APPLIED FLUID MECHANICS

EIGHTH EDITION

Robert L. Mott | Joseph A. Untener

APPLIED FLUID MECHANICS

This page intentionally left blank

APPLIED FLUID MECHANICS

Eighth Edition

Robert L. Mott
University of Dayton

Joseph A. Untener
University of Dayton

Pearson

Please contact https://support.pearson.com/getsupport/s/with any queries on this content
Cover Image by NavinTar/Shutterstock

Acknowledgments of third-party content appear on the appropriate page within the text

Library of Congress Cataloging-in-Publication Data
Names: Mott, Robert L., author. | Untener, Joseph A., author.
Title: Applied Fluid Mechanics / Robert L. Mott (University of Dayton), Joseph A. Untener (University of Dayton).
Description: Eighth edition. | Boston: Pearson Education, Inc., [2022] | Includes bibliographical references and index.
Identifiers: LCCN 2019010619| ISBN 9780135577158 | ISBN 0135577152
Subjects: LCSH: Fluid mechanics.
Classification: LCC TA357 .M67 2019 | DDC 620.1/06--dc23 LC record available at https://lccn.loc.gov/2019010619

ScoutAutomatedPrintCode

Pearson

ISBN-10: 0-13-557715-2
ISBN-13: 978-0-13-557715-8

BRIEF CONTENTS

1 The Nature of Fluids and the Study of Fluid Mechanics 1

2 Viscosity of Fluids 20

3 Pressure Measurement 39

4 Forces Due to Static Fluids 64

5 Buoyancy and Stability 94

6 Flow of Fluids and Bernoulli's Equation 118

7 General Energy Equation 154

8 Reynolds Number, Laminar Flow, Turbulent Flow, and Energy Losses Due to Friction 176

9 Velocity Profiles for Circular Sections and Flow in Noncircular Sections 202

10 Minor Losses 221

11 Series Pipeline Systems 260

12 Parallel and Branching Pipeline Systems 291

13 Pump Selection and Application 312

14 Open-Channel Flow 367

15 Flow Measurement 390

16 Forces Due to Fluids in Motion 413

17 Drag and Lift 427

18 Fans, Blowers, Compressors, and the Flow of Gases 444

19 Flow of Air in Ducts 464

Appendices 482

Answers to Selected Problems 510

Index 519

This page intentionally left blank

CONTENTS

Preface xii

Acknowledgments xv

1 The Nature of Fluids and the Study of Fluid Mechanics 1

The Big Picture 1

1.1 Learning Objectives 3
1.2 Basic Introductory Concepts 3
1.3 The International System of Units (SI) 4
1.4 The U.S. Customary System 5
1.5 Weight and Mass 5
1.6 Temperature 6
1.7 Consistent Units in an Equation 6
1.8 The Definition of Pressure 9
1.9 Compressibility 10
1.10 Density, Specific Weight, and Specific Gravity 11
1.11 Surface Tension 14

References 15
Internet Resources 16
Practice Problems 16
Computer Application Assignments 19

2 Viscosity of Fluids 20

The Big Picture 20

2.1 Learning Objectives 21
2.2 Dynamic Viscosity 22
2.3 Kinematic Viscosity 23
2.4 Newtonian Fluids and Non-Newtonian Fluids 24
2.5 Variation of Viscosity with Temperature 26
2.6 Viscosity Measurement 28
2.7 SAE Viscosity Grades 33
2.8 ISO Viscosity Grades 34
2.9 Hydraulic Fluids for Fluid Power Systems 34

References 35
Internet Resources 36
Practice Problems 36
Computer Application Assignments 38

3 Pressure Measurement 39

The Big Picture 39

3.1 Learning Objectives 40
3.2 Absolute and Gage Pressure 40
3.3 Relationship between Pressure and Elevation 41
3.4 Development of the Pressure–Elevation Relation 44
3.5 Pascal’s Paradox 46
3.6 Manometers 47
3.7 Barometers 52
3.8 Pressure Expressed as the Height of a Column of Liquid 53
3.9 Pressure Gages and Transducers 54

References 56
Internet Resources 56
Practice Problems 56

4 Forces Due To Static Fluids 64

The Big Picture 64

4.1 Learning Objectives 66
4.2 Gases under Pressure 66
4.3 Horizontal Flat Surfaces under Liquids 66
4.4 Rectangular Walls 67
4.5 Submerged Plane Areas—General 70
4.6 Development of the General Procedure for Forces on Submerged Plane Areas 73
4.7 Piezometric Head 74
4.8 Distribution of Force on a Submerged Curved Surface 75
4.9 Effect of a Pressure above the Fluid Surface 79
4.10 Forces on a Curved Surface with Fluid Below It 79
4.11 Forces on Curved Surfaces with Fluid Above and Below 80

Practice Problems 81
Computer Application Assignments 92

5 Buoyancy and Stability 94

The Big Picture 94

5.1 Learning Objectives 95

5.2 Buoyancy 95

5.3 Buoyancy Materials 102

5.4 Stability of Completely Submerged Bodies 103

5.5 Stability of Floating Bodies 104

5.6 Degree of Stability 108

Reference 109

Internet Resources 109

Practice Problems 109

Stability Evaluation Projects 116

6 Flow of Fluids and Bernoulli's Equation 118

The Big Picture 118

6.1 Learning Objectives 119

6.2 Fluid Flow Rate and the Continuity Equation 119

6.3 Commercially Available Pipe and Tubing 123

6.4 Recommended Velocity of Flow in Pipe and Tubing 125

6.5 Conservation of Energy—Bernoulli's Equation 128

6.6 Interpretation of Bernoulli's Equation 129

6.7 Restrictions on Bernoulli's Equation 130

6.8 Applications of Bernoulli's Equation 130

6.9 Torricelli's Theorem 138

6.10 Flow Due to a Falling Head 141

References 143

Internet Resources 143

Practice Problems 144

Software Projects Using Bernoulli's Equation and Torricelli's Theorem 153

7 General Energy Equation 154

The Big Picture 154

7.1 Learning Objectives 156

7.2 Energy Losses and Additions 156

7.3 Nomenclature of Energy Losses and Additions 158

7.4 General Energy Equation 158

7.5 Power Required by Pumps 162

7.6 Power Delivered to Fluid Motors 165

Practice Problems 167

8 Reynolds Number, Laminar Flow, Turbulent Flow, and Energy Losses Due to Friction 176

The Big Picture 176

8.1 Objectives 179

8.2 Reynolds Number 179

8.3 Critical Reynolds Numbers 180

8.4 Darcy's Equation 181

8.5 Friction Loss in Laminar Flow 181

8.6 Friction Loss in Turbulent Flow 182

8.7 Use of Software for Pipe Flow Problems 188

8.8 Equations for the Friction Factor 192

8.9 Hazen–Williams Formula for Water Flow 193

8.10 Other Forms of the Hazen–Williams Formula 194

8.11 Nomograph for Solving the Hazen–Williams Formula 194

References 196

Internet Resources 196

Practice Problems 196

Computer Application Assignments 201

9 Velocity Profiles for Circular Sections and Flow in Noncircular Sections 202

The Big Picture 202

9.1 Learning Objectives 203

9.2 Velocity Profiles 204

9.3 Velocity Profile for Laminar Flow 204

9.4 Velocity Profile for Turbulent Flow 206

9.5 Flow in Noncircular Sections 209

9.6 Computational Fluid Dynamics 213

References 215

Internet Resources 215

Practice Problems 215

Computer Application Assignments 220

10 Minor Losses 221

The Big Picture 221

10.1 Objectives 223

10.2 Resistance Coefficient 223

10.3 Sudden Enlargement 224

10.4 Exit Loss 227

10.5 Gradual Enlargement 227

10.6 Sudden Contraction 229

10.7 Gradual Contraction 232
10.8 Entrance Loss 233
10.9 Resistance Coefficients for Valves and Fittings 234
10.10 Application of Standard Valves 240
10.11 Pipe Bends 242
10.12 Pressure Drop in Fluid Power Valves 244
10.13 Flow Coefficients for Valves Using C_V 247
10.14 Plastic Valves 248
10.15 Using PIPE-FLO® Software for component Losses 249
References 254
Internet Resources 254
Practice Problems 255
Computer Application Assignments 259

