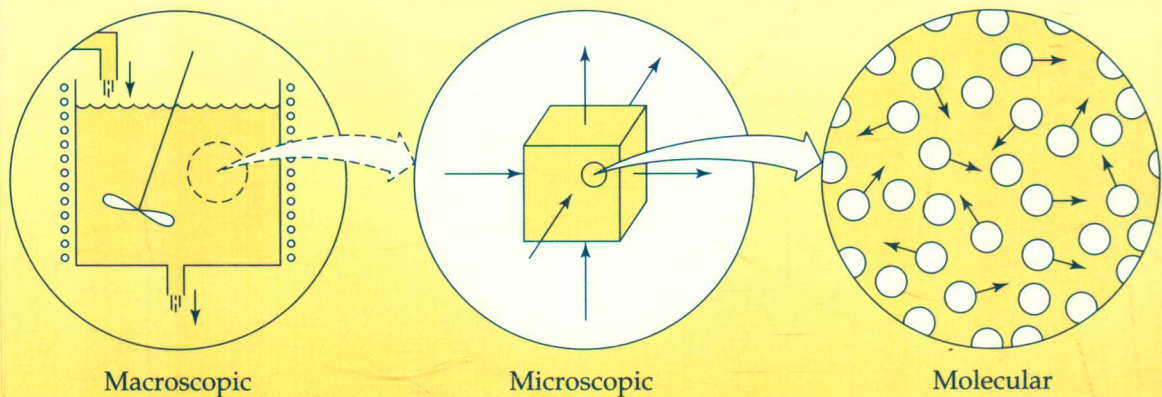


Transport Phenomena

Second Edition



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

Preface

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Second Edition

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Warren E. Stewart
Edwin N. Lightfoot

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•••ALGEBRAIC OPERATIONS FOR VECTORS AND TENSORS IN CARTESIAN COORDINATES

(s is a scalar; \mathbf{v} and \mathbf{w} are vectors; $\boldsymbol{\tau}$ is a tensor; dot or cross operations enclosed within parentheses are scalars, those enclosed in brackets are vectors)

$$(\mathbf{v} \cdot \mathbf{w}) = v_x w_x + v_y w_y + v_z w_z = (\mathbf{w} \cdot \mathbf{v})$$

$$[\mathbf{v} \times \mathbf{w}]_x = v_y w_z - v_z w_y = -[\mathbf{w} \times \mathbf{v}]_x$$

$$[\mathbf{v} \times \mathbf{w}]_y = v_z w_x - v_x w_z = -[\mathbf{w} \times \mathbf{v}]_y$$

$$[\mathbf{v} \times \mathbf{w}]_z = v_x w_y - v_y w_x = -[\mathbf{w} \times \mathbf{v}]_z$$

$$[\boldsymbol{\tau} \cdot \mathbf{v}]_x = \tau_{xx} v_x + \tau_{xy} v_y + \tau_{xz} v_z$$

$$[\boldsymbol{\tau} \cdot \mathbf{v}]_y = \tau_{yx} v_x + \tau_{yy} v_y + \tau_{yz} v_z$$

$$[\boldsymbol{\tau} \cdot \mathbf{v}]_z = \tau_{zx} v_x + \tau_{zy} v_y + \tau_{zz} v_z$$

$$[\mathbf{v} \cdot \boldsymbol{\tau}]_x = v_x \tau_{xx} + v_y \tau_{yx} + v_z \tau_{zx}$$

$$[\mathbf{v} \cdot \boldsymbol{\tau}]_y = v_x \tau_{xy} + v_y \tau_{yy} + v_z \tau_{zy}$$

$$[\mathbf{v} \cdot \boldsymbol{\tau}]_z = v_x \tau_{xz} + v_y \tau_{yz} + v_z \tau_{zz}$$

Note: The above operations may be generalized to cylindrical coordinates by replacing (x, y, z) by (r, θ, z) , and to spherical coordinates by replacing (x, y, z) by (r, θ, ϕ) . Descriptions of curvilinear coordinates are given in Figures 1.2-2, A.6-1, A.8-1, and A.8-2.

