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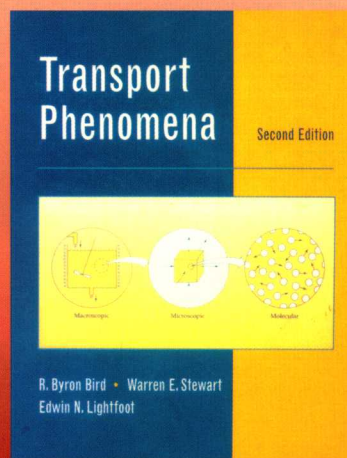
TRANSPORT PHENOMENA

Second Edition

传递现象

第二版

R. Byron Bird Warren E. Stewart
Edwin N. Lightfoot



化学工业出版社

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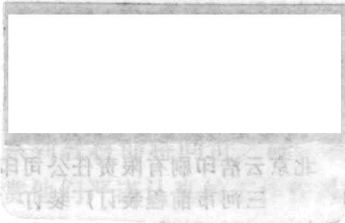
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前 言

随着中国社会主义现代化建设进入新的阶段,以高质量的高等教育培养千百万专门人才,迎接新世纪的挑战,是实现“科教兴国”战略的基础工程,也是完成“十五”计划各项奋斗目标的重要保证。为切实加强高等学校本科教学并提高教学质量,教育部于2001年专门下发文件提出12条意见,对高等学校教学工作从认识、管理、教师队伍到教学方法和教学手段等给予指导。文件强调,按照“教育要面向现代化、面向世界、面向未来”的要求,为适应经济全球化和科技国际化的挑战,本科教育要创造条件使用英语等外语进行公共课和专业课教学。

在文件精神指导下,全国普通高等学校尤其是重点高校中兴起了使用国外教材开展教学活动的潮流。如生物技术与工程、环境科学与工程、材料科学与工程及作为其学科基础理论重要组成部分的化学技术和化学工程技术又是这股潮流中最为活跃的领域之一。在教育部“化工类专业人才培养方案及教学内容体系改革的研究与实践”项目组及“化工类专业创新人才培养模式、教学内容、教学方法和教学改革的研究与实践”项目组和“全国本科化学工程与工艺专业教学指导委员会”的指导和支持下,化学工业出版社及时启动了引进国外名校名著的教材工程。

出版社组织编辑人员多次赴国外学习考察,通过国外出版研究机构对国外著名的高等学校进行调查研究,搜集了一大批国际知名院校的现用教材选题。他们还联络国内重点高校的专家学者组建了“国外名校名著评价委员会”,对国外和国内高等本科教学进行比较研究,对教材内容质量进行审查评议,然后决定是否引进。他们与国外许多著名的出版机构建立了联系,有的还建立了长期合作关系,以掌握世界范围内优秀教材的出版动态。

以其化学化工专业领域的优势资源为基础,化学工业出版社的教材引进主要涉及化学、化学工程与工艺、环境科学与工程、生物技术与工程、材料科学与工程、制药工程等专业,对过程装备与控制工程、自动化等传统专业教材的引进也在规划之中。

他们在影印、翻译出版国外教材的过程中,注意学习国外教材出版的经验,提高编辑素质,密切编读联系,整合课程体系,更新教材内容,科学设计版面,提高印装质量,更好地为教育服务。

在化工版“国外名校名著”系列教材即将问世之际,我们不仅感谢化学工业出版社为高等教育所做的努力,更应赞赏他们严谨认真的工作作风。

中国科学院院士,天津大学教授

余国琮

2002年8月

Preface

While momentum, heat, and mass transfer developed independently as branches of classical physics long ago, their unified study has found its place as one of the fundamental engineering sciences. This development, in turn, less than half a century old, continues to grow and to find applications in new fields such as biotechnology, microelectronics, nanotechnology, and polymer science.

