BASIC HEAT TRANSFER

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TRANSFER

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Preface

The material which must be covered in one semester undergraduate level heat transfer course is so extensive that a systematic and unified presentation of the subject matter is essential for effective teaching. Most textbooks available in the market follow a pedagogy in which the reader is introduced to the subject with the solution of particular problems without first being exposed to the fundamentals. This approach appears to be an easy way to start the instruction, but has the disadvantage that, within the limited time available, it becomes almost impossible to return to the fundamentals. As a result, the student's knowledge on the subject does not extend beyond the specific problems covered during the course.

In teaching heat transfer over the past several years, the author has observed that teaching effectiveness is improved and the student's capacity for dealing with the analysis of heat transfer problems is significantly increased if the fundamentals are presented first and close attention is paid to the proper posing of the physical problems before proceeding to the solutions. At the undergraduate level, the fundamentals should be presented with the minimum amount of mathematical complexity and with careful description of the physical significance of various quantities in the mathematical expressions.

It is in this philosophy of approach that the present text differs fundamentally from the existing undergraduate level heat transfer texts. There is sufficient material in this book, systematically arranged at different levels, for the spectrum of its possible uses to include: a first course in heat transfer at the junior level, a basic heat transfer course at a higher level, or a two-quarter undergraduate heat transfer sequence. The text can also serve as a reference volume for engineering graduates and industry. A background in ordinary differential equations at the sophomore level is sufficient to follow the material in this book.

In Chapter 1 the basic concepts in the area of heat transfer are discussed. Chapter 2 is devoted to the derivation of the heat conduction equation and a discussion of dimensionless parameters, the boundary conditions, and the mathematical formulation of physical problems with a unified approach. The aim of this chapter is to provide a good understanding of the physical significance of the heat conduction equation and the proper formulation of heat conduction problems.

The three chapters that follow are devoted to the methods of solution of heat conduction problems at three distinct levels. In particular, Chapter 3 deals with the analysis of one-dimensional, steady-state heat conduction in slabs, cylinders, spheres and through fins. In Chapter 4, a unified approach for the solution of two physically different heat conduction problems is presented. The solution of two-dimensional steady-state and one-dimensional unsteady heat conduction problems are brought together in this chapter because of their common mathematical base. This aim is achieved by a systematic tabulation, presented in Table 4-1, of the fundamental solutions common to these two different class of problems. Once the reader becomes familiar with the use of this table, the analysis of heat conduction problems discussed in Chapter 4 becomes a relatively easy matter. In Chapter 5, the finite difference technique and its application to the solution of heat conduction problems are presented with a concise and rigorous approach.

In the teaching of convection heat transfer, the physical significance of various quantities in the energy equation should be tied to the fluid mechanics aspects of the problem. To this end, Chapter 6 is devoted to the derivation of the equations of motion and energy. The aim of this chapter is to provide a good appreciation of the physical significance of various terms and the dimensionless groups in the resulting expressions and to serve as a ready reference for the equations needed in the four subsequent chapters on the analysis of convective heat transfer. If individual course objectives do not require it, the detailed derivations of this chapter may be omitted without effecting the continuity of the subject. Emphasis may be placed, instead, on the understanding of the physical significance of these equations.

Chapters 7 and 8 deal with heat transfer in internal and external flow respectively. The aim of these two chapters is to illustrate the mathematical formulation of typical convective heat transfer problems by utilizing the equations given in Chapter 6, to present typical methods of solution, and to provide a good understanding of the physical significance of various heat transfer results. Chapter 9 is devoted to a discussion of heat transfer in internal and external turbulent flow. In order to provide some insight to the implications of turbulent flow, basic concepts of the mechanism of turbulence are discussed and various analogies between momentum and heat transfer are described before a wealth of empirical correlations of heat transfer in turbulent flow is presented. If it is not required by the course objective, the analysis of turbulent flow may be omitted, and emphasis can be placed on the application of the empirical relations. Heat transfer in free convection is presented in Chapter 10.

