# MASS AND HEAT TRANSFER

This book allows instructors to teach a course on heat and mass transfer that will equip students with the pragmatic, applied skills required by the modern chemical industry. This new approach is a combined presentation of heat and mass transfer, maintaining mathematical rigor while keeping mathematical analysis to a minimum. This allows students to develop a strong conceptual understanding and teaches them how to become proficient in engineering analysis of mass contactors and heat exchangers and the transport theory used as a basis for determining how the critical coefficients depend on physical properties and fluid motions.

Students will first study the engineering analysis and design of equipment important in experiments and for the processing of material at the commercial scale. The second part of the book presents the fundamentals of transport phenomena relevant to these applications. A complete teaching package includes a comprehensive instructor's guide, exercises, design case studies, and project assignments.

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# Mass and Heat Transfer

## ANALYSIS OF MASS CONTACTORS AND HEAT EXCHANGERS

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CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521886703



First published 2008

Printed in the United States of America

*A catalog record for this publication is available from the British Library.*

*Library of Congress Cataloging in Publication Data*

Russell, T. W. F., 1934–
Mass and heat transfer : analysis of mass contactors and heat exchangers / T.W. Fraser Russell, Anne Skaja Robinson, Norman J. Wagner.
p. cm. – (Cambridge series in chemical engineering)
Includes bibliographical references and index.
ISBN 978-0-521-88670-3 (hardback)
1. Heat exchangers. 2. Chemical engineering – Equipment and supplies.
I. Robinson, Anne Skaja, 1966– II. Wagner, Norman Joseph, 1962– III. Title.

TP363.R87 2008
621.402'2–dc22

2007045343

ISBN 978-0-521-88670-3 hardback

This book is dedicated to our families:

Shirley, Bruce, Brian, Carey

Clifford, Katherine, Brenna

Sabine

Cambridge University Press
978-0-521-88670-3 - Mass and Heat Transfer: Analysis of Mass Contractors and Heat Exchangers
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## PART II

# Preface

Chemical engineers educated in the undergraduate programs of departments of chemical engineering have received an education that has been proven highly effective. Chemical engineering educational programs have accomplished this by managing to teach a methodology for solving a wide range of problems. They first did so by using case studies from the chemical process industries. They began case studies in the early part of the 20th century by considering the complete processes for the manufacture of certain chemicals and how they were designed, operated, and controlled. This approach was made much more effective when it was recognized that all chemical processes contained elements that had the same characteristics, and the education was then organized around various unit operations. Great progress was made during the 1940s and 1950s in experimental studies that quantified the analysis and design of heat exchangers and equilibrium stage operations such as distillation. The 1960s saw the introduction of reaction and reactor analysis into the curriculum, which emphasized the critical relationship between experiment and mathematical modeling and use of the verified models for practical design. We have built upon this approach, coupled with the tools of transport phenomena, to develop this text.

Our approach to teaching mass and heat transfer has the following goals:

1. Teach students a methodology for rational, engineering analysis of problems in mass and heat transport, i.e., to develop model equations to describe mass and heat transfer based on the relationship between experimental data and model.
2. Using these model equations, teach students to design and interpret laboratory experiments in mass and heat transfer and then to effectively translate this knowledge to the operation and design of mass and heat transfer equipment.
3. Develop the students' molecular understanding of the mechanisms of mass and heat transfer in fluids and solids and application in the estimation and correlation of mass and heat transfer coefficients.

To achieve these goals we use the following methods:

- Emphasize the critical role of experiment coupled with the development of an appropriate model.
- Focus attention on analysis and model development rather than on mathematical manipulation of equations. This is facilitated by organization of the analysis method into *levels*.

- Provide a rational framework for analyzing mass and heat transfer phenomena in fluids and the associated equipment based on a simple fluid mechanical model of the devices.
- Treat mass transfer on an equal level with heat transfer, and, wherever possible, provide a parallel development of mass and heat transfer phenomena.

The *levels of analysis* introduced in Chapter 1, Table 1.1, provide a guide to the rational analysis of engineering transport equipment and transport phenomena in increasing orders of complexity. The information obtainable from each level of analysis is delineated and the order of analysis preserved throughout the textbook.

