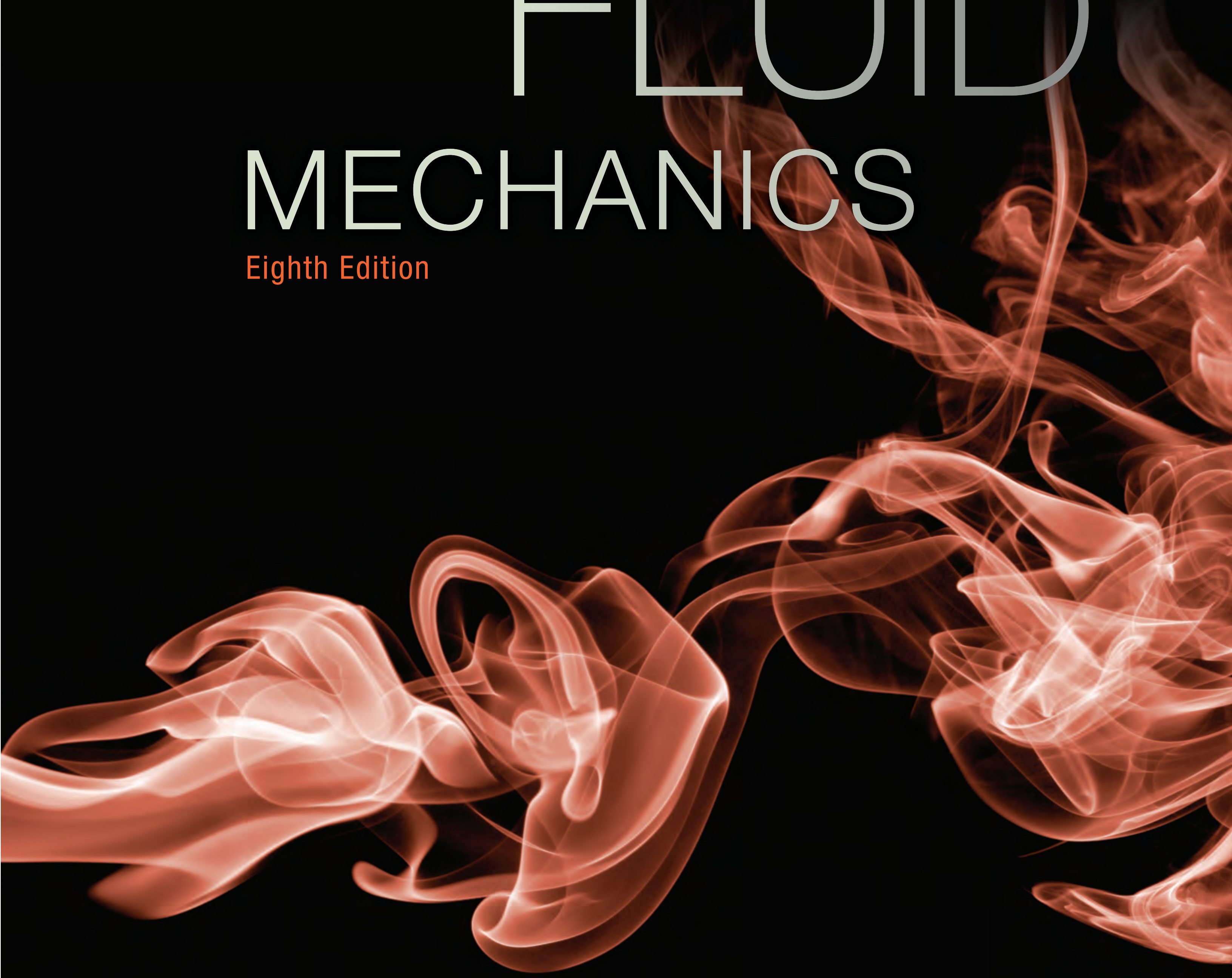
MUNSON, YOUNG AND OKIISHI'S

FUNDAMENTALS OF FLUID MECHANICS

Eighth Edition



Philip M. Gerhart • Andrew L. Gerhart • John I. Hochstein

WILEY

WileyPLUS

ALL THE HELP, RESOURCES, AND PERSONAL SUPPORT YOU AND YOUR STUDENTS NEED!

www.wileyplus.com/resources

1st DAY OF CLASS ... AND BEYOND!

2-Minute Tutorials and all of the resources you and your students need to get started

WileyPLUS Student Partner Program

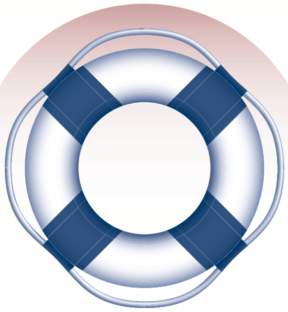
Student support from an experienced student user

Wiley Faculty Network

Collaborate with your colleagues, find a mentor, attend virtual and live events, and view resources
www.WhereFacultyConnect.com

WileyPLUS Quick Start

Pre-loaded, ready-to-use assignments and presentations created by subject matter experts



Technical Support 24/7
FAQs, online chat, and phone support
www.wileyplus.com/support

© Courtney Keating/iStockphoto

Your *WileyPLUS* Account Manager, providing personal training and support

8e

Munson, Young, and Okiishi's

Fundamentals of Fluid Mechanics

Philip M. Gerhart
College of Engineering and Computer Science
University of Evansville
Evansville, Indiana

Andrew L. Gerhart
A. Leon Linton Department of Mechanical Engineering
Lawrence Technological University
Southfield, Michigan

John I. Hochstein
Department of Mechanical Engineering
University of Memphis
Memphis, Tennessee

WILEY

Executive Editor: Linda Ratts
Executive Publisher: Don Fowley
Senior Product Designer: Jennifer Welter
Senior Content Manager: Valerie Zaborski
Associate Product Designer: Wendy Ashenberg
Design Director: Harry Nolan
Senior Designer: Madelyn Lesure
Executive Marketing Manager: Dan Sayre
Photo Researcher: Billy Ray
Editorial Assistant: Courtney Jordan
Senior Production Editor: John Curley
Production Management Services: Aptara Inc./Peggy Kellar
Cover Design: Wendy Lai
Cover Photo: Graham Jeffery/Sensitive Light

This book was set in 10/12 STIX Regular by Aptara®, Inc., and printed and bound by Courier Kendallville.
The cover was printed by Courier Kendallville.

This book is printed on acid free paper. ∞

Founded in 1807, John Wiley & Sons, Inc. has been a valued source of knowledge and understanding for more than 200 years, helping people around the world meet their needs and fulfill their aspirations. Our company is built on a foundation of principles that include responsibility to the communities we serve and where we live and work. In 2008, we launched a Corporate Citizenship Initiative, a global effort to address the environmental, social, economic, and ethical challenges we face in our business. Among the issues we are addressing are carbon impact, paper specifications and procurement, ethical conduct within our business and among our vendors, and community and charitable support. For more information, please visit our website: www.wiley.com/go/citizenship.

ISBN 978-1-119-08070-1 (Binder-Ready Version)

The inside back cover will contain printing identification and country of origin if omitted from this page. In addition, if the ISBN on the back cover differs from the ISBN on this page, the one on the back cover is correct

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

About the Authors

Philip M. Gerhart, Dean of Engineering and Computer Science and Professor of Mechanical and Civil Engineering at the University of Evansville, received his BSME degree from Rose-Hulman Institute of Technology in 1968 and his M.S. and Ph.D. degrees in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 1969 and 1971. Before becoming Chair of Mechanical and Civil Engineering at the University of Evansville, he was on the Mechanical Engineering faculty at the University of Akron from 1971 to 1984.

Dr. Gerhart has taught a variety of courses in fluid mechanics and other thermo-fluid sciences. He has consulted widely in the power generation and process industries and has authored or coauthored two previous books on fluid mechanics and fluid machinery.

Since 1975, he has been deeply involved in the development of the American Society of Mechanical Engineers Performance Test Codes. He served as ASME Vice President for Performance Test Codes from 1998 to 2001, and is currently a member and vice-chair of the Committee on Fans, chair of the Committee on Fired Steam Generators, and a member of the Standing Committee on Performance Test Codes.

Dr. Gerhart is a member of the American Society for Engineering Education and is a Life Fellow of the American Society of Mechanical Engineers. His honors and awards include the Outstanding Teacher Award from the Faculty Senate of the United Methodist Church, and the Performance Test Codes Medal from ASME.

Andrew L. Gerhart, Associate Professor of Mechanical Engineering at Lawrence Technological University, received his BSME degree from the University of Evansville in 1996, his MSME from the University of Wyoming, and his Ph.D. in Mechanical Engineering from the University of New Mexico.

At Lawrence Tech, Dr. Gerhart has developed both undergraduate and graduate courses in viscous flow, turbulence, creative problem solving, and first-year introductory engineering. He has co-developed college-wide curriculum in engineering design and university-wide curriculum in leadership. He is the supervisor of the Thermal Science and Aerodynamics Laboratories, Coordinator of the Aeronautical Engineering Minor/Certificate, chair of the First Year Engineering curriculum committee, and faculty advisor for the student branch of the American Institute of Aeronautics and Astronautics and the SAE Aero Design team.

Dr. Gerhart facilitates workshops worldwide, having trained hundreds of faculty members in active, collaborative, and problem-based learning, as well as training professional engineers and students in creative problem solving and innovation. He is a member of the American Society for Engineering Education and has received four best paper awards from their Annual Conferences.

Dr. Gerhart was awarded the 2010 Michigan Professor of the Year by the Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education, Lawrence Tech's Henry and Barbara Horldt Excellence in Teaching Award, the Engineering Society of Detroit's (ESD) Outstanding Young Engineer, and ESD's Council Leadership Award. He was elected to ESD's College of Fellows, and is actively involved with The American Society of Mechanical Engineers, serving on the Performance Test Code Committee for Air-Cooled Condensers.

John I. Hochstein, Professor of Mechanical Engineering at the University of Memphis, received a BE from Stevens Institute of Technology in 1973, an M.S. in Mechanical Engineering from the Pennsylvania State University in 1979, and his Ph.D. in Mechanical Engineering from the University of Akron in 1984. He has been on the faculty of the mechanical engineering department at the University of Memphis since 1991 and served as department chair from 1996 to 2014.

Working as an engineer in nonacademic positions, Dr. Hochstein contributed to the design of the Ohio-Class submarines at the Electric Boat Division of General Dynamics and to the design of the Clinch River Breeder Reactor while an engineer at the Babcock & Wilcox Company. The focus of his doctoral studies was computational modeling of spacecraft cryogenic propellant management systems, and he has remained involved with NASA research on this topic since that time.

Dr. Hochstein has twice been a NASA Summer Faculty Fellow for two consecutive summers: once at the NASA Lewis (now Glenn) Research Center, and once at the NASA Marshall Space Flight Center. Dr. Hochstein's current primary research focus is on the capture of hydrokinetic energy to produce electricity.

Dr. Hochstein is an Associate Fellow of AIAA and has served on the Microgravity Space Processes Technical Committee since 1986. He joined ASME as an undergraduate student and served for 4 years on the K20 Computational Heat Transfer Committee. He is a member of ASEE and has served the profession as an ABET Program Evaluator since 2002.

A Quarter-Century of Excellence

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.

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 University, 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, Professor Emeritus of Mechanical Engineering at Iowa State University, joined the faculty there in 1967 after receiving his undergraduate and graduate degrees from that institution.

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 and his students have been active in research on turbomachinery fluid dynamics. Some of these projects have involved significant collaboration with government and industrial laboratory researchers, with two of their papers winning the ASME Melville Medal (in 1989 and 1998).

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 a vice president of The American Society of Mechanical Engineers (ASME) and of the American Society for Engineering Education. He is a Life Fellow of The American Society of Mechanical Engineers and past editor of its *Journal of Turbomachinery*. He was recently honored with the ASME R. Tom Sawyer Award.

Wade W. Huebsch, Associate Professor in the Department of Mechanical and Aerospace Engineering at West Virginia University, received his B.S. degree in aerospace engineering from San Jose State University where he played college baseball. He received his M.S. degree in mechanical engineering and his Ph.D. in aerospace engineering from Iowa State University in 2000.

Dr. Huebsch specializes in computational fluid dynamics research and has authored multiple journal articles in the areas of aircraft icing, roughness-induced flow phenomena, and boundary layer flow control. He has taught both undergraduate and graduate courses in fluid mechanics and has developed a new undergraduate course in computational fluid dynamics. He has received multiple teaching awards such as Outstanding Teacher and Teacher of the Year from the College of Engineering and Mineral Resources at WVU as well as the Ralph R. Teetor Educational Award from SAE. He was also named as the Young Researcher of the Year from WVU. He is a member of the American Institute of Aeronautics and Astronautics, the Sigma Xi research society, the Society of Automotive Engineers, and the American Society of Engineering Education.

Alric P. Rothmayer, Professor of Aerospace Engineering at Iowa State University, received his undergraduate and graduate degrees from the Aerospace Engineering Department at the University of Cincinnati, during which time he also worked at NASA Langley Research Center and was a visiting graduate research student at the Imperial College of Science and Technology in London. He joined the faculty at Iowa State University (ISU) in 1985 after a research fellowship sponsored by the Office of Naval Research at University College in London.

Dr. Rothmayer has taught a wide variety of undergraduate fluid mechanics and propulsion courses for over 25 years, ranging from classical low and high speed flows to propulsion cycle analysis.

Dr. Rothmayer was awarded an ISU Engineering Student Council Leadership Award, an ISU Foundation Award for Early Achievement in Research, an ISU Young Engineering Faculty Research Award, and a National Science Foundation Presidential Young Investigator Award. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and was chair of the 3rd AIAA Theoretical Fluid Mechanics Conference.

Dr. Rothmayer specializes in the integration of Computational Fluid Dynamics with asymptotic methods and low order modeling for viscous flows. His research has been applied to diverse areas ranging from internal flows through compliant tubes to flow control and aircraft icing. In 2001, Dr. Rothmayer won a NASA Turning Goals into Reality (TGIR) Award as a member of the Aircraft Icing Project Team, and also won a NASA Group Achievement Award in 2009 as a member of the LEWICE Ice Accretion Software Development Team. He was also a member of the SAE AC-9C Aircraft Icing Technology Subcommittee of the Aircraft Environmental Systems Committee of SAE and the Fluid Dynamics Technical Committee of AIAA.

Preface

This book is intended to help undergraduate engineering students learn the fundamentals of fluid mechanics. It was developed for use in a first course on fluid mechanics, either one or two semesters/terms. While the principles of this course have been well-established for many years, fluid mechanics education has evolved and improved.

With this eighth edition, a new team of authors is working to continue the distinguished tradition of this text. As it has throughout the past seven editions, the original core prepared by Munson, Young, and Okiishi remains. We have sought to augment this fine text, drawing on our many years of teaching experience. Based on our experience and suggestions from colleagues and students, we have made a number of changes to this edition. The changes (listed below, and indicated by the word ***New*** in descriptions in this preface) are made to clarify, update, and expand certain ideas and concepts.

New to This Edition

In addition to the continual effort of updating the scope of the material presented and improving the presentation of all of the material, the following items are new to this edition.

Self-Contained: Material that had been removed from the text and provided only on-line has been brought back into the text. Most notable are Section 5.4 on the second law of thermodynamics and useful energy loss and Appendix E containing units conversion factors.

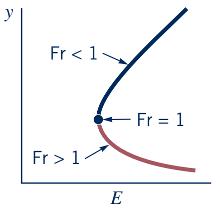
Compressible Flow: Chapter 11 on compressible flow has been extensively reorganized and a limited amount of ***new*** material added. There are ten ***new*** example problems; some of them replace previous examples. All have special emphasis on engineering applications of the material. Example solutions employ tabulated compressible flow functions as well as graphs.

Appendices: Appendix A has been expanded. Compressible flow function tables have been added to Appendix D. A ***new*** extensive set of units conversion factors in a useful and compact format appears in Appendix E.

Computational Fluid Dynamics (CFD): A still unsettled issue in introductory fluid mechanics texts is what to do about computational fluid dynamics. A complete development of the subject is well beyond the scope of an introductory text; nevertheless, highly complex, highly capable CFD codes are being employed for engineering design and analysis in a continually expanding number of industries. We have chosen to provide a description of many of the challenges and practices that characterize widely used CFD codes. Our aim is twofold: to show how reasonably complex flows can be computed and to foster a healthy skepticism in the nonspecialist. This material is presented in an expanded Appendix A.

Problems and Examples: Many ***new*** examples and problems emphasize engineering applications. Approximately 30% ***new*** homework problems have been added for this edition, and there are additional problems in *WileyPLUS*.

Value: Nearly everyone is concerned about the upward spiral of textbook prices (yes, even authors and publishers!). We have taken a few modest steps to keep the price of this book reasonable. Most of these steps involve the removal of "bells and whistles." For example, the thumbnail photos that accompanied the video icons in the 7th edition have been dropped. Wiley has also developed a number of different products to meet differing student needs and budgets.




(© Photograph courtesy of Pend Oreille Public Utility District.)

V1.9 Floating razor blade

Key Features

Illustrations, Photographs, and Videos

Fluid mechanics has always been a "visual" subject—much can be learned by viewing various characteristics of fluid flow. Fortunately this visual component is becoming easier to incorporate into the learning environment, for both access and delivery, and is an important help in learning fluid mechanics. Thus, many photographs and illustrations have been included in the book. Some of these are within the text material; some are used to enhance the example problems; and some are included as margin figures of the type shown in the left margin to more clearly illustrate various points discussed in the text. Numerous video segments illustrate many interesting and practical applications of real-world fluid phenomena. Each video segment is identified at the appropriate location in the text material by a video icon of the type shown in the left margin. Each video segment has a separate associated text description of what is shown in the video. There are many homework problems that are directly related to the topics in the videos.

Examples

One of our aims is to represent fluid mechanics as it really is—an exciting and useful discipline. To this end, we include analyses of numerous everyday examples of fluid-flow phenomena to which students and faculty can easily relate. In this edition there are numerous examples that provide detailed solutions to a variety of problems. Many of the examples illustrate engineering applications of fluid mechanics, as is appropriate in an engineering textbook. Several illustrate what happens if one or more of the parameters is changed. This gives the student a better feel for some of the basic principles involved. In addition, many of the examples contain photographs of the actual device or item involved in the example. Also, all of the examples are outlined and carried out with the problem solving methodology of "Given, Find, Solution, and Comment" as discussed in the "Note to User" before Example 1.1.

The Wide World of Fluids

The set of approximately 60 short "The Wide World of Fluids" stories reflect some important, and novel, ways that fluid mechanics affects our lives. Many of these stories have homework problems associated with them. The title of this feature has been changed from the 7th edition's "Fluids in the News" because the stories cover more than just the latest developments in fluid mechanics.

Homework Problems

A wide variety of homework problems (approximately 30% ***new*** to this edition) stresses the practical application of principles. The problems are grouped and identified according to topic. The following types of problems are included:

1) "standard" problems,
2) computer problems,
3) discussion problems,
4) supply-your-own-data problems,
5) problems based on "The Wide World of Fluids" topics,
6) problems based on the videos,
7) "Lifelong learning" problems,
8) problems that require the user to obtain a photograph/image of a given flow situation and write a brief paragraph to describe it,

Computer Problems—Several problems are designated as computer problems. Depending on the preference of the instructor or student, *any* of the problems with numerical data may be solved with the aid of a personal computer, a programmable calculator, or even a smartphone.

Lifelong Learning Problems—Each chapter has lifelong learning problems that involve obtaining additional information about various fluid mechanics topics and writing a brief report about this material.

Well-Paced Concept and Problem-Solving Development

Since this is an introductory text, we have designed the presentation of material to allow for the gradual development of student confidence in fluid mechanics problem solving. Each important concept or notion is considered in terms of simple and easy-to-understand circumstances before more complicated features are introduced. Many pages contain a brief summary (a highlight) sentence in the margin that serves to prepare or remind the reader about an important concept discussed on that page.

