Oxford Press, 1931).
[2]Absorption and Extraction, by T. K. Sherwood (McGraw-Hill Co., 1937).

called the buffer layer, eddy mixing as well as conduction effects are significant; 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 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

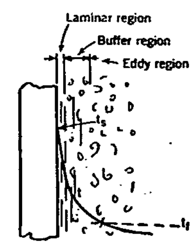

FIG. 1. THERMAL CONVECTION CONDITIONS

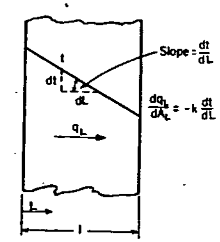

FIG. 2. THERMAL CONDUCTION IN A FLAT SLAB

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 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 per square foot, is proportional to the temperature gradient $(dt)/(dL)$, 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.

$$\frac{dq}{dA} = -k\frac{dt}{dL} \qquad (1)$$

The minus sign on the right side of the equation is introduced to indicate positive current flow in the direction of decreasing temperature.