We present the material in a manner also suitable for nonmajors. Students with a basic college-level understanding of thermodynamics, calculus, and reaction kinetics should be prepared to follow the presentation. By avoiding the more tedious and sophisticated analytical solution methods and relying more on simplified model equations and, where necessary, modern mathematical software packages, we strive to present the philosophy and methodology of engineering analysis of mass and heat transfer suitable for nonmajors as well. Note that a course in fluid mechanics is not a prerequisite for understanding most of the material presented in this book.

Engineering starts with careful analysis of experiment, which naturally inspires the inquiring mind to synthesis and design. Early emphasis on developing model equations and studying their behavior enables the instructor to involve students in problem-based learning exercises and transport-based design projects right from the beginning of the course. This and the ability to challenge students to apply their analysis skills and course knowledge to transport phenomena in the world around them, especially in emerging technologies in the nanosciences and environmental and biological sciences, result, in our experience, in an exciting and motivating classroom environment. We sincerely hope that you as reader will find this approach to transport phenomena to be as fresh and invigorating as we have.

> Get the habit of analysis—analysis will in time enable synthesis to become your habit of mind. — Frank Lloyd Wright

# To the Student

This text is designed to teach you how to carry out quantitative analysis of physical phenomena important to chemical professionals. In the chemical engineering curriculum, this course is typically taught in the junior year. Students with adequate preparation in thermodynamics and reactor design should be successful at learning the material in this book. Students lacking a reactor design course, such as chemists and other professionals, will need to pay additional attention to the material in Chapter 2 and may need to carry out additional preparation by using the references contained in that chapter. This book uses the logic employed in the simple analysis of reacting systems for reactor design to develop the more complex analysis of mass and heat transfer systems.

Analysis is the process of developing a mathematical description (model) of a physical situation of interest, determining behavior of the model, comparing the behavior with data from experiment or other sources, and using the verified model for various practical purposes.

*There are two parts in the analysis process that deserve special attention*:

- developing the mathematical model, and
- comparing model behavior with data.

Our experience with teaching analysis for many years has shown that the model development step can be effectively taught by following well-developed logic. Just what constitutes agreement between model behavior and data is a much more complex matter and is part of the art of analysis. This is more difficult to learn and requires one to consider many different issues; it always depends on the reasons for doing the analysis. Time constraints have a significant impact on this decision, as do resources available. We will illustrate this aspect of analysis by examining chemical reactors, heat exchangers, and mass contactors, equipment of particular interest to chemical professionals.

Determining model behavior requires you to remember some calculus—how to solve algebraic equations and some simple differential equations. This step in analysis is often given too much emphasis because it is the easiest part of analysis to do and is the step for which students have the best background. Do not fall into the common trap of assuming that analysis is primarily concerned with determining model behavior—it is not! Analytical methods to solve algebraic or differential equations are most useful if the manipulations leading to solution give insights into the physical situation being examined. Tedious algebraic manipulations are not helpful and seriously distract one from the real purpose of analysis. You should stop and ask questions of any instructor who performs a lot of algebra at the board without constantly referring back to what the manipulations mean in terms of the physical situation being studied. In this day and age, computer programs that solve sets of equations are so readily available that tedious algebra is not required.

Once you have mastered how to obtain the model equations, you need to devote your creative energies to deciding if behavior matches experiment. Just what constitutes a match is not trivial to determine.

The model development step is simplified by considering the level of complexity required to obtain useful practical results. We define six levels of complexity in this text:

The first level employs only the laws of conservation of mass and/or energy. Time is the only dependent variable in the differential equations considered in Level I analysis, but many problems of considerable significance assume steady state and eliminate time as a variable. In this case the model equations become algebraic.

The second level also employs these two conservation laws, but, in addition, phase, thermal, or chemical equilibrium is assumed. The model equations in a Level II analysis are algebraic because time is not an independent variable when equilibrium is assumed.

