高等学校教材系列

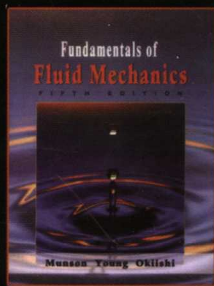
WILEY

工程流体力学

（第五版）（英文改编版）

Fundamentals of Fluid Mechanics

Fifth Edition



［美］Bruce R. Munson
Donald F. Young
Theodore H. Okiishi 著

邵卫云 改编

電子工業出版社
Publishing House of Electronics Industry
http://www.phei.com.cn

高等学校教材系列

工程流体力学

（第五版）（英文改编版）

Fundamentals of Fluid Mechanics

Fifth Edition

Bruce R. Munson
［美］ Donald F. Young 著
Theodore H. Okiishi

邵卫云 改编

電子工業出版社
Publishing House of Electronics Industry
北京 · BEIJING

内容简介

本书是根据美国著名出版商John Wiley & Sons出版的精品教材改编而成的工程流体力学英文教材。为了保持原版教材的特色，同时满足中国高校教学的要求，本书主要依据最新的高等学校土建类专业的《流体力学课程教学基本要求》进行改编，尤其注重理论基础及实际问题的解决，其主要内容有：绪论、流体静力学、流体运动基本原理、控制体法流动分析（恒定总流）、微分法流动分析、量纲分析与流动相似、内流和外流、有压管流、孔口和管嘴出流、明渠流、堰流、渗流和可压缩气体一元流动。

本书可作为高等院校土建、市政、给排水、水利等专业的流体力学（水力学）的双语教学用书，亦可作为专业技术人员和全国注册土木工程师考试的参考书。

Bruce R .Munson, Donald F. Young and Theodore H. Okiishi: **Fundamentals of Fluid Mechanics, Fifth Edition.**

ISBN 0-471-67582-2

版权贸易合同登记号　图字：01-2006-5885

图书在版编目（CIP）数据

工程流体力学：第5版 = Fundamentals of Fluid Mechanics, Fifth Edition：改编版/（美）芒森（Munson, B. R.）等著；邵卫云改编. - 北京：电子工业出版社，2006.11

（高等学校教材系列）

ISBN 7-121-03327-5

Ⅰ.工…　Ⅱ.①芒…　②邵…　Ⅲ.工程力学：流体力学 - 双语教学 - 教材 - 英文　Ⅳ. TB126

中国版本图书馆CIP数据核字（2006）第125391号

责任编辑：余　义

印　　刷：
装　　订：北京牛山世兴印刷厂

出版发行：电子工业出版社

北京市海淀区万寿路173信箱　邮编：100036

开　　本：787 × 980　1/16　　印张：37　　字数：947千字

印　　次：2006年11月第1次印刷

定　　价：59.50元

导 读

流体力学是一门古老的学科，它的发展历程是生产发展对其促进的过程。其中，实验流体力学与理论流体力学交错前进或齐头并进，结果是当代流体力学中不仅有着众多复杂的基于物理起因和数学理论的方程，而且还包含众多的经验公式、经验值（图表）等，并且许多术语、基本原理与方程直接由创立它们的学者姓名命名，如 Bernoulli's equation，Navier-Stokes（N-S）equation，Eulerian description of motion，Poiseuille flow, Reynolds number 等。因此，采用双语传授流体力学，不仅仅是通过有关知识内容的传授，促使学生及早地接受国外前沿科研成果，提高他们参与国际竞争的能力和后期的学术与就业竞争力，更是促使学生对流体力学发展历史的了解，从而更深入地了解知识点的内涵，以及由此引申出的相关技术。

工程流体力学是土建类、水利类的一门专业技术基础课。2003 年，在浙江大学的支持和力学基地的支撑下，我开始试点开设流体力学课程双语教学。通过三年多的实践，我发现仅仅依靠双语版的电子教案和讲义还很不够，双语教学的正常开展还必须依托原版教材，才能让学生接触到正宗的英文表述、流体力学的发展历史及相关背景、知识和发展方向，等等。因此，2005 年，在浙江大学国家工科基础力学教学基地的依托下，在流体力学国家级精品课程的基础上，由我主持申请了国家级教改项目——“流体力学双语教学课程建设”，其重点在于双语教学教材的建设。

Fundamentals of Fluid Mechanics, Fifth Edition 是一本非常适合于教学的教材，已经在美国 Iowa 大学、Colorado 大学、加拿大 Alberta 大学等著名大学使用。改编教材在保留原版教材主要特点的基础上，具有如下特点：(1) 流体力学的理论叙述非常详尽，实践性强，利用大量例题作为理论内容的延伸和讨论，并且通过“Fluids in the News”来说明时刻充实在自然界以及我们日常生活中的流体力学现象。(2) 习题类型丰富多变，且与每章小结相对应。本教材每章的习题不仅包括标准习题（这在国内教材中占绝大多数），而且还包括大量计算性（基于 spreadsheet 或计算机）、讨论性习题，基于“Fluids in the News”及各种视频材料的习题。在一章学习结束并完成有关习题后，每章的小结对学生提出了应该掌握的概念和要点，以及通过本章学习应该能够解决的问题。(3) 教材将全书的制式基本上统一为 SI 单位制，满足了国内教学的需求。(4) 教材的编排别具特色。简图、主要概念及要点、例题与正文紧密结合、互动，“Fluids in the News”与视频紧随各相关知识点。(5) 教辅材料翔实丰富。在 John Wiley & Sons 公司的网站上，有大量的视频材料、学生学习用的辅导材料和教师教学用的辅助材料，既丰富了教学资源，又缩减了教材的容量。

