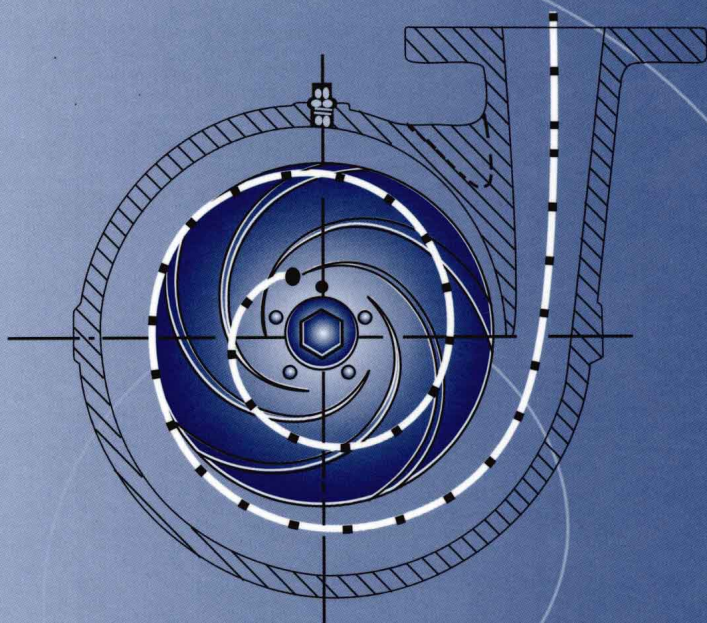


Chemical Engineering Fluid Mechanics

Second Edition, Revised and Expanded



Ron Darby

Chemical Engineering Fluid Mechanics

Second Edition, Revised and Expanded

Ron Darby

*Texas A&M University
College Station, Texas*

江苏工业学院图书馆
藏书章



MARCEL DEKKER, INC.

NEW YORK • BASEL

ISBN: 0-8247-0444-4

This book is printed on acid-free paper.

Headquarters

Marcel Dekker, Inc.
270 Madison Avenue, New York, NY 10016
tel: 212-696-9000; fax: 212-685-4540

Eastern Hemisphere Distribution

Marcel Dekker AG
Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland
tel: 41-61-261-8482; fax: 41-61-261-8896

World Wide Web

<http://www.dekker.com>

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

Copyright © 2001 by Marcel Dekker, Inc. All Rights Reserved.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage and retrieval system, without permission in writing from the publisher.

Current printing (last digit):

10 9 8 7 6 5 4 3 2

PRINTED IN THE UNITED STATES OF AMERICA

Chemical Engineering Fluid Mechanics

Preface

The objectives of this book are twofold: (1) for the student, to show how the fundamental principles underlying the behavior of fluids (with emphasis on one-dimensional macroscopic balances) can be applied in an organized and systematic manner to the solution of practical engineering problems, and (2) for the practicing engineer, to provide a ready reference of current information and basic methods for the analysis of a variety of problems encountered in practical engineering situations.

The scope of coverage includes internal flows of Newtonian and non-Newtonian incompressible fluids, adiabatic and isothermal compressible flows (up to sonic or choking conditions), two-phase (gas-liquid, solid-liquid, and gas-solid) flows, external flows (e.g., drag), and flow in porous media. Applications include dimensional analysis and scale-up, piping systems with fittings for Newtonian and non-Newtonian fluids (for unknown driving force, unknown flow rate, unknown diameter, or most economical diameter), compressible pipe flows up to choked flow, flow measurement and control, pumps, compressors, fluid-particle separation methods (e.g.,

centrifugal, sedimentation, filtration), packed columns, fluidized beds, sedimentation, solids transport in slurry and pneumatic flow, and frozen and flashing two-phase gas–liquid flows. The treatment is from the viewpoint of the process engineer, who is concerned with equipment operation, performance, sizing, and selection, as opposed to the details of mechanical design or the details of flow patterns in such situations.

For the student, this is a basic text for a first-level course in process engineering fluid mechanics, which emphasizes the systematic application of fundamental principles (e.g., macroscopic mass, energy, and momentum balances and economics) to the analysis of a variety of fluid problems of a practical nature. Methods of analysis of many of these operations have been taken from the recent technical literature, and have not previously been available in textbooks. This book includes numerous problems that illustrate these applications at the end of each chapter.