11 Series Pipeline Systems 260

The Big Picture 260
11.1 Objectives 261
11.2 Class I Systems 261
11.3 Spreadsheet Aid for Class I Problems 265
11.4 Class II Systems 268
11.5 Class III Systems 274
11.6 PIPE-FLO® Examples for Series Pipeline Systems 277
11.7 Pipeline Design for Structural Integrity 282
References 283
Internet Resources 284
Practice Problems 284
Computer Application Assignments 290

12 Parallel and Branching Pipeline Systems 291

The Big Picture 291
12.1 Objectives 293
12.2 Systems with Two Branches 293
12.3 Parallel Pipeline Systems and Pressure Boundaries in PIPE-FLO® 299
12.4 Systems with Three or More Branches—Networks 302
References 309
Internet Resources 309
Practice Problems 309
Computer Application Assignments 311

13 Pump Selection and Application 312

The Big Picture 312
13.1 Objectives 313
13.2 Parameters Involved in Pump Selection 314
13.3 Types of Pumps 314
13.4 Positive-Displacement Pumps 314
13.5 Kinetic Pumps 320
13.6 Performance Data for Centrifugal Pumps 324
13.7 Affinity Laws for Centrifugal Pumps 324
13.8 Manufacturers' Data for Centrifugal Pumps 327
13.9 Net Positive Suction Head 335
13.10 Suction Line Details 340
13.11 Discharge Line Details 340
13.12 The System Resistance Curve 341
13.13 Pump Selection and the Operating Point for the System 344
13.14 Using PIPE-FLO® for Selection of Commercially Available Pumps 346
13.15 Alternate System Operating Modes 350
13.16 Pump Type Selection and Specific Speed 355
13.17 Life Cycle Costs for Pumped Fluid Systems 357
13.18 Recommendations for Further Study 358
References 359
Internet Resources 360
Practice Problems 360
Supplemental Problem (PIPE-FLO® only) 362
Design Problems 362
Design Problem Statements 362
Comprehensive Design Problem 364

14 Open-Channel Flow 367

The Big Picture 367
14.1 Objectives 369
14.2 Classification of Open-Channel Flow 369
14.3 Hydraulic Radius and Reynolds Number in Open-Channel Flow 370
14.4 Kinds of Open-Channel Flow 370
14.5 Uniform Steady Flow in Open Channels 371
14.6 The Geometry of Typical Open Channels 375
14.7 The Most Efficient Shapes for Open Channels 377

14.8 Critical Flow and Specific Energy 377
14.9 Hydraulic Jump 379
14.10 Open-Channel Flow Measurement 381
References 385
Digital Publications 385
Internet Resources 386
Practice Problems 386
Computer Application Assignments 389

15 Flow Measurement 390

The Big Picture 390
15.1 Objectives 391
15.2 Flowmeter Selection Factors 391
15.3 Variable-Head Meters 392
15.4 Variable-Area Meters 399
15.5 Turbine Flowmeter 400
15.6 Vortex Flowmeter 400
15.7 Magnetic Flowmeter 401
15.8 Ultrasonic Flowmeters 402
15.9 Positive-Displacement Meters 403
15.10 Mass Flow Measurement 403
15.11 Velocity Probes 405
15.12 Level Measurement 408
15.13 Computer-Based Data Acquisition and Processing 409
References 409
Internet Resources 410
Review Questions 410
Practice Problems 411
Computer Application Assignments 411

16 Forces Due to Fluids in Motion 413

The Big Picture 413
16.1 Objectives 414
16.2 Force Equation 415
16.3 Impulse–Momentum Equation 415
16.4 Problem-Solving Method Using the Force Equations 415
16.5 Forces on Stationary Objects 416
16.6 Forces on Bends in Pipelines 418
16.7 Forces on Moving Objects 421
Practice Problems 422

17 Drag and Lift 427

The Big Picture 427
17.1 Objectives 429
17.2 Drag Force Equation 429
17.3 Pressure Drag 430
17.4 Drag Coefficient 430
17.5 Friction Drag on Spheres in Laminar Flow 433
17.6 Vehicle Drag 436
17.7 Compressibility Effects and Cavitation 438
17.8 Lift and Drag on Airfoils 438
References 440
Internet Resources 440
Practice Problems 441

18 Fans, Blowers, Compressors, and the Flow of Gases 444

The Big Picture 444
18.1 Objectives 445
18.2 Gas Flow Rates and Pressures 445
18.3 Classification of Fans, Blowers, and Compressors 446
18.4 Flow of Compressed Air and Other Gases in Pipes 450
18.5 Flow of Air and Other Gases Through Nozzles 455
References 461
Internet Resources 461
Practice Problems 461
Computer Application Assignments 463

19 Flow of Air in Ducts 464

The Big Picture 464
19.1 Objectives 466
19.2 Energy Losses in Ducts 466
19.3 Duct Design 471
19.4 Energy Efficiency and Practical Considerations in Duct Design 477
References 477
Internet Resources 478
Practice Problems 478

Appendices 482

Appendix A Properties of Water 482
Appendix B Properties of Common Liquids 484
Appendix C Typical Properties of Petroleum Lubricating Oils 486
Appendix D Variation of Viscosity with Temperature 487

Appendix E Properties of Air 490
Appendix F Dimensions of Steel Pipe 494
Appendix G Dimensions of Steel, Copper, and Plastic Tubing 496
Appendix H Dimensions of Type K Copper Tubing 499
Appendix I Dimensions of Ductile Iron Pipe 500
Appendix J Areas of Circles 501
Appendix K Conversion Factors 503
Appendix L Properties of Areas 505
Appendix M Properties of Solids 507
Appendix N Gas Constant, Adiabatic Exponent, and Critical Pressure Ratio for Selected Gases 509

Answers to Selected Problems 510

Index 519

PREFACE

Applied Fluid Mechanics, 8th edition has been completely updated and revised to meet current industry standards. It is available in two general formats–print and eText. The print version is now available as an affordable rent-to-own option for students. Several options for low cost digital eTexts are also available as a subscription or ownership. For access to Pearson eText, visit Pearson.com/learner.

INTRODUCTION

The objective of *Applied Fluid Mechanics*, 8th edition is to present the principles of fluid mechanics and the application of these principles to practical, applied problems. The primary emphasis is on fluid properties; the measurement of pressure, density, viscosity, and flow; fluid statics; flow of fluids in pipes and noncircular conduits; pump selection and application; open-channel flow; forces developed by fluids in motion; the design and analysis of heating, ventilation, and air conditioning (HVAC) ducts; and the flow of air and other gases.