Evolution of transport phenomena has been so rapid and extensive that complete coverage is not possible. While we have included many representative examples, our main emphasis has, of necessity, been on the fundamental aspects of this field. Moreover, we have found in discussions with colleagues that transport phenomena is taught in a variety of ways and at several different levels. Enough material has been included for two courses, one introductory and one advanced. The elementary course, in turn, can be divided into one course on momentum transfer, and another on heat and mass transfer, thus providing more opportunity to demonstrate the utility of this material in practical applications. Designation of some sections as optional (○) and other as advanced (●) may be helpful to students and instructors.

Long regarded as a rather mathematical subject, transport phenomena is most important for its physical significance. The essence of this subject is the careful and compact statement of the conservation principles, along with the flux expressions, with emphasis on the similarities and differences among the three transport processes considered. Often, specialization to the boundary conditions and the physical properties in a specific problem can provide useful insight with minimal effort. Nevertheless, the language of transport phenomena is mathematics, and in this textbook we have assumed familiarity with ordinary differential equations and elementary vector analysis. We introduce the use of partial differential equations with sufficient explanation that the interested student can master the material presented. Numerical techniques are deferred, in spite of their obvious importance, in order to concentrate on fundamental understanding.

Citations to the published literature are emphasized throughout, both to place transport phenomena in its proper historical context and to lead the reader into further extensions of fundamentals and to applications. We have been particularly anxious to introduce the pioneers to whom we owe so much, and from whom we can still draw useful inspiration. These were human beings not so different from ourselves, and perhaps some of our readers will be inspired to make similar contributions.

Obviously both the needs of our readers and the tools available to them have changed greatly since the first edition was written over forty years ago. We have made a serious effort to bring our text up to date, within the limits of space and our abilities, and we have tried to anticipate further developments. Major changes from the first edition include:

- transport properties of two-phase systems
- use of "combined fluxes" to set up shell balances and equations of change
- angular momentum conservation and its consequences
- complete derivation of the mechanical energy balance
- expanded treatment of boundary-layer theory
- Taylor dispersion
- improved discussions of turbulent transport

- Fourier analysis of turbulent transport at high Pr or Sc
- more on heat and mass transfer coefficients
- enlarged discussions of dimensional analysis and scaling
- matrix methods for multicomponent mass transfer
- ionic systems, membrane separations, and porous media
- the relation between the Boltzmann equation and the continuum equations
- use of the "Q+W" convention in energy discussions, in conformity with the leading textbooks in physics and physical chemistry

However, it is always the youngest generation of professionals who see the future most clearly, and who must build on their imperfect inheritance.

Much remains to be done, but the utility of transport phenomena can be expected to increase rather than diminish. Each of the exciting new technologies blossoming around us is governed, at the detailed level of interest, by the conservation laws and flux expressions, together with information on the transport coefficients. Adapting the problem formulations and solution techniques for these new areas will undoubtedly keep engineers busy for a long time, and we can only hope that we have provided a useful base from which to start.

Each new book depends for its success on many more individuals than those whose names appear on the title page. The most obvious debt is certainly to the hard-working and gifted students who have collectively taught us much more than we have taught them. In addition, the professors who reviewed the manuscript deserve special thanks for their numerous corrections and insightful comments: Yu-Ling Cheng (University of Toronto), Michael D. Graham (University of Wisconsin), Susan J. Muller (University of California-Berkeley), William B. Russel (Princeton University), Jay D. Schieber (Illinois Institute of Technology), and John F. Wendt (Von Kármán Institute for Fluid Dynamics). However, at a deeper level, we have benefited from the departmental structure and traditions provided by our elders here in Madison. Foremost among these was Olaf Andreas Hougen, and it is to his memory that this edition is dedicated.

Madison, Wisconsin

R. B. B.
W. E. S.
E. N. L.

- improved discussions of turbulent transport
- Taylor dispersion
- expanded treatment of boundary-layer theory
- complete derivation of the mechanical energy balance
- angular momentum conservation and its consequences
- use of "combined fluxes" to set up shell balances and equations of change
- transport properties of two-phase systems

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The Subject of Transport Phenomena

§0.1 What are the transport phenomena?

