TRANSPORT PHENOMENA

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R. BYRON BIRD
WARREN E. STEWART
EDWIN N. LIGHTFOOT

Department of Chemical Engineering
University of Wisconsin
Madison, Wisconsin

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Preface

This book is intended to be an introduction to the field of transport phenomena for students of engineering and applied science. Herein we present the subjects of momentum transport (viscous flow), energy transport (heat conduction, convection, and radiation), and mass transport (diffusion). In this treatment the media in which the transport phenomena are occurring are regarded as continua, and very little is said about the molecular explanation of these processes. Surely the continuum approach is of more immediate interest to engineering students, although it should be emphasized that both approaches are needed for complete mastery of the subject.

Because of the current demand in engineering education to put more emphasis on understanding basic physical principles than on the blind use of empiricism, we feel there is a very definite need for a book of this kind. Obviously the subject matter is sufficiently basic that it cuts across traditional departmental lines. Our thought has been that the subject of transport phenomena should rank along with thermodynamics, mechanics, and electromagnetism as one of the key "engineering sciences." Knowledge of the basic laws of mass, momentum, and energy transport has certainly become important, if not indispensable, in engineering analysis. In addition, the material in this text may be of interest to some who are working in physical chemistry, soil physics, meteorology, and biology.

Since the field of transport phenomena has not heretofore been recognized as a distinct engineering subject, it seems worthwhile for us to tell the reader how we have organized the material. Diverse methods of organization were studied, and, with the help of our departmental colleagues, we settled on the outline shown in Table I. Each topic has been assigned a pigeonhole in a two-dimensional array in order to emphasize the relation of each subject to other subjects in the same row or column. Division of the material into columns labeled mass, momentum, and energy transport allows for one method of classification, based on the entity being transported. In the various rows another mode of classification, based on the type of transport, is indicated. Clearly, on the basis of this chart, one can organize a course on transport phenomena in one of two ways: by working down the columns (Chapters 1, 2, 3, 4, 5, etc.) or by working across the rows (Chapters 1, 8, 16, 2, 9, 17, 3, etc.). Actually, the text material is arranged in such a way that either method may be used. The "column" approach is probably better for beginners, whereas the "row" approach may be more suited to advanced students.

Each chapter is provided with illustrative examples which show how to use various techniques or which give further elaboration on the text. Discussion questions at the end of the chapter are included in an effort to catalyze thinking about the material from several different viewpoints. The problems at the end of each chapter have been grouped into four classes (designated by a subscript after the problem number):

Class 1: Problems that illustrate direct numerical applications of the formulas in the text.

Class 2: Problems that require elementary analysis of physical situations, based on the subject material in the chapter.

Class 3: Problems that require somewhat more mature analysis, sometimes involving information from several chapters or material not specifically covered in the text.

Class 4: Problems that require mathematical analysis involving Bessel functions, partial differential equations, Laplace transforms, complex variable, and tensor analysis.

Of these four classes of problems the first three should be appropriate for junior and senior courses in transport phenomena; none of the problems in these classes involves mathematics beyond ordinary differential equations.

Obviously there is more material in this book than can be conveniently used in an introductory course. As a guide to prospective teachers of transport phenomena, we have indicated with an asterisk (*) those sections that we feel are suitable for a well-balanced three- or four-credit undergraduate course. Having some additional material in the book

