国外名校名著

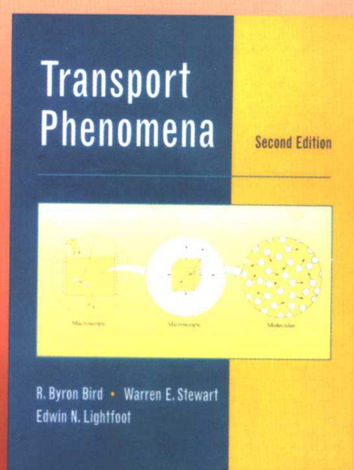
TRANSPORT PHENOMENA

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

国外名校名著

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

（京）新登字 039 号

图书在版编目（CIP）数据

传递现象：英文/（美）伯德（Bird，R. B.）等著．—2 版（影印本）．
北京：化学工业出版社，2002. 6
书名原文：Transport Phenomena
ISBN 7-5025-3267-6

Ⅰ．传…　Ⅱ．伯…　Ⅲ．①传质学-高等学校-教材-英文②传热学-高等学校-教材-英文　Ⅳ．TK124

中国版本图书馆 CIP 数据核字（2002）第 041294 号

R. Byron Bird, Warren E. Stewart, Edwin N. Lightfoot
Transport Phenomena, 2nd ed.
ISBN: 0-471-41077-2

北京市版权局著作权合同登记号：01-2002-4040

Transport Phenomena

Second Edition

传递现象

第二版

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

责任编辑：徐世峰　王丽娜

封面设计：郑小红

*

化学工业出版社出版发行

（北京市朝阳区惠新里 3 号　邮政编码 100029）

发行电话：（010）64982530

http://www.cip.com.cn

*

新华书店北京发行所经销

北京云浩印刷有限责任公司印刷

三河市前程装订厂装订

开本 850×1168 毫米 1/16　印张 57½

2002 年 8 月第 1 版　2002 年 8 月北京第 1 次印刷

ISBN 7-5025-3267-6/G · 850

定　价：89.00 元

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、教学方法和教学技术改革的研究与实践”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.

•••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)

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

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

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

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

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

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

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

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

$$[\nabla s]_x = \frac{\partial s}{\partial x} \qquad [\nabla s]_y = \frac{\partial s}{\partial y} \qquad [\nabla s]_z = \frac{\partial s}{\partial z}$$

$$[\nabla \times \mathbf{v}]_x = \frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z} \qquad [\nabla \times \mathbf{v}]_y = \frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x} \qquad [\nabla \times \mathbf{v}]_z = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

•••MOLECULAR FLUX EXPRESSIONS (SEE APPENDIX B.1, B.2, AND B.3)

Momentum (ρ = constant, Newtonian fluid):

$$\boldsymbol{\pi} = p\boldsymbol{\delta} - \mu(\nabla\mathbf{v} + (\nabla\mathbf{v})^{\dagger}) \qquad \text{or} \qquad \pi_{ij} = p\delta_{ij} - \mu\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j}\right)$$

Heat (pure fluid only):

$$\mathbf{q} = -k\nabla T \qquad \text{or} \qquad q_i = -k\frac{\partial T}{\partial x_i}$$

Mass (for a binary mixture of A and B):

$$\mathbf{j}_A = -\rho\mathscr{D}_{AB}\nabla\omega_A \qquad \text{or} \qquad j_{Ai} = -\rho\mathscr{D}_{AB}\frac{\partial \omega_A}{\partial x_i}$$

•••CONVECTED FLUX EXPRESSIONS (SEE §§1.7, 9.7, 17.7)

Momentum:

$$\rho\mathbf{v}\mathbf{v} \qquad \text{or} \qquad \rho v_i v_j$$

Energy:

$$\rho(\hat{U} + \tfrac{1}{2}v^2)\mathbf{v} \qquad \text{or} \qquad \rho(\hat{U} + \tfrac{1}{2}v^2)v_i$$

Mass:

$$\rho\omega_A\mathbf{v} \qquad \text{or} \qquad \rho\omega_A v_i$$

•••COMBINED FLUX EXPRESSIONS

Momentum:

$$\boldsymbol{\phi} = \rho\mathbf{v}\mathbf{v} + \boldsymbol{\pi} = \rho\mathbf{v}\mathbf{v} + p\boldsymbol{\delta} + \boldsymbol{\tau} \qquad \text{(Eq. 1.7-2)}$$