但是，由于国内外文化传统、教学体系的差异，原版教材与我国教学体系和教学习惯有着较大的差异，部分内容已超出国内的教学要求。由此，为了保持原版教材的特色，同时满足中国高校教学的要求，本教材的改编主要依据最新的高等学校土建类专业的《流体力学课程教学基本要求》，同时亦适用于水利类专业课《工程水力学》的先学课程。

在本教材的改编过程中，对原版教材的结构体系做了一定的调整，主要体现为：原第3章和第4章部分内容合并成为流体运动基本原理；第4章部分内容和第5章内容合并为控制体法流动分析；第8章和第9章合并成为内流和外流，并缩减了第9章中大部分有关边界层和升力、阻力的理论计算内容；第11章保留一元气流的基本理论，删除了其余内容；直接删除了第12章涡轮机械。另外，根据国内教学大纲的要求，主要增补了以下内容：压力体，孔口出流和管嘴出流，明渠均匀流的特性、渐变流的水面曲线及其定性分析，实用堰、堰流的基本理论与流量系数经验公式，渗流的基本理论。根据结构体系的调整，相应地增减了部分习题、例题，删除了部分“Fluids in the News”。改编后教材的内容体系依次为：绪论，流体静力学，流体运动基本原理，控制体法流动分析（恒定总流），微分法流动分析，量纲分析与流动相似，内流和外流，有压管流、孔口和管嘴出流，明渠流，堰流，渗流和可压缩气体一元流动。至于原版教材的习题解答、PPT、图形库以及视频等资源，教师可填写改编教材后的“教学支持说明”，然后通过电子工业出版社向John Wiley & Sons公司申请，便可在网上免费下载。

本改编教材沿袭了原版教材的编排特点和主要的内容结构体系，增补内容主要依据2006年年底将由高等教育出版社出版的国家“十一五”规划教材《应用流体力学》（毛根海、邵卫云、张燕编）。但是，由于删/缩减了原版教材的部分内容并对部分内容结构体系进行了调整，因此，在遵循原版教材使用方式的使用过程中，尚需注意以下几点：(1) 有些内容由于删/缩减可能不能构成完整的独立体系，如外流等，请参考原版教材；(2) 在大多数中文教材中，连续性方程、动量方程和能量方程一般分别由质量守恒定律、动量定律和元流伯努利方程推导而来，但在本教材中，它们分别由质量守恒定律、牛顿第二定律、热力学第一定律结合雷诺传输定理推导而出；(3) 本教材中没有包括有压管道中的非恒定流（水击）理论、明渠渐变流水面曲线的数值计算理论，若需要，请参考各有关文献；(4) 在堰流一章中，虽然在改编时我对堰流流量公式进行了统一，但仍保留了原版教材中不同的堰流经验公式，其中各系数均为经验系数，与国内使用的有一定差异，要注意；(5) 本教材中的公式大多保留了其一般形式，即微分形式，在工程应用时则应根据具体情况选用特定的简化公式计算；(6) 本教材中的BG单位制，除了第1章为了对不同的单位制进行说明保留了部分BG制外，其余基本上已经统一转换为SI单位制，在使用时请注意。

本教材在改编的过程中，得到了毛根海教授的大力支持，朱嵩博士帮助整理了渗流的内容，胡卫红女士提供了增补内容中的原图，在此表示衷心的感谢。同时，电子工业出版社的谭海平先生和余义先生，在对原版教材的调研、编辑加工等方面做了大量的工作，为改编工作提供了很好的支持，在此一并感谢。最后，要感谢我的先生和女儿，在改编的过程中，给了我很多的支持和鼓励。

最后，我希望本改编教材能够为国内流体力学的双语教学尽到一份微薄之力，也恳请各位专家、同行和读者能够提出宝贵的建议，促使本教材在重印或再版时能够更加完美。

邵卫云

于浙江大学求是园

2006年8月30日

About the Authors

Bruce R. Munson, Professor Emeritus of Engineering Mechanics at Iowa State University, received his B.S. and M.S. degrees from Purdue University and his Ph.D. degree from the Aerospace Engineering and Mechanics Department of the University of Minnesota in 1970.

Prior to joining the Iowa State University faculty in 1974, Dr. Munson was on the mechanical engineering faculty of Duke University from 1970 to 1974. From 1964 to 1966, he worked as an engineer in the jet engine fuel control department of Bendix Aerospace Corporation, South Bend, Indiana.

