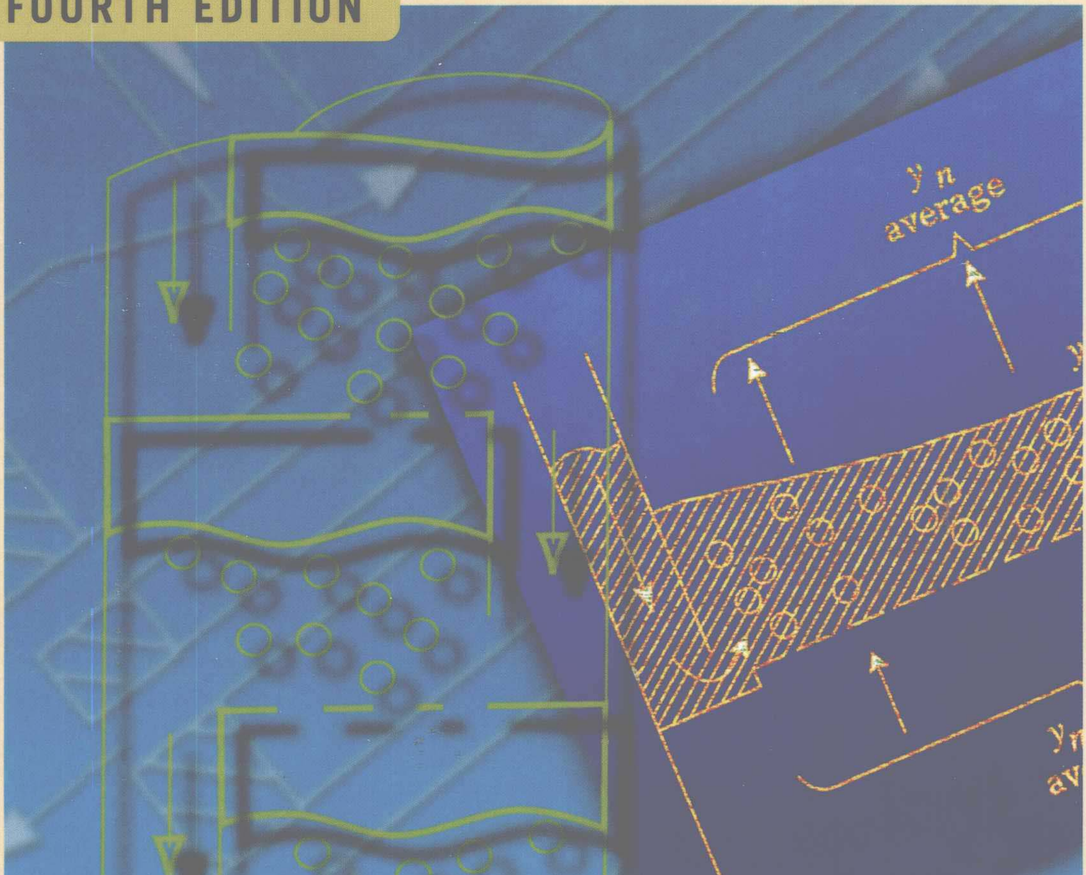
Transport Processes and Separation Process Principles

(INCLUDES UNIT OPERATIONS)

FOURTH EDITION



CHRISTIE JOHN GEANKOPLIS

CHRISTIE JOHN GEANKOPLIS
University of Minnesota

Transport Processes and Separation Process Principles (Includes Unit Operations)

FOURTH EDITION

PRENTICE HALL PTR

PRENTICE HALL
Professional Technical Reference
Upper Saddle River, NJ 07458
www.phptr.com

ISBN 0-13-101367-X
9 790131 013673 90000

Library of Congress Cataloging-in-Publication Data

A CIP record for this book can be obtained from the Library of Congress.

Editorial Production/Composition: *G & S Typesetters, Inc.*
Cover Director: *Jerry Votta*
Art Director: *Gail Cocker-Bogusz*
Manufacturing Buyer: *Maura Zaldivar*
Publisher: *Bernard Goodwin*
Editorial Assistant: *Michelle Vincenti*
Marketing Manager: *Dan DePasquale*

PRENTICE HALL PTR

Publishing as Prentice Hall Professional Technical Reference
Upper Saddle River, New Jersey 07458

Prentice Hall books are widely used by corporations and government agencies for training, marketing, and resale.

For information regarding corporate and government bulk discounts please contact:
Corporate and Government Sales (800) 382-3419 or corpsales@pearsontechgroup.com

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

ISBN 0-13-101367-X

Pearson Education LTD.
Pearson Education Australia PTY, Limited
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd.
Pearson Education Canada, Ltd.
Pearson Educación de Mexico, S.A. de C.V.
Pearson Education—Japan
Pearson Education Malaysia, Pte. Ltd.

