INTRODUCTION TO CHEMICAL ENGINEERING FLUID MECHANICS

Designed for undergraduate courses in fluid mechanics for chemical engineers, this textbook illustrates the fundamental concepts and analytical strategies in a rigorous and systematic, yet mathematically accessible, manner. Dimensional analysis and order-of-magnitude estimation are presented as tools to help students identify which forces are important in different settings. The friction factors for pipes and other conduits, the terminal velocities of particles, drops, and bubbles, and flow in porous media, packed beds, and fluidized beds are explained from an experimental viewpoint. The physical and mathematical distinctions among major flow regimes, including unidirectional flow, lubrication flow, creeping flow, pseudosteady flow, irrotational flow, laminar boundary layers, turbulent shear flow, and compressible flow are described. Including a full solutions manual for instructors available at www.cambridge.org/deen, this is the ideal text for a one-semester course.

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To Meredith and Michael

Contents

Contents

Contents

Contents

Preface

WHAT IS CHEMICAL ENGINEERING FLUID MECHANICS?

Quantitative experimentation with fluids began in antiquity, and the foundations for the mathematical analysis of fluid flow were well established by the mid 1800s. Although a mature subject, fluid mechanics remains a very active area of research in engineering, applied mathematics, and physics. As befits a field that is both fascinating and useful, it has been the subject of innumerable introductory textbooks. However, only a few have focused on the aspects of fluid mechanics that are most vital in chemical engineering.

Certain results that stem from conservation of mass and momentum in fluids cut across all fields. However, the kinds of flow that are of greatest interest differ considerably among the various branches of engineering. One thing that distinguishes fluid mechanics in chemical engineering from that in, say, aeronautical or civil engineering, is the central importance of viscosity. Viscous stresses are at the heart of predicting flow rates in pipes, which has always been the main application of fluid mechanics in process design. Moreover, chemical engineering encompasses many technologies that involve bubbles, drops, particles, porous media, or liquid films, where small length scales amplify the effects of viscosity. Surface tension, usually not a concern in other engineering disciplines, also can be important at such length scales. In addition, in chemical engineering applications even gases usually can be idealized as incompressible. Another feature of chemical engineering fluid mechanics is an emphasis on microscopic analysis to calculate velocity fields. Determining velocities and pressures, and finding the resulting forces or torques, is often not an end in itself. Detailed velocity fields are needed to predict concentration and temperature distributions, which in turn are essential for the analysis and design of reactors and separation devices. Of lesser concern than in some other disciplines are the fluid dynamics of rotating machinery, flow in open channels, and flow at near-sonic velocities (where gas compressibility is important). Thus, chemical engineering fluid mechanics is characterized by a heightened interest in the microscopic analysis of incompressible viscous flows. Biomedical and mechanical engineers share some of the same concerns.

PURPOSE AND ORGANIZATION

This book is designed mainly as a text for chemical engineering undergraduates. The intention is to present fundamental concepts in a rigorous but mathematically accessible manner. A recurring theme is how to identify what is important physically in a novel situation and how to use such insights in modeling. That is illustrated by examples both within and outside the traditional domain of chemical engineering. The end-of-chapter problems tend to be challenging. They are intended not just to provide practice in certain kinds of calculations, but to build confidence in analyzing physical systems and to help develop engineering judgment.

The essential prerequisites are introductory mechanics, multivariable calculus, and ordinary differential equations. The information on vectors and tensors that is needed to understand certain derivations is summarized in an appendix, thereby making that part of the mathematics self-contained. Familiarity with a few numerical methods (e.g., solving first-order differential equations) is helpful but not necessary. No prior experience with partial differential equations is assumed; solution methods are explained as the need arises. A basic background in thermodynamics is presumed only in the last chapter.

The book has four parts. Part I, "Use of Experimental Data" (Chapters 1–3), discusses fluid properties, representative magnitudes of velocities and forces, and certain kinds of design. The information in these chapters is largely empirical. After surveying gas and liquid properties, Chapter 1 introduces dimensional analysis and the several uses of dimensionless groups, with an emphasis on groups that indicate the relative importance of different kinds of forces. Chapter 2 focuses on pressure–flow relationships in long pipes or other conduits. Chapter 3 discusses drag forces, terminal velocities of particles, porous media, packed beds, and fluidized beds. While presenting various experimental results and explaining certain engineering calculations, Chapters 2 and 3 introduce phenomena and relationships that are revisited later from more fundamental viewpoints.