§0.2 Three levels at which transport phenomena can be studied

§0.3 The conservation laws: an example

§0.4 Concluding comments

The purpose of this introductory chapter is to describe the scope, aims, and methods of the subject of transport phenomena. It is important to have some idea about the structure of the field before plunging into the details; without this perspective it is not possible to appreciate the unifying principles of the subject and the interrelation of the various individual topics. A good grasp of transport phenomena is essential for understanding many processes in engineering, agriculture, meteorology, physiology, biology, analytical chemistry, materials science, pharmacy, and other areas. Transport phenomena is a well-developed and eminently useful branch of physics that pervades many areas of applied science.

§0.1 WHAT ARE THE TRANSPORT PHENOMENA?

The subject of transport phenomena includes three closely related topics: fluid dynamics, heat transfer, and mass transfer. Fluid dynamics involves the transport of *momentum*, heat transfer deals with the transport of *energy*, and mass transfer is concerned with the transport of *mass* of various chemical species. These three transport phenomena should, at the introductory level, be studied together for the following reasons:

- They frequently occur simultaneously in industrial, biological, agricultural, and meteorological problems; in fact, the occurrence of any one transport process by itself is the exception rather than the rule.
- The basic equations that describe the three transport phenomena are closely related. The similarity of the equations under simple conditions is the basis for solving problems “by analogy.”
- The mathematical tools needed for describing these phenomena are very similar. Although it is not the aim of this book to teach mathematics, the student will be required to review various mathematical topics as the development unfolds. Learning how to use mathematics may be a very valuable by-product of studying transport phenomena.
- The molecular mechanisms underlying the various transport phenomena are very closely related. All materials are made up of molecules, and the same molecular

motions and interactions are responsible for viscosity, thermal conductivity, and diffusion.

The main aim of this book is to give a balanced overview of the field of transport phenomena, present the fundamental equations of the subject, and illustrate how to use them to solve problems.

There are many excellent treatises on fluid dynamics, heat transfer, and mass transfer. In addition, there are many research and review journals devoted to these individual subjects and even to specialized subfields. The reader who has mastered the contents of this book should find it possible to consult the treatises and journals and go more deeply into other aspects of the theory, experimental techniques, empirical correlations, design methods, and applications. That is, this book should not be regarded as the complete presentation of the subject, but rather as a stepping stone to a wealth of knowledge that lies beyond.

§0.2 THREE LEVELS AT WHICH TRANSPORT PHENOMENA CAN BE STUDIED

In Fig. 0.2-1 we show a schematic diagram of a large system—for example, a large piece of equipment through which a fluid mixture is flowing. We can describe the transport of mass, momentum, energy, and angular momentum at three different levels.

At the *macroscopic level* (Fig. 0.2-1a) we write down a set of equations called the “macroscopic balances,” which describe how the mass, momentum, energy, and angular momentum in the system change because of the introduction and removal of these entities via the entering and leaving streams, and because of various other inputs to the system from the surroundings. No attempt is made to understand all the details of the system. In studying an engineering or biological system it is a good idea to start with this macroscopic description in order to make a global assessment of the problem; in some instances it is only this overall view that is needed.

At the *microscopic level* (Fig. 0.2-1b) we examine what is happening to the fluid mixture in a small region within the equipment. We write down a set of equations called the “equations of change,” which describe how the mass, momentum, energy, and angular momentum change within this small region. The aim here is to get information about velocity, temperature, pressure, and concentration profiles within the system. This more detailed information may be required for the understanding of some processes.