Preface

The title of this text has been changed from *Transport Processes and Unit Operations* to *Transport Processes and Separation Process Principles (Includes Unit Operations).* This was done because the term "unit operations" has been largely superseded by the term "separation processes," which better reflects the modern nomenclature being used.

In this fourth edition, the main objectives and the format of the third edition remain the same. The sections on momentum transfer have been greatly expanded, especially the sections on fluidized beds, flow meters, mixing, and non-Newtonian fluids. Material has been added to the chapters on mass transfer. The chapters on absorption, distillation, and liquid–liquid extraction have also been enlarged. More new material has been added to the sections on ion exchange and crystallization. The chapter on membrane separation processes has been greatly expanded, especially for gas-membrane theory.

The field of chemical engineering involved with physical and physical–chemical changes of inorganic and organic materials and, to some extent, biological materials is overlapping more and more with the other process-engineering fields of ceramic engineering, process metallurgy, agricultural food engineering, wastewater-treatment (civil) engineering, and bioengineering. The principles of momentum, heat, and mass transport and the separation processes are widely used in these processing fields.

The principles of momentum transfer and heat transfer have been taught to all engineers. The study of mass transfer has been limited primarily to chemical engineers. However, engineers in other fields have become more interested in mass transfer in gases, liquids, and solids.

Since chemical and other engineering students must study so many topics today, a more unified introduction to the transport processes of momentum, heat, and mass transfer and to the applications of separation processes is provided. In this text the principles of the transport processes are covered first, and then the separation processes (unit operations). To accomplish this, the text is divided into two main parts.

PART 1: Transport Processes: Momentum, Heat, and Mass

This part, dealing with fundamental principles, includes the following chapters: 1. Introduction to Engineering Principles and Units; 2. Principles of Momentum Transfer and Overall Balances; 3. Principles of Momentum Transfer and Applications; 4. Principles of Steady-State

Heat Transfer; 5. Principles of Unsteady-State Heat Transfer; 6. Principles of Mass Transfer; and 7. Principles of Unsteady-State and Convective Mass Transfer.

PART 2: Separation Process Principles (Includes Unit Operations)

This part, dealing with applications, covers the following separation processes: 8. Evaporation; 9. Drying of Process Materials; 10. Stage and Continuous Gas–Liquid Separation Processes (humidification, absorption); 11. Vapor–Liquid Separation Processes (distillation); 12. Liquid–Liquid and Fluid–Solid Separation Processes (adsorption, ion exchange, extraction, leaching, crystallization); 13. Membrane Separation Processes (dialysis, gas separation, reverse osmosis, ultrafiltration, microfiltration); 14. Mechanical–Physical Separation Processes (filtration, settling, centrifugal separation, mechanical size reduction).

In Chapter 1 elementary principles of mathematical and graphical methods, laws of chemistry and physics, material balances, and heat balances are reviewed. Many readers, especially chemical engineers, may be familiar with most of these principles and may omit all or parts of this chapter.

A few topics, primarily those concerned with the processing of biological materials, may be omitted at the discretion of the reader or instructor; these include Sections 5.5, 6.4, 8.7, 9.11, and 9.12. Over 240 example or sample problems and over 550 homework problems on all topics are included in the text. Some of the homework problems involve biological systems, for those readers who are especially interested in that area.

This text may be used for a course of study following any of the following five suggested plans. In all plans, Chapter 1 may or may not be included.

1. *Study of transport processes of momentum, heat, and mass and separation processes.* In this plan, most of the entire text, covering the principles of the transport processes in Part 1 and the separation processes in Part 2, is covered. This plan would be applicable primarily to chemical engineering as well as to other process-engineering fields in a one-and-one-half-year course of study at the junior and/or senior level.

2. *Study of transport processes of momentum, heat, and mass and selected separation processes.* Only the elementary sections of Part 1 (the principles chapters—2, 3, 4, 5, 6, and 7) are covered, plus selected separation-processes topics in Part 2 applicable to a particular field, in a two-semester or three-quarter course. Students in environmental engineering, food process engineering, and process metallurgy could follow this plan.

3. *Study of transport processes of momentum, heat, and mass.* The purpose of this plan in a two-quarter or two-semester course is to obtain a basic understanding of the transport processes of momentum, heat, and mass transfer. This involves studying sections of the principles chapters—2, 3, 4, 5, 6, and 7 in Part 1—and omitting Part 2, the applied chapters on separation processes.

4. *Study of separations processes.* If the reader has had courses in the transport processes of momentum, heat, and mass, Chapters 2–7 can be omitted and only the separation processes chapters in Part 2 studied in a one-semester or two-quarter course. This plan could be used by chemical and certain other engineers.

