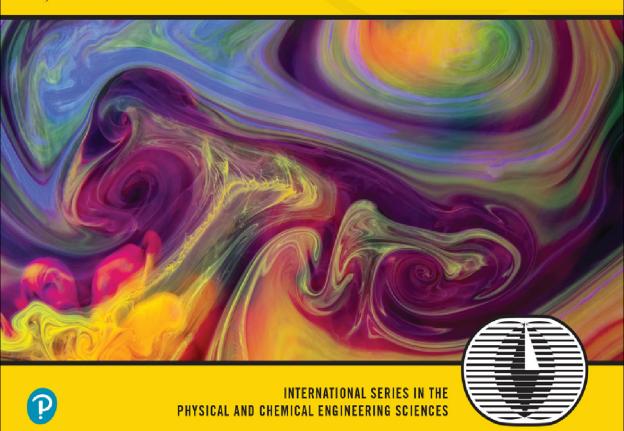
# FLUID MECHANICS FOR CHEMICAL ENGINEERS

WITH MICROFLUIDICS, CFD, AND COMSOL MULTIPHYSICS 5

THIRD EDITION

JAMES O. WILKES



# Fluid Mechanics for Chemical Engineers

 $\begin{array}{c} \text{Third Edition} \\ \text{with Microfluidics, CFD,} \\ \text{and COMSOL Multiphysics 5} \end{array}$ 

# Fluid Mechanics for Chemical Engineers: with Microfluidics, CFD, and COMSOL Multiphysics 5

## **Table of Contents**

Cover
Title Page
Copyright Page
CONTENTS
PREFACE

### PART IMACROSCOPIC FLUID MECHANICS

### CHAPTER 1INTRODUCTION TO FLUID MECHANICS

- 1.1 Fluid Mechanics in Chemical Engineering
  - 1.2 General Concepts of a Fluid
  - 1.3 Stresses, Pressure, Velocity, and the Basic Laws
  - 1.4 Physical Properties Density, Viscosity, and Surface Tension
  - 1.5 Units and Systems of Units

Example 1.1Units Conversion

Example 1.2Mass of Air in a Room

### 1.6 Hydrostatics

Example 1.3Pressure in an Oil Storage Tank

Example 1.4Multiple Fluid Hydrostatics

Example 1.5Pressure Variations in a Gas

Example 1.6Hydrostatic Force on a Curved Surface

Example 1.7Application of Archimedes Law

### 1.7 Pressure Change Caused by Rotation

Example 1.8Overflow from a Spinning Container



#### Problems for Chapter 1

### CHAPTER 2MASS, ENERGY, AND MOMENTUM BALANCES

- 2.1 General Conservation Laws
- 2.2 Mass Balances

Example 2.1Mass Balance for Tank Evacuation

2.3 Energy Balances

Example 2.2Pumping n-Pentane

- 2.4 Bernoullis Equation
- 2.5 Applications of Bernoullis Equation

Example 2.3Tank Filling

2.6 Momentum Balances

Example 2.4Impinging Jet of Water

Example 2.5Velocity of Wave on Water

Example 2.6Flow Measurement by a Rotameter

2.7 Pressure, Velocity, and Flow Rate Measurement

Problems for Chapter 2

### CHAPTER 3FLUID FRICTION IN PIPES

- 3.1 Introduction
- 3.2 Laminar Flow

Example 3.1Polymer Flow in a Pipeline

- 3.3 Models for Shear Stress
- 3.4 Piping and Pumping Problems

Example 3.2Unloading Oil from a Tanker Specified Flow Rate and Diameter

Example 3.3Unloading Oil from a Tanker Specified Diameter and Pressure Drop

Example 3.4Unloading Oil from a Tanker Specified Flow Rate and Pressure Drop

Example 3.5Unloading Oil from a Tanker Miscellaneous Additional Calculations

3.5 Flow in Noncircular Ducts

Example 3.6Flow in an Irrigation Ditch

- 3.6 Compressible Gas Flow in Pipelines
- 3.7 Compressible Flow in Nozzles



#### 3.8 Complex Piping Systems

Example 3.7 Solution of a Piping/Pumping Problem

Problems for Chapter 3

#### CHAPTER 4FLOW IN CHEMICAL ENGINEERING EQUIPMENT

- 4.1 Introduction
- 4.2 Pumps and Compressors

Example 4.1Pumps in Series and Parallel

4.3 Drag Force on Solid Particles in Fluids

Example 4.2Manufacture of Lead Shot

4.4 Flow Through Packed Beds

Example 4.3Pressure Drop in a Packed-Bed Reactor

- 4.5 Filtration
- 4.6 Fluidization
- 4.7 Dynamics of a Bubble-Cap Distillation Column
- 4.8 Cyclone Separators
- 4.9 Sedimentation
- 4.10 Dimensional Analysis