Several brief elements have been included in each chapter to help the student see the "big picture" and recognize the central points developed in the chapter. A brief Learning Objectives section is provided at the beginning of each chapter. It is helpful to read through this list prior to reading the chapter to gain a preview of the main concepts presented. Upon completion of the chapter, it is beneficial to look back at the original learning objectives. Additional reinforcement of these learning objectives is provided in the form of a Chapter Summary and Study Guide at the end of each chapter. In this section a brief summary of the key concepts and principles introduced in the chapter is included along with a listing of important terms with which the student should be familiar. These terms are highlighted in the text. All items in the Learning Objectives and the Study Guide are "action items" stating something that the student should be able to *do*. A list of the main equations in the chapter is included in the chapter summary.

System of Units

Three systems of units are used throughout the text: the International System of Units (newtons, kilograms, meters, and seconds), the British Gravitational System (pounds, slugs, feet, and seconds), and the English Engineering System, sometimes called the U.S. Customary System (pounds (or pounds force), pounds mass, feet, and seconds). Distribution of the examples and homework problems between the three sets of units is about 50%, 40%, 10%.

Prerequisites and Topical Organization

A first course in Fluid Mechanics typically appears in the junior year of a traditional engineering curriculum. Students should have studied statics and dynamics, and mechanics of materials should be at least a co-requisite. Prior mathematics should include calculus, with at least the rudiments of vector calculus, and differential equations.

In the first four chapters of this text the student is made aware of some fundamental aspects of fluid mechanics, including important fluid properties, flow regimes, pressure variation in fluids at rest and in motion, fluid kinematics, and methods of flow description and analysis. The Bernoulli equation is introduced in Chapter 3 to draw attention, early on, to some of the interesting effects and applications of the relationship between fluid motion and pressure in a flow field. We believe that this early consideration of elementary fluid dynamics increases student enthusiasm for the more complicated material that follows. In Chapter 4 we convey the essential elements of flow kinematics, including Eulerian and Lagrangian descriptions of flow fields, and indicate the vital relationship between the two views. For instructors who wish to consider kinematics in detail before the material on elementary fluid dynamics, Chapters 3 and 4 can be interchanged without loss of continuity.

Chapters 5, 6, and 7 expand on the basic methods generally used to solve or to begin solving fluid mechanics problems. Emphasis is placed on understanding how flow phenomena are described mathematically and on when and how to use infinitesimal or finite control volumes. The effects of fluid friction on pressure and velocity are also considered in some detail. Although Chapter 5 considers fluid energy and energy dissipation, a formal course in thermodynamics is not a necessary prerequisite. Chapter 7 features the advantages of using dimensional analysis and similitude for organizing data and for planning experiments and the basic techniques involved.

Owing to the growing importance of computational fluid dynamics (CFD) in engineering design and analysis, material on this subject is included in Appendix A. This material may be omitted without any loss of continuity to the rest of the text.

Chapters 8 through 12 offer students opportunities for the further application of the principles learned earlier in the text. Also, where appropriate, additional important notions such as boundary layers, transition from laminar to turbulent flow, turbulence modeling, and flow separation are introduced. Practical concerns such as pipe flow, open-channel flow, flow measurement, drag and lift, the effects of compressibility, and the fundamental fluid mechanics of turbomachinery are included.

Students who study this text and solve a representative set of the problems will have acquired a useful knowledge of the fundamentals of fluid mechanics. Faculty who use this text are provided with numerous topics to select from in order to meet the objectives of their own courses. More material is included than can be reasonably covered in one term. There is sufficient material for a second course, most likely titled "Applied Fluid Mechanics." All are reminded of the fine collection of supplementary material. We have cited throughout the text various articles and books that are available for enrichment.

Instructor Resources

WileyPLUS provides instructor resources, such as the Instructor Solutions Manual, containing complete, detailed solutions to all of the problems in the text, and figures from the text appropriate for use in lecture slides. Sign up for access at www.wileyplus.com.

Student Resources:

Through a registration process, *WileyPLUS* also provides access to students for appropriate resources such as fluids videos and additional problems, among others.

Harnessing the full power of *WileyPLUS*:

If an educator chooses to require *WileyPLUS* for their course, the educator will set up the *WileyPLUS* course in advance and request students to register and use it. Students obtain access via a registration code that may be added to a print edition or purchased for online-only access.

WileyPLUS builds students' confidence because it takes the guesswork out of studying by providing students with a clear roadmap: **what to do, how to do it, if they did it right**. This interactive approach focuses on:

CONFIDENCE: Research shows that students experience a great deal of anxiety over studying. That's why we provide a structured learning environment that helps students focus on **what to do**, along with the support of immediate resources.

MOTIVATION: To increase and sustain motivation throughout the semester, *WileyPLUS* helps students learn **how to do it** at a pace that's right for them. Our integrated resources—available 24/7—function like a personal tutor, directly addressing each student's demonstrated needs with specific problem-solving techniques.

SUCCESS: *WileyPLUS* helps to assure that each study session has a positive outcome by putting students in control. Through instant feedback and study objective reports, students know **if they did it right,** and where to focus next, so they achieve the strongest results.

With *WileyPLUS*, our efficacy research shows that students improve their outcomes by as much as one letter grade. *WileyPLUS* helps students take more initiative, so you'll have greater impact on their achievement in the classroom and beyond.

What do students receive with *WileyPLUS*?

- The complete digital textbook, saving students up to 60% off the cost of a printed text.
- Question assistance, including links to relevant sections in the online digital textbook.
- Immediate feedback and proof of progress, 24/7.
- Integrated, multimedia resources—including fluids phenomena videos, problem-solving videos, What An Engineer Sees animations, practice reading questions, and much more—that provide multiple study paths and encourage more active learning.

What do instructors receive with *WileyPLUS*?

- Reliable resources that reinforce course goals inside and outside of the classroom.
- The ability to easily identify those students who are falling behind.
- Media-rich course materials and assessment content including Instructor Solutions Manual, figures from the text appropriate for use in lecture slides, Fluids Phenomena Videos, autogradable Reading Questions that can be used in Pre-Lecture Quizzes, autogradable concept questions, autogradable Homework Problems, and much more.

Sign up for access at www.wileyplus.com.

Acknowledgments

First, we wish to express our gratitude to Bruce Munson, Donald Young, Ted Okiishi, Wade Huebsch, and Alric Rothmayer for their part in producing seven editions of this excellent book. Also we thank the people at Wiley, especially Don Fowley, Linda Ratts, and Jenny Welter, for trusting us to assume responsibility for this text. Finally, we thank our families for their continued encouragement during the writing of this edition.

Working with students and colleagues over the years has taught us much about fluid mechanics education. We have drawn from this experience for the benefit of users of this book. Obviously we are still learning, and we welcome any suggestions and comments from you.

Philip M. Gerhart
Andrew L. Gerhart
John I. Hochstein

Contents

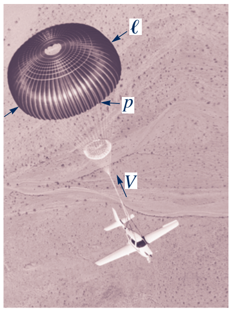
1 Introduction

Learning Objectives

After completing this chapter, you should be able to:

- list the dimensions and units of physical quantities.
- identify the key fluid properties used in the analysis of fluid behavior.
- calculate values for common fluid properties given appropriate information.
- explain effects of fluid compressibility.
- use the concepts of viscosity, vapor pressure, and surface tension.

Fluid mechanics is the discipline within the broad field of applied mechanics that is concerned with the behavior of liquids and gases at rest or in motion. It covers a vast array of phenomena that occur in nature (with or without human intervention), in biology, and in numerous engineered, invented, or manufactured situations. There are few aspects of our lives that do not involve fluids, either directly or indirectly.



(Photograph courtesy of CIRRUS Design Corporation.)

The immense range of different flow conditions is mind-boggling and strongly dependent on the value of the numerous parameters that describe fluid flow. Among the long list of parameters involved are (1) the physical size of the flow, ℓ; (2) the speed of the flow, V; and (3) the pressure, p, as indicated in the figure in the margin for a light aircraft parachute recovery system. These are just three of the important parameters that, along with many others, are discussed in detail in various sections of this book. To get an inkling of the range of some of the parameter values involved and the flow situations generated, consider the following.

- Size, ℓ
  Every flow has a characteristic (or typical) length associated with it. For example, for flow of fluid within pipes, the pipe diameter is a characteristic length. Pipe flows include the flow of water in the pipes in our homes, the blood flow in our arteries and veins, and the airflow in our bronchial tree. They also involve pipe sizes that are not within our everyday experiences. Such examples include the flow of oil across Alaska through a 4-foot-diameter, 799-mile-long pipe and, at the other end of the size scale, the new area of interest involving flow in nano scale pipes whose diameters are on the order of 10^{-8} m. Each of these pipe flows has important characteristics that are not found in the others.
  Characteristic lengths of some other flows are shown in Fig. 1.1*a*.
- Speed, V
  As we note from The Weather Channel, on a given day the wind speed may cover what we think of as a wide range, from a gentle 5-mph breeze to a 100-mph hurricane or a 250-mph

VIDEO *V1.1 Mt. St. Helens eruption*

tornado. However, this speed range is small compared to that of the almost imperceptible flow of the fluid-like magma below the Earth's surface that drives the continental drift motion of the tectonic plates at a speed of about 2×10^{-8} m/s or the hypersonic airflow around a meteor as it streaks through the atmosphere at 3×10^4 m/s.

Characteristic speeds of some other flows are shown in Fig. 1.1*b*.

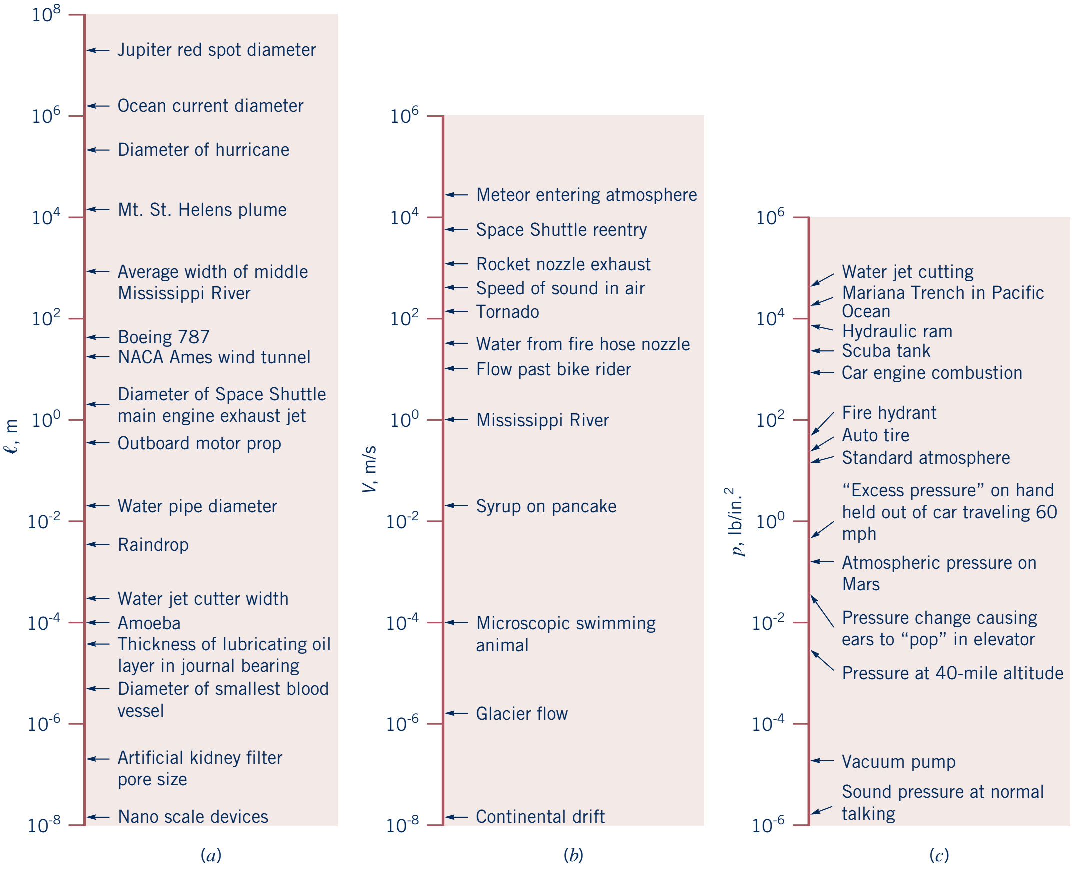
- Pressure, *p*

  The pressure within fluids covers an extremely wide range of values. We are accustomed to the 35 psi (lb/in.^{2}) pressure within our car's tires, the "120 over 70" typical blood pressure reading, or the standard 14.7 psi atmospheric pressure. However, the large 10,000 psi pressure in the hydraulic ram of an earth mover or the tiny 2×10^{-6} psi pressure of a sound wave generated at ordinary talking levels are not easy to comprehend.

  Characteristic pressures of some other flows are shown in Fig. 1.1*c*.

The list of fluid mechanics applications goes on and on. But you get the point. Fluid mechanics is a very important, practical subject that encompasses a wide variety of situations. 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. Although it is not possible to adequately cover all of the important areas of fluid mechanics within one book, it is hoped that this introductory text will provide a sound foundation of the fundamental aspects of fluid mechanics.

VIDEO *V1.2 E. coli swimming*



■ **Figure 1.1 Characteristic values of some fluid flow parameters for a variety of flows: (*a*) object size, (*b*) fluid speed, (*c*) fluid pressure.**

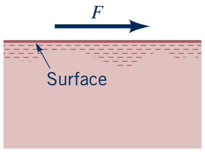
1.1 Some Characteristics of Fluids

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. Both liquids and gases are fluids.

Both liquids and gases are fluids.

THE WIDE WORLD OF FLUIDS

Will what works in air work in water? For the past few years a San Francisco company has been working on small, maneuverable submarines designed to travel through water using wings, controls, and thrusters that are similar to those on jet airplanes. After all, water (for submarines) and air (for airplanes) are both fluids, so it is expected that many of the principles governing the flight of airplanes should carry over to the "flight" of winged submarines. Of course, there are differences. For example, the submarine must be designed to withstand external pressures of nearly 700 pounds per square inch greater than that inside the vehicle. On the other hand, at high altitude where commercial jets fly, the exterior pressure is 3.5 psi rather than standard sea-level pressure of 14.7 psi, so the vehicle must be pressurized internally for passenger comfort. In both cases, however, the design of the craft for minimal drag, maximum lift, and efficient thrust is governed by the same fluid dynamic concepts.



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 as shown by the figure in the margin. 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.

Although the molecular structure of fluids is important in distinguishing one fluid from another, it is not yet practical 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* and we refer to the very small volume as a point in the flow. 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.

1.2 Dimensions, Dimensional Homogeneity, and Units

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

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.***

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

$$V = V_0 + at \qquad \textbf{(1.1)}$$

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

$$LT^{-1} \doteq LT^{-1} + LT^{-2}T$$

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

$$d = 16.1t^2 \qquad \textbf{(1.2)}$$

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}

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 $g = 32.2 \text{ ft/s}^2$ the equation reduces to Eq. 1.2 and thus Eq. 1.2 is valid only for the system of units using feet 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 7.

General homogeneous equations are valid in any system of units.

Note to the users of this text. All of the examples in the text use a consistent problem-solving methodology, which is similar to that in other engineering courses such as statics. Each example highlights the key elements of analysis: ***Given, Find, Solution,*** and ***Comment.***

The ***Given*** and ***Find*** are steps that ensure the user understands what is being asked in the problem and explicitly list the items provided to help solve the problem.

The ***Solution*** step is where the equations needed to solve the problem are formulated and the problem is actually solved. In this step, there are typically several other tasks that help to set up the solution and are required to solve the problem. The first is a drawing of the problem; where appropriate, it is always helpful to draw a sketch of the problem. Here the relevant geometry and coordinate system to be used as well as features such as control volumes, forces and pressures, velocities, and mass flow rates are included. This helps in gaining an understanding of the problem. Making appropriate assumptions to solve the problem is the second task. In a realistic engineering problem-solving environment, the necessary assumptions are developed as an integral part of the solution process. Assumptions can provide appropriate simplifications or offer useful constraints, both of which can help in solving the problem. Throughout the examples in this text, the necessary assumptions are embedded within the ***Solution*** step, as they are in solving a real-world problem. This provides a realistic problem-solving experience.

The final element in the methodology is the ***Comment.*** For the examples in the text, this section is used to provide further insight into the problem or the solution. It can also be a point in the analysis at which certain questions are posed. For example: Is the answer reasonable, and does it make physical sense? Are the final units correct? If a certain parameter were changed, how would the answer change? Adopting this type of methodology will aid in the development of problem-solving skills for fluid mechanics, as well as other engineering disciplines.

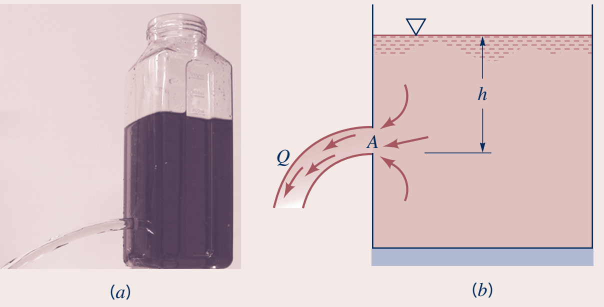
EXAMPLE 1.1 Restricted and General Homogeneous Equations

GIVEN A liquid flows through an orifice located in the side of a tank as shown in Fig. E1.1. A commonly used equation for determining the volume rate of flow, Q, through the orifice is

$$Q = 0.61\, A\sqrt{2gh}$$

where A is the area of the orifice, g is the acceleration of gravity, and h is the height of the liquid above the orifice.

FIND Investigate the dimensional homogeneity of this formula.



■ Figure E1.1

SOLUTION

The dimensions of the various terms in the equation are $Q =$ volume/time $\doteq L^3T^{-1}$, $A =$ area $\doteq L^2$, $g =$ acceleration of gravity $\doteq LT^{-2}$, and $h =$ height $\doteq L$.

These terms, when substituted into the equation, yield the dimensional form:

$$(L^3T^{-1}) \doteq (0.61)(L^2)(\sqrt{2})(LT^{-2})^{1/2}(L)^{1/2}$$

or

$$(L^3T^{-1}) \doteq [0.61\sqrt{2}](L^3T^{-1})$$

It is clear from this result that the equation is dimensionally homogeneous (both sides of the formula have the same dimensions of L^3T^{-1}), and the number $0.61\sqrt{2}$ is dimensionless.

If we were going to use this relationship repeatedly, we might be tempted to simplify it by replacing g with its standard value of 32.2 ft/s^2 and rewriting the formula as

$$Q = 4.90\, A\sqrt{h} \qquad (1)$$

A quick check of the dimensions reveals that

$$L^3T^{-1} \doteq (4.90)(L^{5/2})$$

and, therefore, the equation expressed as Eq. 1 can only be dimensionally correct if the number 4.90 has the dimensions of $L^{1/2}T^{-1}$. Whenever a number appearing in an equation or formula has dimensions, it means that the specific value of the number will depend on the system of units used. Thus, for the case being considered with feet and seconds used as units, the number 4.90 has units of $\text{ft}^{1/2}/\text{s}$. Equation 1 will only give the correct value for Q (in ft^3/s) when A is expressed in square feet and h in feet. Thus, Eq. 1 is a *restricted* homogeneous equation, whereas the original equation is a *general* homogeneous equation that would be valid for any consistent system of units.

COMMENT A quick check of the dimensions of the various terms in an equation is a useful practice and will often be helpful in eliminating errors—that is, as noted previously, all physically meaningful equations must be dimensionally homogeneous. We have briefly alluded to units in this example, and this important topic will be considered in more detail in the next section.

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. For example, if we measure the width of this page in the book and say that it is 10 units wide, the statement has no meaning until the unit of length is defined. If we indicate that the unit of length is a meter, and define the meter as some standard length, a unit system for length has been established (and a numerical value can be given to the page width). In addition to length, a unit must be established for each of the remaining basic quantities (force, mass, time, and temperature). There are several systems of units in use, and we shall consider three systems that are commonly used in engineering.