Applications are shown in the mechanical field, including industrial fluid distribution, fluid power, and HVAC; in the chemical field, including flow in materials processing systems; and in the civil and environmental fields as applied to water and wastewater systems, fluid storage and distribution systems, and open-channel flow. This book is directed to anyone in an engineering field where the ability to apply the principles of fluid mechanics is the primary goal.

Those using this book should understand algebra, trigonometry, and mechanics. After completing the book, students should have the ability to design and analyze practical fluid flow systems, and to continue learning in the field. Following this course students can take other applied courses, such as those on fluid power, HVAC, and civil hydraulics. This book can also be used to teach selected fluid mechanics topics within such courses.

APPROACH

As with previous editions, the approach used encourages students to become intimately involved in learning the principles of fluid mechanics at seven levels:

1. Understanding concepts.
2. Recognizing how the principles of fluid mechanics apply to their own experience.
3. Recognizing and implementing logical approaches to problem solutions.
4. Performing the analyses and calculations required in the solutions.
5. Critiquing the design of a given system and recommending improvements.
6. Designing practical, efficient fluid systems.
7. Using computer applications, both commercially available and self-developed, for design and analysis of fluid flow systems.

This multilevel approach has proven successful for several decades in building students' confidence in their ability to analyze and design fluid systems.

Concepts are presented in clear language and illustrated by reference to physical systems with which the reader should be familiar. An intuitive justification and mathematical basis are given for each concept. The methods of solution to many types of complex problems are presented in step-by-step procedures. The importance of recognizing the relationships among what is known, what is to be found, and the choice of a solution procedure is emphasized.

Many practical problems in fluid mechanics require relatively long solution procedures. It has been the authors' experience that students often have difficulty in carrying out the details of the solution. For this reason, each example problem is worked in complete detail, including the manipulation of units in equations. In the more complex examples, a programmed instruction format is used in which the student is asked to perform a small segment of the solution before being shown the correct result. The programs are of the linear type in which one panel presents a concept and then either poses a question or asks that a certain operation be performed. The following panel gives the correct result and the details of how it was obtained. The program then continues.

The International System of Units (Système International d'Unités, or SI) and the U.S. Customary System of units are used approximately equally. The SI notation in this book follows the guidelines set forth by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce, in its 2019 publication *The International System of Units* (*SI*) (NIST Special Publication 330), edited by David B. Newell and Eite Tiesinga.

COMPUTER-ASSISTED PROBLEM SOLVING AND DESIGN

Computer-assisted approaches to solving fluid flow problems are recommended only after the student has demonstrated competence in solving problems manually. They allow more comprehensive problems to be analyzed and give students tools for considering multiple design options while removing some of the burden of calculations. Also, many employers expect students to have not only the skill to use software, but the inclination to do so, and using software within the course effectively nurtures this skill. We recommend the following classroom learning policy.

Users of computer software must have solid understanding of the principles on which the software is based to ensure that analyses and design decisions are fundamentally sound. Software should be used only after mastering relevant analysis methods by careful study and using manual techniques.

Computer-based assignments are included at the end of many chapters. These can be solved by a variety of techniques such as:

- The use of a spreadsheet such as Microsoft® Excel
- The use of technical computing software
- The use of commercially available software for fluid flow analysis

Chapter 11, Series Pipeline Systems, and Chapter 13, Pump Selection and Application, include example Excel spreadsheet aids for solving fairly complex system design and analysis problems. In this edition, the spreadsheets are shown in color to assist instructors and students in recognizing the nature of input data and results.

Powerful, commercially available software: A feature introduced in the 7th edition of this book continues in this edition. PIPE-FLO® is a software package that is internationally renowned for piping system analysis and design. It is produced and marketed by PIPE-FLO, pipe-flo.com, in Lacey, Washington, and uses the same basic methodology presented in this text for analyzing pumped fluid flow systems. Students who fully understand the principles and manual problem-solving methods presented in this book will be well-prepared to apply them in industrial settings and they will also have learned the fundamentals of using PIPE-FLO® to perform the analyses of the kinds of fluid flow systems they will encounter in their careers. This skill should be an asset to students' career development.

The software can be obtained from PIPE-FLO at no cost. Instructors and students using this book can download the software and receive full installation support from ESI. The tools and techniques for building computer models of fluid flow systems are introduced carefully starting in Chapter 8 on energy losses due to friction in pipes and continuing through Chapter 13, covering minor losses, series pipeline systems, parallel and branching systems, and pump selection and application. As each new concept and problem-solving method is learned from this book, it is then applied to one or more example problems where students can develop their skills in creating and solving real problems. With each chapter, the kinds of systems that students will be able to complete expand in breadth and depth. Several supplemental problems using PIPE-FLO® are in the book so students can extend and demonstrate their abilities in assignments, projects, or self-study. The integrated companion software, PUMP-FLO®, provides access to catalog data for numerous types and sizes of pumps that students can use in assignments and to become more familiar with that method of specifying pumps in their future positions.

Instructors should contact training@pipe-flo.com to obtain download links and license keys to allow for installation on either the institution's or students' machines.

Feedback from users of the 7th edition indicated that the inclusion of PIPE-FLO® in the book is highly valuable. Although some chose not to integrate this in their courses, they advise students that it is an important tool for use in their career when piping design, pump selection, and analysis of existing piping systems are encountered. With the analytical tools students learn from studying from this book, they should be able to implement PIPE-FLO® readily in their industry positions. Instructors who do use the software report that it is an enhancement of the course and it provides natural and seamless computer application. Both the software and the book use the same industry standard, Crane's TP410, as the analytical basis for computations. We encourage your use of the software within your coverage of Chapters 8 through 13 and that you advise students to retain this book as support when applying the software in an industry position. They should also be advised that there is a full commercial version available through ESI that has greatly increased capability. If your institution would like to run the full version with a site license for educational purposes, and avoid the need for individual downloads while also having access to the capabilities of the full version, simply contact ESI to set that up at no cost.

FEATURES OF THE EIGHTH EDITION

The eighth edition continues the pattern of earlier editions in refining the presentation of several topics, enhancing the visual attractiveness and usability of the book, updating data and analysis techniques, and adding selected new material. *The Big Picture* begins each chapter as in the preceding two editions, but each has been radically improved with one or more new, attractive photographs or illustrations, a refined *Exploration* section that gets students personally involved with the concepts presented in the chapter, and brief *Introductory Concepts* that preview the chapter discussions. Feedback from instructors and students about this feature has been very positive. The extensive appendixes continue to be useful learning and problem-solving tools.

HIGHLIGHTS OF CHANGES IN THIS EDITION:

- A large percentage of the illustrations have been upgraded in terms of realism, consistency, and graphic quality. Full color continues to enhance the appearance and effectiveness of illustrations, graphs, and the general layout of the book. Many photographs of commercially available products have been updated and some new ones have been added.