Chapters 11 through 13 provide a systematic analysis of radiative heat transfer in nonparticipating and participating media. Chapter 11 gives the background information on the emission, the absorption, and the reflection of radiation by the matter that are needed in the two succeeding chapters on the analysis of radiative heat exchange. The subject of radiative heat transfer between surfaces in a nonparticipating medium is presented in Chapter 12 using an approach different from those followed in most undergraduate heat transfer texts. The method of analysis is more straightforward and possesses computational advantages. The radiative heat transfer in participating media is considered in Chapter 13. Chapter 13 may be omitted, if not required by the goals of the course, without affecting the continuity of the subject. The empirical results given in this chapter and their applications may be emphasized in these cases.

In Chapters 14 and 15, a comprehensive treatment of the subjects of heat transfer in condensation, boiling and the heat exchangers is given.

Finally, in Chapter 16, the analysis of mass transfer is closely tied to the analysis of heat transfer. The systematic, simple, and rigorous approach followed in this chapter in developing the basic relations will make the teaching of this complicated subject a relatively easy matter.

Heat transfer calculations are commonly performed in engineering by using the English system and the SI (Systéme Internationale) system of units. The SI system has been adopted in a number of countries and a changeover into the SI system in the engineering field is expected to take place in the countries which are currently using the English system. In the transition period it will be necessary for the student and the engineer to be familiar with both systems of units. Therefore, both the English system and the SI system of units are simultaneously used throughout the main body of the text, in the solution of examples, and in the physical property tables.

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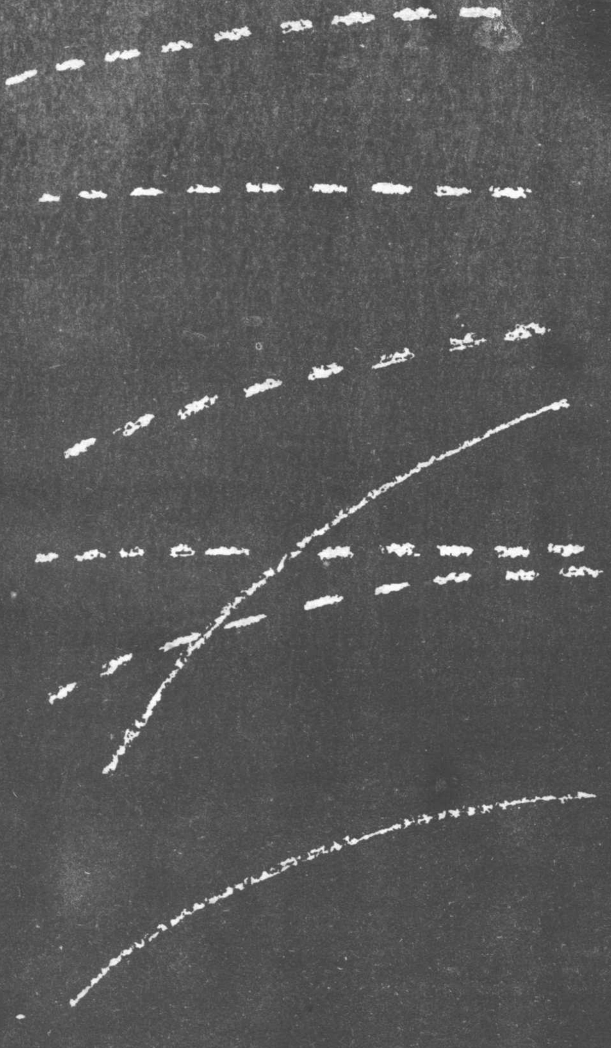

Introduction and Concepts

The concept of *energy* is used in thermodynamics to specify the state of a system. It is a well-known fact that energy is neither created nor destroyed but only changed from one form to another. The science of *thermodynamics* deals with the relation between heat and other forms of energy, but the science of *heat transfer* is concerned with the analysis of the rate of heat transfer taking place in a system. The energy transfer by heat flow cannot be measured directly, but the concept has physical meaning because it is related to the measurable quantity called *temperature*. It has long been established by observations that, when there is temperature difference in a system, heat flows from the region of high temperature to the region of low temperature. Since heat flow takes place whenever there is a temperature gradient in a system, a knowledge of the temperature distribution in a system is essential in heat-transfer studies. Once the temperature distribution is known, a quantity of practical interest, the *heat flux*, which is the amount of heat transfer per unit area, per unit time, is readily determined from the law relating the heat flux to the temperature gradient.