5. *Study of mass transfer.* For those such as chemical or mechanical engineers who have had momentum and heat transfer, or those who desire only a background in mass transfer in a one-quarter or one-semester course, Chapters 6, 7, and 10 would be covered. Chapters 9, 11, 12, and 13 might be covered optionally, depending on the needs of the reader.

Different schools and instructors differ on the use of computers in engineering courses. All of the equations and homework problems in this text can be solved by using ordinary hand-held computers. However, more complicated problems involving numerical integration, finite-difference calculations, steady- and unsteady-state two-dimensional diffusion and conduction, and so on, can easily be solved with a computer using spreadsheets. Almost all undergraduate students are proficient in their use.

The SI (Système International d'Unités) system of units has been adopted by the scientific community. Because of this, the SI system of units has been adopted in this text for use in the equations, example problems, and homework problems. However, the most important equations derived in the text are also given in a dual set of units, SI and English, when different. Many example and homework problems are also given using English units.

Christie John Geankoplis

Contents

PART 1

Transport Processes: Momentum, Heat, and Mass

CHAPTER 1

Introduction to Engineering Principles and Units

1.1 CLASSIFICATION OF TRANSPORT PROCESSES AND SEPARATION PROCESSES (UNIT OPERATIONS)

1.1A Introduction

In the chemical and other physical processing industries and the food and biological processing industries, many similarities exist in the manner in which the entering feed materials are modified or processed into final materials of chemical and biological products. We can take these seemingly different chemical, physical, or biological processes and break them down into a series of separate and distinct steps that were originally called *unit operations.* However, the term "unit operations" has largely been superseded by the more modern and descriptive term "separation processes." These *separation processes* are common to all types of diverse process industries.

For example, the separation process *distillation* is used to purify or separate alcohol in the beverage industry and hydrocarbons in the petroleum industry. Drying of grain and other foods is similar to drying of lumber, filtered precipitates, and wool. The separation process *absorption* occurs in absorption of oxygen from air in a fermentation process or in a sewage treatment plant and in absorption of hydrogen gas in a process for liquid hydrogenation of oil. Evaporation of salt solutions in the chemical industry is similar to evaporation of sugar solutions in the food industry. Settling and sedimentation of suspended solids in the sewage industry and the mining industry are similar. Flow of liquid hydrocarbons in the petroleum refinery and flow of milk in a dairy plant are carried out in a similar fashion.

Many of these separation processes have certain fundamental and basic principles or mechanisms in common. For example, the mechanism of diffusion or mass transfer occurs in drying, membrane separation, absorption, distillation, and crystallization. Heat transfer occurs in drying, distillation, evaporation, and so on. The following classification of a more fundamental nature is often made, according to transfer or transport processes.

1.1B Fundamental Transport Processes

1. Momentum transfer. This is concerned with the transfer of momentum which occurs in moving media, such as in the separation processes of fluid flow, sedimentation, mixing, and filtration.

2. Heat transfer. In this fundamental process, we are concerned with the transfer of heat from one place to another; it occurs in the separation processes of drying, evaporation, distillation, and others.

3. Mass transfer. Here mass is being transferred from one phase to another distinct phase; the basic mechanism is the same whether the phases are gas, solid, or liquid. This includes distillation, absorption, liquid–liquid extraction, membrane separation, adsorption, crystallization, and leaching.

1.1C Classification of Separation Processes

The separation processes deal mainly with the transfer and change of energy and the transfer and change of materials, primarily by physical means but also by physical–chemical means. The important separation processes, which can be combined in various sequences in a process and which are covered in this text, are described next.

1. Evaporation. This refers to the evaporation of a volatile solvent such as water from a nonvolatile solute such as salt or any other material in solution.

2. Drying. In this operation volatile liquids, usually water, are removed from solid materials.

3. Distillation. This is an operation whereby components of a liquid mixture are separated by boiling because of their differences in vapor pressure.

4. Absorption. In this process a component is removed from a gas stream by treatment with a liquid.

5. Membrane separation. This process involves the separation of a solute from a fluid by diffusion of this solute from a liquid or gas through a semipermeable membrane barrier to another fluid.

6. Liquid–liquid extraction. In this case a solute in a liquid solution is removed by contacting with another liquid solvent that is relatively immiscible with the solution.

7. Adsorption. In this process a component of a gas or liquid stream is removed and adsorbed by a solid adsorbent.

8. Ion exchange. Certain ions in solution are removed from a liquid by an ion-exchange solid.

9. Liquid–solid leaching. This involves treating a finely divided solid with a liquid that dissolves out and removes a solute contained in the solid.

10. Crystallization. This concerns the removal of a solute such as a salt from a solution by precipitating the solute from the solution.

11. Mechanical–physical separations. These involve separation of solids, liquids, or gases by mechanical means, such as filtration, settling, centrifugation, and size reduction.