Dr. Munson's main professional activity has been in the area of fluid mechanics education and research. He has been responsible for the development of many fluid mechanics courses for studies in civil engineering, mechanical engineering, engineering science, and agricultural engineering and is the recipient of an Iowa State University Superior Engineering Teacher Award and the Iowa State University Alumni Association Faculty Citation.

He has authored and coauthored many theoretical and experimental technical papers on hydrodynamic stability, low Reynolds number flow, secondary flow, and the applications of viscous incompressible flow. He is a member of The American Society of Mechanical Engineers and The American Physical Society.

Donald F. Young, Anson Marston Distinguished Professor Emeritus in Engineering, received his B.S. degree in mechanical engineering, his M.S. and Ph.D. degrees in theoretical and applied mechanics from Iowa State Uiversity, and has taught both undergraduate and graduate courses in fluid mechanics at Iowa State for many years. In addition to being named a Distinguished Professor in the College of Engineering, Dr. Young has also received the Standard Oil Foundation Outstanding Teacher Award and the Iowa State University Alumni Association Faculty Citation. He has been engaged in fluid mechanics research for more than 35 years, with special interests in similitude and modeling and the interdisciplinary field of biomedical fluid mechanics. Dr. Young has contributed to many technical publications and is the author or coauthor of two textbooks on applied mechanics. He is a Fellow of The American Society of Mechanical Engineers.

Ted H. Okiishi, Associate Dean of Engineering and past Chair of Mechanical Engineering at Iowa State University, has taught fluid mechanics courses there since 1967. He received his undergraduate and graduate degrees at Iowa State.

From 1965 to 1967, Dr. Okiishi served as a U.S. Army officer with duty assignments at the National Aeronautics and Space Administration Lewis Research Center, Cleveland, Ohio, where he participated in rocket nozzle heat transfer research, and at the Combined Intelligence Center, Saigon, Republic of South Vietnam, where he studied seasonal river flooding problems.

Professor Okiishi is active in research on turbomachinery fluid dynamics. He and his graduate students and other colleagues have written a number of journal articles based on their studies. Some of these projects have involved significant collaboration with government and industrial laboratory researchers with two technical papers winning the ASME Melville Medal.

Dr. Okiishi has received several awards for teaching. He has developed undergraduate and graduate courses in classical fluid dynamics as well as the fluid dynamics of turbomachines.

He is a licensed professional engineer. His professional society activities include having been chair of the board of directors of The American Society of Mechanical Engineers (ASME) International Gas Turbine Institute and chair of the Engineering Research Council of the American Society for Engineering Education. He is a Fellow of The American Society of Mechanical Engineers and the past editor of the *Journal of Turbomachinery.*

Contents

Chapter 1 Introduction 1
1.1 Introduction 2
1.2 Dimensions, Dimensional Homogeneity, and Units 3
1.2.1 Systems of Units 5
1.3 Analysis of Fluid Behavior 8
1.4 Measures of Fluid Mass and Weight 8
1.4.1 Density 8
1.4.2 Specific Weight 9
1.4.3 Specific Gravity 9
1.5 Ideal Gas Law 10
1.6 Viscosity 12
1.7 Compressibility of Fluids 17
1.7.1 Bulk Modulus 17
1.7.2 Coefficient of Volume Compressibility 19
1.8 Vapor Pressure 19
1.9 Surface Tension 20
1.10 Forces Descriptions 23
1.11 A Brief Look Back in History 23
1.12 Chapter Summary and Study Guide 26
References 26
Review Problems 27
Problems 27

Chapter 2 Fluid Statics 36
2.1 Pressure at a Point 36
2.2 Basic Equation for Pressure Field 38
2.2.1 Basic Equation for Pressure Field 38
2.2.2 Equipressure Surface 40
2.3 Pressure Variation in a Fluid at Rest 40
2.3.1 Fundamental Equation of a Fluid at Rest 40
2.3.2 Incompressible Fluid 41
2.4 Standard Atmosphere 44
2.5 Measurement of Pressure 46
2.6 Manometry 47
2.6.1 Piezometer Tube 48
2.6.2 U-Tube Manometer 48
2.6.3 Inclined-Tube Manometer 52
2.6.4 Mechanical and Electronic Pressure Measuring Devices 53
2.7 Hydrostatic Force on a Plane Surface 54
2.7.1 Force on a Plane Surface 54
2.7.2 Pressure Prism 61
2.8 Hydrostatic Force on a Curved Surface 64

2.9 Buoyancy, Flotation, and Stability 68
2.9.1 Archimedes' Principle 68
2.9.2 Stability 70
2.10 Pressure Variation in a Fluid with Rigid-Body Motion 72
2.10.1 Linear Motion 73
2.10.2 Rigid-Body Rotation 75
2.11 Chapter Summary and Study Guide 78
References 78
Review Problems 79
Problems 79

