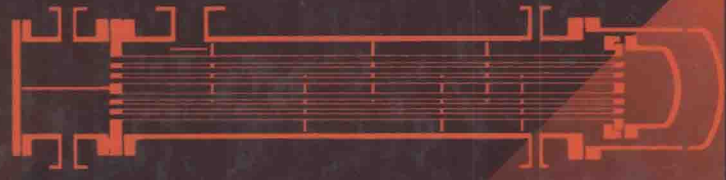
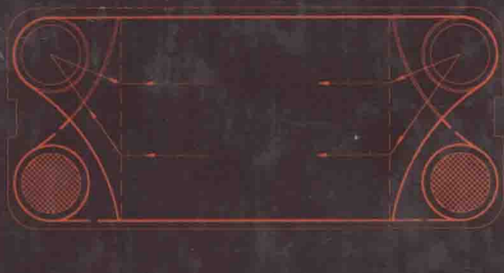
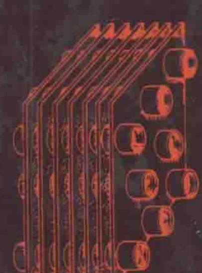


HEAT EXCHANGERS

SELECTION, RATING, and THERMAL DESIGN





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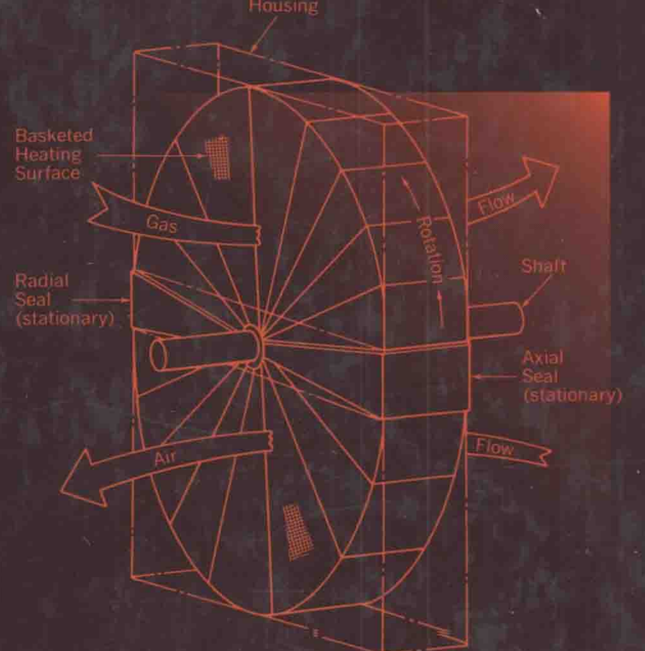

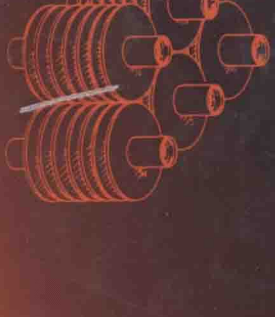

HEAT EXCHANGERS

SELECTION, RATING, and THERMAL DESIGN

Sadık Kakaç
Hongtan Liu
Department of Mechanical Engineering
University of Miami
Coral Gables, Florida

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Preface

Heat exchangers are vital in power producing plants; process and chemical industries; heating, ventilating, air-conditioning, and refrigeration systems; and cooling of electronic systems. A large number of industries are engaged in designing various types of heat exchange equipment. Courses are offered at many colleges and universities on thermal design under various titles.

There is extensive literature on this subject; however, the information has been widely scattered. This is a systematic approach to be used as an up-to-date textbook based on scattered literature for senior undergraduate and first year graduate students in mechanical, nuclear, aerospace, and chemical engineering who have taken introductory courses in thermodynamics, heat transfer, and fluid mechanics. This systematic approach is also essential for the newcomers who are interested in industrial applications of thermodynamics, heat transfer, and fluid mechanics; and for designers and operators of heat exchange equipment. This book focuses on the selection, thermohydraulic design, design processes, and rating and operational problems of various types of heat exchangers.