Example 4.4Thickness of the Laminar Sublayer

Problems for Chapter 4

### PART IIMICROSCOPIC FLUID MECHANICS

### CHAPTER 5DIFFERENTIAL EQUATIONS OF FLUID MECHANICS

- 5.1 Introduction to Vector Analysis
- 5.2 Vector Operations

Example 5.1The Gradient of a Scalar

Example 5.2The Divergence of a Vector

Example 5.3An Alternative to the Differential Element

Example 5.4The Curl of a Vector

Example 5.5The Laplacian of a Scalar

- 5.3 Other Coordinate Systems
- 5.4 The Convective Derivative



#### 5.5 Differential Mass Balance

Example 5.6Physical Interpretation of the Net Rate of Mass Outflow Example 5.7Alternative Derivation of the Continuity Equation

- 5.6 Differential Momentum Balances
- 5.7 Newtonian Stress Components in Cartesian Coordinates

Example 5.8Constant-Viscosity Momentum Balances in Terms of Velocity

Gradients

Example 5.9Vector Form of Variable-Viscosity Momentum Balance

Problems for Chapter 5

### CHAPTER 6SOLUTION OF VISCOUS-FLOW PROBLEMS

- 6.1 Introduction
- 6.2 Solution of the Equations of Motion in Rectangular Coordinates

  Example 6.1 Flow Between Parallel Plates
- 6.3 Alternative Solution Using a Shell Balance

Example 6.2Shell Balance for Flow Between Parallel Plates

Example 6.3Film Flow on a Moving Substrate

Example 6.4Transient Viscous Diffusion of Momentum (COMSOL)

6.4 Poiseuille and Couette Flows in Polymer Processing

Example 6.5The Single-Screw Extruder

Example 6.6Flow Patterns in a Screw Extruder (COMSOL)

6.5 Solution of the Equations of Motion in Cylindrical Coordinates

Example 6.7Flow Through an Annular Die

Example 6.8Spinning a Polymeric Fiber

6.6 Solution of the Equations of Motion in Spherical Coordinates

Example 6.9Analysis of a Cone-and-Plate Rheometer

Problems for Chapter 6

# CHAPTER 7LAPLACES EQUATION, IRROTATIONAL AND POROUS-MEDIA FLOWS

- 7.1 Introduction
- 7.2 Rotational and Irrotational Flows

Example 7.1Forced and Free Vortices



- 7.3 Steady Two-Dimensional Irrotational Flow
- 7.4 Physical Interpretation of the Stream Function
- 7.5 Examples of Planar Irrotational Flow
  - Example 7.2Stagnation Flow
  - Example 7.3Combination of a Uniform Stream and a Line Sink (C)
  - Example 7.4Flow Patterns in a Lake (COMSOL)
- 7.6 Axially Symmetric Irrotational Flow
- 7.7 Uniform Streams and Point Sources
- 7.8 Doublets and Flow Past a Sphere
- 7.9 Single-Phase Flow in a Porous Medium

  Example 7.5Underground Flow of Water
- 7.10 Two-Phase Flow in Porous Media
- 7.11 Wave Motion in Deep Water
- Problems for Chapter 7

# CHAPTER 8BOUNDARY-LAYER AND OTHER NEARLY UNIDIRECTIONAL FLOWS

- 8.1 Introduction
- 8.2 Simplified Treatment of Laminar Flow Past a Flat Plate Example 8.1Flow in an Air Intake (C)
- 8.3 Simplification of the Equations of Motion
- 8.4 Blasius Solution for Boundary-Layer Flow
- 8.5 Turbulent Boundary Layers
  - Example 8.2Laminar and Turbulent Boundary Layers Compared
- 8.6 Dimensional Analysis of the Boundary-Layer Problem
- 8.7 Boundary-Layer Separation
  - Example 8.3Boundary-Layer Flow Between Parallel Plates (COMSOL)
  - Example 8.4Entrance Region for Laminar Flow Between Flat Plates
- 8.8 The Lubrication Approximation
  - Example 8.5Flow in a Lubricated Bearing (COMSOL)
- 8.9 Polymer Processing by Calendering



Example 8.6Pressure Distribution in a Calendered Sheet

8.10 Thin Films and Surface Tension

Problems for Chapter 8

#### CHAPTER 9TURBULENT FLOW

9.1 Introduction

Example 9.1Numerical Illustration of a Reynolds Stress Term

- 9.2 Physical Interpretation of the Reynolds Stresses
- 9.3 Mixing-Length Theory
- 9.4 Determination of Eddy Kinematic Viscosity and Mixing Length
- 9.5 Velocity Profiles Based on Mixing-Length Theory Example 9.2Investigation of the von Kármán Hypothesis
- 9.6 The Universal Velocity Profile for Smooth Pipes
- 9.7 Friction Factor in Terms of Reynolds Number for Smooth Pipes Example 9.3Expression for the Mean Velocity
- 9.8 Thickness of the Laminar Sublayer
- 9.9 Velocity Profiles and Friction Factor for Rough Pipe
- 9.10 Blasius-Type Law and the Power-Law Velocity Profile
- 9.11 A Correlation for the Reynolds Stresses
- 9.12 Computation of Turbulence by the Method

