v_s = specific volume of saturated water vapor, cubic feet per pound.
v_s = volume of moist air at saturation, cubic feet per pound dry air.
v_T = total gas volume, cubic feet.
W = humidity ratio of moist air, pounds water per pound dry air.
W_s = humidity ratio of moist air at saturation, pounds water vapor per pound dry air.
W_s^* = humidity ratio of moist air at saturation at thermodynamic wet-bulb temperature, pounds water vapor per pound dry air.
x_w = mol fraction of water, mols per mol of mixture.
Z = elevation above any datum, feet.

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CHAPTER 4

HEAT TRANSFER

General Characteristics, Steady State Conduction, Thermal Radiation, Natural Convection, Forced Convection, Boiling, Condensing, Extended Surface, Overall Heat Transfer, Thermal Insulation, Transient Heat Flow

THE term heat transfer basically implies the transfer of thermal energy from one region to another. The three modes of heat transmission which are usually distinguished are conduction, convention, and radiation. Each is important to engineers concerned with the design or application of heating, air-conditioning, or refrigeration equipment. Heat transfer is one of the transport phenomena, a general classification which includes mass transfer (discussed in Chapter 5), momentum transfer or fluid friction (discussed in Chapter 6), and electrical conduction. The similarities between these phenomena are discussed by Bosworth.[1] Transport phenomena have similar rate equations; that is, the flux is proportional to a potential difference. In the case of heat transfer by conduction and convection, the potential difference is the temperature difference. Heat, mass, and momentum transfer, because of their similarities and interrelationship in many common physical processes, have received a unified treatment in recent textbooks.[2,3]

The object of this chapter is to present the elementary principles of heat transfer with particular emphasis on those aspects most pertinent to the heating, refrigerating, and air conditioning industry. More specific information regarding heat transfer to or from buildings or refrigerated spaces may be found in Chapters 24 to 28. Heat transfer equipment such as evaporators, condensers, heating and cooling coils, furnaces and radiators is treated in Chapters 42 to 55. Physical properties of substances may be found in Chapters 19, 22, 24, and 69.

GENERAL CHARACTERISTICS

Thermal conduction is the term applied to the mechanism of heat transfer whereby energy is transported between parts of a continuum due to a transfer of kinetic energy between particles or groups of particles at the atomic level. In gases, conduction is due to the elastic collision of molecules; in liquids and electrically non-conducting solids, it is believed to be primarily due to longitudinal oscillations of the lattice structure. On the other hand, thermal conduction in metals takes place in the same manner as electrical conduction, i.e., through the motions of free electrons. Since the temperature of a substance is proportional to the average kinetic energy of its constituent particles, thermal transfer will occur in the direction of decreasing temperature. In solid opaque bodies the significant mechanism of heat transfer is always thermal conduction, since there is no net material flow associated with the process. In the case of flowing fluids, thermal conduction dominates in the region very close to a solid boundary where the flow is *laminar* and parallel to the surface, and there is no eddy motion.

In contrast to the thermal conduction mechanism, *thermal convection* may involve energy transfer by eddy mixing and diffusion[4] in addition to conduction. Consider the case of heat transfer to a fluid flowing inside a pipe. If the Reynolds number is sufficiently great, three different flow regions will exist. Immediately adjacent to the wall is a *laminar sublayer* where the heat transfer occurs by thermal conduction; outside the laminar sublayer is a transition region called the *buffer layer* where both eddy mixing and conduction effects are significant; beyond the buffer layer and extending to the center of the pipe is the *turbulent region* where the dominant mechanism of transfer is eddy mixing.

In most commercial equipment, the main body of the fluid is in turbulent flow, and the laminar layer exists at the solid walls only. In cases of low-velocity flow in small tubes, or with viscous liquids such as oil (i.e., at 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 flow is generated internally, as a result of non-homogeneous densities arising from the temperature variations, the heat transfer is termed *free* or *natural convection*.

In the conduction and convection mechanisms the transfer of heat takes place through 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. Whereas conduction and convection are affected primarily by temperature difference and somewhat by temperature level, the heat transferred by radiation increases rapidly with increase in the temperature level.

Although in some cases generalized heat transfer equations have been mathematically derived from fundamental principles, in the vast majority of practical cases they are obtained from correlations of experimental data. Normally, these correlations employ certain dimensionless numbers which are arrived at by various means (dimensional analysis, analogy, etc.). Table 1 lists some of the more important of these dimensionless numbers.

STEADY STATE CONDUCTION

The fundamental equation for steady state heat conduction in one dimension is the Fourier equation:

$$q = -kA\frac{dt}{dx} \qquad (1)$$

where

q = heat flow rate, Btu per hour.

The general responsibility for this chapter is assigned to TC 1.3, Heat Transfer and Fluid Flow.