D. K. EDWARDS
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Transfer Processes

An Introduction to Diffusion, Convection, and Radiation

SECOND EDITION

SERIES IN THERMAL AND FLUIDS ENGINEERING

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PREFACE

Although this book is intended for use in a first course in heat and mass transfer, we have found it a useful supplement to our second-tier courses. For example, parts of Chapters 3, 7, 8, and 10 that are not discussed in detail in our first course are discussed in our specialized course in mass transfer. Material in Chapters 4–9 is used in our specialized courses in heat transfer, which employ more comprehensive texts on heat transfer. We have found that, after they graduate, students use our textbook in their engineering practices, usually for preliminary design or analysis, because of the convenience of the tables of thermodynamic and transport properties that cover many commonly used substances. We believe that other instructors will find the book useful not only as a primary text but also as a supplementary textbook in advanced courses.

We have witnessed a trend in the United States toward the use of Système International (SI) units in engineering. Many of our ex-students are employed in industries that use SI units, and others are employed by industries that continue to use British engineering units. Thus we have revised our introductory text in several respects. First and most important, the tables that students have found so convenient are presented in SI units in addition to British engineering units. Furthermore, questionable data have been corrected to the best of our knowledge. More correct values of the viscosity of liquid ammonia were substituted for the old data, erroneous Henry numbers for ammonia and chlorine were deleted, and interfacial equilibrium tables for ammonia and sulfur dioxide were substituted. Henry number values for hydrogen sulfide were added, and a new table of Schmidt numbers for dilute aqueous solutions was prepared using more recent diffusion coefficient data. A table of commercial tube sizes was added to the table of commercial pipe sizes. Both tables are in inches, because the so-called metric pipes and tubes available in the United States are simply the same tubes and pipes with the dimensions expressed in metric lengths. Some examples are given in SI units and others in British units, whereas in the first edition British units were used almost exclusively.

The material on mass transfer has been revised. The mass transfer coefficient has been defined more carefully in Chapter 3, and heat and mass transfer coefficients at high rates of mass transfer are treated in a new section of Chapter 5. Sweat cooling is illustrated as an application. These changes do not affect our introductory course; they are intended to make the book more useful as a supplementary text in second-tier courses.

Changes that affect the use of this book in introductory courses include an earlier introduction to interphase equilibria and an emphasis on mass transfer networks (parallel to our emphasis on heat transfer networks) in Chapter 3. Chapter 10 now includes an explicit and more general introduction to the overall mass balance concept, and the sections on interphase mass transfer and countercurrent mass exchangers have been modified to make use of improved interfacial equilibrium data and Schmidt numbers. Better mass transfer coefficient correlations have been used.

Other changes include the addition of a table of Nusselt numbers for established laminar flow in noncircular pipes (Chapter 4), an additional section on boiling and an augmented transfer coefficient correlation table (Table 5.1, Chapter 5), and an explicit definition of the radiation heat transfer coefficient, which was presented as an exercise in the first edition (Chapter 6). A Moody chart for the Nikuradse pipe roughness data and an expression for the influence of roughness on heat transfer are now included in Chapter 8. A short section on heat exchanger design and thermoeconomics and an ϵ-NTU chart for regenerators were added to Chapter 9. Chapter 10 was reworked extensively. A description of macroscopic transfer processes in air separation was substituted for a description of microscopic transfer processes at a semiconductor junction (Chapter 1).

Additional exercises (homework problems) are supplied to augment instruction (for example, the lumped-capacity transient temperature response, Exercise 2–23) and to give the student more experience in problem solving.

We believe that the revisions and additions substantially improve the book while retaining its original approach and uniqueness. For the beginning student the book continues to stress development of the physical understanding of transfer processes while initiating an education in engineering problem solving.

Once again we wish to gratefully acknowledge Mrs. Phyllis Gilbert, who typed the revised manuscript.

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PREFACE TO THE FIRST EDITION

This textbook is intended for use in a first course in transfer processes. Heat and mass transfer and heat exchanger and mass transfer units are described to the extent permitted by *one-dimensional* ordinary differential equations. Formulation of transfer processes in partial differential equations is introduced but only transient diffusion in the semi-infinite solid and off-shoots of this problem (slug flow and the falling film with short contact time) are developed. Momentum transfer is treated to a lesser extent, and neutron transport is introduced very briefly.

The restriction to one-dimensional processes permits teaching a course to an undergraduate student who is still rather unsteady in exercising his newly acquired mathematical skills. Such a student is too easily bewildered by a great deal of mathematical complexity which often serves not to elucidate the physical nature of the phenomena in question but only to obscure it. The undergraduate student has had basic courses in chemistry, physics, and mathematics but has had only limited experience in applying all of it at one time to solving engineering problems. He is led to do so in a series of easy steps in this text.

