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CHAPTER 5

HEAT TRANSFER

Conduction, Convection, Radiation; Equations for Conduction, Convection, Radiation, and Combined Convection and Radiation; Heat-Flow Resistance, in Series and Parallel; Practical Heat Transfer Problems; Periodic and Transient Heat Flow

HEAT is the form of energy that is transferred 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 single term known as the resistance. Energy exchange associated with evaporation, condensation, *etc.*, is treated elsewhere such as in the section Cooling Tower Theory in Chapter 40. 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.
3. Present concise summaries of available methods of analysis for transient and periodic heat transfer problems.

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 the molecules of higher kinetic energy transmit part of their energy to adjacent molecules of lower kinetic energy by direct molecular action. Since the temperature is proportional to the average kinetic energy of the molecules, thermal transfer will occur in the direction of decreasing temperature. The motion of the molecules is random; there is no net material flow associated with the conduction mechanism. In the case of flowing fluids, thermal conduction is significant in the region very close to a solid boundary or wall, where the flow is laminar and parallel with the wall surface, and where practically no cross currents exist in the direction of the heat transfer across the solid fluid boundary. In solid bodies the significant mechanism of heat transfer is always thermal conduction.

In contrast to the thermal conduction mechanism, *thermal convection* involves energy transfer by eddy mixing and diffusion[1] in addition to conduction. This is shown 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 somewhat 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 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. 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 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,