Chapter 3 Introduction to Fluids in Motion 94
3.1 The Velocity Field 94
3.1.1 Eulerian and Lagrangian Flow Descriptions 95
3.1.2 One-, Two-, and Three-Dimensional Flows 97
3.1.3 Steady and Unsteady Flows 98
3.1.4 Streamlines, Streaklines, and Pathlines 98
3.2 The Acceleration Field 103
3.2.1 The Material Derivative 103
3.2.2 Unsteady Effects 105
3.2.3 Convective Effects 105
3.3 The Bernoulli Equation along a Streamline 107
3.3.1 The Bernoulli Equation along a Streamline 108
3.3.2 Physical Interpretation 112
3.3.3 Static, Stagnation, Dynamic, and Total Pressure 114
3.4 Examples of Use of the Bernoulli Equation 119
3.4.1 Free Jets 119
3.4.2 Confined Flows 121
3.4.3 Flowrate Measurement 127
3.5 The Energy Line and the Hydraulic Grade Line 132
3.6 Chapter Summary and Study Guide 135
References 136
Review Problems 136
Problems 136

Chapter 4 Finite Control Volume Analysis 155
4.1 Control Volume and System Representations 156
4.2 The Reynolds Transport Theorem 157
4.2.1 Derivation of the Reynolds Transport Theorem 158
4.2.2 Selection of a Control Volume 162
4.3 The Continuity Equation 162
4.3.1 Derivation of the Continuity Equation 162
4.3.2 Fixed, Nondeforming Control Volume 169
4.3.3 Moving, Nondeforming Control Volume 170
4.4 The Linear Momentum Equation 172
4.4.1 Derivation of the Linear Momentum Equation 172
4.4.2 Application of the Linear Momentum Equation 175
4.5 The Energy Equation 191

4.5.1 Derivation of the Energy Equation 191
4.5.2 The Energy Equation for Steady Uniform Flow 193
4.6 Chapter Summary and Study Guide 206
References 207
Review Problems 207
Problems 207

Chapter 5 Differential Analysis of Fluid Flow 227
5.1 Fluid Element Kinematics 228
5.1.1 Linear Motion and Deformation 229
5.1.2 Angular Motion and Deformation 230
5.1.3 Irrotational Flow 232
5.2 Differential Form of Continuity Equation 234
5.2.1 Differential Form of Continuity Equation 234
5.2.2 The Stream Function 237
5.3 Equations of Motion 240
5.3.1 Description of Forces Acting on the Differential Element 240
5.3.2 Equations of Motion 242
5.3.3 The Navier-Stokes Equations 242
5.4 Inviscid Flow 244
5.4.1 Euler's Equations of Motion 244
5.4.2 The Bernoulli Equation along a Streamline 245
5.4.3 The Bernoulli Equation for Irrotational Flow 246
5.4.4 The Velocity Potential 247
5.5 Plane Potential Flows 250
5.5.1 Some Basic, Plane Potential Flows 252
5.5.2 Source in a Uniform Stream — Half-Body 257
5.5.3 Rankine Ovals 261
5.5.4 Flow around a Circular Cylinder 263
5.6 Chapter Summary and Study Guide 266
References 267
Review Problems 267
Problems 267

Chapter 6 Similitude, Dimensional Analysis, and Modeling 276
6.1 Introduction 277
6.2 Dimensional Analysis 279
6.2.1 Buckingham Pi Theorem 279
6.2.2 Determination of Pi Terms 280
6.3 Common Dimensionless Groups in Fluid Mechanics 286
6.4 Correlation of Experimental Data 289
6.4.1 Problems with One Pi Term 289
6.4.2 Problems with Two or More Pi Terms 291
6.5 Modeling and Similitude 294
6.5.1 Theory of Models 294
6.5.2 Model Scales 298
6.5.3 Flow through Closed Conduits 299
6.5.4 Flow around Immersed Bodies 301

6.5.5 Flow with a Free Surface 303
6.6 Normalized Governing Differential Equations 307
6.7 Chapter Summary and Study Guide 309
References 310
Review Problems 310
Problems 310

Chapter 7 Internal Flow and External Flow 321
7.1 General Characteristics of Pipe Flow 322
7.1.1 Laminar or Turbulent Flow 323
7.1.2 Entrance Region and Fully Developed Flow 325
7.1.3 Pressure and Shear Stress 326
7.2 Fully Developed Laminar Flow 327
7.2.1 Fluid Element Approach 327
7.2.2 Energy Considerations 333
7.3 Fully Developed Turbulent Flow 336
7.3.1 Transition from Laminar to Turbulent Flow 336
7.3.2 Turbulent Shear Stress 338
7.3.3 Turbulent Velocity Profile 341
7.4 Head Losses in Pipe Flow 346
7.4.1 Major Losses 346
7.4.2 Minor Losses 352
7.5 Fundamentals of Boundary layer 360
7.5.1 Introduction of External Flows 360
7.5.2 Characteristics of Flow Past an Object 361
7.5.3 Boundary Layer Structure and Thickness on a Flat Plate 365
7.5.4 Effects of Pressure Gradient 368
7.6 Lift and Drag Concepts 372
7.7 Chapter Summary and Study Guide 376
References 377
Review Problems 379
Problems 379