The problem of determining temperature distribution and heat flow is of interest in many branches of science and engineering. In the design of heat exchangers such as boilers, condensers, radiators, etc., for example, heat-transfer analysis is essential for sizing such equipment. In the design of nuclear-reactor cores, a thorough heat-transfer analysis of fuel elements is important for proper sizing of fuel elements to prevent burnout. In aerospace technology, the temperature-distribution and heat-transfer problems are crucial because of weight limitations and safety considerations. In heating and air-conditioning applications for buildings, a proper heat-transfer analysis is necessary to estimate the amount of insulation needed to prevent excessive heat losses or gains.

In the studies of heat transfer it is customary to consider three distinct modes of heat transfer: *conduction*, *convection*, and *radiation*. In reality, temperature distribution in a medium is controlled by the combined effects of these three modes of heat transfer; therefore it is not actually possible to isolate entirely one mode from interactions with the other modes. However, for simplicity in the analysis, one can consider, for example, conduction separately whenever heat transfer by convection and radiation is negligible. With this qualification, we present below a brief qualitative description of these three distinct modes of heat transfer; they will be studied in greater detail in the following chapters.

1-1 CONDUCTION

Conduction is the mode of heat transfer in which energy exchange takes place from the region of high temperature to the region of low temperature by the kinetic motion or direct impact of molecules, as in the case of fluid at rest, and by the drift of electrons, as in the case of metals. In a solid which is a good electric conductor, a large number of free electrons move about in the lattice; hence materials that are good electric conductors are generally good heat conductors (i.e., copper, silver, etc.).

The basic law of heat conduction based on experimental observations originates from Biot but is generally named after the French mathematical physicist Joseph Fourier [1][1] who used it in his analytic theory of heat. This law states that the rate of heat flow by conduction in a given direction is proportional to the area normal to the direction of heat flow and to the gradient of temperature in that direction. For heat flow in the x direction, for example, the Fourier law is given as

$$Q_x = -kA\frac{\partial T}{\partial x} \qquad \text{Btu/h} \qquad \text{or} \qquad \text{W} \tag{1-1a}$$

or

$$q_x = \frac{Q_x}{A} = -k\frac{\partial T}{\partial x} \qquad \text{Btu/h}\cdot\text{ft}^2 \qquad \text{or} \qquad \text{W/m}^2 \tag{1.1b}$$

where Q_x is the rate of heat flow through area A in the positive x direction, and q_x is called the *heat flux* in the positive x direction. The proportionality constant k is called the *thermal conductivity* of the material and is a positive quantity. The minus sign is included in Eqs. (1-1) to ensure that q_x (or Q_x) is a positive quantity when the heat flow is in the positive x direction. This is apparent from the fact that the temperature should decrease in the positive x direction if the heat should flow in that direction; then $\partial T/\partial x$ is negative, and the inclusion of the negative sign in the above equations ensures that q_x (or Q_x) is a positive quantity.