1.1D Arrangement in Parts 1 and 2

This text is arranged in two parts:

Part 1: Transport Processes: Momentum, Heat, and Mass. These fundamental principles are covered extensively in Chapters 1 through 7 in order to provide the basis for study of separation processes in Part 2 of this text.

Part 2: Separation Process Principles (Includes Unit Operations). The various separation processes and their applications to process areas are studied in Part 2 of this text.

There are a number of elementary engineering principles, mathematical techniques, and laws of physics and chemistry that are basic to a study of the principles of momentum, heat, and mass transfer and the separation processes. These are reviewed for the reader in this first chapter. Some readers, especially chemical engineers, agricultural engineers, civil engineers, and chemists, may be familiar with many of these principles and techniques and may wish to omit all or parts of this chapter.

Homework problems at the end of each chapter are arranged in different sections, each corresponding to the number of a given section in the chapter.

1.2 SI SYSTEM OF BASIC UNITS USED IN THIS TEXT AND OTHER SYSTEMS

There are three main systems of basic units employed at present in engineering and science. The first and most important of these is the *SI* (Système International d'Unités) *system,* which has as its three basic units the meter (m), the kilogram (kg), and the second (s). The others are the English foot (ft)–pound (lb)–second (s), or *English system* and the centimeter (cm)–gram (g)–second (s), or *cgs system.*

At present the SI system has been adopted officially for use exclusively in engineering and science, but the older English and cgs systems will still be used for some time. Much of the physical and chemical data and empirical equations are given in these latter two systems. Hence, the engineer not only should be proficient in the SI system but must also be able to use the other two systems to a limited extent.

1.2A SI System of Units

The basic quantities used in the SI system are as follows: the unit of length is the meter (m); the unit of time is the second (s); the unit of mass is the kilogram (kg); the unit of temperature is the kelvin (K); and the unit of an element is the kilogram mole (kg mol). The other standard units are derived from these basic quantities.

The basic unit of force is the newton (N), defined as

$$1 \text{ newton (N)} = 1 \text{ kg} \cdot \text{m/s}^2$$

The basic unit of work, energy, or heat is the newton-meter, or joule (J).

$$1 \text{ joule (J)} = 1 \text{ newton} \cdot \text{m (N} \cdot \text{m)} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^2$$

Power is measured in joules/s or watts (W).

$$1 \text{ joule/s (J/s)} = 1 \text{ watt (W)}$$

The unit of pressure is the newton/m^2 or pascal (Pa).

$$1 \text{ newton/m}^2 \text{ (N/m}^2\text{)} = 1 \text{ pascal (Pa)}$$

[Pressure in atmospheres (atm) is not a standard SI unit but is being used during the transition period.] The standard acceleration of gravity is defined as

$$1\ g = 9.80665 \text{ m/s}^2$$

A few of the standard prefixes for multiples of the basic units are as follows: giga (G) = 10^9, mega (M) = 10^6, kilo (k) = 10^3, centi (c) = 10^{-2}, milli (m) = 10^{-3}, micro (μ) = 10^{-6}, and nano (n) = 10^{-9}. The prefix c is not a preferred prefix.

Temperatures are defined in kelvin (K) as the preferred unit in the SI system. However, in practice, wide use is made of the degree Celsius (°C) scale, which is defined by

$$t°\text{C} = T(\text{K}) - 273.15$$

Note that 1°C = 1 K and that in the case of temperature difference,

$$\Delta t°\text{C} = \Delta T \text{ K}$$

The standard preferred unit of time is the second (s), but time can be in nondecimal units of minutes (min), hours (h), or days (d).

1.2B CGS System of Units

The cgs system is related to the SI system as follows:

$$1 \text{ g mass (g)} = 1 \times 10^{-3} \text{ kg mass (kg)}$$

$$1 \text{ cm} = 1 \times 10^{-2} \text{ m}$$

$$1 \text{ dyne (dyn)} = 1 \text{ g} \cdot \text{cm/s}^2 = 1 \times 10^{-5} \text{ newton (N)}$$

$$1 \text{ erg} = 1 \text{ dyn} \cdot \text{cm} = 1 \times 10^{-7} \text{ joule (J)}$$

The standard acceleration of gravity is

$$g = 980.665 \text{ cm/s}^2$$

1.2C English fps System of Units

The English system is related to the SI system as follows:

$$1 \text{ lb mass (lb}_m\text{)} = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.30480 \text{ m}$$

$$1 \text{ lb force (lb}_f\text{)} = 4.4482 \text{ newton (N)}$$

$$1 \text{ ft} \cdot \text{lb}_f = 1.35582 \text{ newton} \cdot \text{m (N} \cdot \text{m)} = 1.35582 \text{ joules (J)}$$