The new criterion by the Accreditation Board on Engineering and Technology (ABET) requires engineering design across the curriculum. Therefore, one of the main objectives of this textbook is to introduce thermal design by describing various types of single-phase and two-phase flow heat exchangers, detailing their specific fields of application, selection, and thermohydraulic design and rating; and showing thermal design and rating processes with worked examples and end-of-chapter problems including student design projects.

Much of the text is devoted to double-pipe, shell-and-tube, compact, gasketed-plate heat exchanger types, condensers, and evaporators. Their design processes are described, and thermal–hydraulic design examples are presented. Some other types, mainly specialized ones, are briefly described without design examples. Nevertheless, thermal design factors and methods are common to all heat exchangers regardless their function.

The text begins with the classification of heat exchangers according to different criteria. Chapter 2 provides the basic design methods for sizing and rating of heat exchangers. Chapter 3 is a review of single-phase forced convection correlations in ducts. A large number of experimental and analytic correlations are available for heat transfer coefficient and flow friction factor for laminar and turbulent flow through ducts. Thus, it is often a difficult and confusing task for a student and even a designer to choose appropriate correlations. In this chapter, recommended correlations for the single-phase side of heat exchangers are given with worked examples. Chapter 4 discusses pressure drop and pumping power for heat exchangers and their piping circuit analysis.

One of the major unresolved problems in heat exchanger equipment is fouling; design of heat exchangers subject to fouling is presented in Chapter 5. The thermal design methods and processes for double-pipe, shell-and-tube, compact, and gasketed-plate heat exchangers are presented in Chapters 6, 8, 9, and 10 for single-phase duties, respectively. The important design correlations for the design of two-phase flow heat exchangers are given in Chapter 7. With this arrangement, students and newcomers in industry will achieve better understanding of thermal design and will be better prepared to understand the thermal design of condensers and evaporators that is introduced in Chapter 11. Appendices A and B provide thermophysical properties of various fluids, including the new refrigerants.

In every chapter, worked examples to illustrate the thermal design methods and procedures are given. Although the use of computer programs is essential for thermal design and rating of these exchangers, for students and newcomers manual thermal design analysis is essential in the initial learning period. Fundamental design knowledge is needed before one correctly uses computer design software and develops new reliable and sophisticated computer software for rating to obtain an optimum solution.

The end-of-chapter problems including student design projects are selected to enhance the design applications. A solution manual accompanies the text. Additional problems are added to the solution manual that maybe helpful to the instructors of the course.

Design of a heat exchange equipment requires explicit consideration of mechanical design, economics, optimization techniques, and environmental considerations. Information on these topics is available in various standard references and handbooks, and from manufacturers.

Several individuals have made valuable contributions to this book: E. M. Sparrow and A. Bejan reviewed the manuscript and provided helpful suggestions. We gratefully appreciate their support.

Sadik Kakaç has edited several books on the fundamentals and design of heat exchangers to which many leading scientists and experts made invaluable contributions, and is thankful to them. Both authors are greatly indebted, especially to the following individuals whose contributions to the field of heat exchangers made this book possible: Kenneth J. Bell, David Butterworth, John Collier, Paul J. Marto, Mike B. Pate, Ramesh K. Shah, and J. Taborek.