Energy:

$$\mathbf{e} = \rho(\hat{U} + \tfrac{1}{2}v^2)\mathbf{v} + \mathbf{q} + [\boldsymbol{\pi}\cdot\mathbf{v}] \qquad \text{(Eq. 9.8-5)}$$

$$= \rho(\hat{H} + \tfrac{1}{2}v^2)\mathbf{v} + \mathbf{q} + [\boldsymbol{\tau}\cdot\mathbf{v}] \qquad \text{(Eq. 9.8-6)}$$

Mass:

$$\mathbf{n}_A = \rho\omega_A\mathbf{v} + \mathbf{j}_A \qquad \text{(Eq. 17.8-1)}$$

Note: The quantity $[\boldsymbol{\pi}\cdot\mathbf{v}]$ is the molecular work flux (see §9.8), and $\boldsymbol{\pi} = p\boldsymbol{\delta} + \boldsymbol{\tau}$ (see Table 1.2-21). All fluxes obey the same sign convention: they are positive when the entity being transported is moving from the negative side of a surface to the positive side.

•••EQUATIONS OF CHANGE IN TERMS OF THE COMBINED FLUXES

These equations are valid only for systems in which gravity is the only external force. More information may be found in §19.2.

Momentum:

$$\frac{\partial}{\partial t}\rho\mathbf{v} = -[\nabla\cdot\boldsymbol{\phi}] + \rho\mathbf{g} \qquad \text{(Eq. 3.2-8)}$$

Energy:

$$\frac{\partial}{\partial t}\rho(\hat{U} + \tfrac{1}{2}v^2) = -(\nabla\cdot\mathbf{e}) + \rho(\mathbf{v}\cdot\mathbf{g}) \qquad \text{(Eq. 11.1-6)}$$

Mass:

$$\frac{\partial}{\partial t}\rho\omega_A = -(\nabla\cdot\mathbf{n}_A) + r_A \qquad \text{(Eq. 19.1-6)}$$

•••EQUATIONS OF CHANGE (SPECIAL FORMS)

Momentum (for Newtonian fluids with constant ρ and μ): (§B.6)

$$\rho\frac{D\mathbf{v}}{Dt} \equiv \rho\left(\frac{\partial\mathbf{v}}{\partial t} + [\mathbf{v}\cdot\nabla\mathbf{v}]\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g}$$

Energy (for Newtonian fluids with constant ρ and k): (§B.9)

$$\rho\hat{C}_p\frac{DT}{Dt} \equiv \rho\hat{C}_p\left(\frac{\partial T}{\partial t} + (\mathbf{v}\cdot\nabla T)\right) = k\nabla^2 T + \mu\Phi_v$$

Mass (for binary mixtures of A and B with constant $\rho\mathfrak{D}_{AB}$): (§B.11)

$$\rho\frac{D\omega_A}{Dt} \equiv \rho\left(\frac{\partial\omega_A}{\partial t} + (\mathbf{v}\cdot\nabla\omega_A)\right) = \rho\mathfrak{D}_{AB}\nabla^2\omega_A + r_A$$

•••DIMENSIONLESS GROUPS

(l_0 and v_0 are a characteristic length and a characteristic velocity, respectively)

$\text{Re} = l_0 v_0 \rho/\mu$	$\text{Pr} = \hat{C}_p\mu/k$	$\text{Sc} = \mu/\rho\mathfrak{D}_{AB}$
$\text{Ra} = \text{GrPr}$	$\text{Gr} = g\beta l_0^3\Delta T/\nu^2$	$\text{Gr}_\omega = g\zeta l_0^3\Delta\omega_A/\nu^2$
$\text{Nu} = hl_0/k$	$\text{Pé} = \text{RePr}$	$\text{Pé}_{AB} = \text{ReSc}$
$\text{Sh} = k_c l_0/\mathfrak{D}_{AB}$	$j_H = \text{Nu}/\text{RePr}^{1/3}$	$j_D = \text{Sh}/\text{ReSc}^{1/3}$

Contents

Chapter 5 Velocity Distributions in Turbulent Flow 152

Chapter 6 Interphase Transport in Isothermal Systems 177

Chapter 7 Macroscopic Balances for Isothermal Flow Systems 197

Chapter 8 Polymeric Liquids 231

Part II Energy Transport