A Level III analysis requires a constitutive relationship to be employed. The six constitutive relations needed in studying reactors, heat exchangers, and mass contactors are shown in Tables 1.4 and 1.5. These relations have been verified by various experiments that we will discuss in some detail. Level III analysis assumes simple fluid motions, either well mixed or plug flow. Completely stagnant fluids or solid phases can also be handled at this level of analysis. A background in fluid mechanics is not required. A Level III analysis allows one to complete equipment design at the laboratory, pilot, and commercial scales for most single-phase systems. The Level III model equations for well-mixed fluids contain time as the only independent variable if steady state is not assumed. Plug-flow fluid motions require one independent spatial variable in the steady state and time if the steady state cannot be assumed.

To deal effectively with multiphase systems, a Level IV analysis needs to be performed. The Level IV analysis also assumes simple fluid motions but requires application of the conservation laws of mass and energy coupled with constitutive relations for both phases.

A Level V analysis is restricted to single-phase systems but can employ all the conservation laws. It is the first level in which the law of conservation of momentum is used. In its most complicated form, the model equations of Level V can have time and all three spatial coordinates as independent variables. A Level V analysis considering time and only one spatial direction will be sufficient for most problems we will analyze in this book.

Multiphase systems with complex fluid motion require a Level VI analysis, which we will not consider in this text.

There are two parts to this book. An introduction to the material and method of approach is followed by chapters on chemical reactor analysis (Chapter 2), heat exchanger analysis (Chapter 3), and mass contactor analysis (Chapter 4). These chapters have been developed to highlight the similarities in the analysis methods and in the process equipment used. By using experimentally determined values of the rate constant (k), the heat transfer coefficient (U), the mass transfer coefficient ($K_m$), and the interfacial area (a), you will be able to solve problems in mass and heat transfer and develop operating and design criteria.

Part II features additional chapters that focus on the microscopic analysis of control volumes to estimate U or $K_m$ for a broad range of systems. Correlations for $K_m$ and U are developed that facilitate the design of equipment.

Chapter 7 provides methods for calculating the area for mass transfer in a variety of mass contacting equipment. Chapter 8 illustrates the technically feasible design procedure through case studies of common mass contactors and heat exchangers.

On successful completion of a course using this textbook, you should understand the basic physical principles underlying mass and heat transfer and be able to apply those principles to analyze existing equipment and design and analyze laboratory experiments to obtain data and parameters.

Finally, you should be capable of performing technically feasible designs of mass contactors and heat exchangers, as well as reading the technical literature so as to continue your education and professional development in this field.

Cambridge University Press
978-0-521-88670-3 - Mass and Heat Transfer: Analysis of Mass Contractors and Heat Exchangers
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## Acknowledgments

The preparation of this text has benefited from significant contributions from numerous Teaching Fellows, teaching assistants, undergraduate students, and colleagues in the Department of Chemical Engineering at the University of Delaware. In particular, we wish to acknowledge the Teaching Fellow program in the Chemical Engineering Department at Delaware, which provides a fellowship semester to a senior graduate student who wishes an internship in university education methods and theory. This competitive program has been in existence since 1992 and has supported 24 student Teaching Fellows (1992–2007). To date, more than 10 former Fellows have become faculty members at a number of institutions.

The Teaching Fellows work closely with faculty in lesson planning, classroom delivery, and discussion of classroom performance. All in-class teaching by Fellows is monitored by the faculty mentors. Regular lively discussions over course content and teaching methods have proven to be infectious, such that many more graduate students and faculty also benefit from active discussions about educational methods and theory. This in fact may well be one of the most important aspects of our program.

This textbook represents a course organization that is fundamentally different from all other courses and textbooks on mass and heat transfer. Our approach builds upon the principles of analysis developed in the text by Russell and Denn, *Introduction to Chemical Engineering Analysis*. The authors, our Teaching Fellows, and teaching assistants evolved the present text through much spirited debate. Our first Teaching Fellow to work on the material in this text was *Will Medlin*, who taught with *Anne Skaja Robinson* and *T. W. Fraser Russell*. Will's enthusiastic acceptance of a different approach to teaching mass and heat transfer and his lively debates with other graduate students helped simplify and categorize the types of fluid motions required for modeling mass and heat transfer equipment and the level analysis that is the hallmark of the modeling approach used here. *Jonathan Romero*, our next Teaching Fellow, helped organize the transfer coefficient correlations. Will's office mate was *Suljo Linic*, an undergraduate physics major who came to Delaware to do graduate work in chemical engineering. This serendipity produced some very lively debates, which often migrated to a faculty office. Typical of such discussions was the following:

> "Why can't we solve all problems in mass and heat transfer with Fourier's or Fick's law and the appropriate set of differential equations?"