- The end-of-chapter References provide extensive resources to both instructors and students. Industry standards and additional resources have been updated, revised, and extended.
- Internet resources have become important supplemental references that provide useful information such as commercially available products, additional data for problem solving and design, more in-depth coverage of certain topics, information about fluid mechanics software, and industry standards. These important resources have been updated and many have been added to those in previous editions.
- Use of SI metric units alongside U.S. Customary units has been continued throughout the book. Appendix tables that feature purely metric sizes for steel, copper, and plastic tubing are included. Use of the metric DN-designations for standard Schedules 40 and 80 steel pipes are integrated into the discussions, example problems, and end-of-chapter problems. Almost all metric-based problems use these tables for pipe or tubing designations, dimensions, and flow areas. This should give students strong foundations on which to build a career in the global industrial scene in which they will pursue their careers.
- Many creative supplemental problems are included at the end of the Problems section in several chapters to enhance student learning and to provide more variety for instructors in planning their courses.
- Graphical tools for selecting pipe sizes are included in Chapter 6 and used in later chapters and design projects.
- The discussion of computational fluid mechanics is included in Chapter 9 with attractive graphics that are highly relevant to the study of pipe flow.
- The use of *K*-factors (resistance coefficients), based on the equivalent-length approach, continues according to the latest version of the *Crane Technical Paper 410* (TP 410).
- Use of the flow coefficient C_V for evaluating the relationship between flow rate and pressure drop across valves continues in Chapter 10 with equations for use with both U.S. and SI metric units. It is also included in parts of Chapter 13 that emphasize the use of valves as control elements.
- The section, General Principles of Pipeline System Design, continues to be a useful feature in Chapter 11.
- Several sections in Chapter 13 on pump selection and application provide in-depth coverage that is consistent with TP 410, the development of relevant topics, and use of the PIPE-FLO® software.

AUTHORS OF THIS BOOK—PROFESSORS ROBERT L. MOTT AND JOSEPH A. UNTENER

We are pleased that the eighth edition of *Applied Fluid Mechanics* continues to be authored by **Robert L. Mott** and **Joseph A. Untener,** working as a team.

Professor Mott is the original author of this book, with its first edition appearing in 1970. He was the sole author of the first six editions before inviting Professor Untener to be the co-author of the 7th edition. Bob has significant industry experience along with work through the University of Dayton Research Institute, industrial consulting, and accident reconstruction and analysis. He served in the University of Dayton School of Engineering on the faculty of the Department of Engineering Technology for 35 years prior to retirement. He served as department chair and associate dean. In addition to this book, he is the author of *Machine Elements in Mechanical Design*, and *Applied Strength of Materials,* both of which are in the 6th editions. He was the sole author of the first five editions and took on coauthors for the 6th editions.

Professor Untener has been a faculty member in the Department of Engineering Technology at the University of Dayton since 1987 when he was hired by Professor Mott. Joe's first course taught at UD was Fluid Mechanics, using the 2nd edition of this book, and he continues to include this course in his schedule. Joe is a registered Professional Engineer with a strong background working in industry. He is a respected instructor who focuses on pedagogy and student learning. He brings fresh ideas and a keen sense of methodology and style to the partnership that will continue to develop this textbook into the future. His contributions, including the integration of software and updating the graphics, will continue to be of great value to users of this book, both students and instructors.

ONLINE RESOURCES AVAILABLE TO INSTRUCTORS FROM THE PEARSON INSTRUCTOR RESOURCE CENTER

As an instructor, please take advantage of all of the online resources that accompany this text. Instructors have access to a complete Solutions Manual with clear and detailed step-by-step solutions, including units, for each problem in the text. An entire Image Bank with all figures shown in the text is also available to instructors. Given the graphical nature of fluid systems, we encourage instructors to download this image bank for use in developing course aids such as presentations and test items throughout the entire academic term. In addition, a set of presentation slides for the entire book is available to all instructors in PowerPoint format. To access supplementary materials online, instructors need to request, with proper credentials, an instructor access code. Go to www.pearsonhighered.com/irc to login or register for an instructor access code.

ACKNOWLEDGMENTS

We would like to thank all who helped and encouraged us in the writing of this book, including users of earlier editions and the several reviewers who provided detailed suggestions: William E. Cole, Northeastern University; Gary Crossman, Old Dominion University; Charles Drake, Ferris State University; Mark S. Frisina, Wentworth Institute of Technology; Dr. Roy A. Hartman, P. E., Texas A & M University; Dr. Greg E. Maksi, State Technical Institute at Memphis; Ali Ogut, Rochester Institute of Technology; Paul Ricketts, New Mexico State University; Mohammad E. Taslim, Northeastern University at Boston; Pao-lien Wang, University of North Carolina at Charlotte; and Steve Wells, Old Dominion University. Special thanks go to our colleagues of the University of Dayton, the late Jesse Wilder, David Myszka, and Rebecca Blust, who used earlier editions of this book in class and offered helpful suggestions. Robert Wolff, also of the University of Dayton, has provided much help in the use of the SI system of units, based on his long experience in metrication through the American Society for Engineering Education. Professor Wolff also consulted on fluid power applications. We thank all those from PIPE-FLO for their cooperation and assistance in incorporating the PIPE-FLO® software into this book, particularly Joe Benefield. We are grateful for the expert professional and personal service provided by the editorial and marketing staff of Pearson Education. Comments from students who used the book are also appreciated because the book was written for them.

Robert L. Mott and Joseph A. Untener

REVIEWERS

Michael Costarell
Youngstown State University

Ali Mehrabian
Daytona State College

Russ Marcks
Sinclair Community College

Subha Kumpaty
Milwaukee School of Engineering

Mark Hapstack
Greenville Technical College

This page intentionally left blank

CHAPTER
ONE

THE NATURE OF FLUIDS AND THE STUDY OF FLUID MECHANICS

THE BIG PICTURE

As you begin the study of fluid mechanics, let's look at some fundamental concepts and look ahead to the major topics that you will study in this book. Try to identify where you have encountered either stationary or moving, pressurized fluids in your daily life. Consider the water system in your home, hotels, or commercial buildings. Think about how your car's fuel travels from the tank to the engine or how the cooling water flows through the engine and its cooling system. When enjoying time in an amusement park, consider how fluids are handled in water slides or boat rides. Look carefully at construction equipment to observe how pressurized fluids are used to actuate moving parts and to drive the machines. Visit manufacturing operations where automation equipment, material handling devices, and production machinery utilize pressurized fluids.

Consider fluid systems that we don't often think about but are present in our daily lives. There are many piping arrangements similar to the one shown in Fig. 1.1 that are transferring fluids through various components that we might not even notice. When you walk into the building for your fluid mechanics course, for example, you simply expect it to be the right temperature, but that typically requires pumped fluids. You would expect to be able to get a drink or go to the restroom on the way to class. You would imagine that if a fire began, there would be emergency systems in place to provide fire suppression. Complex piping systems that use pumps to transfer fluids are required to drive all of these systems and many more.

Listed here are several of the major concepts you will study in this book:

- *Fluid mechanics* is the study of the behavior of fluids, either at rest (fluid statics) or in motion (fluid dynamics).
- Fluids can be either *liquids* or *gases*, and they can be characterized by their physical properties such as density, specific weight, specific gravity, surface tension, and viscosity.
- Quantitatively analyzing fluid systems requires careful use of units for all terms. Both the SI metric system of units and the U.S. gravitational system are used in this book. Careful distinction between weight and mass is also essential.
- Fluid statics concepts that you will learn include the measurement of pressure, forces exerted on surfaces due to fluid pressure, buoyancy, and stability of floating bodies.
- Learning how to analyze the behavior of fluids as they flow through circular pipes and tubes and through conduits with other shapes is important.