For the practicing engineer, this book serves as a useful reference for the working equations that govern many applications of practical interest, as well as a source for basic principles needed to analyze other fluid systems not covered explicitly in the book. The objective here is not to provide a mindless set of recipes for rote application, however, but to demonstrate an organized approach to problem analysis beginning with basic principles and ending with results of very practical applicability.

Chemical Engineering Fluid Mechanics is based on notes that I have compiled and continually revised while teaching the junior-level fluid mechanics course for chemical engineering students at Texas A&M University over the last 30 years. It has been my experience that, when being introduced to a new subject, students learn best by starting with simple special cases that they can easily relate to physically, and then progressing to more generalized formulations and more complex problems. That is the philosophy adopted in this book. It will certainly be criticized by some, since it is contrary to the usual procedure followed by most textbooks, in which the basic principles are presented first in the most general and mathematical form (e.g., the divergence theorem, Reynolds transport theorem, Navier Stokes equations, etc.), and the special cases are then derived from these. Esoterically, it is very appealing to progress from the general to the specific, rather than vice versa. However, having taught from both perspectives, it is my observation that most beginning students do not gain an appreciation or understanding from the very general, mathematically complex, theoretical vector expressions until they have gained a certain physical feel for how fluids behave, and the laws governing their behavior, in special situations to which they can easily relate. They also understand and appreciate the principles much better if they see how they can be applied to the analysis of practical and useful situations, with results that actually work

in practice. That is why the multi-dimensional vector generalizations of the basic conservation laws have been eschewed in favor of the simpler component and one-dimensional form of these laws.

It is also important to maintain a balanced perspective between fundamental, or theoretical, and empirical information, for the practicing engineer must use both to be effective. It has been said that all the tools of mathematics and physics in the world are not sufficient to calculate how much water will flow in a given time from a kitchen tap when it is opened. However, by proper formulation and utilization of certain experimental observations, this is a routine problem for the engineer. The engineer must be able to solve certain problems by direct application of theoretical principles only (e.g., laminar flow in uniform conduits), others by utilizing hypothetical models that account for a limited understanding of the basic flow phenomena by incorporation of empirical parameters (e.g., turbulent flow in conduits and fittings), and still other problems in which important information is purely empirical (e.g., pump efficiencies, two-phase flow in packed columns). In many of these problems (of all types), application of dimensional analysis (or the principle of “conservation of dimensions”) for generalizing the results of specific analysis, guiding experimental design, and scaling up both theoretical and experimental results can be a very powerful tool.

This second edition of the book includes a new chapter on two-phase flow, which deals with solid–liquid, solid–gas, and frozen and flashing liquid–gas systems, as well as revised, updated, and extended material throughout each chapter. For example, the method for selecting the proper control valve trim to use with a given piping configuration is presented and illustrated by example in Chapter 10. The section on cyclone separators has been completely revised and updated, and new material has been incorporated in a revision of the material on particles in non-Newtonian fluids. Changes have been made throughout the book in an attempt to improve the clarity and utility of the presentation wherever possible. For example, the equations for compressible flow in pipes have been reformulated in terms of variables that are easier to evaluate and represent in dimensionless form.

It is the aim of this book to provide a useful introduction to the simplified form of basic governing equations and an illustration of a consistent method of applying these to the analysis of a variety of practical flow problems. Hopefully, the reader will use this as a starting point to delve more deeply into the limitless expanse of the world of fluid mechanics.