Answered by:

"In the first place, they are not laws but constitutive equations, which themselves have only been verified for solid control volumes or liquid control volumes with no fluid motion . . ."

Suljo was awarded the Teaching Fellow position the next year, with *Norman J. Wagner* and *T. W. Fraser Russell* coteaching the course. His willingness to question the fundamental principles of our analysis disciplined all of us in systematically using level analysis to approach problems in heat transfer. *Wim Thielemans*, the fourth Fellow, helped redraft the chapter on heat transfer based on undergraduate student comments and solved a number of models numerically to illustrate model behavior. *Mark Snyder* accepted the Teaching Fellow position in our fifth year and made significant contributions by classifying mass transfer unit operations equipment using our simplified fluid mechanics analysis. *Yakov Lapitsky*, *Jennifer O'Donnell*, and *Michelle O'Malley*, our sixth, seventh, and eighth Teaching Fellows contributed to numerous examples and tested material in class.

We have also been blessed by an enthusiastic cadre of Delaware undergraduates, who have both challenged us to become better educators and, in some special cases, have made significant contributions to the course content through original research projects. In particular, we would like to thank *Patrick Schilling*, who contributed to the organization and numerical examples found in Chapter 3. Patrick's interest in the topic expanded over the following summer, when he performed original research under our direction on predicting interfacial areas in fluid–fluid systems for use in mass transfer operations, which are summarized in Chapter 7. Our undergraduate classes in the junior-level course in heat and mass transfer have helped clarify and correct errors in the manuscript that we used in class. Other undergraduates and alumni made significant contributions: *Matt Mische* (heat exchanger design), *Steven Scully* (manuscript review), *Brian J. Russell* (index), and *Josh Selekman* (graphs). Any remaining errors are the authors' responsibility.

We also wish to thank the numerous graduate students who contributed to this manuscript and the course through dedicated service as teaching assistants. *Brian Lefebvre, Kevin Hermanson, Nicole Richardson, Yakov Lapitsky*, *Amit Kumar*, *Matt Helgeson*, and *Rebecca Brummitt* all made significant contributions to the materials found herein. Brian, Kevin, and Yakov were inspired to become the Teaching Fellows in various courses after their positive experience in the mass and heat transfer course. *Damien Thévénin* took great care in preparing some of the figures in this text, and *Claudio Gelmi* helped analyze the fermentor data.

Multiple authors lead to lively and spirited debates, which results in chaos concerning a written manuscript. The authors are indebted to the organizational and secretarial skills of *Lorraine Holton*, who typed the final manuscript, and *Carrie Qualls*, who prepared the figures to Cambridge University Press standards.

*Fraser Russell* would like to recognize the influence on this text of his years at Delaware when he collaborated closely with *M. M. Denn*, who taught him how to effectively interpret mathematical models.

We also benefited from the support and encouragement of the Department of Chemical Engineering, our colleagues, and our families, to whom we are most grateful.

We greatly appreciated the effective efforts of *Michelle Carey*, Cambridge University Press, and *Katie Greczylo*, Aptara, Inc., in the production of this book.

# Instructors' and Readers' Guide

This book is designed to teach students how to become proficient in engineering analysis by studying mass and heat transfer, transport phenomena critical to chemical engineers and other chemical professionals. It is organized differently than traditional courses in mass and heat transfer in that more emphasis is placed on mass transfer and the importance of systematic analysis. The course in mass and heat transfer in the chemical engineering curriculum is typically taught in the junior year and is a prerequisite for the design course in the senior year and, in some curricula, also a prerequisite for a course in equilibrium stage design. An examination of most mass and heat transfer courses shows that the majority of the time is devoted to heat transfer and, in particular, conductive heat transfer in solids. This often leads to overemphasis of mathematical manipulation and solution of ordinary and partial differential equations at the expense of engineering analysis, which should stress the development of the model equations and study of model behavior. It has been the experience of the authors that the "traditional" approach to teaching undergraduate transport phenomena frequently neglects the more difficult problem of mass transfer, despite its being an area that is critical to chemical professionals.