Part II, "Fundamentals of Fluid Dynamics" (Chapters 4–6), lays the groundwork for predictive modeling. Chapter 4, on static fluids, explains the interactions among pressure, gravity, and surface tension and begins to make force calculations more precise. Chapter 5 introduces the continuity equation (the differential equation that embodies conservation of mass), the concept of rate of strain, and other aspects of kinematics, the description of fluid motion. Chapter 6 provides a general description of viscous stresses and combines that with conservation of linear momentum. The main result is the Navier–Stokes equation, the differential equation that ordinarily governs momentum changes within fluids. As aspects of vectors, tensors, and analytical geometry become relevant, the reader is referred to specific sections of the Appendix.

Part III, "Microscopic Analysis" (Chapters 7–10), illustrates how to use the governing equations of Chapter 6 to predict velocity and pressure fields, and how then to calculate fluid forces and torques. Chapter 7 is devoted to unidirectional flow, the simplest set of applications. Chapter 8 discusses how to anticipate and justify simplifications of the Navier–Stokes equation when viscous stresses are much more important than the inertia of the fluid. Introduced there are the lubrication, creeping flow, and pseudosteady approximations. Chapter 9 extends the discussion of approximations to laminar flows where inertia is prominent, as in boundary layers. Concepts unique to turbulent flow (Kolmogorov scales, time-smoothing, Reynolds stress, and mixing lengths) are presented in Chapter 10. Numerous connections are made between results derived in Part III and the experimental observations in Part I.

Part IV, "Macroscopic Analysis" (Chapters 11–12), focuses on flow problems that are too complex for the approaches in Part III, but where a less detailed kind of analysis is useful. Integral forms of the conservation equations are derived in Chapter 11 and simplified to algebraic equations that are practical for applications, such as the engineering Bernoulli equation. Key assumptions are justified by referring to the microscopic results of Part III. The simplified macroscopic balances are applied to a variety of systems in Chapter 11. Chapter 12 revisits pipe flow, including now resistances due to entrance regions and pipe fittings. It concludes with an introduction to compressible flow.

Although proofs of all key theoretical results are provided, some derivations are put in "additional notes" at the ends of sections. Any subsection so labeled can be skipped without loss of continuity. In contrast, all the examples illustrate core material and merit study. Many of the end-of-chapter problems present additional theoretical or experimental results or describe new kinds of applications. It is recommended that all the problem statements be read as part of the chapter, even if solutions are not to be worked out.

In manuscript form, the book has been used successfully as the text in a one-semester course for chemical engineering undergraduates. In a fast-paced course with four contact hours per week over 14 weeks, approximately 80% of the material was covered. Overall, the content provides a reasonable foundation for practicing chemical engineers and good preparation for graduate-level study of fluid mechanics. If supplemented by a comparable introduction to heat and mass transfer, it would be good preparation for graduate study of transport phenomena.

ACKNOWLEDGMENTS

Some of the examples and problems originated with MIT colleagues or faculty elsewhere. I have identified such unpublished sources with footnotes that state "this problem was suggested by," a phrase intended to give credit without blame. I have revised what others had written in homework or exam problems, often extensively, or elaborated on what they and I discussed, and therefore take all responsibility for errors or confusion.

I have learned a great deal over the years from MIT faculty with whom I have taught fluid mechanics or otherwise discussed the subject. Among those present or former colleagues are Robert C. Armstrong, Martin Z. Bazant, Robert A. Brown, Fikile R. Brushett, Arup K. Chakraborty, Patrick S. Doyle, Kenneth A. Smith, James W. Swan, and Preetinder S. Virk. As a graduate student at Stanford long ago, I was inspired by a course in viscous flow theory taught by Andreas Acrivos. My education has been advanced no less by interactions with generations of MIT students, who have always impressed me with their curiosity and determination to learn. Responding to their questions has continually sharpened my own understanding of the subject.

Although undertaken after retirement, the writing of this book was supported in part by the Carbon P. Dubbs Chair in the Department of Chemical Engineering at MIT. I am appreciative of that support and the other encouragement I have received from the Department.

Last but not least are those at Cambridge University Press who helped improve the book and make it a reality, including acquisition editor Michelle Carey, copy-editor Steven Holt, and production editor Charles Howell.

W. M. D.

Symbols

Following is a list of the more commonly used symbols. Omitted are coordinates (defined in Section A.5) and many quantities that appear in just one chapter. In general, scalars are italic Roman or Greek (e.g., a or δ), vectors are bold Roman (e.g., $\mathbf{v}$), and tensors are bold Greek (e.g., $\boldsymbol{\tau}$). Magnitudes of vectors and tensors are denoted usually by the corresponding italic letter (e.g., v or τ), and vector and tensor components are represented using subscripted italics (e.g., v_x or τ_{yx}). Natural and base-10 logarithms are written as “ln” and “log,” respectively.