At the *molecular level* (Fig. 0.2-1c) we seek a fundamental understanding of the mechanisms of mass, momentum, energy, and angular momentum transport in terms of mol-

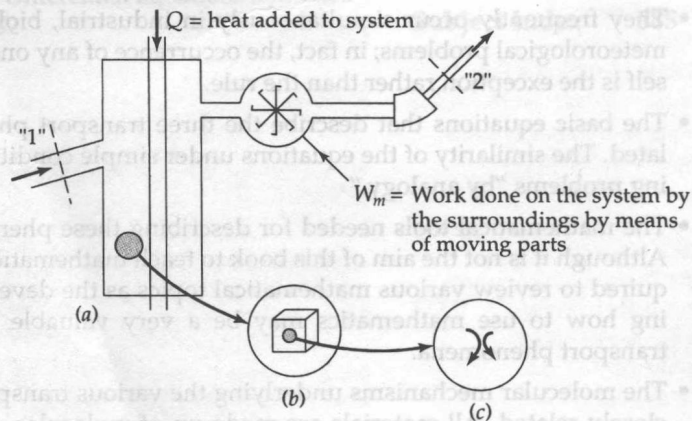


Fig. 0.2-1 (a) A macroscopic flow system containing N_2 and O_2 ; (b) a microscopic region within the macroscopic system containing N_2 and O_2 , which are in a state of flow; (c) a collision between a molecule of N_2 and a molecule of O_2 .

ecular structure and intermolecular forces. Generally this is the realm of the theoretical physicist or physical chemist, but occasionally engineers and applied scientists have to get involved at this level. This is particularly true if the processes being studied involve complex molecules, extreme ranges of temperature and pressure, or chemically reacting systems.

It should be evident that these three levels of description involve different “length scales”: for example, in a typical industrial problem, at the macroscopic level the dimensions of the flow systems may be of the order of centimeters or meters; the microscopic level involves what is happening in the micron to the centimeter range; and molecular-level problems involve ranges of about 1 to 1000 nanometers.

This book is divided into three parts dealing with

- Flow of pure fluids at constant temperature (with emphasis on viscous and convective momentum transport)—Chapters 1–8
- Flow of pure fluids with varying temperature (with emphasis on conductive, convective, and radiative energy transport)—Chapters 9–16
- Flow of fluid mixtures with varying composition (with emphasis on diffusive and convective mass transport)—Chapters 17–24

That is, we build from the simpler to the more difficult problems. Within each of these parts, we start with an initial chapter dealing with some results of the molecular theory of the transport properties (viscosity, thermal conductivity, and diffusivity). Then we proceed to the microscopic level and learn how to determine the velocity, temperature, and concentration profiles in various kinds of systems. The discussion concludes with the macroscopic level and the description of large systems.

As the discussion unfolds, the reader will appreciate that there are many connections between the levels of description. The transport properties that are described by molecular theory are used at the microscopic level. Furthermore, the equations developed at the microscopic level are needed in order to provide some input into problem solving at the macroscopic level.

There are also many connections between the three areas of momentum, energy, and mass transport. By learning how to solve problems in one area, one also learns the techniques for solving problems in another area. The similarities of the equations in the three areas mean that in many instances one can solve a problem “by analogy”—that is, by taking over a solution directly from one area and, then changing the symbols in the equations, write down the solution to a problem in another area.

The student will find that these connections—among levels, and among the various transport phenomena—reinforce the learning process. As one goes from the first part of the book (momentum transport) to the second part (energy transport) and then on to the third part (mass transport) the story will be very similar but the “names of the players” will change.

Table 0.2-1 shows the arrangement of the chapters in the form of a 3×8 “matrix.” Just a brief glance at the matrix will make it abundantly clear what kinds of interconnections can be expected in the course of the study of the book. We recommend that the book be studied by columns, particularly in undergraduate courses. For graduate students, on the other hand, studying the topics by rows may provide a chance to reinforce the connections between the three areas of transport phenomena.

At all three levels of description—molecular, microscopic, and macroscopic—the *conservation laws* play a key role. The derivation of the conservation laws for molecular systems is straightforward and instructive. With elementary physics and a minimum of mathematics we can illustrate the main concepts and review key physical quantities that will be encountered throughout this book. That is the topic of the next section.