Chapter 8 Pipe Flow, Orifice Flow and Nozzle Flow 388
8.1 Single Pipes 389
8.2 Multiple Pipe Systems 403
8.2.1 Series Pipe System 404
8.2.2 Parallel Pipe System 405
8.2.3 Loop Pipe System 406
8.2.4 Branching System 406
8.2.5 Pipe Network 410
8.3 Pipe Flowrate Measurement 411
8.4 Orifice Flow 416
8.4.1 General Characteristics of Orifice Flow 416
8.4.2 Outflow through Sharp-edged Small Orifice 417
8.4.3 Outflow through Sharp-edged Big Orifice 419
8.5 Nozzle Flow 420

8.5.1 Introduction 420
8.5.2 Steady Flow through Cylindrical Outer Nozzle 420
8.5.3 Vacuum in Cylindrical Outer Nozzle 421
8.6 Chapter Summary and Study Guide 422
References 422
Review Problems 423
Problems 423

Chapter 9 Open-Channel Flow 432
9.1 Introduction 433
9.1.1 General Characteristics of Open-Channel Flow 433
9.1.2 Channel Geometry 434
9.2 Uniform Flow 435
9.2.1 Uniform Flow Approximations 435
9.2.2 The Chezy and Manning Equations 437
9.2.3 Uniform Flow Examples 439
9.2.4 Best Hydraulic Cross Section 446
9.3 Surface Waves 449
9.3.1 Wave Speed 449
9.3.2 Froude Number Effects 451
9.4 Fundamental of Nonuniform Flow 452
9.4.1 Specific Energy 453
9.4.2 Channel Depth Variations 458
9.5 Gradually Varied Flow 459
9.5.1 Water Surface Profiles 460
9.5.2 Some Representations of Surface profiles 463
9.5.3 Numerical Solution of Water Surface Profiles 465
9.6 Rapidly Varied Flow 465
9.6.1 The Hydraulic Jump 466
9.7 Chapter Summary and Study Guide 473
References 473
Review Problems 474
Problems 474

Chapter 10 Weir Flow 485
10.1 General Characteristics of Weir Flow 485
10.1.1 General Characteristics of Weirs 485
10.1.2 Classification of Weirs 486
10.2 Sharp-Crested Weirs 487
10.2.1 Basic Flowrate Formula 487
10.2.2 Rectangular Weir 488
10.2.3 Triangular Weir 489
10.3 Ogee-crested weirs 491
10.4 Broad-Crested Weirs 492
10.5 Underflow Gates 496
10.6 Chapter Summary and Study Guide 498
References 498
Review Problems 499

Problems 499

Chapter 11 Seepage Flow 501
11.1 Basic Principle of Seepage Flow 501
11.1.1 Seepage Flow Model 502
11.1.2 Darcy Law 502
11.1.3 Coefficient of Permeability 504
11.2 Steady Gradually Varied Seepage Flow 504
11.2.1 General Formula for Gradually Varied Seepage Flow 504
11.2.2 Differential Equation of Gradually Varied Seepage Flow 505
11.2.3 Water Surface Profiles of the Gradually Varied Seepage Flow 505
11.3 Seepage Flow of Storage Gallery 508
11.4 Seepage Flow of Well 508
11.4.1 Completely General Well 508
11.4.2 Completely Artesian Well 510
11.4.3 Multiple-well 511
11.5 Chapter Summary and Study Guide 514
References 514
Problems 514

Chapter 12 One Dimensional Compressible Flow 517
12.1 Ideal Gas Relationships 518
12.2 Mach Number and Speed of Sound 521
12.3 Categories of Compressible Flow 524
12.4 Isentropic Flow of an Ideal Gas 529
12.4.1 Effect of Variations in Flow Cross-Sectional Area 530
12.4.2 Converging-Diverging Duct Flow 532
12.4.3 Constant Area Duct Flow 535
12.5 Adiabatic Constant Area Duct Flow with Friction 536
12.6 Chapter Summary and Study Guide 545
References 546
Review Problems 547
Problems 547