TABLE I. SCHEMATIC DIAGRAM OF THE ORGANIZATION OF TRANSPORT PHENOMENA

Entity Being Transported → / Type of Transport ↓	Momentum	Energy	Mass
TRANSPORT BY MOLECULAR MOTION	1 VISCOSITY μ Newton's law of viscosity Temperature, pressure, and composition dependence of μ Kinetic theory of μ	8 THERMAL CONDUCTIVITY k Fourier's law of heat conduction Temperature, pressure, and composition dependence of k Kinetic theory of k	16 DIFFUSIVITY $\mathfrak{D}_{AB}$ Fick's law of diffusion Temperature, pressure, and composition dependence of $\mathfrak{D}_{AB}$ Kinetic theory of $\mathfrak{D}_{AB}$
TRANSPORT IN LAMINAR FLOW OR IN SOLIDS, IN ONE DIMENSION	2 SHELL MOMENTUM BALANCES Velocity profiles Average velocity Momentum flux at surfaces	9 SHELL ENERGY BALANCES Temperature profiles Average temperature Energy flux at surfaces	17 SHELL MASS BALANCES Concentration profiles Average concentration Mass flux at surfaces
TRANSPORT IN AN ARBITRARY CONTINUUM	3 EQUATIONS OF CHANGE (ISOTHERMAL) Equation of continuity Equation of motion Equation of energy (isothermal)	10 EQUATIONS OF CHANGE (NONISOTHERMAL) Equation of continuity Equation of motion for forced and free convection Equation of energy (nonisothermal)	18 EQUATIONS OF CHANGE (MULTICOMPONENT) Equations of continuity for each species Equation of motion for forced and free convection Equation of energy (multicomponent)
TRANSPORT IN LAMINAR FLOW OR IN SOLIDS, WITH TWO INDEPENDENT VARIABLES	4 MOMENTUM TRANSPORT WITH TWO INDEPENDENT VARIABLES Unsteady viscous flow Two-dimensional viscous flow Ideal two-dimensional flow Boundary-layer momentum transport	11 ENERGY TRANSPORT WITH TWO INDEPENDENT VARIABLES Unsteady heat conduction Heat conduction in viscous flow Two-dimensional heat conduction in solids Boundary-layer energy transport	19 MASS TRANSPORT WITH TWO INDEPENDENT VARIABLES Unsteady diffusion Diffusion in viscous flow Two-dimensional diffusion in solids Boundary-layer mass transport
TRANSPORT IN TURBULENT FLOW	5 TURBULENT MOMENTUM TRANSPORT Time-smoothing of equations of change Eddy viscosity Turbulent velocity profiles	12 TURBULENT ENERGY TRANSPORT Time-smoothing of equations of change Eddy thermal conductivity Turbulent temperature profiles	20 TURBULENT MASS TRANSPORT Time-smoothing of equations of change Eddy diffusivity Turbulent concentration profiles
TRANSPORT BETWEEN TWO PHASES	6 INTERPHASE MOMENTUM TRANSPORT Friction factor f Dimensionless correlations	13 INTERPHASE ENERGY TRANSPORT Heat-transfer coefficient h Dimensionless correlations (forced and free convection)	21 INTERPHASE MASS TRANSPORT Mass-transfer coefficient k_x Dimensionless correlations (forced and free convection)
TRANSPORT BY RADIATION	*Numbers refer to the chapters in this book*	14 RADIANT ENERGY TRANSPORT Planck's radiation law Stefan-Boltzmann law Geometrical problems Radiation through absorbing media	*This book may be studied either by "columns" or by "rows"*
TRANSPORT IN LARGE FLOW SYSTEMS	7 MACROSCOPIC BALANCES (ISOTHERMAL) Mass balance Momentum balance Mechanical energy balance (Bernoulli equation)	15 MACROSCOPIC BALANCES (NONISOTHERMAL) Mass balance Momentum balance Mechanical and total energy balance	22 MACROSCOPIC BALANCES (MULTICOMPONENT) Mass balances for each species Momentum balance Mechanical and total energy balance

will be helpful to instructors and advanced students and will, in addition, serve as a warning to the undergraduate that the "boundaries of the course" do not coincide with the "boundaries of the subject."

Our notation is uniform throughout the text, and a table of notation has been appended for the readers' convenience. Unfortunately, it is not possible to adopt notation in agreement with that used by all our readers, inasmuch as the subject material includes several fields that have developed independently. Generally, our notation represents a compromise between that used by physicists and that used by engineers.

Early in 1957 the Chemical Engineering Department of the University of Wisconsin decided, after considerable deliberation, to inaugurate a required one-semester junior course in transport phenomena. No textbook was available; hence mimeographed notes were prepared for the students' use and in the fall of 1958 were published as *Notes on Transport Phenomena*. These notes have also been used at several other universities, and we have benefited immensely from the comments sent to us by both students and teachers.

This book represents the result of an exhaustive revision of the *Notes on Transport Phenomena*. The text has been completely rewritten, several chapters have been entirely reorganized, and numerous problems and examples have been added. Most of the changes were made in an effort to provide a better text for beginning students.

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

Madison, Wisconsin
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Professor O. A. Hougen and Dean W. R. Marshall, Jr., of the University of Wisconsin deserve many thanks for their continued interest in the field of transport phenomena and their enthusiasm for promoting increased instruction in this area.

Professor R. A. Ragatz, Chairman, of the Chemical Engineering Department, University of Wisconsin, assisted us by handling the administrative problems associated with the introduction of this course into the new chemical engineering curriculum and by providing us with some additional time for preparation of the manuscript.

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Professor Eric Weger (Johns Hopkins University) and Professor K. M. Watson (Illinois Institute of Technology) also offered their comments after experiences in teaching with *Notes on Transport Phenomena.*

A number of our students have read certain chapters of the manuscript of this book and have contributed materially to the accuracy of the final text: Donald R. Woods, Allyn J. Ziegenhàgen, David O. Edwards, Paul F. Korbach, Donald W. McEachern, Rosendo J. Sánchez Palma, James P. Hutchins, Raffi M. Turian, Davis W. Hubbard, Boudewijn van Nederveen, Willam A. Hunt, John P. Lawler. In addition the following students have checked the statements and solutions to all of the Class 1 and Class 2 problems: Vipin D. Shah, Thomas J. Sadowski, Richard H. Weaver, Gary F. Kuether.

Professors J. O. Hirschfelder and C. F. Curtiss of the University of Wisconsin, with whom we have had many years of pleasant association, first introduced our chemical engineering department to the subject of transport phenomena some ten years ago via a graduate course; our present course is in a sense a direct descendent of theirs.

Professor H. Kramers (Technische Hogeschool, Delft, Holland) in 1956 prepared a set of lecture notes entitled *Physische Transportverschijnselen*, which represented the first attempt that we know of to teach transport phenomena to engineering students; one of us (R.B.B.) had the pleasure of spending a semester at Professor Kramers' laboratory as a Fulbright Lecturer and Guggenheim Fellow, during which period he profited very much from discussions related to the teaching of transport phenomena.

Miss Jeanne O. Lippert deserves our warmest thanks for typing the bulk of the manuscript and some parts of it several times. We are deeply indebted to Mr. Stuart E. Schreiber for his tireless efforts in mimeographing and assembling the original set of notes. Also we wish to thank Miss Ellen Gunderson for her part in assisting us with the preparation of the manuscript.

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