At the University of Delaware, chemical engineering students take this course in mass and heat transfer the spring semester of their junior year, after having courses in thermodynamics, kinetics and reactor design, and fluid mechanics. The students' analytical skills developed through analysis of problems in kinetics and reactor design provide a basis for building an engineering methodology for the analysis of problems in mass and heat transfer. This text is presented in two parts, as illustrated in Figure I. Part I of this text, shown on the figure as "Equipment-Scale Fluid Motion," consists of Chapters 1–4. Part II of the text is represented by the other two elements in the figure, titled "Transport Phenomena Fluid Motion" (Chapters 5 and 6) and "Microscale Fluid Motion" (Chapter 7). Chapter 8 draws on Parts I and II to illustrate the design of mass contactors and heat exchangers.

Part I of this text is devoted to the analysis of reactors, heat exchangers, and mass contactors in which the fluid motion can be characterized as well mixed or plug flow. Table I indicates how Chapters 2, 3, and 4 are structured and details the fluid motions in each of these pieces of equipment. Such fluid motions are a very good approximation of what is achieved pragmatically and in those situations in which the fluid motion is more complex. The Table I analysis provides useful limits on performance. The model equations developed in Part I are essential for the analysis of

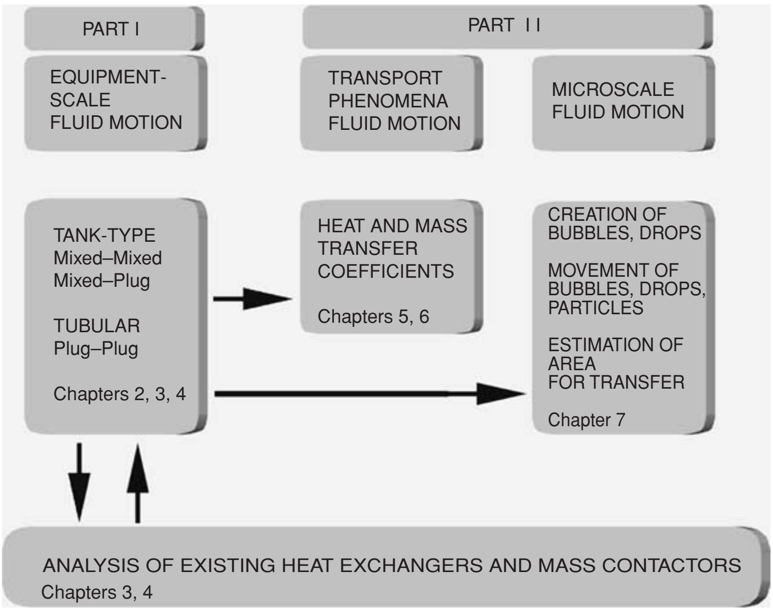


Figure I. Analysis of existing heat exchangers and mass contactors.

existing equipment and for the design of new equipment. Experiments performed in existing equipment, particularly at the laboratory scale, determine reaction-rate constants, heat transfer coefficients, mass transfer coefficients, and interfacial area and are necessary to complete the correlations developed in Part II. Carefully planned experiments are also critical to improving operation or control of existing laboratory-, pilot-, or commercial-scale equipment.

Another way to characterize our approach to organizing the analysis of equipment and transport problems is shown in Table II (see p. xxiv). This is presented to give guidance to the emphasis instructors might like to place on the way they teach from

Table I. Equipment fluid motion classification

| Reactors: Single phase | Reactors: Two phase | Heat exchangers | Mass contactors |
|---|---|---|---|
| Single control volume | Two control volumes | Two control volumes | Two control volumes |
| Tank type | Tank type | Tank type | Tank type |
| *Mixed–mixed* | *Mixed–mixed* | *Mixed–mixed* | *Mixed–mixed* |
| • Batch | • Batch | • Batch | • Batch |
| • Semibatch | • Semibatch | • Semibatch | • Semibatch |
| • Continuous | • Continuous | • Continuous | • Continuous |
| | *Mixed–plug* | *Mixed–plug* | *Mixed–plug* |
| | • Semibatch | • Semibatch | • Semibatch |
| | • Continuous | • Continuous | • Continuous |
| Tubular | Tubular | Tubular | Tubular |
| *Plug flow* | *Plug flow* | *Plug–plug flow* | *Plug–plug flow* |
| | • Cocurrent | • Cocurrent | • Cocurrent |
| | | • Countercurrent | • Countercurrent |