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Sadık Kakaç
Hongtan Liu

The Authors

Sadık Kakaç is a Professor of Mechanical Engineering at University of Miami, Coral Gables, Florida. He received the Dipl. Ing. (1955) in Mechanical Engineering from Technical University of Istanbul; his S.M. (1959) in Mechanical Engineering and his S.M. (1960) in Nuclear Engineering, both from Massachusetts Institute of Technology. In 1965, he received his Ph.D. in the field of heat transfer from Victoria University of Manchester, U.K. He was elected as a member of the Turkish Scientific and Technical Research Council in 1972 and the general secretary of the Turkish Atomic Energy Commission in 1978, and represented Turkey in a number of scientific endeavors abroad. He is a recipient of the Alexander von Humboldt Research Award for Senior U.S. Scientists (1989), the Science Award of the Association of Turkish–American Scientists (1994), and the ASME Heat Transfer Memorial Award (1997). He is a fellow of the American Society of Mechanical Engineers (ASME). Formerly, Dr. Kakaç was a Professor of Mechanical Engineering at the Middle East Technical University in Ankara, Türkiye. Dr. Kakaç has focused his research efforts on steady-state and transient forced convection in single-phase flows and on two-phase flow instabilities in flow boiling. He is the author or coauthor of 5 heat transfer textbooks and more than 165 research papers; and edited 15 volumes in the field of thermal sciences and heat exchanger fundamentals and design, including *The Handbook of Single-Phase Convective Heat Transfer.*

Hongtan Liu is an Assistant Professor of Mechanical Engineering at University of Miami, Coral Gables, Florida. He received his B.S. degree (1982) in Mechanical Engineering from Shenyang Civil and Architectural Engineering Institute, and both his M.S. (1989) and Ph.D. (1993) degrees in Mechanical Engineering from University of Miami. He spent one year as a research fellow at the Institute of Thermodynamics A, Technical University of Munich in Germany. During the period of 1996–1997, Dr. Liu was a Senior Research Engineer at Energy Partners, Inc., where he was mainly responsible for the research in fluid flow, heat and mass transfer in fuel cells. As a graduate student, he received a Graduate Student Academic Excellence Award (1993) and was listed in Who's Who Among Students in American Colleges and Universities (1991–1992). As a faculty member, he received the Eliahu I. Jury Excellence in Research Award from the College of Engineering, University of Miami (1995). Dr. Liu has focused his research efforts on fuel cells, solar energy applications, boiling two-phase flow instabilities, and hydrogen energy systems. He is the author or co-author of more than 30 research papers.

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1

Classification of Heat Exchangers

1.1 Introduction

Heat exchangers are devices that provide the flow of thermal energy between two or more fluids at different temperatures. Heat exchangers are used in a wide variety of applications. These include power production; process, chemical, and food industries; electronics; environmental engineering; waste heat recovery; manufacturing industry; and air-conditioning, refrigeration, and space applications. Heat exchangers may be classified according to the following main criteria:[1,2]

1. Recuperators and regenerators
2. Transfer processes: direct contact and indirect contact
3. Geometry of construction: tubes, plates, and extended surfaces
4. Heat transfer mechanisms: single phase and two phase
5. Flow arrangements: parallel, counter, and cross flows

The preceding five main criteria are illustrated in Figure 1.1.[1]

1.2 Recuperation and Regeneration

The conventional heat exchangers shown diagramatically in Figure 1.1a with heat transfer between two fluids is called a recuperator, because the hot stream A recovers (recuperates) some of the heat from stream B. The heat transfer is through a separating wall or through the interface between the streams as in the case of direct contact type of heat exchangers (Figure 1.1c). Some examples of the recuperative-type exchangers are shown in Figure 1.2.

In regenerators or in storage-type heat exchangers, the same flow passage (matrix) is alternately occupied by one of the two fluids. The hot fluid stores the thermal energy in the matrix; during the cold-fluid flow through the same passage later, energy stored will be extracted from the matrix. Therefore, thermal energy is not transferred through the wall as in a direct transfer type of heat exchanger. This cyclic principle is illustrated in Figure 1.1b. While the solid is in the cold stream A it loses heat; while it is in the hot stream B it gains heat (i.e., it is regenerated). Some examples of storage-type heat exchangers are rotary regenerator for preheating the air in a large coal-fired steam power plant, gas turbine rotary regenerator, fixed-matrix air preheaters for blast furnace stoves, steel furnaces, open-hearth steel melting furnaces, and glass furnaces.