ROMAN LETTERS

A	Surface area or cross-sectional area.
Ar	Archimedes number.
Bo	Bond number.
C_D	Drag coefficient [Eq. (3.2-1)].
C_f	Friction factor or drag coefficient for a flat plate [Eq. (3.2-13)].
Ca	Capillary number.
D	Diameter (also d).
D_H	Hydraulic diameter [Eq. (2.4-1)].
$\mathbf{e_i}$	Unit vector associated with coordinate i.
E_c	Rate of mechanical energy loss due to compression [Eq. (11.4-2)].
E_v	Rate of mechanical energy loss due to viscous dissipation [Eq. (11.4-3)].
f	Friction factor for a tube or other conduit [Eq. (2.2-4)].
F_D	Drag force.
$\mathbf{F}$	Force vector.
$\mathbf{F_0}$	Force due to static pressure variations.
$\mathbf{F_B}$	Net buoyancy force, $\mathbf{F_0} - \mathbf{F_G}$.
$\mathbf{F_G}$	Gravitational force.
$\mathbf{F_P}$	Pressure force.
$\mathbf{F}_{\mathcal{P}}$	Flow-dependent part of pressure force.
$\mathbf{F}_{\boldsymbol{\tau}}$	Viscous force.
Fr	Froude number.
$\mathbf{g}$	Gravitational acceleration vector.
$\mathbf{G}$	Torque vector.
h	Height (usually).
k	Wall roughness parameter (usually) or Darcy permeability (Chapter 3).
K_i	Loss coefficient for event or device i [Eq. (12.3-1)].
L	Length as a dimension.

L	Object length or characteristic length.
L_E	Entrance length for tubes or other conduits.
m	Mass.
M	Mass as a dimension.
Ma	Mach number.
$\mathbf{n}$	Unit vector normal to a surface, directed outward from a control volume or from phase 1 to phase 2.
P	Absolute or thermodynamic pressure.
$\mathcal{P}$	Dynamic pressure (also called modified pressure or equivalent pressure).
q	Volume flow rate per unit width in two-dimensional flows.
Q	Volume flow rate.
$\mathbf{r}$	Position vector.
R	Radius (usually) or universal gas constant (Sections 1.2, 12.4, and 12.5).
Re	Reynolds number.
$\mathbf{s}$	Stress vector.
S	Surface area.
t	Time.
$\mathbf{t}$	Unit vector tangent to a surface.
T	Absolute temperature.
T	Time as a dimension.
$\mathbf{u}$	Interfacial velocity (Chapter 6), turbulent velocity fluctuation (Chapter 10), or control-surface velocity (Chapter 11).
u	In boundary-layer flows, the outer velocity evaluated at the surface (Chapters 9 and 10).
u_τ	Friction velocity [Eq. (10.2-4)].
U	Characteristic velocity, usually a mean fluid velocity or particle velocity.
v_s	Superficial velocity [Eq. (3.4-1)].
$\mathbf{v}$	Fluid velocity.
V	Volume (usually) or velocity.
w	Mass flow rate (Chapters 11 and 12).
$\mathbf{w}$	Vorticity vector.
W_m	Rate of work done on a system by moving surfaces (shaft work).

GREEK LETTERS

α	Contact angle at a three-phase contact line.
β	At a contraction or expansion, the smaller diameter divided by the larger one.
δ	Boundary-layer thickness (usually).
δ_{ij}	Kronecker delta [Eq. (A.3-6)].
$\boldsymbol{\delta}$	Identity tensor.
Δ	Difference along the direction of flow (downstream value minus upstream value) or differential change.
ε	Volume fraction of fluid (void fraction) in porous media or packed beds.
ε_{ijk}	Permutation symbol [Eq. (A.3-15)].
ϕ	Volume fraction of solids in porous media (Chapter 3) or velocity potential (Chapters 5 and 9).
$\boldsymbol{\Gamma}$	Rate-of-strain tensor [Eq. (6.5-1)].
γ	Surface tension (usually) or heat-capacity ratio [Eq. (12.4-1)].
μ	Viscosity.

ν	Kinematic viscosity, μ/ρ.
ρ	Density.
$\boldsymbol{\sigma}$	Total stress tensor.
$\boldsymbol{\tau}$	Viscous stress tensor.
τ_w	Shear stress at a wall or other solid surface (also τ_0).
$\boldsymbol{\Omega}$	Vorticity tensor [Eq. (6.5-3)].
ψ	Stream function.

SPECIAL SYMBOLS

D/Dt	Material derivative, $\partial/\partial t + \mathbf{v} \cdot \nabla$.
∇	Gradient operator.
∇^2	Laplacian operator, $\nabla \cdot \nabla$.
$\sim$	Order-of-magnitude (OM) equality.