Appendix A 550

Appendix B 554

Appendix C 559

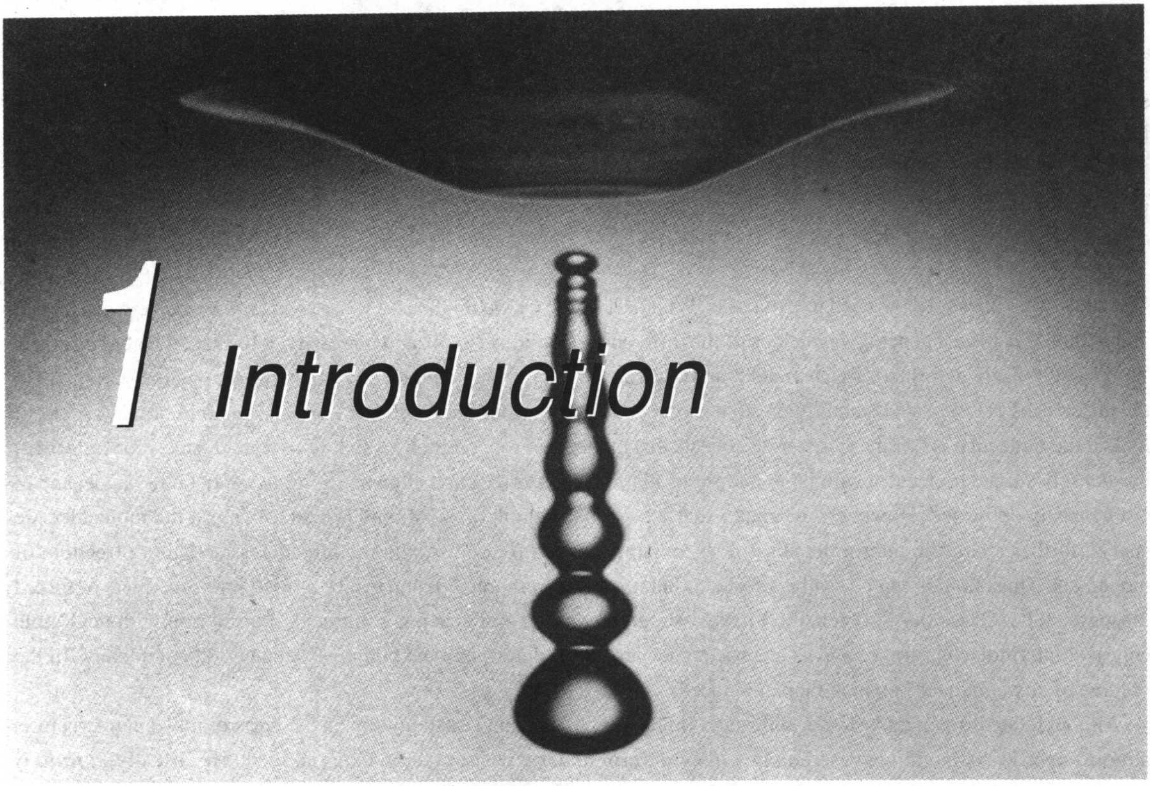
Appendix D 561

Online Appendix List 564

Answers to Selected Homework Problems 565

Index 570

1 Introduction



CHAPTER OPENING PHOTO: The breakup of a fluid jet into drops is a function of fluid properties such as density, viscosity, and surface tension. [Reprinted with permission from American Institute of Physics (Ref. 6) and the American Association for the Advancement of Science (Ref. 7).]

Fluid mechanics is that discipline within the broad field of applied mechanics concerned with the behavior of liquids and gases at rest or in motion. This field of mechanics obviously encompasses a vast array of problems that may vary from the study of blood flow in the capillaries (which are only a few microns in diameter) to the flow of crude oil across Alaska through an 1287-km-long, 1.22-m-diameter pipe. Fluid mechanics principles are needed to explain why airplanes are made streamlined with smooth surfaces for the most efficient flight, whereas golf balls are made with rough surfaces (dimpled) to increase their efficiency. Numerous interesting questions can be answered by using relatively simple fluid mechanics ideas. For example:

- How can a rocket generate thrust without having any air to push against in outer space?
- Why can't you hear a supersonic airplane until it has gone past you?
- How can a river flow downstream with a significant velocity even though the slope of the surface is so small that it could not be detected with an ordinary level?
- How can information obtained from model airplanes be used to design the real thing?
- Why does a stream of water from a faucet sometimes appear to have a smooth surface, but sometimes a rough surface?
- How much greater gas mileage can be obtained by improved aerodynamic design of cars and trucks?

The list of applications and questions goes on and on—but you get the point; fluid mechanics is a very important, practical subject. It is very likely that during your career as an engineer you will be involved in the analysis and design of systems that require a good understanding of fluid mechanics. It is hoped that this introductory text will provide a sound foundation of the fundamental aspects of fluid mechanics.

Fluid mechanics is concerned with the behavior of liquids and gases at rest and in motion.

1.1 Introduction

One of the first questions we need to explore is, What is a fluid? Or we might ask, What is the difference between a solid and a fluid? We have a general, vague idea of the difference. A solid is "hard" and not easily deformed, whereas a fluid is "soft" and is easily deformed (we can readily move through air). Although quite descriptive, these casual observations of the differences between solids and fluids are not very satisfactory from a scientific or engineering point of view. A closer look at the molecular structure of materials reveals that matter that we commonly think of as a solid (steel, concrete, etc.) has densely spaced molecules with large intermolecular cohesive forces that allow the solid to maintain its shape, and to not be easily deformed. However, for matter that we normally think of as a liquid (water, oil, etc.), the molecules are spaced farther apart, the intermolecular forces are smaller than for solids, and the molecules have more freedom of movement. Thus, liquids can be easily deformed (but not easily compressed) and can be poured into containers or forced through a tube. Gases (air, oxygen, etc.) have even greater molecular spacing and freedom of motion with negligible cohesive intermolecular forces and as a consequence are easily deformed (and compressed) and will completely fill the volume of any container in which they are placed.