FIGURE 1.1 Complex industrial and commercial fluid piping systems, often unnoticed but critical in our daily lives, require careful design and analysis. The system shown here is required to maintain comfortable temperatures in a commercial building. (*Source:* Tinnarat Suwanna/123RF)

- We will consider the energy possessed by the fluid because of its velocity, elevation, and pressure.
- Accounting for energy losses, additions, or purposeful removals that occur as the fluid flows through the components of a fluid flow system enables you to analyze the performance of the system.
- A flowing fluid loses energy due to friction as it moves along a conduit and as it encounters obstructions (like in a control valve) or changes its direction (like in a pipe elbow).
- Energy can be added to a flowing fluid by pumps that create flow and increase the fluid's pressure.
- Energy can be purposely removed by using it to drive a fluid motor, a turbine, or a hydraulic actuator.
- Measurements of fluid pressure, temperature, and the fluid flow rate in a system are critical to understanding its performance.

Exploration

Now let's consider a variety of systems that use fluids and that illustrate some of the applications of concepts learned from this book. As you read this section, consider such factors as:

- The basic function or purpose of the system
- The kind of fluid or fluids that are in the system
- The kinds of containers for the fluid or the conduits through which it flows
- If the fluid flows, what causes the flow to occur? Describe the flow path.
- What components of the system resist the flow of the fluid?
- What characteristics of the fluid are important to the proper performance of the system?

1. In your home, you use water for many different purposes such as drinking, cooking, bathing, cleaning, and watering lawns and plants. Water also eliminates wastes from the home through sinks, drains, and toilets. Rain water, melting snow, and water in the ground must be managed to conduct it away from the home using gutters, downspouts, ditches, and sump pumps. Consider how the water is delivered to your home. What is the ultimate source of the water—a river, a reservoir, or natural groundwater? Is the water stored in tanks at some points in the process of getting it to your home? Notice that the water system needs to be at a fairly high pressure to be effective for its uses and to flow reliably through the system. How is that pressure created? Are there pumps in the system? Describe their function and how they operate. From where does each pump draw the water? To what places is the water delivered? What quantities of fluid are needed at the delivery points? What

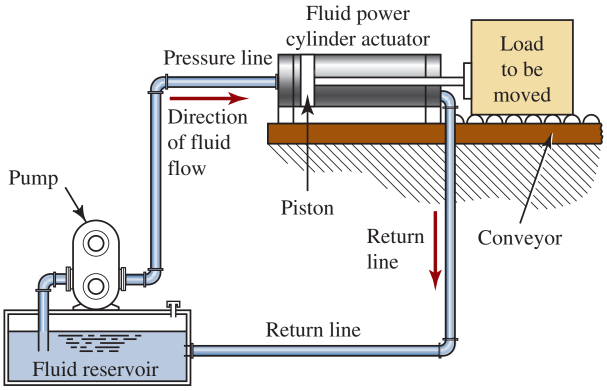


FIGURE 1.2 Typical piping system for fluid power.

pressures are required? How is the flow of water controlled? What materials are used for the pipes, tubes, tanks, and other containers or conduits? As you study Chapters 6–13, you will learn how to analyze and design systems in which the water flows in a pipe or a tube. Chapter 14 discusses the cases of open-channel flow such as that in the gutters that catch the rain from the roof of your home.

2. In your car, describe the system that stores gasoline and then delivers it to the car's engine. How is the windshield washer fluid managed? How does the coolant move from the engine to the radiator? Describe what happens when you apply the brakes, particularly as it relates to the hydraulic fluid in the braking system. The concepts in Chapters 6–13 will help you to describe and analyze these kinds of systems.
3. Consider the performance of an automated manufacturing system that is actuated by fluid power systems such as the one shown in Fig. 1.2. Describe the fluids, pumps, tubes, valves, and other components of the system. What is the function of the system? How does the fluid accomplish that function? How is energy introduced to the system and how is it dissipated away from the system?
4. Consider the kinds of objects that must float in fluids such as boats, jet skis, rafts, barges, and buoys. Why do they float? In what position or orientation do they float? Why do they maintain their orientation? The principles of buoyancy and stability are discussed in Chapter 5.
5. What examples can you think of where fluids at rest or in motion exert forces on an object? Any vessel containing a fluid under pressure should yield examples. Consider a swimming pool, a hydraulic cylinder, a dam or a retaining wall holding a fluid, a high-pressure washer system, a fire hose, wind during a tornado or a hurricane, and water flowing through a turbine to generate power. What other examples can you think of? Chapters 4, 16, and 17 discuss these cases.

6. Think of the many situations in which it is important to measure the flow rate of fluid in a system or the total quantity of fluid delivered. Consider measuring the gasoline that goes into your car so you can pay for just what you get. The water company wants to know how much water you use in a given month. Fluids often must be metered carefully into production processes in a factory. Liquid medicines and oxygen delivered to a patient in a hospital must be measured continuously for patient safety. Chapter 15 covers flow measurement.

There are many ways in which fluids affect your life. Completion of a fluid mechanics course using this book will help you understand how those fluids can be controlled. Studying this book will help you learn how to design and analyze fluid systems to determine the kind of components that should be used and their size.

1.1 LEARNING OBJECTIVES

After completing this chapter, you should be able to:

1. Differentiate between a gas and a liquid.
2. Define *pressure*.
3. Identify the units for the basic quantities of time, length, force, mass, and temperature in the SI metric unit system and in the U.S. Customary unit system.
4. Properly set up equations to ensure consistency of units.
5. Define the relationship between force and mass.
6. Define *density*, *specific weight*, and *specific gravity* and the relationships among them.
7. Define *surface tension.*

1.2 BASIC INTRODUCTORY CONCEPTS

- ***Pressure*** Pressure is defined as the amount of force exerted on a unit area of a substance or on a surface. This can be stated by the equation

$$p = \frac{F}{A} \tag{1–1}$$

Fluids are subjected to large variations in pressure depending on the type of system in which they are used. Milk sitting in a glass is at the same pressure as the air above it. Water in the piping system in your home has a pressure somewhat greater than atmospheric pressure so that it will flow rapidly from a faucet. Oil in a fluid power system is typically maintained at high pressure to enable it to exert large forces to actuate construction equipment or automation devices in a factory. Gases such as oxygen, nitrogen, and helium are often stored in strong cylinders or spherical tanks under high pressure to permit rather large amounts to be held in a relatively small volume. Compressed air is often used in service stations and manufacturing facilities to operate tools or to inflate tires. More discussion about pressure is given in Chapter 3.

- ***Liquids and Gases*** Fluids can be either liquids or gases. When a liquid is held in a container, it tends to take the shape of the container, covering the bottom and the sides. The top surface, in contact with the atmosphere above it, maintains a uniform level. As the container is tipped, the liquid tends to pour out.

When a gas is held under pressure in a closed container, it tends to expand and completely fill the container. If the container is opened, the gas tends to expand more and escape from the container.