this text. Level I and Level II analyses are discussed in the first sections of Chapters 2, 3 and 4. Chapters 2 and 3 require a Level III analysis. Chapter 4 demonstrates the importance of a Level IV analysis. Part II continues with Level I, II, and III analyses in Chapter 5 but introduces two new constitutive equations, shown in Table 1.4. Chapter 6 requires a Level V analysis to develop relationships for mass and heat transfer coefficients. This text does not deal with any Level VI issues except in a minor way in Chapter 7, which provides methods for estimating interfacial areas in mass contactors. In teaching the material in this text it is crucial that students understand the critical role of experiment in verifying the constitutive equations for rate of reaction, rate of heat transfer, and rate of mass transfer summarized in Table 1.5. It is these constitutive equations that are used in Chapters 2, 3, and 4 in the model equations for the fluid motions, as outlined in Table I. The most critical elements in Part I of this text are therefore

- 2.1 The Batch Reactor
- 2.2 Reaction Rate and Determination by Experiment
- 3.1 Batch Heat Exchangers
- 3.2 Rate of Heat Transfer and Determination by Experiment
- 4.1 Batch Mass Contactors
- 4.2 Rate of Mass Transfer and Determination by Experiment

The students in our course at the University of Delaware have taken a course in chemical engineering kinetics, so we expect students to know how to obtain reaction-rate expressions and how to use the verified rate expression in the design of continuous tank-type and tubular reactors. Of course, some review is always necessary because it is important for students to realize that we build carefully on the reaction analysis to study mass and heat transfer. We try to limit this review to one to two class periods with appropriate homework.

In teaching Chapter 3 on heat transfer we believe that one should cover, in addition to Sections 3.1 and 3.2, the following sections, which demonstrate the utility of the constitutive equation for heat transfer:

- 3.3.2.1 Semibatch Heat Exchanger, Mixed–Mixed Fluid Motions
- 3.4 Tubular Heat Exchangers

We often add another heat exchanger analysis, such as Subsection 3.3.3, so we have model equations that we can compare with the mass contactor analysis. We normally devote between 6 and 8 class hours to heat exchanger analysis of existing equipment for which the heat transfer coefficient U is known. Prediction of U is covered in Chapters 5 and 6.

Our major emphasis in the course we teach is Chapter 4, and we believe that it deserves between 9 and 12 hours of class time. The model equations are developed for the two control volumes as for heat exchangers so one can draw comparisons that are useful to cement the students' understanding of the modeling process. The major differences between heat exchanger analysis and mass contactor analysis are the equilibrium issues, the approach to equilibrium conclusions, and the issues raised by direct contact of the two phases. In addition to the mass transfer coefficient $K_m$,

Table II. Level definitions

| | Level I | Level II | Level III | Level IV | Level V | Level VI |
|---|---|---|---|---|---|---|
| **Outcome** | Overall mass and energy balances | Allows number of equilibrum stages to be determined *but does not allow stage design to be achieved* | Equipment design *at the laboratory, pilot, and commercial scale* can be achieved | | *Molecular conduction and diffusion analysis are quantified*; mass and heat transfer coefficient correlations *are developed* | |
| **Conservation of mass** | Required | Required | Required | Required | Required | Required |
| **Conservation of energy** | Required | Required | Required | Required | Required | Required |
| **Conservation of momentum** | Not required | Not required | Not required | Not required | Required | Required |
| **Equilibrium constitutive relations** | Not required | Required | May be required | May be required | May be required | May be required |
| **Rate equations** | Not required | Not required | Required | Required | Not required | Not required |
| **Conduction–diffusion–viscosity relations** | Not required | Not required | Not required | Not required | Required | Required |

there is the interfacial area a to be considered. Methods to estimate $K_m$ are covered in Chapters 5 and 6. Procedures for estimating a are given in Chapter 7.