Although the differences between solids and fluids can be explained qualitatively on the basis of molecular structure, a more specific distinction is based on how they deform under the action of an external load. Specifically, *a **fluid** is defined as a substance that deforms continuously when acted on by a shearing stress of any magnitude*. A shearing stress (force per unit area) is created whenever a tangential force acts on a surface. When common solids such as steel or other metals are acted on by a shearing stress, they will initially deform (usually a very small deformation), but they will not continuously deform (flow). However, common fluids such as water, oil, and air satisfy the definition of a fluid—that is, they will flow when acted on by a shearing stress. Some materials, such as slurries, tar, putty, toothpaste, and so on, are not easily classified since they will behave as a solid if the applied shearing stress is small, but if the stress exceeds some critical value, the substance will flow. The study of such materials is called *rheology* and does not fall within the province of classical fluid mechanics. Thus, all the fluids we will be concerned with in this text will conform to the definition of a fluid given previously.

A fluid, such as water or air, deforms continuously when acted on by shearing stresses of any magnitude.

Although the molecular structure of fluids is important in distinguishing one fluid from another, it is not possible to study the behavior of individual molecules when trying to describe the behavior of fluids at rest or in motion. Rather, we characterize the behavior by considering the average, or macroscopic, value of the quantity of interest, where the average is evaluated over a small volume containing a large number of molecules. Thus, when we say that the velocity at a certain point in a fluid is so much, we are really indicating the average velocity of the molecules in a small volume surrounding the point. The volume is small compared with the physical dimensions of the system of interest, but large compared with the average distance between molecules. Is this a reasonable way to describe the behavior of a fluid? The answer is generally yes, since the spacing between molecules is typically very small. For gases at normal pressures and temperatures, the spacing is on the order of 10^{-6} mm, and for liquids it is on the order of 10^{-7} mm. The number of molecules per cubic millimeter is on the order of 10^{18} for gases and 10^{21} for liquids. It is thus clear that the number of molecules in a very tiny volume is huge and the idea of using average values taken over this volume is certainly reasonable. We thus assume that all the fluid characteristics we are interested in (pressure, velocity, etc.) vary continuously throughout the fluid—that is, we treat the fluid as a ***continuum***. This concept will certainly be valid for all the circumstances considered in this text. One area of fluid mechanics for which the continuum concept breaks down is in the study of rarefied gases such as would be encountered at very high altitudes. In this case the spacing between air molecules can become large and the continuum concept is no longer acceptable.

Continuum assumption is an assumption that the fluid characteristics vary continuously throughout the region of interest.

1.2 Dimensions, Dimensional Homogeneity, and Units

Since in our study of fluid mechanics we will be dealing with a variety of fluid characteristics, it is necessary to develop a system for describing these characteristics both *qualitatively* and *quantitatively*. The qualitative aspect serves to identify the nature, or type, of the characteristics (such as length, time, stress, and velocity), whereas the quantitative aspect provides a numerical measure of the characteristics. The quantitative description requires both a number and a standard by which various quantities can be compared. A standard for length might be a meter or foot, for time an hour or second, and for mass a slug or kilogram. Such standards are called ***units,*** and several systems of units are in common use as described in the following section. The qualitative description is conveniently given in terms of certain *primary quantities,* such as length, L, time, T, mass, M, and temperature, Θ. These primary quantities can then be used to provide a qualitative description of any other *secondary quantity*: for example, area $\doteq L^2$, velocity $\doteq LT^{-1}$, density $\doteq ML^{-3}$, and so on, where the symbol $\doteq$ is used to indicate the *dimensions* of the secondary quantity in terms of the primary quantities. Thus, to describe qualitatively a velocity, V, we would write

$$V \doteq LT^{-1}$$

and say that "the dimensions of a velocity equal length divided by time." The primary quantities are also referred to as ***basic dimensions***. Those dimensions derived from basic dimensions are *derived dimensions*.

Fluid characteristics can be described qualitatively in terms of certain basic quantities such as length, time, and mass.

For a wide variety of problems involving fluid mechanics, only the three basic dimensions, L, T, and M are required. Alternatively, L, T, and F could be used, where F is the basic dimensions of force. Since Newton's law states that force is equal to mass times acceleration, it follows that $F \doteq MLT^{-2}$ or $M \doteq FL^{-1}T^{2}$. Thus, secondary quantities expressed in terms of M can be expressed in terms of F through the relationship above. For example, stress, σ, is a force per unit area, so that $\sigma \doteq FL^{-2}$, but an equivalent dimensional equation is $\sigma \doteq ML^{-1}T^{-2}$. Table 1.1 provides a list of dimensions for a number of common physical quantities.