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 is widely used (although certainly not exclusively) in the United States. It is expected that the long-term trend will be for all countries to accept SI as the accepted standard and it is imperative that engineering students become familiar with this system. In SI the unit of length is the meter (m), the time unit is the second (s), the mass unit is the kilogram (kg), and the temperature unit is the kelvin (K). Note that there is no degree symbol used when expressing a temperature in kelvin units. The kelvin temperature scale is an absolute scale and is related to the Celsius (centigrade) scale (°C) through the relationship

$$\mathrm{K} = {}^\circ\mathrm{C} + 273.15$$

Although the Celsius scale is not in itself part of SI, it is common practice to specify temperatures in degrees Celsius when using SI units.

The force unit, called the newton (N), is defined from Newton's second law as

$$1\ \mathrm{N} = (1\ \mathrm{kg})(1\ \mathrm{m/s^2})$$

In mechanics it is very important to distinguish between weight and mass.

Thus, a 1-N force acting on a 1-kg mass will give the mass an acceleration of $1\ \mathrm{m/s^2}$. Standard gravity in SI is $9.807\ \mathrm{m/s^2}$ (commonly approximated as $9.81\ \mathrm{m/s^2}$) so that a 1-kg mass weighs 9.81 N under standard gravity. Note that weight and mass are different, both qualitatively and quantitatively! The unit of *work* in SI is the joule (J), which is the work done when the point of application of a 1-N force is displaced through a 1-m distance in the direction of a force. Thus,

$$1\ \mathrm{J} = 1\ \mathrm{N \cdot m}$$

The unit of *power* is the watt (W) defined as a joule per second. Thus,

$$1\ \mathrm{W} = 1\ \mathrm{J/s} = 1\ \mathrm{N \cdot m/s}$$

Prefixes for forming multiples and fractions of SI units are given in Table 1.2. For example, the notation kN would be read as "kilonewtons" and stands for 10^3 N. Similarly, mm would be read as "millimeters" and stands for 10^{-3} m. The centimeter is not an accepted unit of length in the SI system, so for most problems in fluid mechanics in which SI units are used, lengths will be expressed in millimeters or meters.

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

$${}^\circ\mathrm{R} = {}^\circ\mathrm{F} + 459.67$$

Table 1.2
Prefixes for SI Units

Factor by Which Unit Is Multiplied	Prefix	Symbol	Factor by Which Unit Is Multiplied	Prefix	Symbol
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10	deka	da	10^{-18}	atto	a
10^{-1}	deci	d			

The mass unit, called the *slug,* is defined from Newton's second law (force = mass × acceleration) as

$$1 \text{ lb} = (1 \text{ slug})(1 \text{ ft/s}^2)$$

This relationship indicates that a 1-lb force acting on a mass of 1 slug will give the mass an acceleration of 1 ft/s^2.

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

The weight, $\mathcal{W}$ (which is the force due to gravity, g), of a mass, m, is given by the equation

$$\mathcal{W} = mg$$

and in BG units

$$\mathcal{W}(\text{lb}) = m(\text{slugs})\, g(\text{ft/s}^2)$$

Since Earth's standard gravity is taken as $g = 32.174$ ft/s^2 (commonly approximated as 32.2 ft/s^2), it follows that a mass of 1 slug weighs 32.2 lb under standard gravity.

THE WIDE WORLD OF FLUIDS

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 one-quarter 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 meter. Our simple rulers and yardsticks indeed have an intriguing history.

English Engineering (EE) System. In the EE system, units for force *and* mass are defined independently; thus special care must be exercised when using this system in conjunction with Newton's second law. The basic unit of mass is the pound mass (lbm), and the unit of force is the pound (lb).[1] The unit of length is the foot (ft), the unit of time is the second (s), and the absolute temperature scale is the degree Rankine (°R). To make the equation expressing Newton's second law dimensionally homogeneous we write it as

$$\mathbf{F} = \frac{m\mathbf{a}}{g_c} \tag{1.4}$$

where g_c is a constant of proportionality, which allows us to define units for both force and mass. For the BG system, only the force unit was prescribed and the mass unit defined in a consistent manner such that $g_c = 1$. Similarly, for SI the mass unit was prescribed and the force unit defined in a consistent manner such that $g_c = 1$. For the EE system, a 1-lb force is defined as that force which gives a 1 lbm a standard acceleration of gravity, which is taken as 32.174 ft/s^2. Thus, for Eq. 1.4 to be both numerically and dimensionally correct

$$1 \text{ lb} = \frac{(1 \text{ lbm})(32.174 \text{ ft/s}^2)}{g_c}$$

so that

$$g_c = \frac{(1 \text{ lbm})(32.174 \text{ ft/s}^2)}{(1 \text{ lb})}$$

[1]It is also common practice to use the notation, lbf, to indicate pound force.

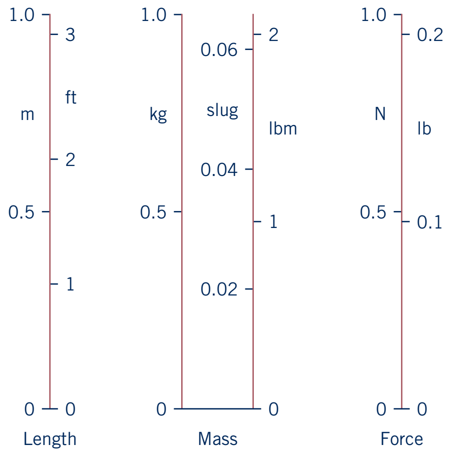


Figure 1.2 Comparison of SI, BG, and EE units.

With the EE system, weight and mass are related through the equation

$$\mathcal{W} = \frac{mg}{g_c}$$

where g is the local acceleration of gravity. Under conditions of standard gravity $(g = g_c)$ the weight in pounds and the mass in pound mass are numerically equal. Also, since a 1-lb force gives a mass of 1 lbm an acceleration of 32.174 ft/s^2 and a mass of 1 slug an acceleration of 1 ft/s^2, it follows that

$$1 \text{ slug} = 32.174 \text{ lbm}$$

When solving problems it is important to use a consistent system of units, e.g., don't mix BG and SI units.

We cannot overemphasize the importance of paying close attention to units when solving problems. It is very easy to introduce huge errors into problem solutions through the use of incorrect units. Get in the habit of using a *consistent* system of units throughout a given solution. It really makes no difference which system you use as long as you are consistent; for example, don't mix slugs and newtons. If problem data are specified in SI units, then use SI units throughout the solution. If the data are specified in BG units, then use BG units throughout the solution. The relative sizes of the SI, BG, and EE units of length, mass, and force are shown in Fig. 1.2.

Extensive tables of conversion factors between unit systems, and within unit systems, are provided in Appendix E. For your convenience, abbreviated tables of conversion factors for some quantities commonly encountered in fluid mechanics are presented in Tables 1.3 and 1.4 on the inside back cover (using a slightly different format than Appendix E). Note that numbers in these tables are presented in computer exponential notation. For example, the number 5.154 E+2 is the number 5.154×10^2 in scientific notation. You should note that each conversion factor can be thought of as a fraction in which the numerator and denominator are equivalent. For example, an entry for "Length" from Table 1.4 instructs the user "To convert from … m … to … ft … Multiply by 3.281." Therefore 1 m is the same length as 3.281 ft. Therefore a fraction formed with a numerator of 1 m and a denominator of 3.281 ft is the very definition of a fraction with a value of one, as is its reciprocal. This may seem obvious when the units of the denominator and numerator are of the same dimension. It is equally true for the more complicated conversion factors that include multiple dimensions and therefore a greater number of units. You already know that you can multiply any quantity by one without changing its value. Likewise, you can multiply (or divide) any quantity by any conversion factor in the tables, provided you use both the number and the units. The result will not be incorrect, even if it does not yield the result you hoped for.

EXAMPLE 1.2 BG and SI Units

GIVEN A tank of liquid having a total mass of 36 kg rests on a support in the equipment bay of the Space Shuttle.

FIND Determine the force (in newtons) that the tank exerts on the support shortly after lift off when the shuttle is accelerating upward as shown in Fig. E1.2*a* at 15 ft/s².

■ Figure E1.2*a* (Photograph courtesy of NASA.)

SOLUTION

A free-body diagram of the tank is shown in Fig. E1.2*b*, where $\mathcal{W}$ is the weight of the tank and liquid, and F_f is the reaction of the floor on the tank. Application of Newton's second law of motion to this body gives

$$\sum \mathbf{F} = m\mathbf{a}$$

or

$$F_f - \mathcal{W} = ma \quad \textbf{(1)}$$

where we have taken upward as the positive direction. Since $\mathcal{W} = mg$, Eq. 1 can be written as

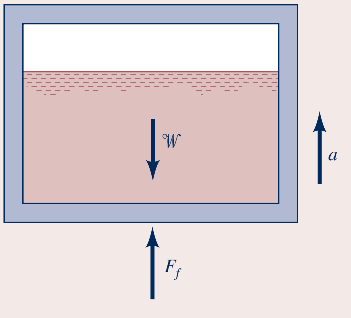
$$F_f = m(g + a) \quad \textbf{(2)}$$

Before substituting any number into Eq. 2, we must decide on a system of units, and then be sure all of the data are expressed in these units. Since we want F_f in newtons, we will use SI units so that

$$F_f = 36 \text{ kg}[9.81 \text{ m/s}^2 + (15 \text{ ft/s}^2)(0.3048 \text{ m/ft})]$$
$$= 518 \text{ kg} \cdot \text{m/s}^2$$

Since $1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$, it follows that

$$F_f = 518 \text{ N} \qquad \text{(downward on floor)} \qquad \textbf{(Ans)}$$



■ Figure E1.2*b*

The direction is downward since the force shown on the free-body diagram is the force of the support *on the tank* so that the force the tank exerts *on the support* is equal in magnitude but opposite in direction.

COMMENT As you work through a large variety of problems in this text, you will find that units play an essential role in arriving at a numerical answer. Be careful! It is easy to mix units and cause large errors. If in the above example the acceleration had been left as 15 ft/s² with m and g expressed in SI units, we would have calculated the force as 893 N and the answer would have been 72% too large!

THE WIDE WORLD OF FLUIDS

Units and space travel A NASA spacecraft, the Mars Climate Orbiter, was launched in December 1998 to study the Martian geography and weather patterns. The spacecraft was slated to begin orbiting Mars on September 23, 1999. However, NASA officials lost communication with the spacecraft early that day and it is believed that the spacecraft broke apart or overheated because it came too close to the surface of Mars. Errors in the maneuvering commands sent from earth caused the Orbiter to sweep within 37 miles of the surface rather than the intended 93 miles. The subsequent investigation revealed that the errors were due to a simple mix-up in *units*. One team controlling the Orbiter used SI units, whereas another team used BG units. This costly experience illustrates the importance of using a consistent system of units.

1.3 Analysis of Fluid Behavior

The study of fluid mechanics involves the same fundamental laws you have encountered in physics and other mechanics courses. These laws include Newton's laws of motion, conservation of mass, and the first and second laws of thermodynamics. Thus, there are strong similarities between the general approach to fluid mechanics and to rigid-body and deformable-body solid mechanics. This is indeed helpful since many of the concepts and techniques of analysis used in fluid mechanics will be ones you have encountered before in other courses.

The broad subject of fluid mechanics can be generally subdivided into *fluid statics,* in which the fluid is at rest, and *fluid dynamics,* in which the fluid is moving. In the following chapters we will consider both of these areas in detail. Before we can proceed, however, it will be necessary to define and discuss certain fluid *properties* that are intimately related to fluid behavior. It is obvious that different fluids can have grossly different characteristics. For example, gases are light and compressible, whereas liquids are heavy (by comparison) and relatively incompressible. A syrup flows slowly from a container, but water flows rapidly when poured from the same container. To quantify these differences, certain fluid properties are used. In the following several sections, properties that play an important role in the analysis of fluid behavior are considered.

1.4 Measures of Fluid Mass and Weight

1.4.1 Density

The density of a fluid is defined as its mass per unit volume.

The ***density*** of a fluid, designated by the Greek symbol ρ (rho), is defined as its mass per unit volume. Density is typically used to characterize the mass of a fluid system. In the BG system, ρ has units of $slugs/ft^3$ and in SI the units are kg/m^3.

The value of density can vary widely between different fluids, but for liquids, variations in pressure and temperature generally have only a small effect on the value of ρ. The small change in the density of water with large variations in temperature is illustrated in Fig. 1.3. Tables 1.5 and 1.6 list values of density for several common liquids. The density of water at 60 °F is 1.94 $slugs/ft^3$ or 999 kg/m^3. The large numerical difference between those two values illustrates the importance of paying attention to units! Unlike liquids, the density of a gas is strongly influenced by both pressure and temperature, and this difference will be discussed in the next section.

The *specific volume,* υ, is the *volume* per unit mass and is therefore the reciprocal of the density—that is,

$$\upsilon = \frac{1}{\rho} \tag{1.5}$$

This property is not commonly used in fluid mechanics but is used in thermodynamics.

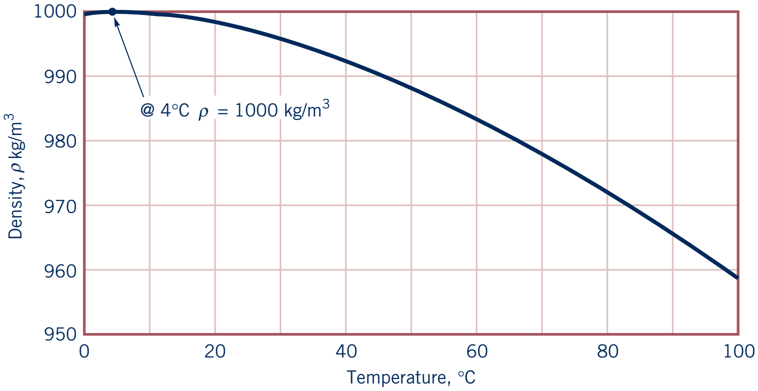


Figure 1.3 **Density of water as a function of temperature.**

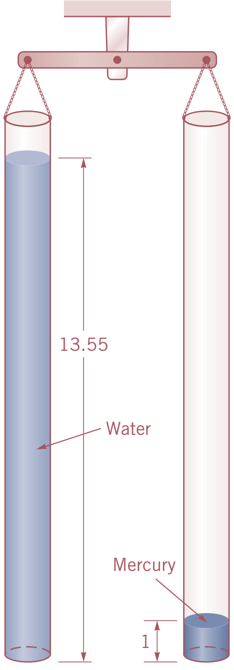
1.4.2 Specific Weight

Specific weight is weight per unit volume; specific gravity is the ratio of fluid density to the density of water at a certain temperature.

The ***specific weight*** of a fluid, designated by the Greek symbol γ (gamma), is defined as its *weight* per unit volume. Thus, specific weight is related to density through the equation

$$\gamma = \rho g \tag{1.6}$$

where g is the local acceleration of gravity. Just as density is used to characterize the mass of a fluid system, the specific weight is used to characterize the weight of the system. In the BG system, γ has units of lb/ft^3 and in SI the units are N/m^3. Under conditions of standard gravity ($g = 32.174\ \text{ft/s}^2 = 9.807\ \text{m/s}^2$), water at 60 °F has a specific weight of $62.4\ \text{lb/ft}^3$ and $9.80\ \text{kN/m}^3$. Tables 1.5 and 1.6 list values of specific weight for several common liquids (based on standard gravity). More complete tables for water can be found in Appendix B (Tables B.1 and B.2).



1.4.3 Specific Gravity

The ***specific gravity*** of a fluid, designated as *SG*, is defined as the ratio of the density of the fluid to the density of water at some specified temperature. Usually the specified temperature is taken as 4 °C (39.2 °F), and at this temperature the density of water is $1.94\ \text{slugs/ft}^3$ or $1000\ \text{kg/m}^3$. In equation form, specific gravity is expressed as

$$SG = \frac{\rho}{\rho_{H_2O@4\,°C}} \tag{1.7}$$

and since it is the *ratio* of densities, the value of *SG* does not depend on the system of units used. For example, the specific gravity of mercury at 20 °C is 13.55. This is illustrated by the figure in the margin. Thus, the density of mercury can be readily calculated in either BG or SI units through the use of Eq. 1.7 as

$$\rho_{Hg} = (13.55)(1.94\ \text{slugs/ft}^3) = 26.3\ \text{slugs/ft}^3$$

or

$$\rho_{Hg} = (13.55)(1000\ \text{kg/m}^3) = 13.6 \times 10^3\ \text{kg/m}^3$$

It is clear that density, specific weight, and specific gravity are all interrelated, and from a knowledge of any one of the three the others can be calculated.

1.5 Ideal Gas Law

Gases are highly compressible in comparison to liquids, with changes in gas density directly related to changes in pressure and temperature through the equation

$$\rho = \frac{p}{RT}$$

or, in the more standard form,

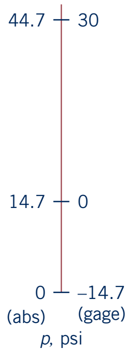
$$p = \rho RT, \tag{1.8}$$

In the ideal gas law, absolute pressures and temperatures must be used.

where p is the absolute pressure, ρ the density, T the absolute temperature,[2] and R is a gas constant. Equation 1.8 is commonly termed the ***ideal*** or *perfect* ***gas law,*** or the *equation of state* for an ideal gas. It is known to closely approximate the behavior of real gases under typical conditions when the gases are not approaching liquefaction.

Pressure in a fluid at rest is defined as the normal force per unit area exerted on a plane surface (real or imaginary) immersed in a fluid and is created by the bombardment of the surface with the fluid molecules. From the definition, pressure has the dimension of FL^{-2} and in BG units

[2]We will use T to represent temperature in thermodynamic relationships although T is also used to denote the basic dimension of time.



is expressed as lb/ft^2 (psf) or lb/in.^{2} (psi) and in SI units as N/m^2. In SI, 1 N/m^2 defined as a *pascal,* abbreviated as Pa, and pressures are commonly specified in pascals. The pressure in the ideal gas law must be expressed as an ***absolute pressure,*** denoted (abs), which means that it is measured relative to absolute zero pressure (a pressure that would only occur in a perfect vacuum). Standard sea-level atmospheric pressure (by international agreement) is 14.696 psi (abs) or 101.33 kPa (abs). For most calculations these pressures can be rounded to 14.7 psi and 101 kPa, respectively. In engineering it is common practice to measure pressure relative to the local atmospheric pressure, and when measured in this fashion it is called ***gage pressure.*** Thus, the absolute pressure can be obtained from the gage pressure by adding the value of the atmospheric pressure. For example, as shown by the figure in the margin, a pressure of 30 psi (gage) in a tire is equal to 44.7 psi (abs) at standard atmospheric pressure. Pressure is a particularly important fluid characteristic and it will be discussed more fully in the next chapter.

EXAMPLE 1.3 Ideal Gas Law

GIVEN The compressed air tank shown in Fig. E1.3*a* has a volume of 0.84 ft^3. The temperature is 70 °F and the atmospheric pressure is 14.7 psi (abs).

FIND When the tank is filled with air at a gage pressure of 50 psi, determine the density of the air and the weight of air in the tank.

SOLUTION

The air density can be obtained from the ideal gas law (Eq. 1.8)

$$\rho = \frac{p}{RT}$$

so that

$$\rho = \frac{(50 \text{ lb/in.}^2 + 14.7 \text{ lb/in.}^2)(144 \text{ in.}^2/\text{ft}^2)}{(1716 \text{ ft} \cdot \text{lb/slug} \cdot {}^\circ\text{R})[(70 + 460)^\circ\text{R}]}$$

$$= 0.0102 \text{ slugs/ft}^3 \qquad \textbf{(Ans)}$$

Note that both the pressure and temperature were changed to absolute values.