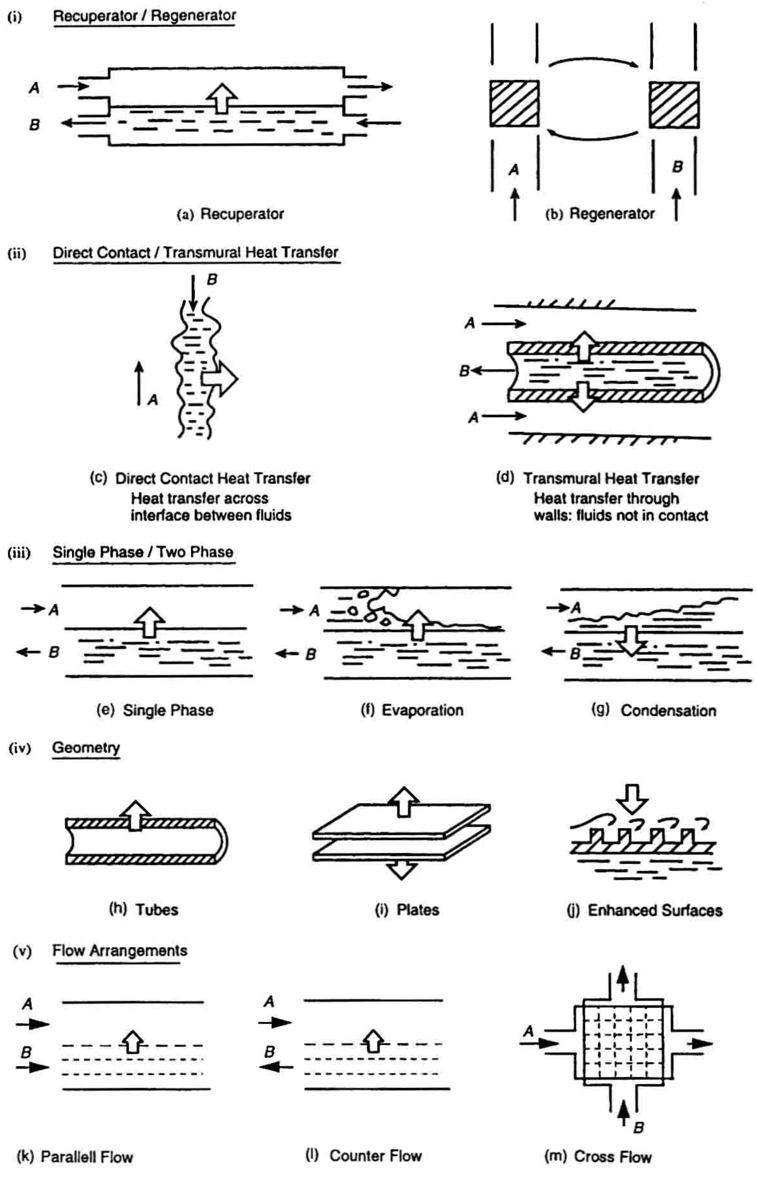

FIGURE 1.1
Criteria used in the classification of heat exchangers. (From Hewitt, G. F., Shires, G. L., and Bott, T. R. [1994] *Process Heat Transfer*, CRC Press, Boca Raton, FL.)