The thermal conductivity k in Eqs. (1-1) has units Btu/h·ft·°F (or W/m·°C) if heat flux q_x is in Btu/h·ft^2 (or W/m^2), and the temperature gradient $\partial T/\partial x$ is in °F/ft (or °C/m). There is a wide difference in the thermal conductivities of various engineering materials, as shown in Fig. 1-1. The highest value is given by pure metals and the lowest value by gases and vapors; the amorphous insulating materials and inorganic liquids have thermal conductivities that lie in between. To give some idea of the order of magnitude of thermal conductivity for various materials we list below some typical values of k:

Metals: 30 to 240 Btu/h·ft·°F (or 52 to 415 W/m·°C)
Alloys: 7 to 70 Btu/h·ft·°F (or 12 to 120 W/m·°C)
Nonmetallic liquids: 0.1 to 0.4 Btu/h·ft·°F (or 0.173 to 0.69 W/m·°C)
Insulating materials: 0.02 to 0.1 Btu/h·ft·°F (or 0.035 to 0.173 W/m·°C)
Gases at atmospheric pressure: 0.004 to 0.1 Btu/h·ft·°F (or 0.0069 to 0.173 W/m·°C)

Thermal conductivity also varies with temperature. For most pure metals it decreases with temperature, whereas for gases and insulating materials it increases with temperature. At very low temperatures thermal conductivity varies very rapidly with temperature, as shown in Fig. 1-2. A comprehensive compilation of thermal conductivities of materials may be found in Refs. [2, 3, 4].

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[1] Bracketed numbers indicate references at the end of the chapter.