Ron Darby

Unit Conversion Factors

<i>Dimension</i>	<i>Equivalent Units</i>
Mass	1 kg = 1000 g = 0.001 metric ton (tonne) = 2.20461 lb _m = 35.27392 oz 1 lb _m = 453.593 g = 0.453593 kg = 5 × 10 ⁻⁴ ton = 16 oz
Force	1 N = 1 kg m/s ² = 10 ⁵ dyn = 10 ⁵ g cm/s ² = 0.22418 lb _f 1 lb _f = 32.174 lb _m ft/s ² = 4.4482 N = 4.4482 × 10 ⁵ dyn
Length	1 m = 100 cm = 10 ⁶ μm = 10 ¹⁰ Å = 39.37 in. = 3.2808 ft = 1.0936 yd = 0.0006214 mi 1 ft = 12 in. = 1/3 yd = 0.3048 m = 30.48 cm
Volume	1 m ³ = 1000 liters = 10 ⁶ cm ³ = 35.3145 ft ³ = 264.17 gal 1 ft ³ = 1728 in. ³ = 7.4805 gal = 0.028317 m ³ = 28.317 liters = 28,317 cm ³
Pressure	1 atm = 1.01325 × 10 ⁵ N/m ² (Pa) = 1.01325 bar = 1.01325 × 10 ⁶ dyn/cm ² = 760 mm Hg @ 0°C (torr) = 10.333 m H ₂ O @ 4°C = 33.9 ft H ₂ O @ 4°C = 29.921 in. Hg @ 0°C = 14.696 lb _f /in. ² (psi)
Energy	1 J = 1 N m = 10 ⁷ erg = 10 ⁷ dyn cm = 2.667 × 10 ⁻⁷ kWh = 0.23901 cal = 0.7376 ft lb _f = 9.486 × 10 ⁻⁴ Btu [550 ft lb _f /(hp s)]
Power	1 W = 1 J/s = 0.23901 cal/s = 0.7376 ft lb _f /s = 9.486 × 10 ⁻⁴ Btu/s = 1 × 10 ⁻³ kW = 1.341 × 10 ⁻³ hp
Flow Rate	1 m ³ /s = 35.3145 ft ³ /s = 264.17 gal/s = 1.585 × 10 ⁴ gal/min = 10 ⁶ cm ³ /s 1 gpm = 6.309 × 10 ⁻⁵ m ³ /s = 2.228 × 10 ⁻³ ft ³ /s = 63.09 cm ³ /s

Example: The factor to convert Pa to psi is 14.696 psi/(1.01325 × 10⁵ Pa)

Some values of the gas constant: R = 8.314 × 10³ kg m²/(s² kg mol K)
= 8.314 × 10⁷ g cm²/(s² g mol K)
= 82.05 cm³ atm/(g mol K)
= 1.987 cal/(g mol K) or Btu/(lb mol °R)
= 1545 ft lb_f/(lb mol °R)
= 10.73 ft³ psi/(lb mol °R)
= 0.730 ft³ atm/(lb mol °R)

Chemical Engineering Fluid Mechanics

Contents

<i>Preface</i>	<i>iii</i>
<i>Unit Conversion Factors</i>	<i>xvi</i>

1. BASIC CONCEPTS	1
I. FUNDAMENTALS	1
A. Basic Laws	1
B. Experience	2
II. OBJECTIVE	2
III. PHENOMENOLOGICAL RATE OR TRANSPORT LAWS	3
A. Fourier's Law of Heat Conduction	4
B. Fick's Law of Diffusion	5
C. Ohm's Law of Electrical Conductivity	5
D. Newton's Law of Viscosity	6

IV.	THE “SYSTEM”	9
V.	TURBULENT MACROSCOPIC (CONVECTIVE) TRANSPORT MODELS	10
	PROBLEMS	11
	NOTATION	13
2.	DIMENSIONAL ANALYSIS AND SCALE-UP	15
I.	INTRODUCTION	15
II.	UNITS AND DIMENSIONS	16
	A. Dimensions	16
	B. Units	18
	C. Conversion Factors	19
III.	CONSERVATION OF DIMENSIONS	20
	A. Numerical Values	21
	B. Consistent Units	22
IV.	DIMENSIONAL ANALYSIS	22
	A. Pipeline Analysis	25
	B. Uniqueness	28
	C. Dimensionless Variables	28
	D. Problem Solution	29
	E. Alternative Groups	29
V.	SCALE-UP	30
VI.	DIMENSIONLESS GROUPS IN FLUID MECHANICS	35
VII.	ACCURACY AND PRECISION	35
	PROBLEMS	40
	NOTATION	52
3.	FLUID PROPERTIES IN PERSPECTIVE	55
I.	CLASSIFICATION OF MATERIALS AND FLUID PROPERTIES	55
II.	DETERMINATION OF FLUID VISCOUS (RHEOLOGICAL) PROPERTIES	59
	A. Cup-and-Bob (Couette) Viscometer	60
	B. Tube Flow (Poiseuille) Viscometer	63
III.	TYPES OF OBSERVED FLUID BEHAVIOR	64
	A. Newtonian Fluid	65
	B. Bingham Plastic Model	65
	C. Power Law Model	66