Regenerators can be classified as follows:

1. Rotary regenerator
2. Fixed-matrix regenerator

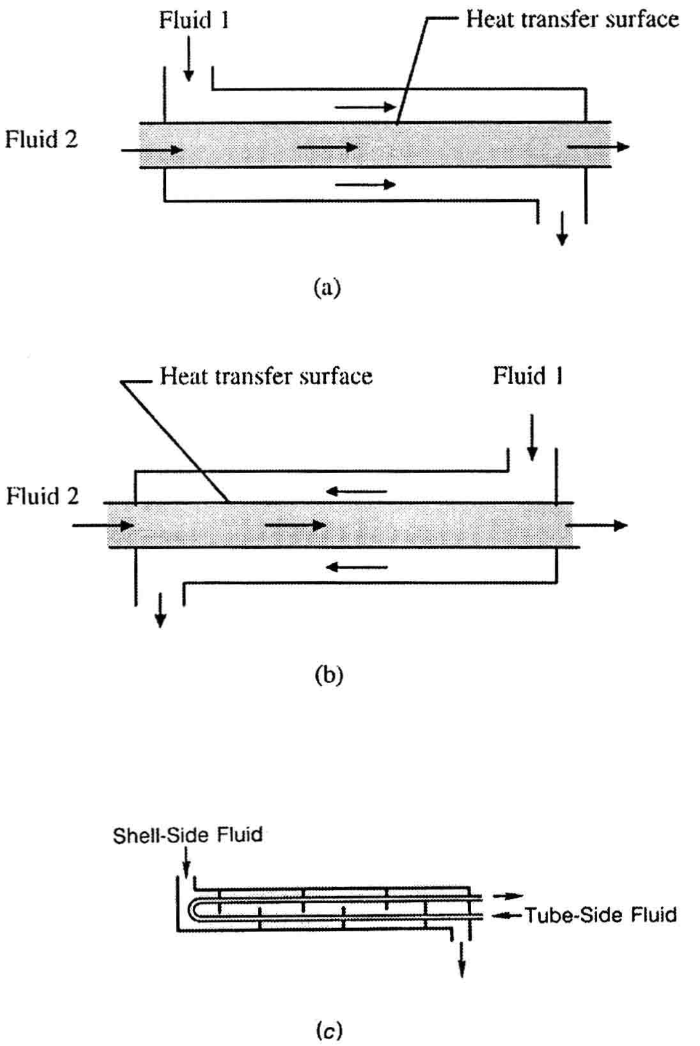

FIGURE 1.2
Indirect contact types of heat exchangers. (a) (b) Double-pipe type; (c) shell-and-tube type.

Rotary regenerators can be further subclassified as:

1. Disk type
2. Drum type

The disk-type and drum-type regenerators are shown schematically in Figure 1.3. In a disk-type regenerator, the heat transfer surface is in a disk form and fluids flow axially. In a drum type, the matrix is in a hollow drum form and fluids flow radially.

These regenerators are periodic flow heat exchangers. In rotary regenerators, the operation is continuous. To have this, the matrix moves periodically in and out of the fixed

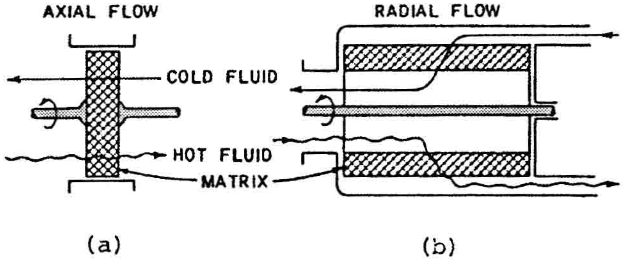

FIGURE 1.3
Rotary regenerators. (a) Disk type; (b) drum type. (From Shah, R. K. [1981] In *Heat Exchangers — Thermo–Hydraulic Fundamentals and Design*, Wiley, New York. With permission.)