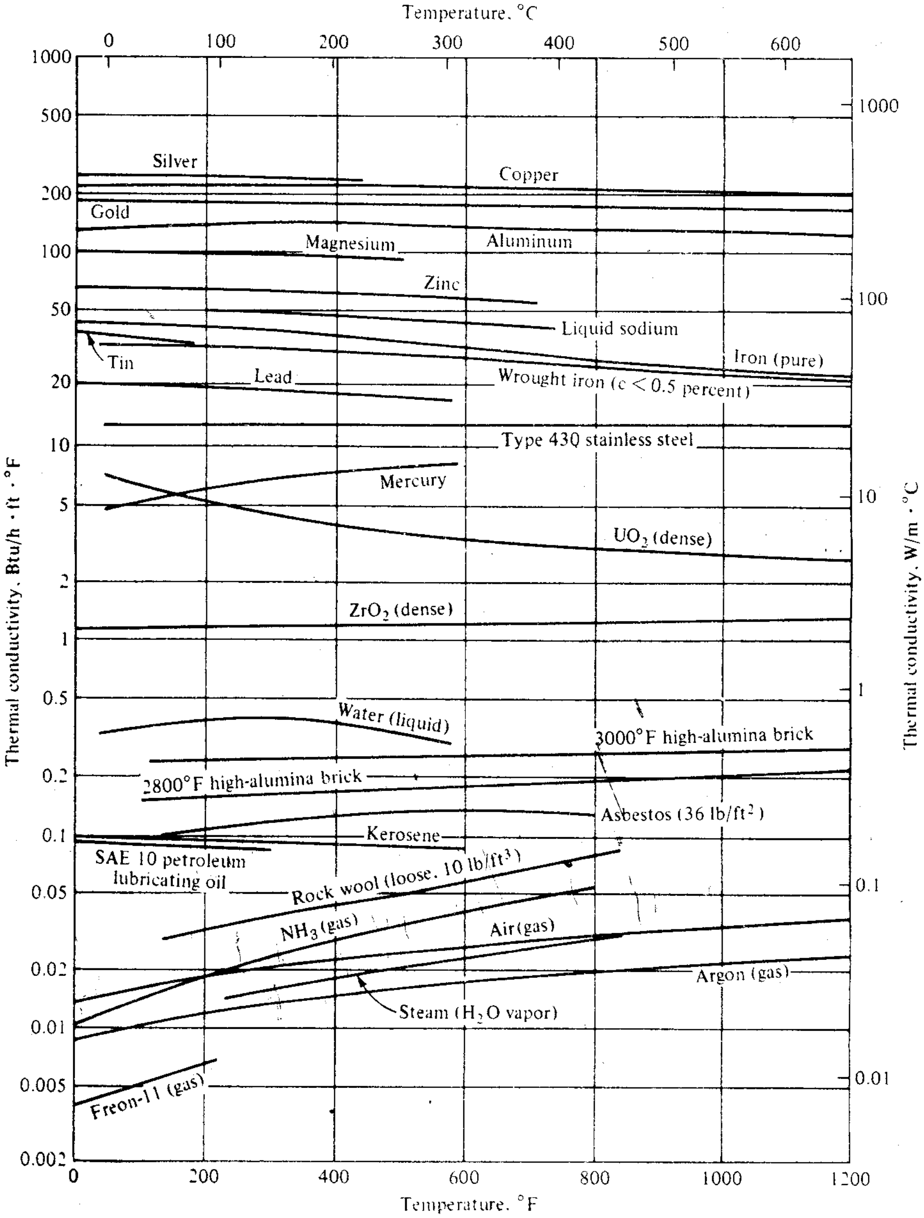

FIG. 1-1 Thermal conductivity of typical engineering materials.