The viewpoint taken in the presentation is first macroscopic, then microscopic, then macroscopic on a systems scale. This sequence of viewpoints was arrived at after some thought and experimentation. The micro-macro sequence has appeal in that it permits a highly ordered development using deductive logic. However, there is difficulty in sustaining student interest and motivation through the rather tedious early phases, and this approach was shunned. In Chapters 2 through 5, Appendix A, and the first half of Chapter 6 the macroscopic view is used to introduce the student to heat conduction, mass diffusion, convection, and the macroscopic concepts used in radiation and free molecule transfer. Starting in the second half of Chapter 6 and continuing through the first half of Chapter 8 use is made of the idea of microscopic carriers of heat, mass, and momentum moving in straight lines between collisions or interactions with walls or molecules. The idea of a transport mean free path is introduced, and this idea is used to develop transport properties: mass diffusivity, viscosity, thermal conductivity, and neutron diffusivity. In the first half of Chapter 8 the phenomenon of turbulence is introduced using the mean free path concept. The latter half of Chapter 8 and Chapters 9 and 10 return to the macroscopic world by considering systems of ducts, heat exchangers, and mass transfer units.

Both the instructor and the student are urged not to get bogged down in Chapters 2 or 3. It is true that many institutions teaching engineering and/or applied science devote approximately a full course to conduction, a full course to convective heat transfer, a full course to convective mass transfer, a full course to radiation, a full course to free molecule flow, one or two full courses to neutron transport, and often additional courses in specialized topics. It is so at our own institution. This text and the course intended to be offered from it are not to replace all these specialized courses. Rather the text is to introduce the subjects of these courses so that they may start at a somewhat higher level and may proceed at a somewhat faster pace. It is intended that the student who does not specialize in heat and mass transfer, fluid mechanics, or neutron transport obtain a broader view of these subjects than a first course in conduction.

The instructor is also urged not to neglect the engineering content of a course in transfer processes. Differential equations are certainly important in engineering and, furthermore, are enjoyable to teach. But the engineering student needs to be introduced to the practice of his profession, a profession in which algebra and logic are important too, and in which judgment in selecting the approach to a given problem is of paramount importance. It is our experience that appreciable lecture time should be devoted to the presentation of examples and applications which both reflect the subject matter of the text and relate to current engineering problems.

As mentioned earlier, momentum transfer is treated to a lesser extent than heat and mass transfer. For curricula in which fluid mechanics is not taught apart from heat and mass transfer, the instructor should augment this text with a fluid mechanics book of his choice. To cover the present text thoroughly, including Appendix A, and to augment the fluid mechanics would require 90 lecture hours. It is feasible to offer a 40 lecture-hour course by emphasizing only a portion of the text. For example, courses in (essentially)

1. convective heat and mass transfer, or
2. heat transfer, or
3. transport phenomena

could be taught by emphasizing Chapters 2, 3, 4, 5, 9, and 10; Chapters 2, 4, 5, the first half of 6, and 8 and 9; and Chapters 2 through 8 and Appendix A (the latter in conjunction with Chapter 5), respectively. Alternatively or additionally, the instructor may choose to emphasize fundamental macroscopic concepts treated in early sections of a given chapter and pass over the later sections. In this case, the instructor might omit in a first course Sections 2.11, 2.12.3–4, 2.13; 3.7–3.12; the whole of Chapter 4; Sections 6.5–6.9; 7.4–7.7; 8.2–8.3; 9.5–9.9; 10.5–10.7; and the whole of Appendix A.

We acknowledge the assistance of I. Catton, H. Buchberg, and D. N. Bennion, colleagues who contributed to Chapters 8, 9, and 10, respectively. Section 1.2.4 was based in part on notes prepared by Mr. Anil Vasudeva. Messrs. Richard Clever, John Rauscher, and Robert Turner assisted in the collection of the property data in Appendix B. Grateful acknowledgment is made to Mrs. Phyllis Gilbert, who typed the manuscript.

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TRANSFER PROCESSES

CONTENTS

CHAPTER 1

TRANSFER PROCESSES

1.1 INTRODUCTION

Transfers of heat, momentum, and species of matter pose recurring problems to engineers and scientists. Unless a uniform condition exists – that is, unless thermodynamic equilibrium exists – such transfer processes will take place. The rates at which these transfers occur are important considerations in the design of technological systems as diverse as aerospace vehicles, chemical process plants, nuclear power stations, sewage treatment units, and thermal control devices for electronic gear. In planning such systems, the engineer analyzes and designs heat shields and exchangers, mass exchangers, chemical and nuclear reactors, settling tanks, filters, separators, and other such devices in which heat, momentum, and/or mass are transferred. The scientist, too, is concerned with transfer processes, for he frequently must understand and solve transfer problems in order to plan an experiment and interpret laboratory data. Experiments investigating superconductivity at cryogenic temperatures or nuclear fusion in high temperature gas plasmas or chemical syntheses involve transfer processes.

The physical mechanisms by which transfer processes occur are complex. Three broad categories are treated in this text: **diffusion**, **convection**, and **radiation**. In the *diffusion* category are such processes as heat conduction, viscous transfer of momentum, and mass diffusion. *Convection* is the transport of heat,