The weight, $\mathcal{W}$, of the air is equal to

$$\mathcal{W} = \rho g \times (\text{volume})$$
$$= (0.0102 \text{ slug/ft}^3)(32.2 \text{ ft/s}^2)(0.84 \text{ ft}^3)$$
$$= 0.276 \text{ slug} \cdot \text{ft/s}^2$$

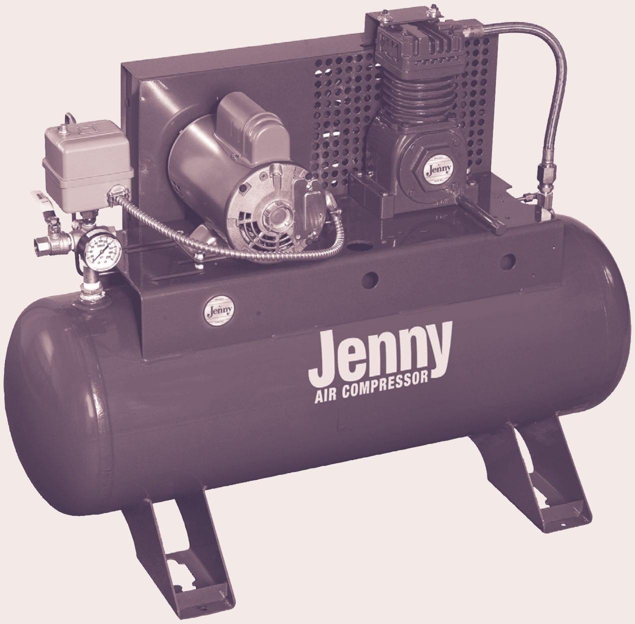


Figure E1.3*a* **(Photograph courtesy of Jenny Products, Inc.)**

so that since 1 lb = 1 slug · ft/s^2

$$\mathcal{W} = 0.276 \text{ lb} \qquad \textbf{(Ans)}$$

COMMENT By repeating the calculations for various values of the pressure, p, the results shown in Fig. E1.3*b* are obtained. Note that doubling the gage pressure does not double the amount of air in the tank, but doubling the absolute pressure does. Thus, a scuba diving tank at a gage pressure of 100 psi does not contain twice the amount of air as when the gage reads 50 psi.

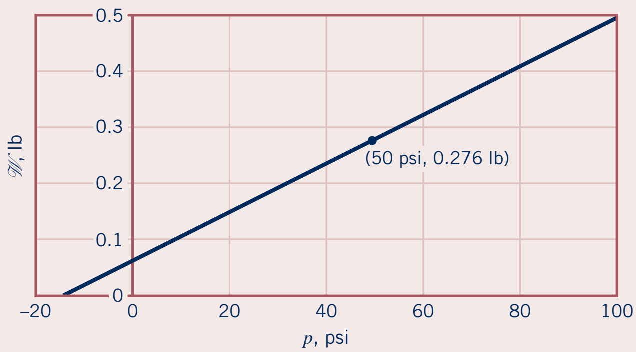


Figure E1.3*b*

The gas constant, R, which appears in Eq. 1.8, depends on the particular gas and is related to the molecular weight of the gas. Values of the gas constant for several common gases are listed in Tables 1.7 and 1.8. Also in these tables the gas density and specific weight are given for standard atmospheric pressure and gravity and for the temperature listed. More complete tables for air at standard atmospheric pressure can be found in Appendix B (Tables B.3 and B.4).

1.6 Viscosity

VIDEO *V1.3 Viscous fluids*

VIDEO *V1.4 No-slip condition*

Real fluids, even though they may be moving, always "stick" to the solid boundaries that contain them.

The properties of density and specific weight are measures of the "heaviness" of a fluid. It is clear, however, that these properties are not sufficient to uniquely characterize how fluids behave since two fluids (such as water and oil) can have approximately the same value of density but behave quite differently when flowing. Apparently, some additional property is needed to describe the "fluidity" of the fluid.

To determine this additional property, consider a hypothetical experiment in which a material is placed between two very wide parallel plates as shown in Fig. 1.4*a*. The bottom plate is rigidly fixed, but the upper plate is free to move. If a solid, such as steel, were placed between the two plates and loaded with the force P as shown, the top plate would be displaced through some small distance, δa (assuming the solid was mechanically attached to the plates). The vertical line AB would be rotated through the small angle, $\delta\beta$, to the new position AB'. We note that to resist the applied force, P, a shearing stress, τ, would be developed at the plate–material interface, and for equilibrium to occur, $P = \tau A$ where A is the effective upper plate area (Fig. 1.4*b*). It is well known that for elastic solids, such as steel, the small angular displacement, $\delta\beta$ (called the shearing strain), is proportional to the shearing stress, τ, that is developed in the material.

What happens if the solid is replaced with a fluid such as water? We would immediately notice a major difference. When the force P is applied to the upper plate, it will move continuously with a velocity, U (after the initial transient motion has died out) as illustrated in Fig. 1.5. This behavior is consistent with the definition of a fluid—that is, if a shearing stress is applied to a fluid it will deform continuously. A closer inspection of the fluid motion between the two plates would reveal that the fluid in contact with the upper plate moves with the plate velocity, U, and the fluid in contact with the bottom fixed plate has a zero velocity. The fluid between the two plates moves with velocity $u = u(y)$ that would be found to vary linearly, $u = Uy/b$, as illustrated in Fig. 1.5. Thus, a *velocity gradient, du/dy*, is developed in the fluid between the plates. In this particular case the velocity gradient is a constant since $du/dy = U/b$, but in more complex flow situations, such as that shown by the photograph in the margin, this is not true. The experimental observation that the fluid "sticks" to the solid boundaries is a very important one in fluid mechanics and is usually referred to as the ***no-slip condition.*** All fluids, both liquids and gases, satisfy this condition for typical flows.

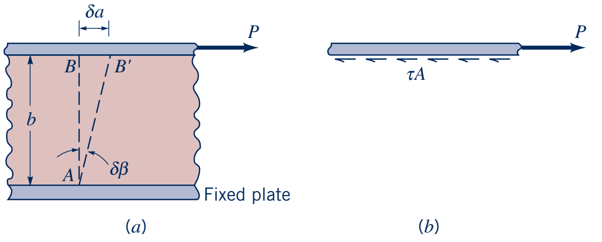


Figure 1.4 **(*a*) Deformation of material placed between two parallel plates. (*b*) Forces acting on upper plate.**

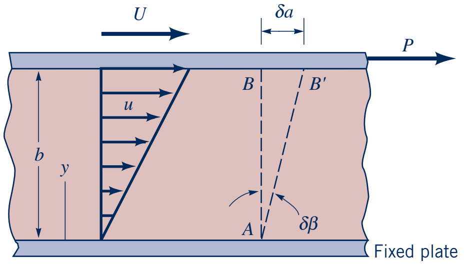
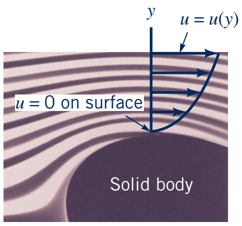


Figure 1.5 **Behavior of a fluid placed between two parallel plates.**



In a small time increment, δt, an imaginary vertical line AB in the fluid would rotate through an angle, $\delta\beta$, so that

$$\delta\beta \approx \tan\delta\beta = \frac{\delta a}{b}$$

Since $\delta a = U\,\delta t$, it follows that

$$\delta\beta = \frac{U\,\delta t}{b}$$

We note that in this case, $\delta\beta$ is a function not only of the force P (which governs U) but also of time. Thus, it is not reasonable to attempt to relate the shearing stress, τ, to $\delta\beta$ as is done for solids. Rather, we consider the *rate* at which $\delta\beta$ is changing and define the ***rate of shearing strain,*** $\dot{\gamma}$, as

$$\dot{\gamma} = \lim_{\delta t \to 0} \frac{\delta\beta}{\delta t}$$

which in this instance is equal to

$$\dot{\gamma} = \frac{U}{b} = \frac{du}{dy}$$

A continuation of this experiment would reveal that as the shearing stress, τ, is increased by increasing P (recall that $\tau = P/A$), the rate of shearing strain is increased in direct proportion—that is,

$$\tau \propto \dot{\gamma}$$

or

$$\tau \propto \frac{du}{dy}$$

VIDEO *V1.5 Capillary tube viscometer*

This result indicates that for common fluids such as water, oil, gasoline, and air the shearing stress and rate of shearing strain (velocity gradient) can be related with a relationship of the form

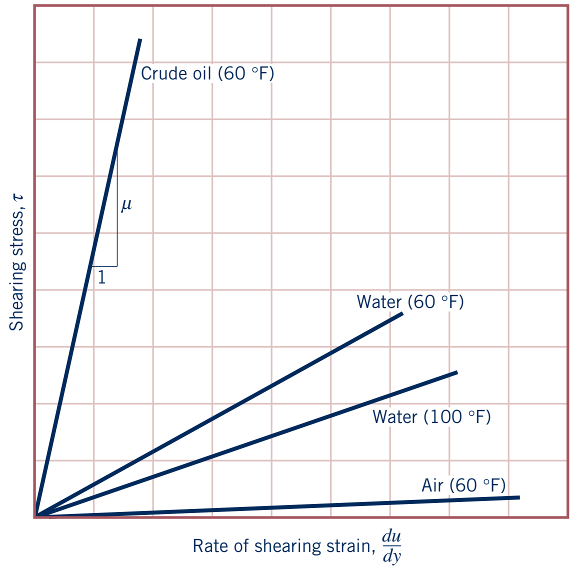
$$\tau = \mu \frac{du}{dy} \tag{1.9}$$

Dynamic viscosity is the fluid property that relates shearing stress and fluid motion.

where the constant of proportionality is designated by the Greek symbol μ (mu) and is called the ***absolute viscosity,*** *dynamic viscosity,* or simply the *viscosity* of the fluid. In accordance with Eq. 1.9, plots of τ versus du/dy should be linear with the slope equal to the viscosity as illustrated in Fig. 1.6. The actual value of the viscosity depends on the particular fluid, and for a particular fluid the viscosity is also highly dependent on temperature as illustrated in Fig. 1.6 with the two curves for water. Fluids for which the shearing stress is *linearly* related to the rate of shearing strain (also referred to as the rate of angular deformation) are designated as ***Newtonian fluids*** after Isaac Newton (1642–1727). Fortunately, most common fluids, both liquids and gases, are Newtonian. A more general formulation of Eq. 1.9 which applies to more complex flows of Newtonian fluids is given in Section 6.8.1.

THE WIDE WORLD OF FLUIDS

An extremely viscous fluid Pitch is a derivative of tar once used for waterproofing boats. At elevated temperatures it flows quite readily. At room temperature it feels like a solid—it can even be shattered with a blow from a hammer. However, it is a liquid. In 1927 Professor Parnell heated some pitch and poured it into a funnel. Since that time it has been allowed to flow freely (or rather, drip slowly) from the funnel. The flowrate is quite small. In fact, to date only seven drops have fallen from the end of the funnel, although the eighth drop is poised ready to fall "soon." While nobody has actually seen a drop fall from the end of the funnel, a beaker below the funnel holds the previous drops that fell over the years. It is estimated that the pitch is about 100 billion times more viscous than water.



■ **Figure 1.6 Linear variation of shearing stress with rate of shearing strain for common fluids.**

For non-Newtonian fluids, the apparent viscosity is a function of the shear rate.

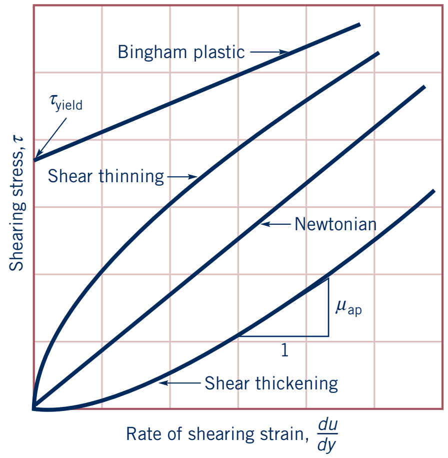
The various types of non-Newtonian fluids are distinguished by how their apparent viscosity changes with shear rate.

Fluids for which the shearing stress is not linearly related to the rate of shearing strain are designated as ***non-Newtonian fluids.*** Although there is a variety of types of non-Newtonian fluids, the simplest and most common are shown in Fig. 1.7. The slope of the shearing stress versus rate of shearing strain graph is denoted as the *apparent viscosity,* μ_{ap}. For Newtonian fluids the apparent viscosity is the same as the viscosity and is independent of shear rate.

For *shear thinning fluids* the apparent viscosity decreases with increasing shear rate—the harder the fluid is sheared, the less viscous it becomes. Many colloidal suspensions and polymer solutions are shear thinning. For example, latex paint does not drip from the brush because the shear rate is small and the apparent viscosity is large. However, it flows smoothly onto the wall because the thin layer of paint between the wall and the brush causes a large shear rate and a small apparent viscosity.

For *shear thickening fluids* the apparent viscosity increases with increasing shear rate—the harder the fluid is sheared, the more viscous it becomes. Common examples of this type of fluid include water–corn starch mixture and water–sand mixture ("quicksand"). Thus, the difficulty in removing an object from quicksand increases dramatically as the speed of removal increases.

The other type of behavior indicated in Fig. 1.7 is that of a *Bingham plastic,* which is neither a fluid nor a solid. Such material can withstand a finite, nonzero shear stress, τ_{yield}, the yield stress, without motion (therefore, it is not a fluid), but once the yield stress is exceeded it flows like a fluid (hence, it is not a solid). Toothpaste and mayonnaise are common examples of Bingham plastic



■ **Figure 1.7 Variation of shearing stress with rate of shearing strain for several types of fluids, including common non-Newtonian fluids.**

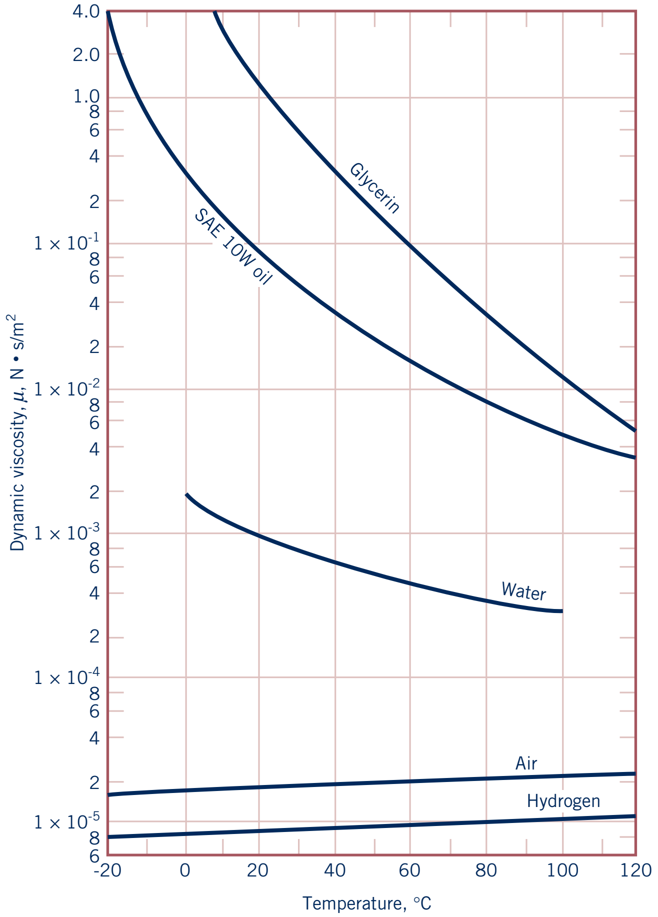
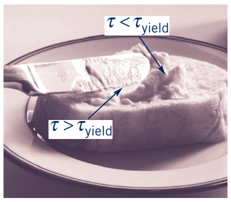


Figure 1.8 **Dynamic (absolute) viscosity of some common fluids as a function of temperature.**



materials. As indicated in the figure in the margin, mayonnaise can sit in a pile on a slice of bread (the shear stress less than the yield stress), but it flows smoothly into a thin layer when the knife increases the stress above the yield stress.

From Eq. 1.9 it can be readily deduced that the dimensions of viscosity are FTL^{-2}. Thus, in BG units viscosity is given as $lb \cdot s/ft^2$ and in SI units as $N \cdot s/m^2$. Values of viscosity for several common liquids and gases are listed in Tables 1.5 through 1.8. A quick glance at these tables reveals the wide variation in viscosity among fluids. Viscosity is only mildly dependent on pressure and the effect of pressure is usually neglected. However, as previously mentioned, and as illustrated in Fig. 1.8, viscosity is very sensitive to temperature. For example, as the temperature of water changes from 60 to 100 °F the density decreases by less than 1%, but the viscosity decreases by about 40%. It is thus clear that particular attention must be given to temperature when determining viscosity.

VIDEO *V1.6 Non-Newtonian behavior*

Figure 1.8 shows in more detail how the viscosity varies from fluid to fluid and how for a given fluid it varies with temperature. It is to be noted from this figure that the viscosity of liquids decreases with an increase in temperature, whereas for gases an increase in temperature causes an increase in viscosity. This difference in the effect of temperature on the viscosity of liquids and gases can again be traced back to the difference in molecular structure. The liquid molecules are closely spaced, with strong cohesive forces between molecules, and the resistance to relative motion between adjacent layers of fluid is related to these intermolecular forces. As the temperature increases, these cohesive forces are reduced with a corresponding reduction in resistance to motion. Since viscosity is an index of this resistance, it follows that the viscosity is reduced by an increase in temperature. In gases, however, the molecules are widely spaced and intermolecular forces negligible. In this case, resistance to relative motion arises due to the exchange of momentum of gas molecules between adjacent layers. As molecules are transported by random motion from a region of low bulk velocity to mix with molecules in a region of higher bulk velocity (and vice versa), there is an effective momentum exchange that resists the relative motion between the layers. As the temperature of the gas increases, the random molecular activity increases with a corresponding increase in viscosity.

The effect of temperature on viscosity can be closely approximated using two empirical formulas. For gases the *Sutherland equation* can be expressed as

Viscosity is very sensitive to temperature.

$$\mu = \frac{CT^{3/2}}{T + S} \quad \textbf{(1.10)}$$

where C and S are empirical constants, and T is absolute temperature. Thus, if the viscosity is known at two temperatures, C and S can be determined. Or, if more than two viscosities are known, the data can be correlated with Eq. 1.10 by using some type of curve-fitting scheme.

For liquids an empirical equation that has been used is

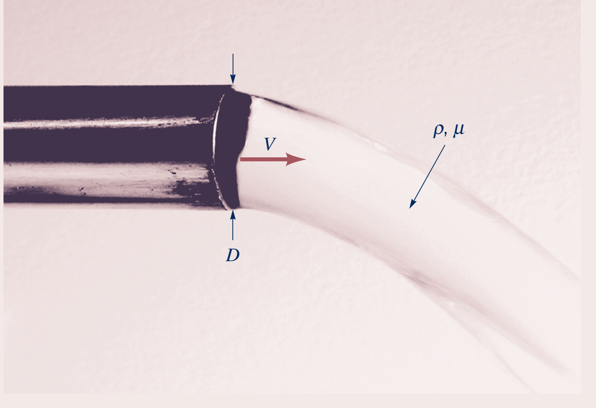
$$\mu = De^{B/T} \quad \textbf{(1.11)}$$

where D and B are constants and T is absolute temperature. This equation is often referred to as *Andrade's equation.* As was the case for gases, the viscosity must be known at least for two temperatures so the two constants can be determined. A more detailed discussion of the effect of temperature on fluids can be found in Ref. 1.

EXAMPLE 1.4 Viscosity and Dimensionless Quantities

GIVEN A dimensionless combination of variables that is important in the study of viscous flow through pipes is called the *Reynolds number,* Re, defined as $\rho VD/\mu$ where, as indicated in Fig. E1.4, ρ is the fluid density, V the mean fluid velocity, D the pipe diameter, and μ the fluid viscosity. A Newtonian fluid having a viscosity of $0.38 \text{ N}\cdot\text{s/m}^2$ and a specific gravity of 0.91 flows through a 25-mm-diameter pipe with a velocity of 2.6 m/s.

FIND Determine the value of the Reynolds number using (a) SI units and (b) BG units.