Example 9.4Flow Through an Orifice Plate (COMSOL)

Example 9.5Turbulent Flow in an Obstructed U-Duct (COMSOL)

9.13 Analogies Between Momentum and Heat Transfer Example 9.6Evaluation of the Momentum/Heat-Transfer Analogies

9.14 Turbulent Jets

Problems for Chapter 9

# CHAPTER 10BUBBLE MOTION, TWO-PHASE FLOW, AND FLUIDIZATION

- 10.1 Introduction
- 10.2 Rise of Bubbles in Unconfined Liquids

Example 10.1Rise Velocity of Single Bubbles



### 10.3 Pressure Drop and Void Fraction in Horizontal Pipes

Example 10.2Two-Phase Flow in a Horizontal Pipe

### 10.4 Two-Phase Flow in Vertical Pipes

Example 10.3Limits of Bubble Flow

Example 10.4Performance of a Gas-Lift Pump

Example 10.5Two-Phase Flow in a Vertical Pipe

- 10.5 Flooding
- 10.6 Introduction to Fluidization
- 10.7 Bubble Mechanics
- 10.8 Bubbles in Aggregatively Fluidized Beds

Example 10.6Fluidized Bed with Reaction (C)

Problems for Chapter 10

#### CHAPTER 11NON-NEWTONIAN FLUIDS

- 11.1 Introduction
- 11.2 Classification of Non-Newtonian Fluids
- 11.3 Constitutive Equations for Inelastic Viscous Fluids

Example 11.1Pipe Flow of a Power-Law Fluid

Example 11.2Pipe Flow of a Bingham Plastic

Example 11.3Non-Newtonian Flow in a Die (COMSOL)

- 11.4 Constitutive Equations for Viscoelastic Fluids
- 11.5 Response to Oscillatory Shear
- 11.6 Characterization of the Rheological Properties of Fluids

Example 11.4Proof of the Rabinowitsch Equation

Example 11.5Working Equation for a Coaxial- Cylinder Rheometer: Newtonian Fluid

Problems for Chapter 11

# CHAPTER 12MICROFLUIDICS AND ELECTROKINETIC FLOW EFFECTS

- 12.1 Introduction
- 12.2 Physics of Microscale Fluid Mechanics



12.3 Pressure-Driven Flow Through Microscale Tubes

Example 12.1 Calculation of Reynolds Numbers

- 12.4 Mixing, Transport, and Dispersion
- 12.5 Species, Energy, and Charge Transport
- 12.6 The Electrical Double Layer and Electrokinetic Phenomena

Example 12.2Relative Magnitudes of Electroosmotic and Pressure-Driven Flows

Example 12.3 Electroosmotic Flow Around a Particle

Example 12.4Electroosmosis in a Microchannel (COMSOL)

Example 12.5 Electroosmotic Switching in a Branched Microchannel (COMSOL)

12.7 Measuring the Zeta Potential

Example 12.6Magnitude of Typical Streaming Potentials

- 12.8 Electroviscosity
- 12.9 Particle and Macromolecule Motion in Microfluidic Channels

Example 12.7Gravitational and Magnetic Settling of Assay Beads

Problems for Chapter 12

# CHAPTER 13AN INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS AND ANSYS FLUENT

- 13.1 Introduction and Motivation
- 13.2 Numerical Methods
- 13.3 Learning CFD by Using ANSYS Fluent
- 13.4 Practical CFD Examples

Example 13.1Fluent: Developing Flow in a Pipe Entrance Region

Example 13.2Fluent: Pipe Flow Through a Sudden Expansion

Example 13.3Fluent: A Two-Dimensional Mixing Junction

Example 13.4Fluent: Flow over a Cylinder

References for Chapter 13

# CHAPTER 14COMSOL MULTIPHYSICS FOR SOLVING FLUID MECHANICS PROBLEMS

- 14.1 COMSOL MultiphysicsAn Overview
- 14.2 The Steps for Solving Problems in COMSOL



# 14.3 How to Run COMSOL Example 14.1Flow in a Porous Medium with an Impervious Hole (COMSOL) Example 14.2Drawing a Complex Shape (COMSOL) 14.4 Variables, Constants, Expressions, and Units 14.5 Boundary Conditions 14.6 Variables Used by COMSOL 14.7 Wall Functions in Turbulent-Flow Problems 14.8 Streamline Plotting in COMSOL 14.9 Special COMSOL Features Used in the Examples 14.10 Drawing Tools 14.11 Fluid Mechanics Problems Solvable by COMSOL 14.12 ConclusionProblems and Learning Tools APPENDIX A: USEFUL MATHEMATICAL RELATIONSHIPS APPENDIX B: ANSWERS TO THE TRUE/FALSE **ASSERTIONS** APPENDIX C: SOME VECTOR AND TENSOR **OPERATIONS** GENERAL INDEX Α В C D Ε F G



Н

J

K

L

Μ

Ν

Ο

Р

R

S

Т

U

٧

W

Υ

Z

COMSOL MULTIPHYSICS INDEX THE AUTHORS