All theoretically derived equations are ***dimensionally homogeneous***—that is, the dimensions of the left side of the equation must be the same as those on the right side, and all additive separate terms must have the same dimensions. We accept as a fundamental premise that all equations describing physical phenomena must be dimensionally homogeneous. If this were not true, we would be attempting to equate or add unlike physical quantities, which would not make sense. For example, the equation for the velocity, V, of a uniformly accelerated body is

TABLE 1.1 Dimensions Associated with Common Physical Quantities

	FLT System	*MLT* System
Acceleration	LT^{-2}	LT^{-2}
Angle	$F^0L^0T^0$	$M^0L^0T^0$
Angular acceleration	T^{-2}	T^{-2}
Angular velocity	T^{-1}	T^{-1}
Area	L^2	L^2
Density	$FL^{-4}T^2$	ML^{-3}
Energy	FL	ML^2T^{-2}
Force	F	MLT^{-2}
Frequency	T^{-1}	T^{-1}
Heat	FL	ML^2T^{-2}
Length*	L	L
Mass*	$FL^{-1}T^2$	M
Modulus of elasticity	FL^{-2}	$ML^{-1}T^{-2}$
Moment of a force	FL	ML^2T^{-2}
Moment of inertia (area)	L^4	L^4
Moment of inertia (mass)	FLT^2	ML^2
Momentum	FT	MLT^{-1}
Power	FLT^{-1}	ML^2T^{-3}
Pressure	FL^{-2}	$ML^{-1}T^{-2}$
Specific heat	$L^2T^{-2}\Theta^{-1}$	$L^2T^{-2}\Theta^{-1}$
Specific weight	FL^{-3}	$ML^{-2}T^{-2}$
Strain	$F^0L^0T^0$	$M^0L^0T^0$
Stress	FL^{-2}	$ML^{-1}T^{-2}$
Surface tension	FL^{-1}	MT^{-2}
Temperature	Θ	Θ
Time*	T	T
Torque	FL	ML^2T^{-2}
Velocity	LT^{-1}	LT^{-1}
Viscosity (dynamic)	$FL^{-2}T$	$ML^{-1}T^{-1}$
Viscosity (kinematic)	L^2T^{-1}	L^2T^{-1}
Volume	L^3	L^3
Work	FL	ML^2T^{-2}

* Those primary quantities are referred to as basic dimensions (or fundamental dimensions)

$$V = V_0 + at \tag{1.1}$$

where V_0 is the initial velocity, a the acceleration, and t the time interval. In terms of dimensions the equation is

$$LT^{-1} \doteq LT^{-1} + LT^{-1}$$

and thus Eq. 1.1 is dimensionally homogeneous.

Some equations that are known to be valid contain constants having dimensions. The equation for the distance, d, traveled by a freely falling body can be written as

$$d = 4.905t^2 \tag{1.2}$$

and a check of the dimensions reveals that the constant must have the dimensions of LT^{-2} if the equation is to be dimensionally homogeneous. Actually, Eq. 1.2 is a special form of the well-known equation from physics for freely falling bodies,

$$d = \frac{gt^2}{2} \tag{1.3}$$

in which g is the acceleration of gravity. Equation 1.3 is dimensionally homogeneous and valid in any system of units. For $g = 9.81$ m/s^2 the equation reduces to Eq. 1.2 and thus Eq. 1.2 is valid only for the system of units using meters and seconds. Equations that are restricted to a particular system of units can be denoted as *restricted homogeneous equations*, as opposed to equations valid in any system of units, which are *general homogeneous equations*. The preceding discussion indicates one rather elementary, but important, use of the concept of dimensions: the determination of one aspect of the generality of a given equation simply based on a consideration of the dimensions of the various terms in the equation. The concept of dimensions also forms the basis for the powerful tool of ***dimensional analysis***, which is considered in detail in Chapter 6.

General homogeneous equations are valid in any system of units.

1.2.1 Systems of Units

In addition to the qualitative description of the various quantities of interest, it is generally necessary to have a quantitative measure of any given quantity. There are several systems of units in use and we shall consider three systems that are commonly used in engineering.

British Gravitational (BG) System. In the BG system the unit of length is the foot (ft), the time unit is the second (s), the force unit is the pound (lb), and the temperature unit is the degree Fahrenheit (°F) or the absolute temperature unit is the degree Rankine (°R), where

$$°R = °F + 459.67$$

The mass unit is the slug.

Two systems of units that are widely used in engineering are the British Gravitational (BG) System and the International System (SI).

Fluids in the News

How long is a foot? Today, in the United States, the common length unit is the foot, but throughout antiquity the unit used to measure length has quite a history. The first length units were based on the lengths of various body parts. One of the earliest units was the Egyptian cubit, first used around 3000 B.C. and defined as the length of the arm from elbow to extended fingertips. Other measures followed with the foot simply taken as the length of a man's foot. Since this length obviously varies from person to person it was often "standardized" by using the length of the current reigning royalty's foot. In 1791 a special French commission proposed that a new universal length unit called a meter (metre) be defined as the distance of onequarter of the earth's meridian (north pole to the equator) divided by 10 million. Although controversial, the meter was accepted in 1799 as the standard. With the development of advanced technology, the length of a meter was redefined in 1983 as the distance traveled by light in a vacuum during the time interval of 1/299,792,458 s. The foot is now defined as 0.3048 meters. Our simple rulers and yardsticks indeed have an intriguing history. ■

International System (SI). In 1960 the Eleventh General Conference on Weights and Measures, the international organization responsible for maintaining precise uniform standards of measurements, formally adopted the *International System of Units* as the international standard. This system, commonly termed SI, has been widely adopted worldwide and