■ Figure E1.4

SOLUTION

(a) The fluid density is calculated from the specific gravity as

$$\rho = SG\,\rho_{H_2O@4\,^\circ C} = 0.91\,(1000 \text{ kg/m}^3) = 910 \text{ kg/m}^3$$

and from the definition of the Reynolds number

$$\text{Re} = \frac{\rho VD}{\mu} = \frac{(910 \text{ kg/m}^3)(2.6 \text{ m/s})(25 \text{ mm})(10^{-3} \text{ m/mm})}{0.38 \text{ N}\cdot\text{s/m}^2}$$
$$= 156\,(\text{kg}\cdot\text{m/s}^2)/\text{N}$$

However, since $1 \text{ N} = 1 \text{ kg}\cdot\text{m/s}^2$ it follows that the Reynolds number is unitless—that is,

$$\text{Re} = 156 \qquad \textbf{(Ans)}$$

The value of any dimensionless quantity does not depend on the system of units used if all variables that make up the quantity are expressed in a consistent set of units. To check this, we will calculate the Reynolds number using BG. units.

(b) We first convert all the SI values of the variables appearing in the Reynolds number to BG values. Thus,

$$\rho = (910 \text{ kg/m}^3)(1.940 \times 10^{-3}) = 1.77 \text{ slugs/ft}^3$$
$$V = (2.6 \text{ m/s})(3.281) = 8.53 \text{ ft/s}$$
$$D = (0.025 \text{ m})(3.281) = 8.20 \times 10^{-2} \text{ ft}$$
$$\mu = (0.38 \text{ N}\cdot\text{s/m}^2)(2.089 \times 10^{-2}) = 7.94 \times 10^{-3} \text{ lb}\cdot\text{s/ft}^2$$

and the value of the Reynolds number is

$$\text{Re} = \frac{(1.77 \text{ slugs/ft}^3)(8.53 \text{ ft/s})(8.20 \times 10^{-2} \text{ ft})}{7.94 \times 10^{-3} \text{ lb}\cdot\text{s/ft}^2}$$
$$= 156\,(\text{slug}\cdot\text{ft/s}^2)/\text{lb} = 156 \qquad \textbf{(Ans)}$$

since $1 \text{ lb} = 1 \text{ slug}\cdot\text{ft/s}^2$.

COMMENTS The values from part (a) and part (b) are the same, as expected. Dimensionless quantities play an important role in fluid mechanics, and the significance of the Reynolds number as well as other important dimensionless combinations will be discussed in detail in Chapter 7. It should be noted that in the Reynolds number it is actually the ratio μ/ρ that is important, and this is the property that is defined as the kinematic viscosity.

EXAMPLE 1.5 Newtonian Fluid Shear Stress

GIVEN The velocity distribution for the flow of a Newtonian fluid between two fixed wide, parallel plates (see Fig. E1.5*a*) is given by the equation

$$u = \frac{3V}{2}\left[1 - \left(\frac{y}{h}\right)^2\right]$$

where V is the mean velocity. The fluid has a viscosity of $0.04\ \text{lb} \cdot \text{s/ft}^2$. Also, $V = 2$ ft/s and $h = 0.2$ in.

FIND Determine: (a) the shearing stress acting on the bottom wall, and (b) the shearing stress acting on a plane parallel to the walls and passing through the centerline (midplane).

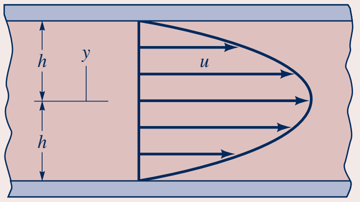


Figure E1.5*a*

SOLUTION

For this type of parallel flow the shearing stress is obtained from Eq. 1.9,

$$\tau = \mu \frac{du}{dy} \tag{1}$$

Thus, if the velocity distribution $u = u(y)$ is known, the shearing stress can be determined at all points by evaluating the velocity gradient, du/dy. For the distribution given

$$\frac{du}{dy} = -\frac{3Vy}{h^2} \tag{2}$$

(a) Along the bottom wall $y = -h$ so that (from Eq. 2)

$$\frac{du}{dy} = \frac{3V}{h}$$

and therefore the shearing stress is

$$\tau_{\substack{\text{bottom}\\\text{wall}}} = \mu\left(\frac{3V}{h}\right) = \frac{(0.04\ \text{lb} \cdot \text{s/ft}^2)(3)(2\ \text{ft/s})}{(0.2\ \text{in.})(1\ \text{ft/12 in.})}$$

$$= 14.4\ \text{lb/ft}^2 \text{ (in direction of flow)} \qquad \textbf{(Ans)}$$

A positive shear stress seems intuitively satisfying. To check your intuition, sketch a sheared fluid particle adjacent to the bottom plate (Fig. E1.5*b*). The fluid motion seems to be trying to drag the plate in the flow direction. Reference to the section in which the concept of viscosity was introduced, and Fig. 1.4 in particular, makes clear that the shear stress on the fluid at the wall is indeed positive. A review of Eq. 2 and the answers to parts a and b of this example makes it clear that the shear stress varies linearly across the flow field.

(b) Along the midplane where $y = 0$ it follows from Eq. 2 that

$$\frac{du}{dy} = 0$$

and thus the shearing stress is

$$\tau_{\text{midplane}} = 0 \qquad \textbf{(Ans)}$$

COMMENT Equation 2 has been evaluated at the bottom plate and mid-plane to provide the answers to parts a and b of this example. If you use it to compute the shear stress at the top plate, you will notice that it produces a shear stress of the same magnitude as at the bottom plate, but of opposite sign. A plot of τ versus y between the plates, Fig. E1.5*b*, confirms both the difference in sign and the earlier observation of the linear relationship. Can you explain the change of sign? [Hint: Sketch a sheared fluid particle adjacent to the top plate.]

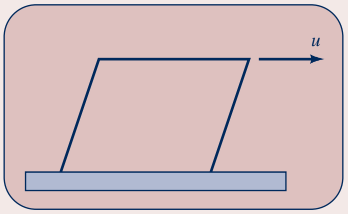


Figure E1.5*b*

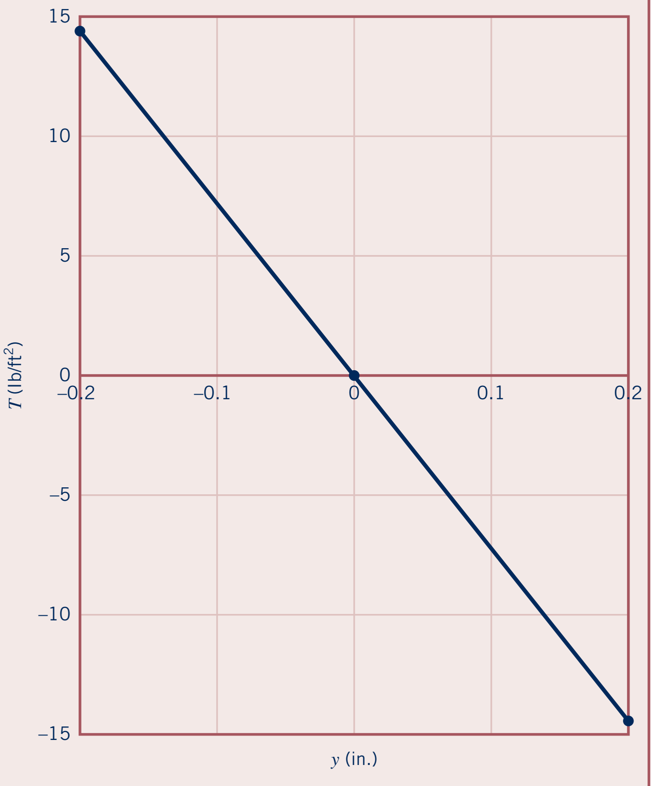


Figure E1.5*c*

Quite often viscosity appears in fluid flow problems combined with the density in the form

$$\nu = \frac{\mu}{\rho}$$

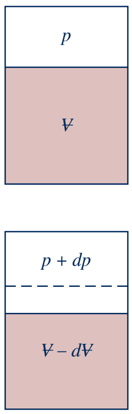
Kinematic viscosity is defined as the ratio of the absolute viscosity to the fluid density.

This ratio is called the ***kinematic viscosity*** and is denoted with the Greek symbol ν (nu). The dimensions of kinematic viscosity are L^2/T, and the BG units are ft^2/s and SI units are m^2/s. Values of kinematic viscosity for some common liquids and gases are given in Tables 1.5 through 1.8. More extensive tables giving both the dynamic and kinematic viscosities for water and air can be found in Appendix B (Tables B.1 through B.4), and graphs showing the variation in both dynamic and kinematic viscosity with temperature for a variety of fluids are also provided in Appendix B (Figs. B.1 and B.2).

Although in this text we are primarily using BG and SI units, dynamic viscosity is often expressed in the metric CGS (centimeter-gram-second) system with units of $\text{dyne} \cdot \text{s/cm}^2$. This combination is called a *poise,* abbreviated P. In the CGS system, kinematic viscosity has units of cm^2/s, and this combination is called a *stoke,* abbreviated St.

1.7 Compressibility of Fluids

1.7.1 Bulk Modulus



An important question to answer when considering the behavior of a particular fluid is how easily can the volume (and thus the density) of a given mass of the fluid be changed when there is a change in pressure? That is, how compressible is the fluid? A property that is commonly used to characterize compressibility is the ***bulk modulus,*** E_v, defined as

$$E_v = -\frac{dp}{d\mathcal{V}/\mathcal{V}} \tag{1.12}$$

where dp is the differential change in pressure needed to create a differential change in volume, $d\mathcal{V}$, of a volume $\mathcal{V}$. This is illustrated by the figure in the margin. The negative sign is included since an increase in pressure will cause a decrease in volume. Since a decrease in volume of a given mass, $m = \rho\mathcal{V}$, will result in an increase in density, Eq. 1.12 can also be expressed as

$$E_v = \frac{dp}{d\rho/\rho} \tag{1.13}$$

VIDEO *V1.7 Water balloon*

The bulk modulus (also referred to as the *bulk modulus of elasticity*) has dimensions of pressure, FL^{-2}. In BG units, values for E_v are usually given as lb/in.^2 (psi) and in SI units as N/m^2 (Pa). Large values for the bulk modulus indicate that the fluid is relatively incompressible—that is, it takes a large pressure change to create a small change in volume. As expected, values of E_v for common liquids are large (see Tables 1.5 and 1.6). For example, at atmospheric pressure and a temperature of 60 °F it would require a pressure of 3120 psi to compress a unit volume of water 1%. This result is representative of the compressibility of liquids. Since such large pressures are required to effect a change in volume, we conclude that liquids can be considered as *incompressible* for most practical engineering applications. As liquids are compressed the bulk modulus increases, but the bulk modulus near atmospheric pressure is usually the one of interest. The use of bulk modulus as a property describing compressibility is most prevalent when dealing with liquids, although the bulk modulus can also be determined for gases.

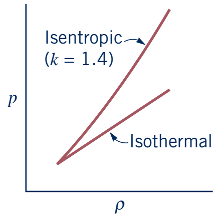
THE WIDE WORLD OF FLUIDS

This water jet is a blast Usually liquids can be treated as incompressible fluids. However, in some applications the *compressibility* of a liquid can play a key role in the operation of a device. For example, a water pulse generator using compressed water has been developed for use in mining operations. It can fracture rock by producing an effect comparable to a conventional explosive such as gunpowder. The device uses the energy stored in a water-filled accumulator to generate an ultrahigh-pressure water pulse ejected through a 10- to 25-mm-diameter discharge valve. At the ultrahigh pressures used (300 to 400 MPa, or 3000 to 4000 atmospheres), the water is compressed (i.e., the volume reduced) by about 10 to 15%. When a fast-opening valve within the pressure vessel is opened, the water expands and produces a jet of water that upon impact with the target material produces an effect similar to the explosive force from conventional explosives. Mining with the water jet can eliminate various hazards that arise with the use of conventional chemical explosives, such as those associated with the storage and use of explosives and the generation of toxic gas by-products that require extensive ventilation. (See Problem 1.110.)

1.7.2 Compression and Expansion of Gases

When gases are compressed (or expanded), the relationship between pressure and density depends on the nature of the process. If the compression or expansion takes place under constant temperature conditions (*isothermal process*), then from Eq. 1.8

$$\frac{p}{\rho} = \text{constant} \tag{1.14}$$



If the compression or expansion is frictionless and no heat is exchanged with the surroundings (*isentropic process*), then

$$\frac{p}{\rho^k} = \text{constant} \tag{1.15}$$

where k is the ratio of the specific heat at constant pressure, c_p, to the specific heat at constant volume, c_v (i.e., $k = c_p/c_v$). The two specific heats are related to the gas constant, R, through the equation $R = c_p - c_v$. As was the case for the ideal gas law, the pressure in both Eqs. 1.14 and 1.15 must be expressed as an absolute pressure. Values of k for some common gases are given in Tables 1.7 and 1.8 and for air over a range of temperatures, in Appendix B (Tables B.3 and B.4). The pressure–density variations for isothermal and isentropic conditions are illustrated in the margin figure.

The value of the bulk modulus depends on the type of process involved.

With explicit equations relating pressure and density, the bulk modulus for gases can be determined by obtaining the derivative $dp/d\rho$ from Eq. 1.14 or 1.15 and substituting the results into Eq. 1.13. It follows that for an isothermal process

$$E_v = p \tag{1.16}$$

and for an isentropic process,

$$E_v = kp \tag{1.17}$$

Note that in both cases the bulk modulus varies directly with pressure. For air under standard atmospheric conditions with $p = 14.7$ psi (abs) and $k = 1.40$, the isentropic bulk modulus is 20.6 psi. A comparison of this figure with that for water under the same conditions ($E_v = 312{,}000$ psi) shows that air is approximately 15,000 times as compressible as water. It is thus clear that in dealing with gases, greater attention will need to be given to the effect of compressibility on fluid behavior. However, as will be discussed further in later sections, gas flows can often be treated as incompressible flows if the changes in pressure are small.

EXAMPLE 1.6 Isentropic Compression of a Gas

GIVEN A cubic foot of air at an absolute pressure of 14.7 psi is compressed isentropically to $\frac{1}{2}$ ft^3 by the tire pump shown in Fig. E1.6*a*.

FIND What is the final pressure?

SOLUTION

For an isentropic compression

$$\frac{p_i}{\rho_i^k} = \frac{p_f}{\rho_f^k}$$

where the subscripts i and f refer to initial and final states, respectively. Since we are interested in the final pressure, p_f, it follows that

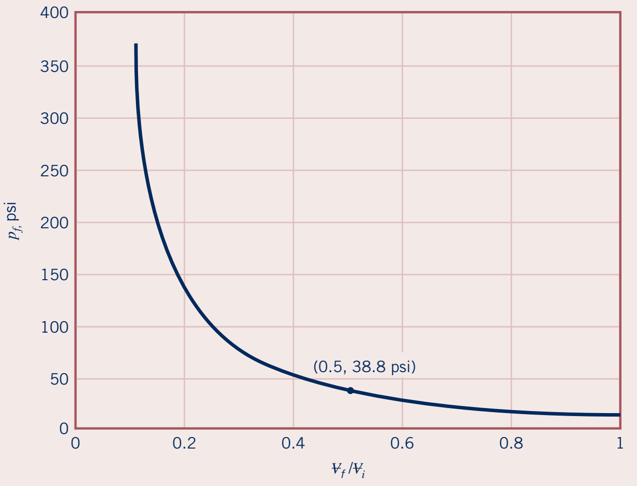
$$p_f = \left(\frac{\rho_f}{\rho_i}\right)^k p_i$$

Figure E1.6*a*

As the volume, $\forall$. is reduced by one-half, the density must double, since the mass, $m = \rho \forall$. of the gas remains constant. Thus, with $k = 1.40$ for air

$$p_f = (2)^{1.40}(14.7 \text{ psi}) = 38.8 \text{ psi (abs)} \qquad \textbf{(Ans)}$$

COMMENT By repeating the calculations for various values of the ratio of the final volume to the initial volume, V_f/V_i, the results shown in Fig. E1.6*b* are obtained. Note that even though air is often considered to be easily compressed (at least compared to liquids), it takes considerable pressure to significantly reduce a given volume of air as is done in an automobile engine where the compression ratio is on the order of $\forall_f/\forall_i = 1/8 = 0.125$.

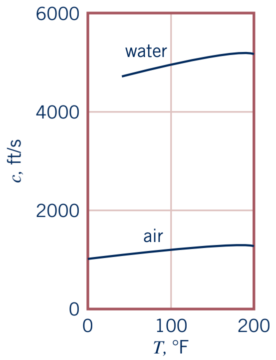


■ **Figure E1.6*b***

1.7.3 Speed of Sound

The velocity at which small disturbances propagate in a fluid is called the speed of sound.

Another important consequence of the compressibility of fluids is that disturbances introduced at some point in the fluid propagate at a finite velocity. For example, if a fluid is flowing in a pipe and a valve at the outlet is suddenly closed (thereby creating a localized disturbance), the effect of the valve closure is not felt instantaneously upstream. It takes a finite time for the increased pressure created by the valve closure to propagate to an upstream location. Similarly, a loudspeaker diaphragm causes a localized disturbance as it vibrates, and the small change in pressure created by the motion of the diaphragm is propagated through the air with a finite velocity. The velocity at which these small disturbances propagate is called the *acoustic velocity* or the ***speed of sound,*** *c*. It will be shown in Chapter 11 that the speed of sound is related to changes in pressure and density of the fluid medium through the equation



$$c = \sqrt{\frac{dp}{d\rho}} \tag{1.18}$$

or in terms of the bulk modulus defined by Eq. 1.13

$$c = \sqrt{\frac{E_v}{\rho}} \tag{1.19}$$

Since the disturbance is small, there is negligible heat transfer and the process is assumed to be isentropic. Thus, the pressure–density relationship used in Eq. 1.18 is that for an isentropic process.

For gases undergoing an isentropic process, $E_v = kp$ (Eq. 1.17) so that

$$c = \sqrt{\frac{kp}{\rho}}$$

and making use of the ideal gas law, it follows that

$$c = \sqrt{kRT} \tag{1.20}$$

VIDEO *V1.8 As fast as a speeding bullet*

Thus, for ideal gases the speed of sound is proportional to the square root of the absolute temperature. For example, for air at 60 °F with $k = 1.40$ and $R = 1716 \text{ ft} \cdot \text{lb/slug} \cdot {}^\circ\text{R}$, it follows that $c = 1117 \text{ ft/s}$. The speed of sound in air at various temperatures can be found in Appendix B (Tables B.3 and B.4). Equation 1.19 is also valid for liquids, and values of E_v can be used to determine the speed of sound in liquids. For water at 20 °C, $E_v = 2.19 \text{ GN/m}^2$ and $\rho = 998.2 \text{ kg/m}^3$ so that $c = 1481 \text{ m/s}$ or 4860 ft/s. As shown by the figure in the margin, the speed of sound is much higher in water than in air. If a fluid were truly incompressible ($E_v = \infty$) the speed of sound would be infinite. The speed of sound in water for various temperatures can be found in Appendix B (Tables B.1 and B.2).

EXAMPLE 1.7 Speed of Sound and Mach Number

GIVEN A jet aircraft flies at a speed of 550 mph at an altitude of 35,000 ft, where the temperature is −66 °F and the specific heat ratio is $k = 1.4$.

FIND Determine the ratio of the speed of the aircraft, V, to that of the speed of sound, c, at the specified altitude.

SOLUTION

From Eq. 1.20 the speed of sound can be calculated as

$$\begin{aligned} c &= \sqrt{kRT} \\ &= \sqrt{(1.40)(1716 \text{ ft lb/slug °R})(-66 + 460)\text{ °R}} \\ &= 973 \text{ ft/s} \end{aligned}$$

Since the air speed is

$$V = \frac{(550 \text{ mi/hr})(5280 \text{ ft/mi})}{(3600 \text{ s/hr})} = 807 \text{ ft/s}$$

the ratio is

$$\frac{V}{c} = \frac{807 \text{ ft/s}}{973 \text{ ft/s}} = 0.829 \qquad \textbf{(Ans)}$$

COMMENT This ratio is called the *Mach number,* Ma. If Ma < 1.0 the aircraft is flying at *subsonic* speeds, whereas for Ma > 1.0 it is flying at *supersonic* speeds. The Mach number is an important dimensionless parameter used in the study of the flow of gases at high speeds and will be further discussed in Chapters 7 and 11.