While gases and liquids are similar in their ability to flow and fill containers, there is a key difference that is important in the study of fluid mechanics. Consider what happens to a liquid or a gas as the pressure on it is increased. If air, a gas, is trapped in a cylinder with a tight-fitting, movable piston inside it, you could compress the air fairly easily by pushing on the piston. In other words, if you push on the piston, the piston would move substantially because the volume of air changes with the change in pressure. If, on the other hand, a liquid such as water is in the cylinder, pushing on the piston would not result in any perceptible change in volume. In other words, the piston would not move noticeably because you could not compress the liquid in the same way as the gas. You could apply a large force, which would increase the pressure in the water, but the volume of the water would change very little. This observation leads to the following general descriptions of liquids and gases that we will use in this book:

1. Gases are readily compressible.
2. Liquids are only slightly compressible.

More discussion on compressibility is given later in this chapter. We will deal mostly with liquids in this book.

- ***Weight and Mass*** An understanding of fluid properties requires a careful distinction between *mass* and *weight*. The following definitions apply:

Mass is the property of a body of fluid that is a measure of its inertia or resistance to a change in motion. It is also a measure of the quantity of fluid.

We use the symbol m for mass in this book.

Weight is the amount that a body of fluid weighs, that is, the force with which the fluid is attracted toward Earth by gravitation.

We use the symbol w for weight.

The relationship between weight and mass is discussed in Section 1.5 as we review the unit systems used in this book. You must be familiar with both the International System of Units, called *SI*, and the U.S. Customary System of units.

- ***Fluid Properties*** The latter part of this chapter presents other fluid properties: *specific weight*, *density*, *specific gravity*, and *surface tension*. Chapter 2 presents an additional property, *viscosity*, which is a measure of the ease with which a fluid flows. It is also important in determining the character of the flow of fluids and the amount of energy that is lost from a fluid flowing in a system as discussed in Chapters 8–13.
- ***Quantifying Physical Phenomena*** Technical systems require accurate accounting of properties and behaviors of physical phenomena. For many students, the course in fluid mechanics brings a new level of complexity with regard to tracking physical phenomena in equations, and greater care needs to be taken. Students should track units explicitly, using something like the unit cancellation method shown in Section 1.7, to ensure that the dimensions of all entities are appropriate. Taking care with regard to units will ensure that pressure and force are kept separate, for example, and that specific gravity will not be confused with specific weight. Explicit and careful use of units in all calculations will aid in understanding and will greatly increase student success.

1.3 THE INTERNATIONAL SYSTEM OF UNITS (SI)

In any technical work the units in which physical properties are measured must be stated. A system of units specifies the units of the basic quantities of length, time, force, and mass. The units of other terms are then derived from these.

The ultimate reference for the standard use of metric units throughout the world is the International System of Units (Système International d'Unités), abbreviated as SI. In the United States, the standard is given in the 2008 publication of the National Institute of Standards and Technology (NIST), U.S. Department of Commerce, *The International System of Units* (*SI*) (NIST Special Publication 330), edited by Barry N. Taylor and Ambler Thompson (see Reference 1). This is the standard used in this book.

The SI units for the basic quantities are as follows:

$$\begin{aligned} \text{length} &= \text{meter (m)} \\ \text{time} &= \text{second (s)} \\ \text{mass} &= \text{kilogram (kg) or N} \cdot \text{s}^2/\text{m} \\ \text{force} &= \text{newton (N) or kg} \cdot \text{m/s}^2 \end{aligned}$$

An equivalent unit for force is kg · m/s^2 as indicated above. This is derived from the relationship between force and mass,

$$F = ma$$

TABLE 1.1 SI unit prefixes

Prefix	SI Symbol	Factor
terra	T	10^{12} = 1 000 000 000 000
giga	G	10^{9} = 1 000 000 000
mega	M	10^{6} = 1 000 000
kilo	k	10^{3} = 1000
milli	m	10^{-3} = 0.001
micro	μ	10^{-6} = 0.000 001
nano	n	10^{-9} = 0.000 000 001
pico	p	10^{-12} = 0.000 000 000 001

where a is the acceleration expressed in units of m/s^2. Therefore, the derived unit for force is

$$F = ma = \text{kg} \cdot \text{m/s}^2 = \text{N}$$

Thus, a force of 1.0 N would give a mass of 1.0 kg an acceleration of 1.0 m/s^2. This means that either N or kg · m/s^2 can be used as the unit for force. In fact, some calculations in this book require that you be able to use both or to convert from one to the other.

Similarly, besides using the kg as the standard unit mass, we can use the equivalent unit N · s^2/m. This can be derived again from $F = ma$:

$$m = \frac{F}{a} = \frac{N}{\text{m/s}^2} = \frac{\text{N} \cdot \text{s}^2}{\text{m}}$$

Therefore, either kg or N · s^2/m can be used for the unit of mass.

1.3.1 SI Unit Prefixes

Because the actual size of physical quantities in the study of fluid mechanics covers a wide range, prefixes are added to the basic quantities. Table 1.1 shows these prefixes. Standard usage in the SI system calls for only those prefixes varying in steps of 10^3 as shown. Results of calculations should normally be adjusted so that the number is between 0.1 and 10 000 times some multiple of 10^3*. Then the proper unit with a prefix can be specified. Note that some technical professionals and companies in Europe often use the prefix *centi*, as in centimeters, indicating a factor of 10^{-2}. Some examples follow showing how quantities are given in this book.

* Because commas are used as decimal markers in many countries, we will not use commas to separate groups of digits. We will separate the digits into groups of three, counting both to the left and to the right from the decimal point, and use a space to separate the groups of three digits. We will not use a space if there are only four digits to the left or right of the decimal point unless required in tabular matter.

Computed Result	Reported Result
0.004 23 m	4.23×10^{-3} m, or 4.23 mm (millimeters)
15 700 kg	15.7×10^{3} kg, or 15.7 Mg (megagrams)
86 330 N	86.33×10^{3} N, or 86.33 kN (kilonewtons)

1.4 THE U.S. CUSTOMARY SYSTEM

The SI convention discussed above is the most common throughout the world. The United States, however, continues to use a different system for much of its industry. Sometimes called the *English gravitational unit system* or the *pound-foot-second* system, the U.S. Customary System defines the basic quantities as follows:

$$\text{length} = \text{foot (ft)}$$
$$\text{time} = \text{second (s)}$$
$$\text{force} = \text{pound (lb)}$$
$$\text{mass} = \text{slug or lb-s}^2/\text{ft}$$

Probably the most difficult of these units to understand is the slug because we are more familiar with measuring in terms of pounds, seconds, and feet. It may help to note the relationship between force and mass,

$$F = ma$$

where a is acceleration expressed in units of ft/s^2. Therefore, the derived unit for mass is

$$m = \frac{F}{a} = \frac{\text{lb}}{\text{ft/s}^2} = \frac{\text{lb-s}^2}{\text{ft}} = \text{slug}$$

This means that you may use either slugs or lb-s^2/ft for the unit of mass. In fact, some calculations in this book require that you be able to use both or to convert from one to the other.

1.5 WEIGHT AND MASS

A rigid distinction is made between weight and mass in this book. Weight is a force and mass is the quantity of a substance. We relate these two terms by applying Newton's law of gravitation stated as *force equals mass times acceleration*, or

$$F = ma$$

When we speak of weight w, we imply that the acceleration is equal to g, the acceleration due to gravity. Then Newton's law becomes

➩ Weight–mass relationship

$$w = mg \qquad \textbf{(1–2)}$$

In this book, we will use $g = 9.81$ m/s^2 in the SI system and $g = 32.2$ ft/s^2 in the U.S. Customary System. These are the standard values on Earth for g to three significant digits. To a greater degree of precision, we have the standard values $g = 9.806\,65$ m/s^2 and $g = 32.1740$ ft/s^2. For high-precision work and at high elevations (such as aerospace operations) where the actual value of g is different from the standard, the local value should be used.