stream of gases. A rotary regenerator for air heating is illustrated in Figure 1.4. There are two kinds of regenerative air preheaters used in convectional power plants:[3] the rotating-plate type (Figures 1.4 and 1.5) and the stationary-plate type (Figure 1.6). The rotor of the rotating-plate air heater is mounted within a box housing and is installed with the heating surface in the form of plates as shown in Figure 1.5. As the rotor rotates slowly, the heating surface is exposed alternately to flue gases and to the entering air. When the heating surface is placed in the flue gas stream, the heating surface is heated; and then when it is rotated by mechanical devices into the air stream, the stored heat is released to the air flow. Thus, the air stream is heated. In the stationary-plate air heater (Figure 1.6), the heating plates are stationary, while cold-air hoods — both top and bottom — are rotated across the heating plates; the heat transfer principles are the same as those of the rotating-plate regenerative air heater. In a fixed-matrix regenerator, the gas flows must be diverted to and from the fixed matrices. Regenerators are compact heat exchangers and they are designed for surface area density of up to approximately 6600 m^2/m^3.

1.3 Transfer Processes

According to transfer processes, heat exchangers are classified as direct contact type and indirect contact type (transmural heat transfer).

In *direct contact* type heat exchangers, heat is transferred between the cold and hot fluids through a direct contact between these fluids. There is no wall between hot and cold streams, and the heat transfer occurs through the interface between two streams as illustrated in Figure 1.1c. In direct contact-type heat exchangers the streams are two immiscible liquids, a gas–liquid pair, or a solid particle–fluid combination. Spray and tray condensers (Figure 1.7) and cooling towers are good examples of such heat exchangers.[4,5] Very often in such exchangers, heat and mass transfer occur simultaneously. In a cooling tower a spray of water falling from the top of the tower is directly contacted and cooled by a stream of air flowing upward (Figures 11.14 and 11.15).

In an *indirect contact* type heat exchanger, the heat energy is exchanged between hot and cold fluids through a heat transfer surface (i.e., a wall separating the fluids). The cold and hot fluids flow simultaneously while heat energy is transferred through a separating wall as illustrated in Figure 1.1d. The fluids are not mixed. Examples of this type of heat exchanger are shown in Figure 1.2.

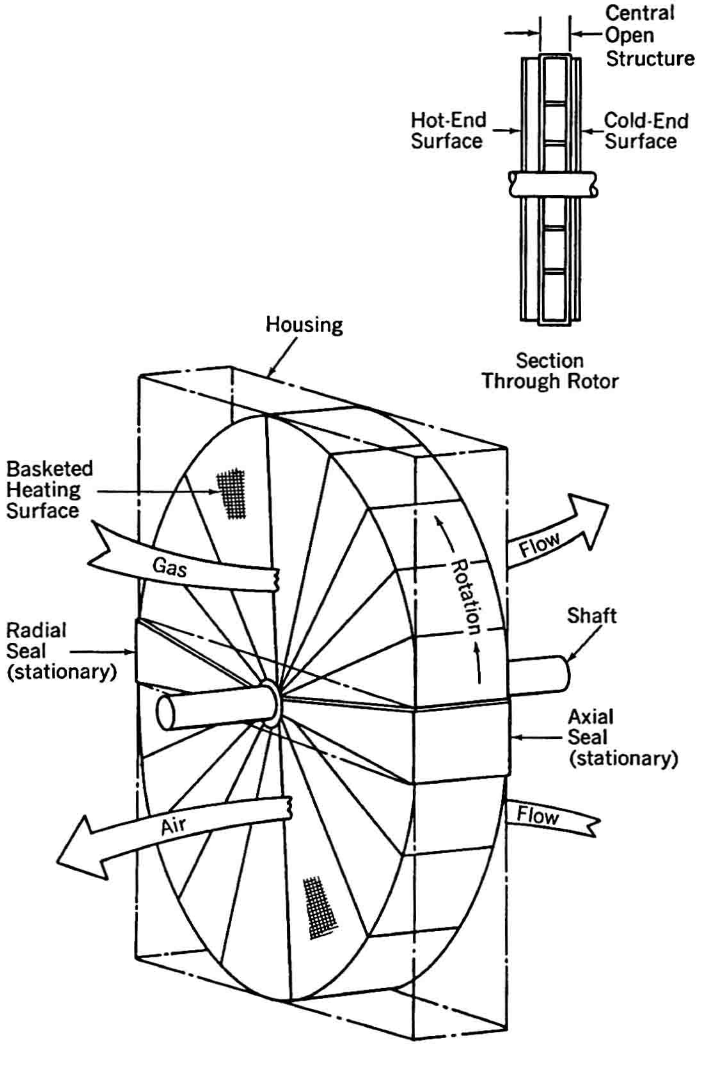

FIGURE 1.4
Rotary storage-type heat exchanger.