By repeating the calculations for different temperatures, the results shown in Fig. E1.7 are obtained. Because the speed of sound increases with increasing temperature, for a constant airplane speed, the Mach number decreases as the temperature increases.

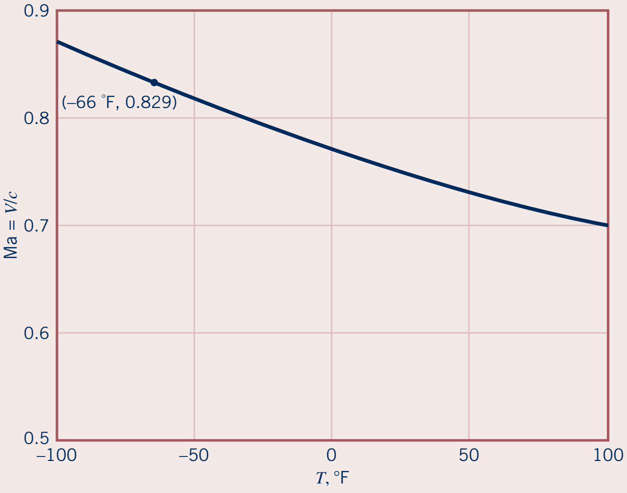
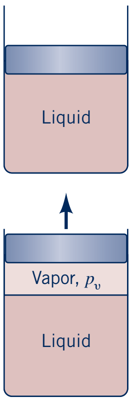


Figure E1.7

1.8 Vapor Pressure

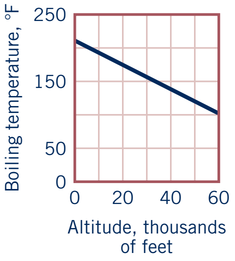


A liquid boils when the pressure is reduced to the vapor pressure.

It is a common observation that liquids such as water and gasoline will evaporate if they are simply placed in a container open to the atmosphere. Evaporation takes place because some liquid molecules at the surface have sufficient momentum to overcome the intermolecular cohesive forces and escape into the atmosphere. If the container is closed with a small air space left above the surface, and this space evacuated to form a vacuum, a pressure will develop in the space as a result of the vapor that is formed by the escaping molecules. When an equilibrium condition is reached so that the number of molecules leaving the surface is equal to the number entering, the vapor is said to be saturated and the pressure that the vapor exerts on the liquid surface is termed the ***vapor pressure,*** p_v. Similarly, if the end of a completely liquid-filled container is moved as shown in the figure in the margin without letting any air into the container, the space between the liquid and the end becomes filled with vapor at a pressure equal to the vapor pressure.

Since the development of a vapor pressure is closely associated with molecular activity, the value of vapor pressure for a particular liquid depends on temperature. Values of vapor pressure for water at various temperatures can be found in Appendix B (Tables B.1 and B.2), and the values of vapor pressure for several common liquids at room temperatures are given in Tables 1.5 and 1.6.

Boiling, which is the formation of vapor bubbles within a fluid mass, is initiated when the absolute pressure in the fluid reaches the vapor pressure. As commonly observed in the kitchen, water at standard atmospheric pressure will boil when the temperature reaches 212 °F (100 °C)—



In flowing liquids it is possible for the pressure in localized regions to reach vapor pressure, thereby causing cavitation.

that is, the vapor pressure of water at 212 °F is 14.7 psi (abs). However, if we attempt to boil water at a higher elevation, say 30,000 ft above sea level (the approximate elevation of Mt. Everest), where the atmospheric pressure is 4.37 psi (abs), we find that boiling will start when the temperature is about 157 °F. At this temperature the vapor pressure of water is 4.37 psi (abs). For the U.S. Standard Atmosphere (see Section 2.4), the boiling temperature is a function of altitude as shown in the figure in the margin. Thus, boiling can be induced at a given pressure acting on the fluid by raising the temperature, or at a given fluid temperature by lowering the pressure.

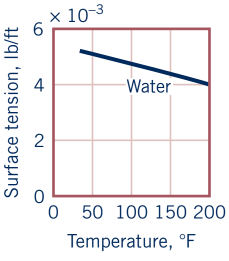
An important reason for our interest in vapor pressure and boiling lies in the common observation that in flowing fluids it is possible to develop very low pressure due to the fluid motion, and if the pressure is lowered to the vapor pressure, boiling will occur. For example, this phenomenon may occur in flow through the irregular, narrowed passages of a valve or pump. When vapor bubbles are formed in a flowing fluid, they are swept along into regions of higher pressure where they suddenly collapse with sufficient intensity to actually cause structural damage. The formation and subsequent collapse of vapor bubbles in a flowing fluid, called *cavitation,* is an important fluid flow phenomenon to be given further attention in Chapters 3 and 7.

1.9 Surface Tension

VIDEO *V1.9 Floating razor blade*

At the interface between a liquid and a gas, or between two immiscible liquids, forces develop in the liquid surface that cause the surface to behave as if it were a "skin" or "membrane" stretched over the fluid mass. Although such a skin is not actually present, this conceptual analogy allows us to explain several commonly observed phenomena. For example, a steel needle or a razor blade will float on water if placed gently on the surface because the tension developed in the hypothetical skin supports it. Small droplets of mercury will form into spheres when placed on a smooth surface because the cohesive forces in the surface of the mercury tend to hold all the molecules together in a compact shape. Similarly, discrete bubbles will form in a liquid. (See the photograph at the beginning of Chapter 1.)

These various types of surface phenomena are due to the unbalanced cohesive forces acting on the liquid molecules at the fluid surface. Molecules in the interior of the fluid mass are surrounded by molecules that are attracted to each other equally. However, molecules along the surface are subjected to a net force toward the interior. The apparent physical consequence of this unbalanced force along the surface is to create the hypothetical skin or membrane. A tensile force may be considered to be acting in the plane of the surface along any line in the surface. The intensity of the molecular attraction per unit length along any line in the surface is called the ***surface tension*** and is designated by the Greek symbol σ (sigma). For a given liquid the surface tension depends on temperature as well as the other fluid it is in contact with at the interface. The dimensions of surface tension are FL^{-1} with BG units of lb/ft and SI units of N/m. Values of surface tension for some common liquids (in contact with air) are given in Appendix B (Tables B.1 and B.2) for water at various temperatures. As indicated by the figure in the margin, the value of the surface tension decreases as the temperature increases.



THE WIDE WORLD OF FLUIDS

Walking on water Water striders are insects commonly found on ponds, rivers, and lakes that appear to "walk" on water. A typical length of a water strider is about 0.4 in., and they can cover 100 body lengths in one second. It has long been recognized that it is *surface tension* that keeps the water strider from sinking below the surface. What has been puzzling is how they propel themselves at such a high speed. They can't pierce the water surface or they would sink. A team of mathematicians and engineers from the Massachusetts Institute of Technology (MIT) applied conventional flow visualization techniques and high-speed video to examine in detail the movement of the water striders. They found that each stroke of the insect's legs creates dimples on the surface with underwater swirling vortices sufficient to propel it forward. It is the rearward motion of the vortices that propels the water strider forward. To further substantiate their explanation, the MIT team built a working model of a water strider, called Robostrider, which creates surface ripples and underwater vortices as it moves across a water surface. Waterborne creatures, such as the water strider, provide an interesting world dominated by surface tension. (See Problem 1.131.)

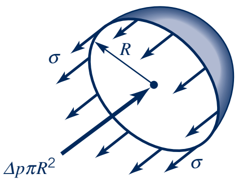


Figure 1.9 **Forces acting on one-half of a liquid drop.**

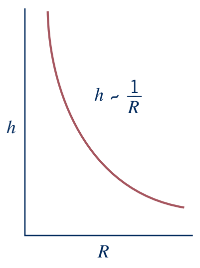
The pressure inside a drop of fluid can be calculated using the free-body diagram in Fig. 1.9. If the spherical drop is cut in half (as shown), the force developed around the edge due to surface tension is $2\pi R\sigma$. This force must be balanced by the pressure difference, Δp, between the internal pressure, p_i, and the external pressure, p_e, acting over the circular area, πR^2. Thus,

VIDEO *V1.10 Capillary rise*

$$2\pi R\sigma = \Delta p\, \pi R^2$$

or

$$\Delta p = p_i - p_e = \frac{2\sigma}{R} \tag{1.21}$$



It is apparent from this result that the pressure inside the drop is greater than the pressure surrounding the drop. (Would the pressure on the inside of a bubble of water be the same as that on the inside of a drop of water of the same diameter and at the same temperature?)

Among common phenomena associated with surface tension is the rise (or fall) of a liquid in a capillary tube. If a small open tube is inserted into water, the water level in the tube will rise above the water level outside the tube, as is illustrated in Fig. 1.10*a*. In this situation we have a liquid–gas–solid interface. For the case illustrated there is an attraction (adhesion) between the wall of the tube and liquid molecules which is strong enough to overcome the mutual attraction (cohesion) of the molecules and pull them up the wall. Hence, the liquid is said to *wet* the solid surface.

The height, h, is governed by the value of the surface tension, σ, the tube radius, R, the specific weight of the liquid, γ, and the *angle of contact,* θ, between the fluid and tube. From the free-body diagram of Fig. 1.10*b* we see that the vertical force due to the surface tension is equal to $2\pi R\sigma \cos\theta$ and the weight is $\gamma\pi R^2 h$, and these two forces must balance for equilibrium. Thus,

VIDEO *V1.11 Contact angle*

$$\gamma\pi R^2 h = 2\pi R\sigma \cos\theta$$

so that the height is given by the relationship

$$h = \frac{2\sigma \cos\theta}{\gamma R} \tag{1.22}$$

The angle of contact is a function of both the liquid and the surface. For water in contact with clean glass $\theta \approx 0°$. It is clear from Eq. 1.22 that the height is inversely proportional to the tube radius, and therefore, as indicated by the figure in the margin, the rise of a liquid in a tube as a result of capillary action becomes increasingly pronounced as the tube radius is decreased.

Capillary action in small tubes, which involves a liquid–gas–solid interface, is caused by surface tension.

If adhesion of molecules to the solid surface is weak compared to the cohesion between molecules, the liquid will not wet the surface and the level in a tube placed in a nonwetting liquid will actually be depressed, as shown in Fig. 1.10*c*. Mercury is a good example of a nonwetting liquid when it is in contact with a glass tube. For nonwetting liquids the angle of contact is greater than 90°, and for mercury in contact with clean glass $\theta \approx 130°$.

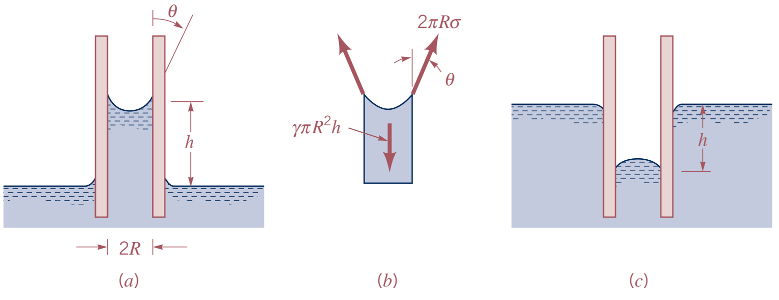


Figure 1.10 **Effect of capillary action in small tubes. (*a*) Rise of column for a liquid that wets the tube. (*b*) Free-body diagram for calculating column height. (*c*) Depression of column for a nonwetting liquid.**

EXAMPLE 1.8 Capillary Rise in a Tube

GIVEN Pressures are sometimes determined by measuring the height of a column of liquid in a vertical tube.

FIND What diameter of clean glass tubing is required so that the rise of water at 20 °C in a tube due to capillary action (as opposed to pressure in the tube) is less than $h = 1.0$ mm?

SOLUTION

From Eq. 1.22

$$h = \frac{2\sigma \cos\theta}{\gamma R}$$

so that

$$R = \frac{2\sigma \cos\theta}{\gamma h}$$

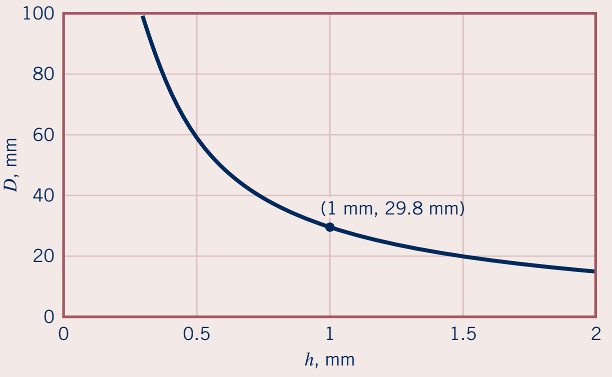
For water at 20 °C (from Table B.2), $\sigma = 0.0728$ N/m and $\gamma = 9.789$ kN/m^3. Since $\theta \approx 0°$ it follows that for $h = 1.0$ mm,

$$R = \frac{2(0.0728 \text{ N/m})(1)}{(9.789 \times 10^3 \text{ N/m}^3)(1.0 \text{ mm})(10^{-3} \text{ m/mm})}$$
$$= 0.0149 \text{ m}$$

and the minimum required tube diameter, D, is

$$D = 2R = 0.0298 \text{ m} = 29.8 \text{ mm} \qquad \textbf{(Ans)}$$

COMMENT By repeating the calculations for various values of the capillary rise, h, the results shown in Fig. E1.8 are obtained. Note that as the allowable capillary rise is decreased, the diameter of the tube must be significantly increased. There is always some capillarity effect, but it can be minimized by using a large enough diameter tube.



■ Figure E1.8

(Photograph copyright 2007 by Andrew Davidhazy, Rochester Institute of Technology.)

Surface tension effects play a role in many fluid mechanics problems, including the movement of liquids through soil and other porous media, flow of thin films, formation of drops and bubbles, and the breakup of liquid jets. For example, surface tension is a main factor in the formation of drops from a leaking faucet, as shown in the photograph in the margin. Surface phenomena associated with liquid–gas, liquid–liquid, and liquid–gas–solid interfaces are exceedingly complex, and a more detailed and rigorous discussion of them is beyond the scope of this text. Fortunately, in many fluid mechanics problems, surface phenomena, as characterized by surface tension, are not important, since inertial, gravitational, and viscous forces are much more dominant.

THE WIDE WORLD OF FLUIDS

Spreading of oil spills With the large traffic in oil tankers there is great interest in the prevention of and response to oil spills. As evidenced by the famous *Exxon Valdez* oil spill in Prince William Sound in 1989, oil spills can create disastrous environmental problems. A more recent example of this type of catastrophe is the oil spill that occurred in the Gulf of Mexico in 2010. It is not surprising that much attention is given to the rate at which an oil spill spreads. When spilled, most oils tend to spread horizontally into a smooth and slippery surface, called a slick. There are many factors that influence the ability of an oil slick to spread, including the size of the spill, wind speed and direction, and the physical properties of the oil. These properties include *surface tension, specific gravity*, and *viscosity*. The higher the surface tension the more likely a spill will remain in place. Since the specific gravity of oil is less than one, it floats on top of the water, but the specific gravity of an oil can increase if the lighter substances within the oil evaporate. The higher the viscosity of the oil, the greater the tendency to stay in one place.

1.10 A Brief Look Back in History

Some of the earliest writings that pertain to modern fluid mechanics can be traced back to the ancient Greek civilization and subsequent Roman Empire.

Before proceeding with our study of fluid mechanics, we should pause for a moment to consider the history of this important engineering science. As is true of all basic scientific and engineering disciplines, their actual beginnings are only faintly visible through the haze of early antiquity. But we know that interest in fluid behavior dates back to the ancient civilizations. Through necessity there was a practical concern about the manner in which spears and arrows could be propelled through the air, in the development of water supply and irrigation systems, and in the design of boats and ships. These developments were, of course, based on trial-and-error procedures. However, it was the accumulation of such empirical knowledge that formed the basis for further development during the emergence of the ancient Greek civilization and the subsequent rise of the Roman Empire. Some of the earliest writings that pertain to modern fluid mechanics are those of Archimedes (287–212 B.C.), a Greek mathematician and inventor who first expressed the principles of hydrostatics and flotation. Elaborate water supply systems were built by the Romans during the period from the fourth century B.C. through the early Christian period, and Sextus Julius Frontinus (A.D. 40–103), a Roman engineer, described these systems in detail. However, for the next 1000 years during the Middle Ages (also referred to as the Dark Ages), there appears to have been little added to further understanding of fluid behavior.

As shown in Fig. 1.11, beginning with the Renaissance period (about the fifteenth century) a rather continuous series of contributions began that forms the basis of what we consider to be the science of fluid mechanics. Leonardo da Vinci (1452–1519) described through sketches and writings many different types of flow phenomena. The work of Galileo Galilei (1564–1642) marked the beginning of experimental mechanics. Following the early Renaissance period and during the seventeenth and eighteenth centuries, numerous significant contributions were made. These include theoretical and mathematical advances associated with the famous names of Newton, Bernoulli, Euler, and d'Alembert. Experimental aspects of fluid mechanics were also advanced during this period, but unfortunately the two different approaches, theoretical and experimental, developed along separate paths. *Hydrodynamics* was the term associated with the theoretical or mathematical study of idealized, frictionless fluid behavior, with the term *hydraulics* being used to describe the applied or experimental aspects of real fluid behavior, particularly the behavior of water. Further contributions and refinements were made to both theoretical hydrodynamics and experimental hydraulics during the nineteenth century, with the general differential equations describing fluid motions that are used in modern fluid mechanics being developed in this period. Experimental hydraulics became more of a science, and many of the results of experiments performed during the nineteenth century are still used today.

At the beginning of the twentieth century, both the fields of theoretical hydrodynamics and experimental hydraulics were highly developed, and attempts were being made to unify the two. In 1904 a classic paper was presented by a German professor, Ludwig Prandtl (1875–1953), who introduced the concept of a "fluid boundary layer," which laid the foundation for the unification of the theoretical and experimental aspects of fluid mechanics. Prandtl's idea was that for flow next to a

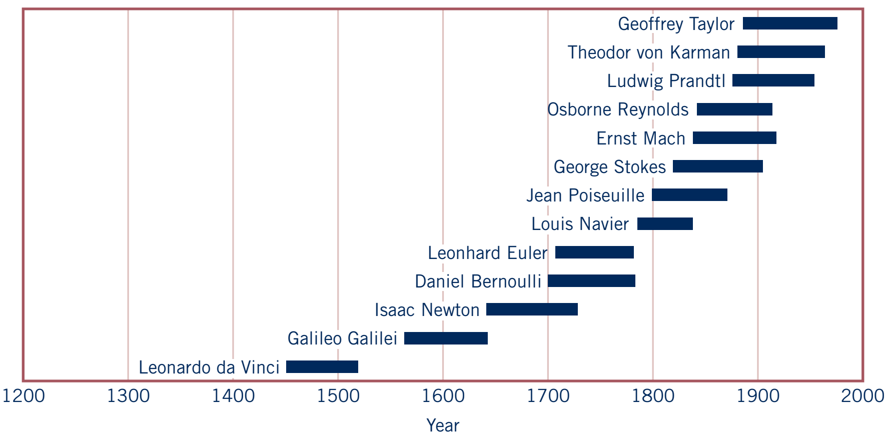


Figure 1.11 **Time line of some contributors to the science of fluid mechanics.**

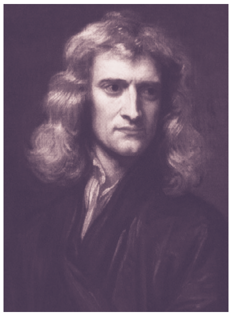
The rich history of fluid mechanics is fascinating, and many of the contributions of the pioneers in the field are noted in the succeeding chapters.

solid boundary a thin fluid layer (boundary layer) develops in which friction (viscous force) is important, but outside this layer the fluid behaves very much like a frictionless fluid. This relatively simple concept provided the necessary impetus for the resolution of the conflict between the hydrodynamicists and the hydraulicists. Prandtl is generally accepted as the founder of modern fluid mechanics.