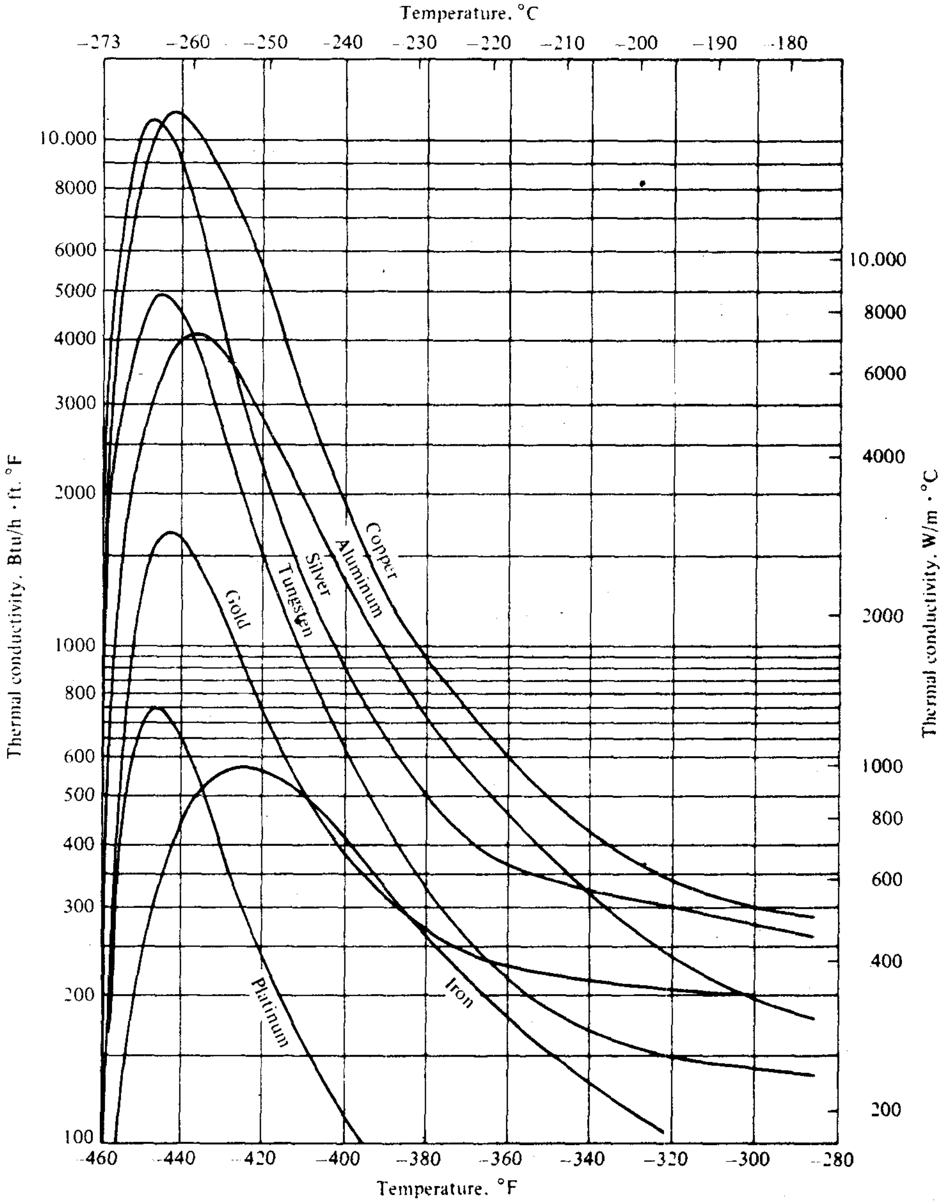

FIG. 1-2 Thermal conductivity of metals at low temperatures. (*From Powell et al.* [2].)

1-2 CONVECTION

When fluid flows over a solid body or inside a channel while temperatures of the fluid and the solid surface are different, heat transfer between the fluid and the solid surface takes place as a consequence of the motion of fluid relative to the surface; this mechanism of heat transfer is called *convection.* If the fluid motion is artificially induced, say with a pump or a fan that forces the fluid flow over the surface, the heat transfer is said to be by *forced convection.* If the fluid motion is set up by buoyancy effects resulting from density difference caused by temperature difference in the fluid, the heat transfer is said to be by *free* (or *natural*) *convection.* For example, a hot plate vertically suspended in stagnant cool air causes a motion in the air layer adjacent to the plate surface because the temperature gradient in the air gives rise to a density gradient which in turn sets up the air motion. As the temperature field in the fluid is influenced by the fluid motion, the determination of temperature distribution and of heat transfer in convection for most practical situations is a complicated matter. In engineering applications, to simplify the heat-transfer calculations between a

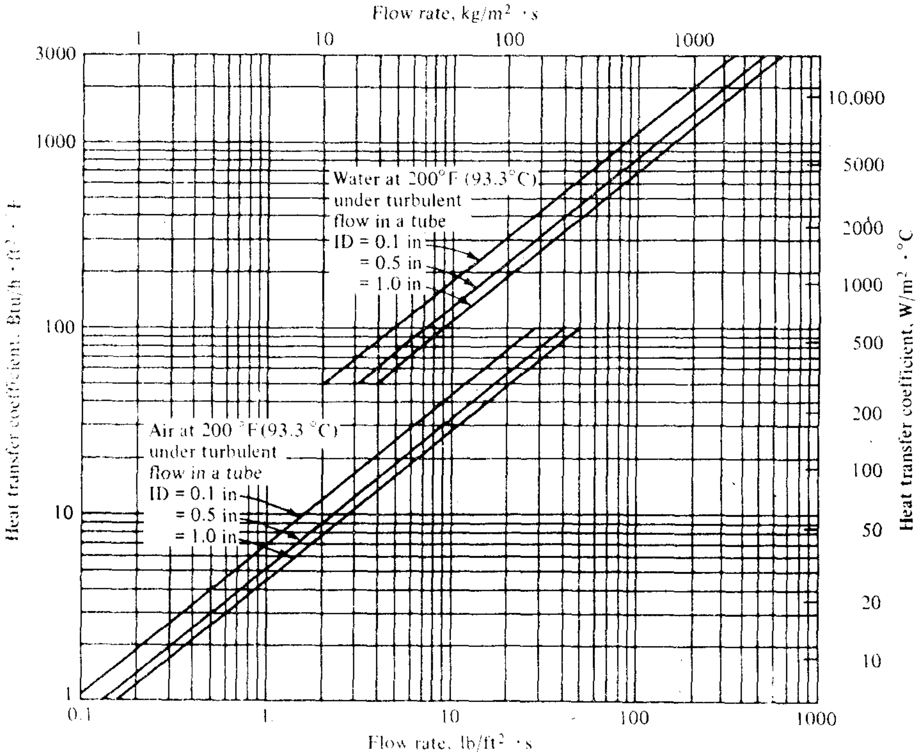

FIG. 1-3 Heat-transfer coefficient for turbulent flow of water and air at 200°F in tubes.