Chapter 5 is devoted to experimental justification of the two constitutive relations commonly referred to as Fourier's and Fick's "Laws." This development, in Sections 5.1 and 5.2, thus parallels our discussions in Chapters 2, 3, and 4 that provide experimental evidence for the constitutive relations for rate of reaction, rate of heat transfer, and rate of mass transfer. The derivations for the overall coefficients, U and $K_m$, in terms of individual resistances can be skipped if time is short, but the resulting expressions are essential. The material on membrane diffusion may be of interest in some situations.

Chapter 6 also contains more material than one can reasonably cover in a typical 40 hours of class time, so choices have to be made depending on the emphasis one desires. It is probably necessary to cover most of Sections 6.2, 6.3, and 6.4, but one needs to avoid long lectures in which there is excessive algebraic manipulation—it is the resulting correlations that are critical. These are summarized in Section 6.4.

In Chapter 7 we treat the challenging problem of estimating interfacial areas in both tank-type and tubular mass contactors. This is an area of active research today, but we have tried to present the current state of the art so this critical parameter for rational scale-up and design can be estimated.

Part II concludes with Chapter 8, which presents designs that can be completed once the mathematical models from Part I are available and methods for estimating U, $K_m$, and a are available from Part II. This is illustrated in Figure II. These design

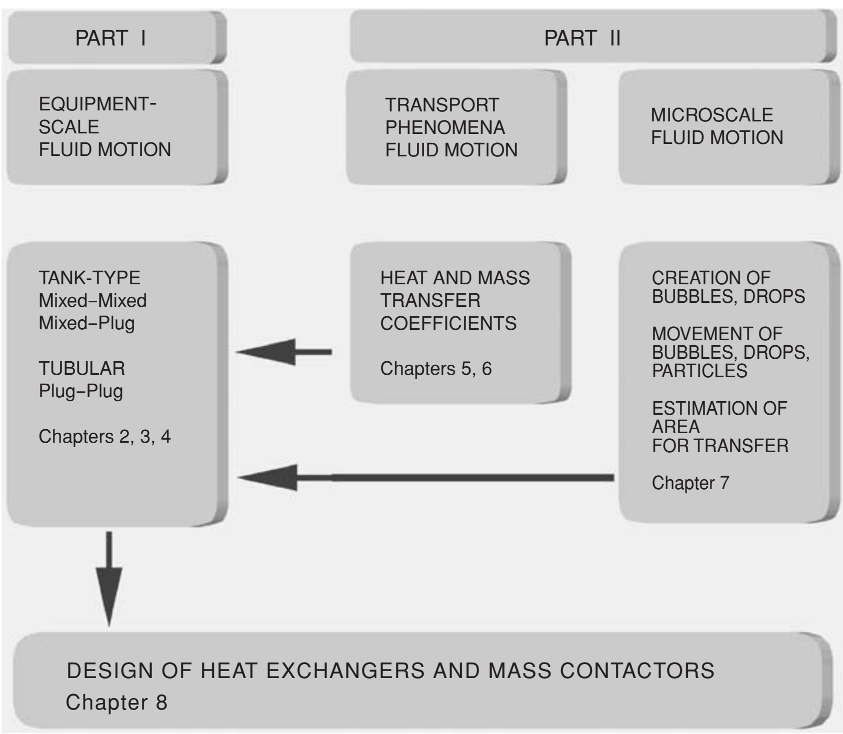


Figure II. Design of heat exchangers and mass contactors.

case studies evolved from in-class problem-based learning exercises as well as from group semester project assignments and can be used as bases for such activities.

There is a good deal more material in this text than one can reasonably cover in 40 hours of class time. We have endeavored to produce a text that gives the instructor and student maximum flexibility without sacrificing the logic of sound engineering analysis.

This book is not a reference book, nor is it an exhaustive compendium of phenomena, knowledge, and solved problems in mass and heat transfer. Suitable references are provided in each chapter for further study and for aid in the analysis of phenomena not treated herein in depth. As a first course in mass and heat transfer, this book is limited in scope and content by design. As an instructor, we hope you can build upon this book and tailor your lectures to incorporate your own expertise and experiences within this framework to enrich the course for your students.

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