Also, during the first decade of the twentieth century, powered flight was first successfully demonstrated with the subsequent vastly increased interest in *aerodynamics.* Because the design of aircraft required an understanding of fluid flow and an ability to make accurate predictions of the effect of airflow on bodies, the field of aerodynamics provided a great stimulus for the many rapid developments in fluid mechanics that took place during the twentieth century.

As we proceed with our study of the fundamentals of fluid mechanics, we will continue to note the contributions of many of the pioneers in the field. Table 1.9 provides a chronological listing

Leonardo da Vinci



Isaac Newton

Daniel Bernoulli

Ernst Mach

Table 1.9

Chronological Listing of Some Contributors to the Science of Fluid Mechanics Noted in the Text[a]

ARCHIMEDES (287– 212 B.C.)
Established elementary principles of buoyancy and flotation.

SEXTUS JULIUS FRONTINUS (A.D. 40–103)
Wrote treatise on Roman methods of water distribution.

LEONARDO da VINCI (1452–1519)
Expressed elementary principle of continuity; observed and sketched many basic flow phenomena; suggested designs for hydraulic machinery.

GALILEO GALILEI (1564–1642)
Indirectly stimulated experimental hydraulics; revised Aristotelian concept of vacuum.

EVANGELISTA TORRICELLI (1608–1647)
Related barometric height to weight of atmosphere, and form of liquid jet to trajectory of free fall.

BLAISE PASCAL (1623–1662)
Finally clarified principles of barometer, hydraulic press, and pressure transmissibility.

ISAAC NEWTON (1642–1727)
Explored various aspects of fluid resistance—inertial, viscous, and wave; discovered jet contraction.

HENRI de PITOT (1695–1771)
Constructed double-tube device to indicate water velocity through differential head.

DANIEL BERNOULLI (1700–1782)
Experimented and wrote on many phases of fluid motion, coining name "hydrodynamics"; devised manometry technique and adapted primitive energy principle to explain velocity-head indication; proposed jet propulsion.

LEONHARD EULER (1707–1783)
First explained role of pressure in fluid flow; formulated basic equations of motion and so-called Bernoulli theorem; introduced concept of cavitation and principle of centrifugal machinery.

JEAN le ROND d'ALEMBERT (1717–1783)
Originated notion of velocity and acceleration components, differential expression of continuity, and paradox of zero resistance to steady nonuniform motion.

ANTOINE CHEZY (1718–1798)
Formulated similarity parameter for predicting flow characteristics of one channel from measurements on another.

GIOVANNI BATTISTA VENTURI (1746–1822)
Performed tests on various forms of mouthpieces—in particular, conical contractions and expansions.

LOUIS MARIE HENRI NAVIER (1785–1836)
Extended equations of motion to include "molecular" forces.

AUGUSTIN LOUIS de CAUCHY (1789–1857)
Contributed to the general field of theoretical hydrodynamics and to the study of wave motion.

GOTTHILF HEINRICH LUDWIG HAGEN (1797–1884)
Conducted original studies of resistance in and transition between laminar and turbulent flow.

JEAN LOUIS POISEUILLE (1799–1869)
Performed meticulous tests on resistance of flow through capillary tubes.

HENRI PHILIBERT GASPARD DARCY (1803–1858)
Performed extensive tests on filtration and pipe resistance; initiated open-channel studies carried out by Bazin.

JULIUS WEISBACH (1806–1871)
Incorporated hydraulics in treatise on engineering mechanics, based on original experiments; noteworthy for flow patterns, nondimensional coefficients, weir, and resistance equations.

WILLIAM FROUDE (1810–1879)
Developed many towing-tank techniques, in particular the conversion of wave and boundary layer resistance from model to prototype scale.

ROBERT MANNING (1816–1897)
Proposed several formulas for open-channel resistance.

GEORGE GABRIEL STOKES (1819–1903)
Derived analytically various flow relationships ranging from wave mechanics to viscous resistance—particularly that for the settling of spheres.

ERNST MACH (1838–1916)
One of the pioneers in the field of supersonic aerodynamics.


Osborne Reynolds


Ludwig Prandtl

Table 1.9 (continued)

OSBORNE REYNOLDS (1842–1912)
Described original experiments in many fields—cavitation, river model similarity, pipe resistance—and devised two parameters for viscous flow; adapted equations of motion of a viscous fluid to mean conditions of turbulent flow.

JOHN WILLIAM STRUTT, LORD RAYLEIGH (1842–1919)
Investigated hydrodynamics of bubble collapse, wave motion, jet instability, laminar flow analogies, and dynamic similarity.

VINCENZ STROUHAL (1850–1922)
Investigated the phenomenon of "singing wires."

EDGAR BUCKINGHAM (1867–1940)
Stimulated interest in the United States in the use of dimensional analysis.

MORITZ WEBER (1871–1951)
Emphasized the use of the principles of similitude in fluid flow studies and formulated a capillarity similarity parameter.

LUDWIG PRANDTL (1875–1953)
Introduced concept of the boundary layer and is generally considered to be the father of present-day fluid mechanics.

LEWIS FERRY MOODY (1880–1953)
Provided many innovations in the field of hydraulic machinery. Proposed a method of correlating pipe resistance data that is widely used.

THEODOR VON KÁRMÁN (1881–1963)
One of the recognized leaders of twentieth century fluid mechanics. Provided major contributions to our understanding of surface resistance, turbulence, and wake phenomena.

PAUL RICHARD HEINRICH BLASIUS (1883–1970)
One of Prandtl's students who provided an analytical solution to the boundary layer equations. Also demonstrated that pipe resistance was related to the Reynolds number.

[a]Used by permission of IIHR—Hydroscience & Engineering, The University of Iowa.

of some of these contributors and reveals the long journey that makes up the history of fluid mechanics. This list is certainly not comprehensive with regard to all past contributors but includes those who are mentioned in this text. As mention is made in succeeding chapters of the various individuals listed in Table 1.9, a quick glance at this table will reveal where they fit into the historical chain.

It is, of course, impossible to summarize the rich history of fluid mechanics in a few paragraphs. Only a brief glimpse is provided, and we hope it will stir your interest. References 2 to 5 are good starting points for further study, and in particular Ref. 2 provides an excellent, broad, easily read history. Try it—you might even enjoy it!

1.11 Chapter Summary and Study Guide

This introductory chapter discussed several fundamental aspects of fluid mechanics. Methods for describing fluid characteristics both quantitatively and qualitatively are considered. For a quantitative description, units are required. The concept of dimensions is introduced in which basic dimensions such as length, L, time, T, and mass, M, are used to provide a description of various quantities of interest. The use of dimensions is helpful in checking the generality of equations, as well as serving as the basis for the powerful tool of dimensional analysis discussed in detail in Chapter 7.

Various important fluid properties are defined, including fluid density, specific weight, specific gravity, viscosity, bulk modulus, speed of sound, vapor pressure, and surface tension. The ideal gas law is introduced to relate pressure, temperature, and density in common gases, along with a brief discussion of the compression and expansion of gases. The distinction between absolute and gage pressure is introduced. This important idea is explored more fully in Chapter 2.

The following checklist provides a study guide for this chapter. When your study of the entire chapter and end-of-chapter exercises has been completed you should be able to

- write out meanings of the terms listed here in the margin and understand each of the related concepts. These terms are particularly important and are set in ***italic, bold, and color*** type in the text.
- determine the dimensions of common physical quantities.
- determine whether an equation is a general or restricted homogeneous equation.

fluid
units
basic dimensions
dimensionally homogeneous
density
specific weight
specific gravity
ideal gas law
absolute pressure
gage pressure
no-slip condition
rate of shearing strain
absolute viscosity
Newtonian fluid
non-Newtonian fluid
kinematic viscosity
bulk modulus
speed of sound
vapor pressure
surface tension

- correctly use units and systems of units in your analyses and calculations.
- calculate the density, specific weight, or specific gravity of a fluid from a knowledge of any two of the three.
- calculate the density, pressure, or temperature of an ideal gas (with a given gas constant) from a knowledge of any two of the three.
- relate the pressure and density of a gas as it is compressed or expanded using Eqs. 1.14 and 1.15.
- use the concept of viscosity to calculate the shearing stress in simple fluid flows.
- calculate the speed of sound in fluids using Eq. 1.19 for liquids and Eq. 1.20 for gases.
- determine whether boiling or cavitation will occur in a liquid using the concept of vapor pressure.
- use the concept of surface tension to solve simple problems involving liquid–gas or liquid–solid–gas interfaces.

Some of the important equations in this chapter are:

Specific weight	$\gamma = \rho g$	**(1.6)**
Specific gravity	$SG = \dfrac{\rho}{\rho_{H_2O@4\,°C}}$	**(1.7)**
Ideal gas law	$p = \rho RT$	**(1.8)**
Newtonian fluid shear stress	$\tau = \mu \dfrac{du}{dy}$	**(1.9)**
Bulk modulus	$E_v = -\dfrac{dp}{d\forall/\forall}$	**(1.12)**
Speed of sound in an ideal gas	$c = \sqrt{kRT}$	**(1.20)**
Capillary rise in a tube	$h = \dfrac{2\sigma \cos \theta}{\gamma R}$	**(1.22)**

References

1. Reid, R. C., Prausnitz, J. M., and Sherwood, T. K., *The Properties of Gases and Liquids,* 3rd Ed., McGraw-Hill, New York, 1977.
2. Rouse, H. and Ince, S., *History of Hydraulics,* Iowa Institute of Hydraulic Research, Iowa City, 1957, Dover, New York, 1963.
3. Tokaty, G. A., *A History and Philosophy of Fluid Mechanics,* G. T. Foulis and Co., Ltd., Oxfordshire, Great Britain, 1971.
4. Rouse, H., *Hydraulics in the United States 1776–1976,* Iowa Institute of Hydraulic Research, Iowa City, Iowa, 1976.
5. Garbrecht, G., ed., *Hydraulics and Hydraulic Research—A Historical Review,* A. A. Balkema, Rotterdam, Netherlands, 1987.
6. Brenner, M. P., Shi, X. D., Eggens, J., and Nagel, S. R., *Physics of Fluids,* Vol. 7, No. 9, 1995.
7. Shi, X. D., Brenner, M. P., and Nagel, S. R., *Science,* Vol. 265, 1994.

▶ Problem is related to a chapter video available in *WileyPLUS.*

* Problem to be solved with aid of programmable calculator or computer.

† Open-ended problem that requires critical thinking. These problems require various assumptions to provide the necessary input data. There are no unique answers to these problems.

Problems

Note: Unless specific values of required fluid properties are given in the problem statement, use the values found in the tables on the inside of the front cover.

Section 1.2 Dimensions, Dimensional Homogeneity, and Units

1.1 The force, F, of the wind blowing against a building is given by $F = C_D \rho V^2 A/2$, where V is the wind speed, ρ the density of the air, A the cross-sectional area of the building, and C_D is a constant termed the drag coefficient. Determine the dimensions of the drag coefficient.

1.2 The Mach number is a dimensionless ratio of the velocity of an object in a fluid to the speed of sound in the fluid. For an airplane flying at velocity V in air at absolute temperature T, the Mach number Ma is

$$\text{Ma} = \frac{V}{\sqrt{kRT}},$$

where k is a dimensionless constant and R is the specific gas constant for air. Show that Ma is dimensionless.

1.3 Verify the dimensions, in both the FLT and MLT systems, of the following quantities which appear in Table 1.1: **(a)** volume, **(b)** acceleration, **(c)** mass, **(d)** moment of inertia (area), and **(e)** work.

1.4 Verify the dimensions, in both the FLT and MLT systems, of the following quantities which appear in Table 1.1: **(a)** angular velocity, **(b)** energy, **(c)** moment of inertia (area), **(d)** power, and **(e)** pressure.

1.5 Verify the dimensions, in both the FLT system and the MLT system, of the following quantities which appear in Table 1.1: **(a)** frequency, **(b)** stress, **(c)** strain, **(d)** torque, and **(e)** work.

1.6 If u is a velocity, x a length, and t a time, what are the dimensions (in the MLT system) of **(a)** $\partial u/\partial t$, **(b)** $\partial^2 u/\partial x \partial t$, and **(c)** $\int (\partial u/\partial t)\, dx$?

1.7 Verify the dimensions, in both the FLT system and the MLT system, of the following quantities which appear in Table 1.1: **(a)** acceleration, **(b)** stress, **(c)** moment of a force, **(d)** volume, and **(e)** work.

1.8 If p is a pressure, V a velocity, and ρ a fluid density, what are the dimensions (in the MLT system) of **(a)** p/ρ, **(b)** $pV\rho$, and **(c)** $p/\rho V^2$?

1.9 If P is a force and x a length, what are the dimensions (in the FLT system) of **(a)** dP/dx, **(b)** d^3P/dx^3, and **(c)** $\int P\, dx$?

1.10 If V is a velocity, ℓ a length, and ν a fluid property (the kinematic viscosity) having dimensions of L^2T^{-1}, which of the following combinations are dimensionless: **(a)** $V\ell\nu$, **(b)** $V\ell/\nu$, **(c)** $V^2\nu$, **(d)** $V/\ell\nu$?

1.11 The momentum flux (discussed in Chapter 5) is given by the product $\dot{m}V$, where $\dot{m}$ is mass flow rate and V is velocity. If mass flow rate is given in units of mass per unit time, show that the momentum flux can be expressed in units of force.

1.12 An equation for the frictional pressure loss Δp (inches H_2O) in a circular duct of inside diameter d (in.) and length L (ft) for air flowing with velocity V (ft/min) is

$$\Delta p = 0.027\left(\frac{L}{d^{1.22}}\right)\left(\frac{V}{V_0}\right)^{1.82},$$

where V_0 is a reference velocity equal to 1000 ft/min. Find the units of the "constant" 0.027.

1.13 The volume rate of flow, Q, through a pipe containing a slowly moving liquid is given by the equation

$$Q = \frac{\pi R^4 \Delta p}{8\mu\ell}$$

where R is the pipe radius, Δp the pressure drop along the pipe, μ a fluid property called viscosity $(FL^{-2}T)$, and ℓ the length of pipe. What are the dimensions of the constant $\pi/8$? Would you classify this equation as a general homogeneous equation? Explain.

1.14 Show that each term in the following equation has units of lb/ft^3. Consider u a velocity, y a length, x a length, p a pressure, and μ an absolute viscosity.

$$0 = -\frac{\partial p}{\partial x} + \mu\frac{\partial^2 u}{\partial y^2}.$$

1.15 The pressure difference, Δp, across a partial blockage in an artery (called a *stenosis*) is approximated by the equation

$$\Delta p = K_v \frac{\mu V}{D} + K_u\left(\frac{A_0}{A_1} - 1\right)^2 \rho V^2$$

where V is the blood velocity, μ the blood viscosity $(FL^{-2}T)$, ρ the blood density (ML^{-3}), D the artery diameter, A_0 the area of the unobstructed artery, and A_1 the area of the stenosis. Determine the dimensions of the constants K_v and K_u. Would this equation be valid in any system of units?

1.16 Assume that the speed of sound, c, in a fluid depends on an elastic modulus, E_v, with dimensions FL^{-2}, and the fluid density, ρ, in the form $c = (E_v)^a(\rho)^b$. If this is to be a dimensionally homogeneous equation, what are the values for a and b? Is your result consistent with the standard formula for the speed of sound? (See Eq. 1.19.)

1.17 A formula to estimate the volume rate of flow, Q, flowing over a dam of length, B, is given by the equation

$$Q = 3.09\, BH^{3/2}$$

where H is the depth of the water above the top of the dam (called the head). This formula gives Q in ft^3/s when B and H are in feet. Is the constant, 3.09, dimensionless? Would this equation be valid if units other than feet and seconds were used?

1.18 A commercial advertisement shows a pearl falling in a bottle of shampoo. If the diameter D of the pearl is quite small and the shampoo sufficiently viscous, the drag $\mathcal{D}$ on the pearl is given by Stokes's law,

$$\mathcal{D} = 3\pi\mu VD,$$

where V is the speed of the pearl and μ is the fluid viscosity. Show that the term on the right side of Stokes's law has units of force.

†**1.19** Cite an example of a restricted homogeneous equation contained in a technical article found in an engineering journal in your field of interest. Define all terms in the equation, explain why it is a restricted equation, and provide a complete journal citation (title, date, etc.).

1.20 Express the following quantities in SI units: **(a)** 10.2 in./min, **(b)** 4.81 slugs, **(c)** 3.02 lb, **(d)** 73.1 ft/s^2, **(e)** 0.0234 $\text{lb} \cdot \text{s/ft}^2$.

1.21 Express the following quantities in BG units: **(a)** 14.2 km, **(b)** 8.14 N/m^3, **(c)** 1.61 kg/m^3, **(d)** 0.0320 $\text{N} \cdot \text{m/s}$, **(e)** 5.67 mm/hr.

1.22 Express the following quantities in SI units: **(a)** 160 acres, **(b)** 15 gallons (U.S.), **(c)** 240 miles, **(d)** 79.1 hp, **(e)** 60.3 °F.

1.23 Water flows from a large drainage pipe at a rate of 1200 gal/min. What is this volume rate of flow in **(a)** $\text{m}^3\text{/s}$, **(b)** liters/min, and **(c)** $\text{ft}^3\text{/s}$?

1.24 The universal gas constant R_0 is equal to 49,700 $\text{ft}^2/(\text{s}^2 \cdot °\text{R})$, or 8310 $\text{m}^2/(\text{s}^2 \cdot \text{K})$. Show that these two magnitudes are equal.

1.25 Dimensionless combinations of quantities (commonly called dimensionless parameters) play an important role in fluid mechanics. Make up five possible dimensionless parameters by using combinations of some of the quantities listed in Table 1.1.

1.26 An important dimensionless parameter in certain types of fluid flow problems is the *Froude number* defined as $V/\sqrt{g\ell}$, where V is a velocity, g the acceleration of gravity, and ℓ a length. Determine the value of the Froude number for $V = 10$ ft/s, $g = 32.2$ ft/s^2, and $\ell = 2$ ft. Recalculate the Froude number using SI units for V, g, and ℓ. Explain the significance of the results of these calculations.

Section 1.4 Measures of Fluid Mass and Weight

1.27 Obtain a photograph/image of a situation in which the density or specific weight of a fluid is important. Print this photo and write a brief paragraph that describes the situation involved.

1.28 A tank contains 500 kg of a liquid whose specific gravity is 2. Determine the volume of the liquid in the tank.

1.29 A stick of butter at 35 °F measures 1.25 in. × 1.25 in. × 4.65 in. and weighs 4 ounces. Find its specific weight.

1.30 Clouds can weigh thousands of pounds due to their liquid water content. Often this content is measured in grams per cubic meter (g/m^3). Assume that a cumulus cloud occupies a volume of one cubic kilometer, and its liquid water content is 0.2 g/m^3. **(a)** What is the volume of this cloud in cubic miles? **(b)** How much does the water in the cloud weigh in pounds?

1.31 A tank of oil has a mass of 25 slugs. **(a)** Determine its weight in pounds and in newtons at the Earth's surface. **(b)** What would be its mass (in slugs) and its weight (in pounds) if located on the moon's surface where the gravitational attraction is approximately one-sixth that at the Earth's surface?

1.32 A certain object weighs 300 N at the Earth's surface. Determine the mass of the object (in kilograms) and its weight (in newtons) when located on a planet with an acceleration of gravity equal to 4.0 ft/s^2.

1.33 The density of a certain type of jet fuel is 775 kg/m^3. Determine its specific gravity and specific weight.

1.34 At 4 °C a mixture of automobile antifreeze (50% water and 50% ethylene glycol by volume) has a density of 1064 kg/m^3. If the water density is 1000 kg/m^3, find the density of the ethylene glycol.

1.35 A *hydrometer* is used to measure the specific gravity of liquids. (See **Video V2.8**.) For a certain liquid, a hydrometer reading indicates a specific gravity of 1.15.What is the liquid's density and specific weight?Express your answer in SI units.