•••DIFFERENTIAL OPERATIONS FOR SCALARS, VECTORS, AND TENSORS IN CARTESIAN COORDINATES

$$[\nabla s]_x = \frac{\partial s}{\partial x}$$

$$[\nabla s]_y = \frac{\partial s}{\partial y}$$

$$[\nabla s]_z = \frac{\partial s}{\partial z}$$

$$[\nabla \times \mathbf{v}]_x = \frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}$$

$$[\nabla \times \mathbf{v}]_y = \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}$$

$$[\nabla \times \mathbf{v}]_z = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}$$

$$(\nabla \cdot \mathbf{v}) = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$$

$$(\mathbf{v} \cdot \nabla s) = v_x \frac{\partial s}{\partial x} + v_y \frac{\partial s}{\partial y} + v_z \frac{\partial s}{\partial z}$$

$$\nabla^2 s \equiv (\nabla \cdot \nabla s) = \frac{\partial^2 s}{\partial x^2} + \frac{\partial^2 s}{\partial y^2} + \frac{\partial^2 s}{\partial z^2}$$

$$[\nabla^2 \mathbf{v}]_x \equiv [\nabla \cdot \nabla \mathbf{v}]_x = \frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}$$

$$[\nabla^2 \mathbf{v}]_y \equiv [\nabla \cdot \nabla \mathbf{v}]_y = \frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2}$$

$$[\nabla^2 \mathbf{v}]_z \equiv [\nabla \cdot \nabla \mathbf{v}]_z = \frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}$$

$$[\mathbf{v} \cdot \nabla \mathbf{v}]_x = v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z}$$

$$[\mathbf{v} \cdot \nabla \mathbf{v}]_y = v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} + v_z \frac{\partial v_y}{\partial z}$$

$$[\mathbf{v} \cdot \nabla \mathbf{v}]_z = v_x \frac{\partial v_z}{\partial x} + v_y \frac{\partial v_z}{\partial y} + v_z \frac{\partial v_z}{\partial z}$$

$$[\nabla \cdot \mathbf{v} \mathbf{v}]_x = \frac{\partial(v_x v_x)}{\partial x} + \frac{\partial(v_y v_x)}{\partial y} + \frac{\partial(v_z v_x)}{\partial z}$$

$$[\nabla \cdot \mathbf{v} \mathbf{v}]_y = \frac{\partial(v_x v_y)}{\partial x} + \frac{\partial(v_y v_y)}{\partial y} + \frac{\partial(v_z v_y)}{\partial z}$$

$$[\nabla \cdot \mathbf{v} \mathbf{v}]_z = \frac{\partial(v_x v_z)}{\partial x} + \frac{\partial(v_y v_z)}{\partial y} + \frac{\partial(v_z v_z)}{\partial z}$$

$$[\nabla \cdot \boldsymbol{\tau}]_x = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}$$

$$[\nabla \cdot \boldsymbol{\tau}]_y = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}$$

$$[\nabla \cdot \boldsymbol{\tau}]_z = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}$$

$$\begin{aligned} (\boldsymbol{\tau} : \nabla \mathbf{v}) &= \tau_{xx} \frac{\partial v_x}{\partial x} + \tau_{xy} \frac{\partial v_x}{\partial y} + \tau_{xz} \frac{\partial v_x}{\partial z} \\ &\quad + \tau_{yx} \frac{\partial v_y}{\partial x} + \tau_{yy} \frac{\partial v_y}{\partial y} + \tau_{yz} \frac{\partial v_y}{\partial z} \\ &\quad + \tau_{zx} \frac{\partial v_z}{\partial x} + \tau_{zy} \frac{\partial v_z}{\partial y} + \tau_{zz} \frac{\partial v_z}{\partial z} \end{aligned}$$

Note: the differential operations may *not* be simply generalized to curvilinear coordinates; see Tables A.7-2 and A.7-3.

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.

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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-

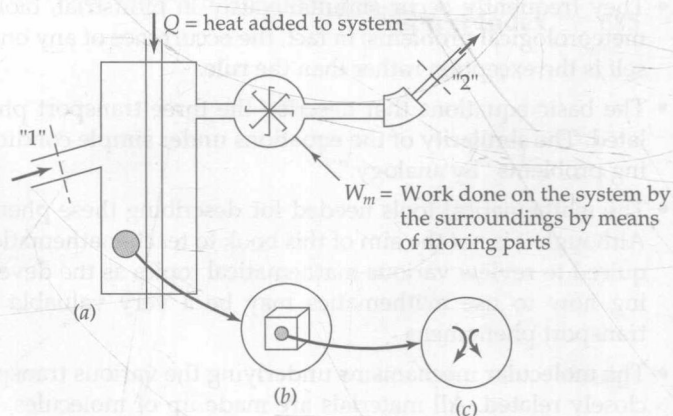


Fig. 0.2-1 (a) A macroscopic flow system containing N_2 and O_2 ; (b) a microscopic region within the macroscopic system containing N_2 and O_2 , which are in a state of flow; (c) a collision between a molecule of N_2 and a molecule of O_2 .