D. Structural Viscosity Models	67
IV. TEMPERATURE DEPENDENCE OF VISCOSITY	71
A. Liquids	71
B. Gases	72
V. DENSITY	72
PROBLEMS	73
NOTATION	83
REFERENCES	84
4. FLUID STATICS	85
I. STRESS AND PRESSURE	85
II. THE BASIC EQUATION OF FLUID STATICS	86
A. Constant Density Fluids	88
B. Ideal Gas—Isothermal	89
C. Ideal Gas—Isentropic	90
D. The Standard Atmosphere	90
III. MOVING SYSTEMS	91
A. Vertical Acceleration	91
B. Horizontally Accelerating Free Surface	92
C. Rotating Fluid	93
IV. BUOYANCY	94
V. STATIC FORCES ON SOLID BOUNDARIES	94
PROBLEMS	96
NOTATION	104
5. CONSERVATION PRINCIPLES	105
I. THE SYSTEM	105
II. CONSERVATION OF MASS	106
A. Macroscopic Balance	106
B. Microscopic Balance	107
III. CONSERVATION OF ENERGY	108
A. Internal Energy	110
B. Enthalpy	112
IV. IRREVERSIBLE EFFECTS	113
A. Kinetic Energy Correction	116
V. CONSERVATION OF MOMENTUM	120
A. One-Dimensional Flow in a Tube	121
B. The Loss Coefficient	123
C. Conservation of Angular Momentum	127

D. Moving Boundary Systems and Relative Motion	128
E. Microscopic Momentum Balance	130
PROBLEMS	134
NOTATION	146

6. PIPE FLOW 149

I. FLOW REGIMES	149
II. GENERAL RELATIONS FOR PIPE FLOWS	151
A. Energy Balance	151
B. Momentum Balance	152
C. Continuity	153
D. Energy Dissipation	153
III. NEWTONIAN FLUIDS	154
A. Laminar Flow	154
B. Turbulent Flow	155
C. All Flow Regimes	164
IV. POWER LAW FLUIDS	164
A. Laminar Flow	165
B. Turbulent Flow	166
C. All Flow Regimes	166
V. BINGHAM PLASTICS	167
A. Laminar Flow	168
B. Turbulent Flow	169
C. All Reynolds Numbers	169
VI. PIPE FLOW PROBLEMS	169
A. Unknown Driving Force	170
B. Unknown Flow Rate	172
C. Unknown Diameter	174
D. Use of Tables	177
VII. TUBE FLOW (POISEUILLE) VISCOMETER	177
VIII. TURBULENT DRAG REDUCTION	178
PROBLEMS	184
NOTATION	192
REFERENCES	193

7. INTERNAL FLOW APPLICATIONS 195

I. NONCIRCULAR CONDUITS	195
A. Laminar Flows	195
B. Turbulent Flows	198

II.	MOST ECONOMICAL DIAMETER	200
	A. Newtonian Fluids	203
	B. Non-Newtonian Fluids	205
III.	FRICTION LOSS IN VALVES AND FITTINGS	206
	A. Loss Coefficient	207
	B. Equivalent L/D Method	207
	C. Crane Method	208
	D. 2-K (Hooper) Method	209
	E. 3-K (Darby) Method	209
IV.	NON-NEWTONIAN FLUIDS	214
V.	PIPE FLOW PROBLEMS WITH FITTINGS	215
	A. Unknown Driving Force	216
	B. Unknown Flow Rate	217
	C. Unknown Diameter	218
VI.	SLACK FLOW	221
VII.	PIPE NETWORKS	225
	PROBLEMS	228
	NOTATION	237
	REFERENCES	238

8. PUMPS AND COMPRESSORS 239

I.	PUMPS	239
	A. Positive Displacement Pumps	239
	B. Centrifugal Pumps	240
II.	PUMP CHARACTERISTICS	241
III.	PUMPING REQUIREMENTS AND PUMP SELECTION	243
	A. Required Head	244
	B. Composite Curves	245
IV.	CAVITATION AND NET POSITIVE SUCTION HEAD (NPSH)	247
	A. Vapor Lock and Cavitation	247
	B. NPSH	248
	C. Specific Speed	249
	D. Suction Specific Speed	250
V.	COMPRESSORS	252
	A. Isothermal Compression	254
	B. Isentropic Compression	254
	C. Staged Operation	255
	D. Efficiency	256