1.36 An open, rigid-walled, cylindrical tank contains 4 ft^3 of water at 40 °F. Over a 24-hour period of time the water temperature varies from 40 to 90 °F. Make use of the data in Appendix B to determine how much the volume of water will change. For a tank diameter of 2 ft, would the corresponding change in water depth be very noticeable? Explain.

†**1.37** Estimate the number of pounds of mercury it would take to fill your bathtub. List all assumptions and show all calculations.

1.38 A mountain climber's oxygen tank contains 1 lb of oxygen when he begins his trip at sea level where the acceleration of gravity is 32.174 ft/s^2. What is the weight of the oxygen in the tank when he reaches the top of Mt. Everest where the acceleration of gravity is 32.082 ft/s^2? Assume that no oxygen has been removed from the tank; it will be used on the descent portion of the climb.

1.39 The information on a can of pop indicates that the can contains 355 mL. The mass of a full can of pop is 0.369 kg, while an empty can weighs 0.153 N. Determine the specific weight, density, and specific gravity of the pop and compare your results with the corresponding values for water at 20 °C. Express your results in SI units.

***1.40** The variation in the density of water, ρ, with temperature, T, in the range 20 °C ≤ T ≤ 50 °C, is given in the following table.

Density (kg/m^3)	998.2	997.1	995.7	994.1	992.2	990.2	988.1
Temperature (°C)	20	25	30	35	40	45	50

Use these data to determine an empirical equation of the form $\rho = c_1 + c_2T + c_3T^2$ which can be used to predict the density over the range indicated. Compare the predicted values with the data given. What is the density of water at 42.1 °C?

1.41 If 1 cup of cream having a density of 1005 kg/m^3 is turned into 3 cups of whipped cream, determine the specific gravity and specific weight of the whipped cream.

1.42 With the exception of the 410 bore, the gauge of a shotgun barrel indicates the number of round lead balls, each having the bore diameter of the barrel, that together weigh 1 lb. For example, a shotgun is called a 12-gauge shotgun if a $\frac{1}{12}$-lb lead ball fits the bore of the barrel. Find the diameter of a 12-gauge shotgun in inches and millimeters. Lead has a specific weight of 0.411 lb/in^3.

†**1.43** The presence of raindrops in the air during a heavy rainstorm increases the average density of the air–water mixture. Estimate by what percent the average air–water density is greater than that of just still air. State all assumptions and show calculations.

Section 1.5 Ideal Gas Law

1.44 A regulation basketball is initially flat and is then inflated to a pressure of approximately 24 lb/in^2 absolute. Consider the air temperature to be constant at 70 °F. Find the mass of air required to inflate the basketball. The basketball's inside radius is 4.67 in.

1.45 Nitrogen is compressed to a density of 4 kg/m^3 under an absolute pressure of 400 kPa. Determine the temperature in degrees Celsius.

1.46 The temperature and pressure at the surface of Mars during a Martian spring day were determined to be -50 °C and 900 Pa, respectively. **(a)** Determine the density of the Martian atmosphere for these conditions if the gas constant for the Martian atmosphere is assumed to be equivalent to that of carbon dioxide. **(b)** Compare the answer from part (a) with the density of the Earth's atmosphere during a spring day when the temperature is 18 °C and the pressure 101.6 kPa (abs).

1.47 A closed tank having a volume of 2 ft^3 is filled with 0.30 lb of a gas. A pressure gage attached to the tank reads 12 psi when the gas temperature is 80 °F. There is some question as to whether the gas in the tank is oxygen or helium. Which do you think it is? Explain how you arrived at your answer.

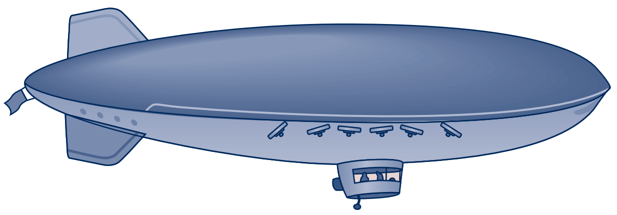
1.48 Assume that the air volume in a small automobile tire is constant and equal to the volume between two concentric cylinders 13 cm high with diameters of 33 cm and 52 cm. The air in the tire is initially at 25 °C and 202 kPa. Immediately after air is pumped into the tire, the temperature is 30 °C and the pressure is 303 kPa. What mass of air was added to the tire? What would be the air pressure after the air has cooled to a temperature of 0 °C?

1.49 A compressed air tank contains 5 kg of air at a temperature of 80 °C. A gage on the tank reads 300 kPa. Determine the volume of the tank.

1.50 A rigid tank contains air at a pressure of 90 psia and a temperature of 60 °F. By how much will the pressure increase as the temperature is increased to 110 °F?

1.51 The density of oxygen contained in a tank is 2.0 kg/m^3 when the temperature is 25 °C. Determine the gage pressure of the gas if the atmospheric pressure is 97 kPa.

1.52 The helium-filled blimp shown in Fig. P1.52 is used at various athletic events. Determine the number of pounds of helium within it if its volume is 68,000 ft^3 and the temperature and pressure are 80 °F and 14.2 psia, respectively.



■ Figure P1.52

***1.53** Develop a computer program for calculating the density of an ideal gas when the gas pressure in pascals (abs), the temperature in degrees Celsius, and the gas constant in J/kg · K are specified. Plot the density of helium as a function of temperature from 0 °C to 200 °C and pressures of 50, 100, 150, and 200 kPa (abs).

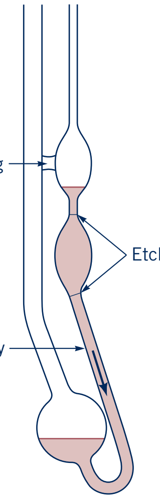
Section 1.6 Viscosity (also see Lab Problems 1.1LP and 1.2LP)

1.54 Obtain a photograph/image of a situation in which the viscosity of a fluid is important. Print this photo and write a brief paragraph that describes the situation involved.

1.55 For flowing water, what is the magnitude of the velocity gradient needed to produce a shear stress of 1.0 N/m^2?

1.56 Make use of the data in Appendix B to determine the dynamic viscosity of glycerin at 85 °F. Express your answer in both SI and BG units.

1.57 One type of *capillary-tube viscometer* is shown in **Video V1.5** and in Fig. P1.57. For this device the liquid to be tested is drawn into the tube to a level above the top etched line. The time is then obtained for the liquid to drain to the bottom etched line. The kinematic viscosity, ν, in m^2/s is then obtained from the equation $\nu = KR^4t$ where K is a constant, R is the radius of the capillary tube in mm, and t is the drain time in seconds. When glycerin at 20 °C is used as a calibration fluid in a particular viscometer, the drain time is 1430 s. When a liquid having a density of 970 kg/m^3 is tested in the same viscometer the drain time is 900 s. What is the dynamic viscosity of this liquid?



■ Figure P1.57

1.58 The viscosity of a soft drink was determined by using a capillary tube viscometer similar to that shown in Fig. P1.58 and **Video V1.5**. For this device the kinematic viscosity, ν, is directly proportional to the time, t, that it takes for a given amount of liquid to flow through a small capillary tube. That is, $\nu = Kt$. The following data were obtained from regular pop and diet pop. The corresponding measured specific gravities are also given. Based on these data, by what percent is the absolute viscosity, μ, of regular pop greater than that of diet pop?

	Regular pop	Diet pop
t(s)	377.8	300.3
SG	1.044	1.003

1.59 The viscosity of a certain fluid is 5×10^{-4} poise. Determine its viscosity in both SI and BG units.

1.60 The kinematic viscosity and specific gravity of a liquid are 3.5×10^{-4} m^2/s and 0.79, respectively. What is the dynamic viscosity of the liquid in SI units?

1.61 A liquid has a specific weight of 59 lb/ft^3 and a dynamic viscosity of 2.75 lb · s/ft^2. Determine its kinematic viscosity.

1.62 The kinematic viscosity of oxygen at 20 °C and a pressure of 150 kPa (abs) is 0.104 stokes. Determine the dynamic viscosity of oxygen at this temperature and pressure.

*1.63 ▶ Fluids for which the shearing stress, τ, is not linearly related to the rate of shearing strain, $\dot{\gamma}$, are designated as non-Newtonian fluids. Such fluids are commonplace and can exhibit unusual behavior, as shown in **Video V1.6**. Some experimental data obtained for a particular non-Newtonian fluid at 80 °F are shown below.

$\tau\ (\text{lb/ft}^2)$	0	2.11	7.82	18.5	31.7
$\dot{\gamma}\ (\text{s}^{-1})$	0	50	100	150	200

Plot these data and fit a second-order polynomial to the data using a suitable graphing program. What is the apparent viscosity of this fluid when the rate of shearing strain is 70 s^{-1}? Is this apparent viscosity larger or smaller than that for water at the same temperature?

1.64 ▶ Water flows near a flat surface and some measurements of the water velocity, u, parallel to the surface, at different heights, y, above the surface are obtained. At the surface $y = 0$. After an analysis of the data, the lab technician reports that the velocity distribution in the range $0 < y < 0.1$ ft is given by the equation

$$u = 0.81 + 9.2y + 4.1 \times 10^3 y^3$$

with u in ft/s when y is in ft. (**a**) Do you think that this equation would be valid in any system of units? Explain. (**b**) Do you think this equation is correct? Explain. You may want to look at **Video 1.4** to help you arrive at your answer.

1.65 Calculate the Reynolds numbers for the flow of water and for air through a 4-mm-diameter tube, if the mean velocity is 3 m/s and the temperature is 30 °C in both cases (see Example 1.4). Assume the air is at standard atmospheric pressure.

1.66 SAE 30 oil at 60 °F flows through a 2-in.-diameter pipe with a mean velocity of 5 ft/s. Determine the value of the Reynolds number (see Example 1.4).

1.67 For air at standard atmospheric pressure the values of the constants that appear in the Sutherland equation (Eq. 1.10) are $C = 1.458 \times 10^{-6}\ \text{kg/(m} \cdot \text{s} \cdot \text{K}^{1/2})$ and $S = 110.4$ K. Use these values to predict the viscosity of air at 10 °C and 90 °C and compare with values given in Table B.4 in Appendix B.

*1.68 Use the values of viscosity of air given in Table B.4 at temperatures of 0, 20, 40, 60, 80, and 100 °C to determine the constants C and S which appear in the Sutherland equation (Eq. 1.10). Compare your results with the values given in Problem 1.67. (*Hint:* Rewrite the equation in the form

$$\frac{T^{3/2}}{\mu} = \left(\frac{1}{C}\right)T + \frac{S}{C}$$

and plot $T^{3/2}/\mu$ versus T. From the slope and intercept of this curve, C and S can be obtained.)

1.69 ▶ The viscosity of a fluid plays a very important role in determining how a fluid flows. (See **Video V1.3**.) The value of the viscosity depends not only on the specific fluid but also on the fluid temperature. Some experiments show that when a liquid, under the action of a constant driving pressure, is forced with a low velocity, V, through a small horizontal tube, the velocity is given by the equation $V = K/\mu$. In this equation K is a constant for a given tube and pressure, and μ is the dynamic viscosity. For a particular liquid of interest, the viscosity is given by Andrade's equation (Eq. 1.11) with $D = 5 \times 10^{-7}\ \text{lb} \cdot \text{s/ft}^2$ and $B = 4000$ °R. By what percentage will the velocity increase as the liquid temperature is increased from 40 °F to 100 °F? Assume all other factors remain constant.

*1.70 Use the value of the viscosity of water given in Table B.2 at temperatures of 0, 20, 40, 60, 80, and 100 °C to determine the constants D and B which appear in Andrade's equation (Eq. 1.11). Calculate the value of the viscosity at 50 °C and compare with the value given in Table B.2. (*Hint:* Rewrite the equation in the form

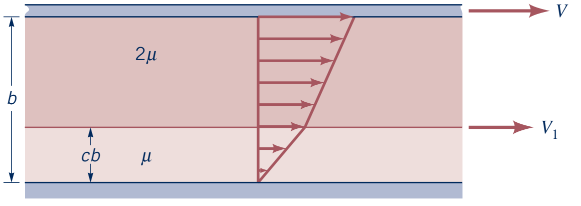
$$\ln \mu = (B)\frac{1}{T} + \ln D$$

and plot $\ln \mu$ versus $1/T$. From the slope and intercept of this curve, B and D can be obtained. If a nonlinear curve-fitting program is available, the constants can be obtained directly from Eq. 1.11 without rewriting the equation.)

1.71 For a certain liquid $\mu = 7.1 \times 10^{-5}\ \text{lb} \cdot \text{s/ft}^2$ at 40 °F and $\mu = 1.9 \times 10^{-5}\ \text{lb} \cdot \text{s/ft}^2$ at 150 °F. Make use of these data to determine the constants D and B which appear in Andrade's equation (Eq. 1.11). What would be the viscosity at 80 °F?

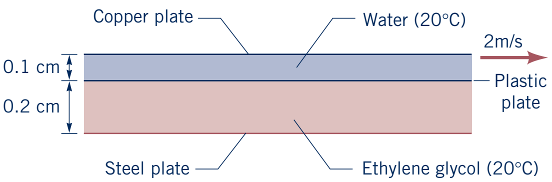
1.72 For a parallel plate arrangement of the type shown in Fig. 1.5 it is found that when the distance between plates is 2 mm, a shearing stress of 150 Pa develops at the upper plate when it is pulled at a velocity of 1 m/s. Determine the viscosity of the fluid between the plates. Express your answer in SI units.

1.73 Two flat plates are oriented parallel above a fixed lower plate as shown in Fig. P1.73. The top plate, located a distance b above the fixed plate, is pulled along with speed V. The other thin plate is located a distance cb, where $0 < c < 1$, above the fixed plate. This plate moves with speed V_1, which is determined by the viscous shear forces imposed on it by the fluids on its top and bottom. The fluid on the top is twice as viscous as that on the bottom. Plot the ratio V_1/V as a function of c for $0 < c < 1$.



■ Figure P1.73

1.74 Three large plates are separated by thin layers of ethylene glycol and water, as shown in Fig. P1.74. The top plate moves to the right at 2 m/s. At what speed and in what direction must the bottom plate be moved to hold the center plate stationary?



■ Figure P1.74

1.75 ▶ There are many fluids that exhibit non-Newtonian behavior (see, for example, **Video V1.6**). For a given fluid the distinction between Newtonian and non-Newtonian behavior is usually based on measurements of shear stress and rate of shearing strain. Assume that the viscosity of blood is to be determined by measurements of shear stress, τ, and rate of shearing strain, du/dy, obtained from a small blood sample tested in a suitable viscometer. Based on the data given below, determine if the blood is a Newtonian or non-Newtonian fluid. Explain how you arrived at your answer.

τ(N/m^2)	0.04	0.06	0.12	0.18	0.30	0.52	1.12	2.10
du/dy (s^{-1})	2.25	4.50	11.25	22.5	45.0	90.0	225	450

1.76 The sled shown in Fig. P1.76 slides along on a thin horizontal layer of water between the ice and the runners. The horizontal force that the water puts on the runners is equal to 1.2 lb when the sled's speed is 50 ft/s. The total area of both runners in contact with the water is 0.08 ft^2, and the viscosity of the water is 3.5×10^{-5} lb · s/ft^2. Determine the thickness of the water layer under the runners. Assume a linear velocity distribution in the water layer.

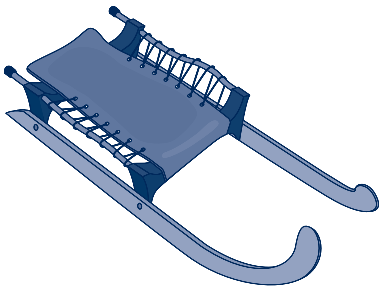


Figure P1.76

1.77 A 25-mm-diameter shaft is pulled through a cylindrical bearing as shown in Fig. P1.77. The lubricant that fills the 0.3-mm gap between the shaft and bearing is an oil having a kinematic viscosity of 8.0×10^{-4} m^2/s and a specific gravity of 0.91. Determine the force P required to pull the shaft at a velocity of 3 m/s. Assume the velocity distribution in the gap is linear.

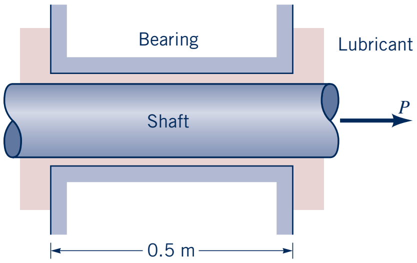


Figure P1.77

1.78 A hydraulic lift in a service station has a 32.50-cm-diameter ram that slides in a 32.52-cm-diameter cylinder. The annular space is filled with SAE 10 oil at 20 °C. The ram is traveling upward at the rate of 0.10 m/s. Find the frictional force when 3.0 m of the ram is engaged in the cylinder.

1.79 A piston having a diameter of 5.48 in. and a length of 9.50 in. slides downward with a velocity V through a vertical pipe. The downward motion is resisted by an oil film between the piston and the pipe wall. The film thickness is 0.002 in., and the cylinder weighs 0.5 lb. Estimate V if the oil viscosity is 0.016 lb · s/ft^2. Assume the velocity distribution in the gap is linear.

1.80 A 10-kg block slides down a smooth inclined surface as shown in Fig. P1.80. Determine the terminal velocity of the block if the 0.1-mm gap between the block and the surface contains SAE 30 oil at 60 °F. Assume the velocity distribution in the gap is linear, and the area of the block in contact with the oil is 0.1 m^2.

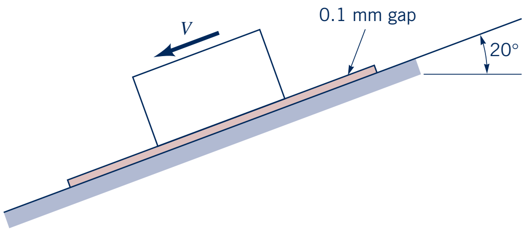


Figure P1.80

1.81 A layer of water flows down an inclined fixed surface with the velocity profile shown in Fig. P1.81. Determine the magnitude and direction of the shearing stress that the water exerts on the fixed surface for U = 2 m/s and h = 0.1 m.

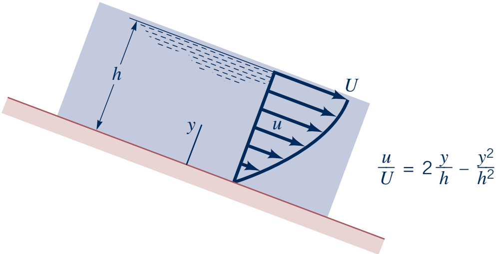


Figure P1.81

1.82 Oil (absolute viscosity = 0.0003 lb · s/ft^2, density = 50 lbm/ft^3) flows in the boundary layer, as shown in Fig. P1.82. The plate is 1 ft wide perpendicular to the paper. Calculate the shear stress at the plate surface.

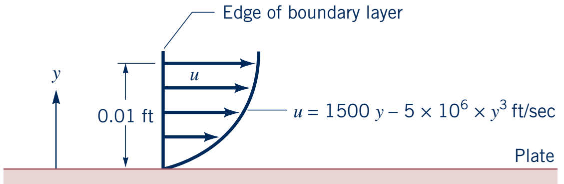


Figure P1.82

***1.83** Standard air flows past a flat surface, and velocity measurements near the surface indicate the following distribution:

y (ft)	0.005	0.01	0.02	0.04	0.06	0.08
u (ft/s)	0.74	1.51	3.03	6.37	10.21	14.43

The coordinate y is measured normal to the surface and u is the velocity parallel to the surface. **(a)** Assume the velocity distribution is of the form

$$u = C_1 y + C_2 y^3$$

and use a standard curve-fitting technique to determine the constants C_1 and C_2. **(b)** Make use of the results of part (a) to determine the magnitude of the shearing stress at the wall ($y = 0$) and at y = 0.05 ft.

1.84 A new computer drive is proposed to have a disc, as shown in Fig. P1.84. The disc is to rotate at 10,000 rpm, and the reader head is to be positioned 0.0005 in. above the surface of the disc.