Indirect contact- and direct transfer-type heat exchangers are also called *recuperators*. Tubular (double-pipe, shell-and-tube), plate, and extended surface heat exchangers; cooling towers; and tray condensers are examples of recuperators.

1.4 Geometry of Construction

Direct transfer-type heat exchangers (transmural heat exchangers) are often described in terms of their construction features. The major construction types are tubular, plate, and extended surface heat exchangers.

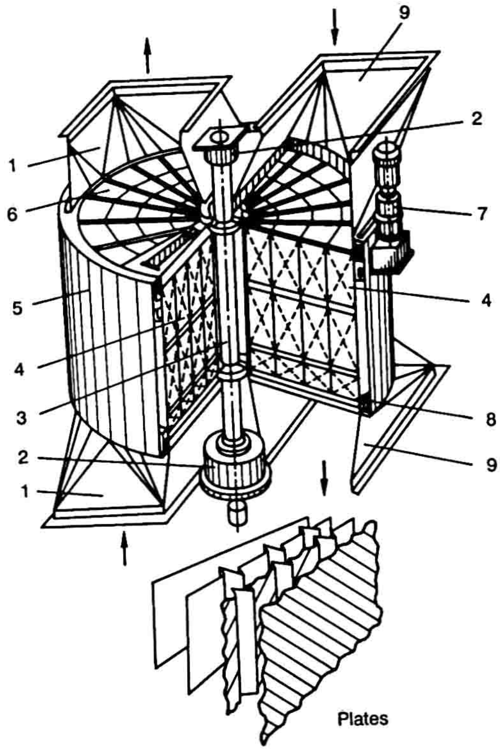

FIGURE 1.5
Rotating-plate regenerative air preheater in a large coal-fired steam power plant. (1) Air ducts; (2) bearings; (3) shaft; (4) plates; (5) outer case; (6) rotor; (7) motor; (8)sealings; (9) flue gas ducts. (From Lin, Z. H. [1991] In *Boilers, Evaporators and Condensers*, Wiley, New York. With permission.)

1.4.1 Tubular Heat Exchangers

These heat exchangers are built of circular tubes. One fluid flows inside the tubes and the other, on the outside of the tube. Tube diameter, number of tubes, tube length, pitch of the tubes, and tube arrangement can be changed. Therefore, there is a considerable flexibility in their design.

Tubular heat exchangers can be further classified as follows:

1. Double pipe
2. Shell and tube
3. Spiral tube type

(1) Double-Pipe Heat Exchangers

A typical double-pipe heat exchanger consists of one pipe placed concentrically inside another of larger diameter with appropriate fittings to direct the flow from one section to the next, as shown in Figures 1.2 and 1.8. Double-pipe heat exchangers can be arranged in various series and parallel arrangements to meet pressure drop and mean temperature difference requirements. The major use of double-pipe exchangers is for sensible heating or cooling of process fluids where small heat transfer areas (to 50 m^2) are required. This configuration is also suitable when one or both fluids are at high pressure. The major disadvantage is that these exchangers are bulky and expensive per unit transfer surface. Inner tubing may be single tube or multitubes (Figure 1.8). If the heat transfer coefficient is poor in the annulus, axially finned inner tube (or tubes) can be used. Double-pipe heat exchangers are built in modular concept (i.e., in the form of hairpins).