PROBLEMS	256
NOTATION	265
REFERENCES	266
9. COMPRESSIBLE FLOWS	267
I. GAS PROPERTIES	267
A. Ideal Gas	267
B. The Speed of Sound	268
II. PIPE FLOW	270
A. Isothermal Flow	271
B. Adiabatic Flow	273
C. Choked Flow	273
D. The Expansion Factor	275
E. Ideal Adiabatic Flow	277
III. GENERALIZED EXPRESSIONS	279
A. Governing Equations	279
B. Applications	281
C. Solution of High-Speed Gas Problems	283
PROBLEMS	286
NOTATION	290
REFERENCES	291
10. FLOW MEASUREMENT AND CONTROL	293
I. SCOPE	293
II. THE PITOT TUBE	293
III. THE VENTURI AND NOZZLE	295
IV. THE ORIFICE METER	304
A. Incompressible Flow	305
B. Compressible Flow	306
V. LOSS COEFFICIENT	308
VI. ORIFICE PROBLEMS	310
A. Unknown Pressure Drop	311
B. Unknown Flow Rate	311
C. Unknown Diameter	312
VII. CONTROL VALVES	312
A. Valve Characteristics	313
B. Valve Sizing Relations	314
C. Compressible Fluids	327
D. Viscosity Correction	330
PROBLEMS	333

NOTATION	338
REFERENCES	339
 11. EXTERNAL FLOWS	 341
I. DRAG COEFFICIENT	341
A. Stokes Flow	342
B. Form Drag	343
C. All Reynolds Numbers	343
D. Cylinder Drag	344
E. Boundary Layer Effects	345
II. FALLING PARTICLES	347
A. Unknown Velocity	348
B. Unknown Diameter	349
C. Unknown Viscosity	349
III. CORRECTION FACTORS	350
A. Wall Effects	350
B. Drops and Bubbles	351
IV. NON-NEWTONIAN FLUIDS	352
A. Power Law Fluids	352
B. Wall Effects	357
C. Carreau Fluids	358
D. Bingham Plastics	358
PROBLEMS	361
NOTATION	363
REFERENCES	364
 12. FLUID-SOLID SEPARATIONS BY FREE SETTLING	 365
I. FLUID-SOLID SEPARATIONS	365
II. GRAVITY SETTLING	366
III. CENTRIFUGAL SEPARATION	367
A. Fluid-Solid Separation	367
B. Separation of Immiscible Liquids	371
IV. CYCLONE SEPARATIONS	375
A. General Characteristics	375
B. Aerocyclones	376
C. Hydrocyclones	382
PROBLEMS	385
NOTATION	389
REFERENCES	390

13. FLOW IN POROUS MEDIA	391
I. DESCRIPTION OF POROUS MEDIA	391
A. Hydraulic Diameter	392
B. Porous Medium Friction Factor	393
C. Porous Medium Reynolds Number	394
II. FRICTION LOSS IN POROUS MEDIA	394
A. Laminar Flow	394
B. Turbulent Flow	395
C. All Reynolds Numbers	395
III. PERMEABILITY	395
IV. MULTIDIMENSIONAL FLOW	396
V. PACKED COLUMNS	398
VI. FILTRATION	401
A. Governing Equations	401
B. Constant Pressure Operation	405
C. Constant Flow Operation	406
D. Cycle Time	406
E. Plate-and-Frame Filters	407
F. Rotary Drum Filter	408
G. Compressible Cake	408
PROBLEMS	409
NOTATION	417
REFERENCES	418
 14. FLUIDIZATION AND SEDIMENTATION	 419
I. FLUIDIZATION	419
A. Governing Equations	420
B. Minimum Bed Voidage	421
C. Nonspherical Particles	421
II. SEDIMENTATION	423
A. Hindered Settling	423
B. Fine Particles	425
C. Coarse Particles	428
D. All Flow Regimes	428
III. GENERALIZED SEDIMENTATION/ FLUIDIZATION	430
IV. THICKENING	430
PROBLEMS	436
NOTATION	441
REFERENCES	442