1.5.1 Weight and Mass in the SI Unit System

For example, consider a rock with a mass of 5.60 kg suspended by a wire. To determine what force is exerted on the wire, we use Newton's law of gravitation ($w = mg$):

$$w = mg = \text{mass} \times \text{acceleration due to gravity}$$

Under standard conditions, however, $g = 9.81$ m/s^2. Then, we have

$$w = 5.60\text{ kg} \times 9.81\text{ m/s}^2 = 54.9\text{ kg}\cdot\text{m/s}^2 = 54.9\text{ N}$$

Thus, a 5.60 kg rock weighs 54.9 N.

We can also compute the mass of an object if we know its weight. For example, assume that we have measured the weight of a valve to be 8.25 N. What is its mass? We write

$$w = mg$$
$$m = \frac{w}{g} = \frac{8.25\text{ N}}{9.81\text{ m/s}^2} = \frac{0.841\text{ N}\cdot\text{s}^2}{\text{m}} = 0.841\text{ kg}$$

1.5.2 Weight and Mass in the U.S. Customary Unit System

For an example of the weight–mass relationship in the U.S. Customary System, assume that we have measured the weight of a container of oil to be 84.6 lb. What is its mass? We write

$$w = mg$$
$$m = w/g = 84.6\text{ lb}/32.2\text{ ft/s}^2 = 2.63\text{ lb-s}^2/\text{ft} = 2.63\text{ slugs}$$

1.5.3 Mass Expressed as lbm (Pounds-Mass)

In the analysis of fluid systems, some professionals use the unit lbm (pounds-mass) for the unit of mass instead of the unit of slugs. In this system, an object or a quantity of fluid having a weight of 1.0 lb has a mass of 1.0 lbm. The pound-force is then sometimes designated lbf. It must be noted that the numerical equivalence of lbf and lbm applies *only* when the value of g is equal to the standard value.

This system is avoided in this book because it is not a coherent system. When one tries to relate force and mass units using Newton's law, one obtains

$$F = ma = \text{lbm}(\text{ft/s}^2) = \text{lbm-ft/s}^2$$

This is *not* the same as the lbf.

To overcome this difficulty, a conversion constant, commonly called g_c, is defined having both a numerical value and units. That is,

$$g_c = \frac{32.2\text{ lbm}}{\text{lbf}/(\text{ft/s}^2)} = \frac{32.2\text{ lbm-ft/s}^2}{\text{lbf}}$$

Then, to convert from lbm to lbf, we use a modified form of Newton's law:

$$F = m(a/g_c)$$

Letting the acceleration $a = g$, we find

$$F = m(g/g_c)$$

For example, to determine the weight of material in lbf that has a mass of 100 lbm, and assuming that the local value of g is equal to the standard value of 32.2 ft/s^2, we have

$$w = F = m\frac{g}{g_c} = 100 \text{ lbm} \frac{32.2 \text{ ft/s}^2}{\dfrac{32.2 \text{ lbm-ft/s}^2}{\text{lbf}}} = 100 \text{ lbf}$$

This shows that weight in lbf is numerically equal to mass in lbm *provided* $g = 32.2$ ft/s^2.

If the analysis were to be done for an object or fluid on the Moon, however, where g is approximately 1/6 of that on Earth, 5.4 ft/s^2, we would find

$$w = F = m\frac{g}{g_c} = 100 \text{ lbm} \frac{5.4 \text{ ft/s}^2}{\dfrac{32.2 \text{ lbm-ft/s}^2}{\text{lbf}}} = 16.8 \text{ lbf}$$

This is a dramatic difference.

In summary, because of the cumbersome nature of the relationship between lbm and lbf, we avoid the use of lbm in this book. Mass will be expressed in the unit of slugs when problems are in the U.S. Customary System of units.

1.6 TEMPERATURE

Temperature is most often indicated in °C (degrees Celsius) or °F (degrees Fahrenheit). You are probably familiar with the following values at sea level on Earth:

Water freezes at 0°C and boils at 100°C.

Water freezes at 32°F and boils at 212°F.

Thus, there are 100 Celsius degrees and 180 Fahrenheit degrees between the same two physical data points, and 1.0 Celsius degree equals 1.8 Fahrenheit degrees exactly. From these observations we can define the conversion procedures between these two systems as follows:

Given the temperature T_F in °F, the temperature T_C in °C is

$$T_C = (T_F - 32)/1.8$$

Given the temperature T_C in °C, the temperature T_F in °F is

$$T_F = 1.8T_C + 32$$

For example, given $T_F = 180$°F, we have

$$T_C = (T_F - 32)/1.8 = (180 - 32)/1.8 = 82.2°\text{C}$$

Given $T_C = 33$°C, we have

$$T_F = 1.8T_C + 32 = 1.8(33) + 32 = 91.4°\text{F}$$

In this book we will use the Celsius scale when problems are in SI units and the Fahrenheit scale when they are in U.S. Customary units.

1.6.1 Absolute Temperature

The Celsius and Fahrenheit temperature scales were defined according to arbitrary reference points, although the Celsius scale has convenient points of reference to the properties of water. The absolute temperature, on the other hand, is defined so the zero point corresponds to the condition where all molecular motion stops. This is called *absolute zero*.

In the SI unit system, the standard unit of temperature is the kelvin, for which the standard symbol is K and the reference (zero) point is absolute zero. Note that there is no degree symbol attached to the symbol K. The interval between points on the kelvin scale is the same as the interval used for the Celsius scale. Measurements have shown that the freezing point of water is 273.15 K above absolute zero. We can then make the conversion from the Celsius to the kelvin scale by using

$$T_K = T_C + 273.15$$

For example, given $T_C = 33$°C, we have

$$T_K = T_C + 273.15 = 33 + 273.15 = 306.15 \text{ K}$$

It has also been shown that absolute zero on the Fahrenheit scale is at −459.67°F. In some references you will find another absolute temperature scale called the Rankine scale, where the interval is the same as for the Fahrenheit scale. Absolute zero is 0°R and any Fahrenheit measurement can be converted to °R by using

$$T_R = T_F + 459.67$$

Also, given the temperature in °F, we can compute the absolute temperature in K from

$$T_K = (T_F + 459.67)/1.8 = T_R/1.8$$

For example, given $T_F = 180$°F, the absolute temperature in K is

$$\begin{aligned} T_K = (T_F + 459.67)/1.8 &= (180 + 459.67)/1.8 \\ &= (639.67°\text{R})/1.8 = 355.37 \text{ K} \end{aligned}$$

1.7 CONSISTENT UNITS IN AN EQUATION

The analyses required in fluid mechanics involve the algebraic manipulation of several terms. The equations are often complex, and it is extremely important that the results be dimensionally correct. That is, they must have their proper units. Indeed, answers will have the wrong numerical value if the units in the equation are not consistent. Table 1.2 summarizes standard and other common units for the quantities used in fluid mechanics.

A simple straightforward procedure called *unit cancellation* will ensure proper units in any kind of calculation, not only in fluid mechanics but also in virtually all your technical work. The six steps of the procedure are listed subsequently.

TABLE 1.2 Units for common quantities used in fluid mechanics in SI units and U.S. Customary units

Quantity	Basic Definition	Standard SI Units	Other Metric Units Often Used	Standard U.S. Units	Other U.S. Units Often Used
Length (L)	—	meter (m)	millimeter (mm); kilometer (km)	foot (ft)	inch (in); mile (mi)
Time	—	second (s)	hour (h); minute (min)	second (s)	hour (h); minute (min)
Mass (m)	Quantity of a substance	kilogram (kg)	$N \cdot s^2/m$	slug	$lb \cdot s^2/ft$
Force (F) or weight (w)	Push or pull on an object	newton (N)	$kg \cdot m/s^2$	pound (lb)	kip (1000 lb)
Pressure (p)	Force/area	N/m^2 or pascal (Pa)	kilopascals (kPa); bar	lb/ft^2 or psf	lb/in^2 or psi; kip/in^2 or ksi
Energy	Force times distance	$N \cdot m$ or Joule (J)	$kg \cdot m^2/s^2$	$lb \cdot ft$	$lb \cdot in$
Power (P)	Energy/time	watt (W) or $N \cdot m/s$ or J/s	kilowatt (kW)	$lb \cdot ft/s$	horsepower (hp)
Volume (V)	L^3	m^3	liter (L)	ft^3	gallon (gal)
Area (A)	L^2	m^2	mm^2	ft^2	in^2
Volume flow rate (Q)	V/time	m^3/s	L/s; L/min; m^3/h	ft^3/s or cfs	gal/min (gpm); ft^3/min (cfm)
Weight flow rate (W)	w/time	N/s	kN/s; kN/min	lb/s	lb/min; lb/h
Mass flow rate (M)	m/time	kg/s	kg/h	slugs/s	slugs/min; slugs/h
Specific weight (γ)	w/V	N/m^3 or $kg/m^2{\cdot}s^2$		lb/ft^3	
Density (ρ)	m/V	kg/m^3 or $N \cdot s^2/m^4$		$slugs/ft^3$	

Unit-Cancellation Procedure

1. Solve the equation algebraically for the desired term.
2. Decide on the proper units for the result.
3. Substitute known values, including units.
4. Cancel units that appear in both the numerator and the denominator of any term.
5. Use conversion factors to eliminate unwanted units and obtain the proper units as decided in Step 2.
6. Perform the calculation.

This procedure, properly executed, will work for any equation. It is really very simple, but some practice may be required to use it. We are going to borrow some material from elementary physics, with which you should be familiar, to illustrate the method. However, the best way to learn how to do something is to do it. The following example problems are presented in a form called *programmed instruction*. You will be guided through the problems in a step-by-step fashion with your participation required at each step.

To proceed with the program, you should cover all material under the heading Programmed Example Problem, using an opaque sheet of paper or a card. You should have a blank piece of paper handy on which to perform the requested operations. Then successively uncover one panel at a time down to the heavy line that runs across the page. The first panel presents a problem and asks you to perform some operation or to answer a question. After doing what is asked, uncover the next panel, which will contain information that you can use to check your result. Then continue with the next panel, and so on through the program.

Remember, the purpose of this is to help you learn how to get correct answers using the unit-cancellation method. You may want to refer to the table of conversion factors in Appendix K.

PROGRAMMED EXAMPLE PROBLEM

Example Problem 1.1

Imagine you are traveling in a car at a constant speed of 80 kilometers per hour (km/h). How many seconds (s) would it take to travel 1.5 km?

For the solution, use the equation

$$s = vt$$

where s is the distance traveled, v is the speed, and t is the time. Using the unit-cancellation procedure outlined above, what is the first thing to do?

The first step is to solve for the desired term. Because you were asked to find time, you should have written

$$t = \frac{s}{v}$$

Now perform Step 2 of the procedure described above.

Step 2 is to decide on the proper units for the result, in this case time. From the problem statement the proper unit is seconds. If no specification had been given for units, you could choose any acceptable time unit such as hours.

Proceed to Step 3.

The result should look something like this:

$$t = \frac{s}{v} = \frac{1.5 \text{ km}}{80 \text{ km/h}}$$

For the purpose of cancellation, it is not convenient to have the units in the form of a compound fraction as we have above. To clear this to a simple fraction, write it in the form

$$t = \frac{\dfrac{1.5 \text{ km}}{1}}{\dfrac{80 \text{ km}}{\text{h}}}$$

This can be reduced to

$$t = \frac{1.5 \text{ km} \cdot \text{h}}{80 \text{ km}}$$

After some practice, equations may be written in this form directly. Now perform Step 4 of the procedure.

The result should now look like this:

$$t = \frac{1.5 \cancel{\text{km}} \cdot \text{h}}{80 \cancel{\text{km}}}$$

This illustrates that units can be cancelled just as numbers can if they appear in both the numerator and the denominator of a term in an equation.

Now do Step 5.

The answer looks like this:

$$t = \frac{1.5 \cancel{\text{km}} \cdot \cancel{\text{h}}}{80 \cancel{\text{km}}} \times \frac{3600 \text{ s}}{1 \cancel{\text{h}}}$$

The equation in the preceding panel showed the result for time in hours after kilometer units were cancelled. Although hours is an acceptable time unit, our desired unit is seconds as determined in Step 2. Thus, the conversion factor 3600 s/1 h is required.

How did we know we have to multiply by 3600 instead of dividing?

The units determine this. Our objective in using the conversion factor was to eliminate the hour unit and obtain the second unit. Because the unwanted hour unit was in the numerator of the original equation, the hour unit in the conversion factor must be in the denominator in order to cancel.

Now that we have the time unit of seconds, we can proceed with Step 6.

The correct answer is $t = 67.5$ s.

1.8 THE DEFINITION OF PRESSURE

Pressure is defined as the amount of force exerted on a unit area of a substance. This can be stated by the equation

Pressure

$$p = \frac{F}{A} \qquad \textbf{(1–3)}$$

Two important principles about pressure were described by Blaise Pascal, a seventeenth-century scientist:

- Pressure acts uniformly in all directions on a small volume of a fluid.
- In a fluid confined by solid boundaries, pressure acts perpendicular to the boundary.

These principles, sometimes called *Pascal's laws*, are illustrated in Figs. 1.3 and 1.4.

Using Eq. (1–3) and the second of Pascal's laws, we can compute the magnitude of the pressure in a fluid if we know the amount of force exerted on a given area.

FIGURE 1.3 Pressure acting uniformly in all directions on a small volume of fluid.

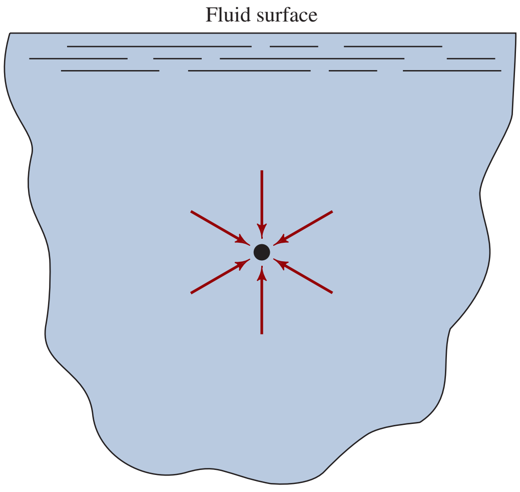
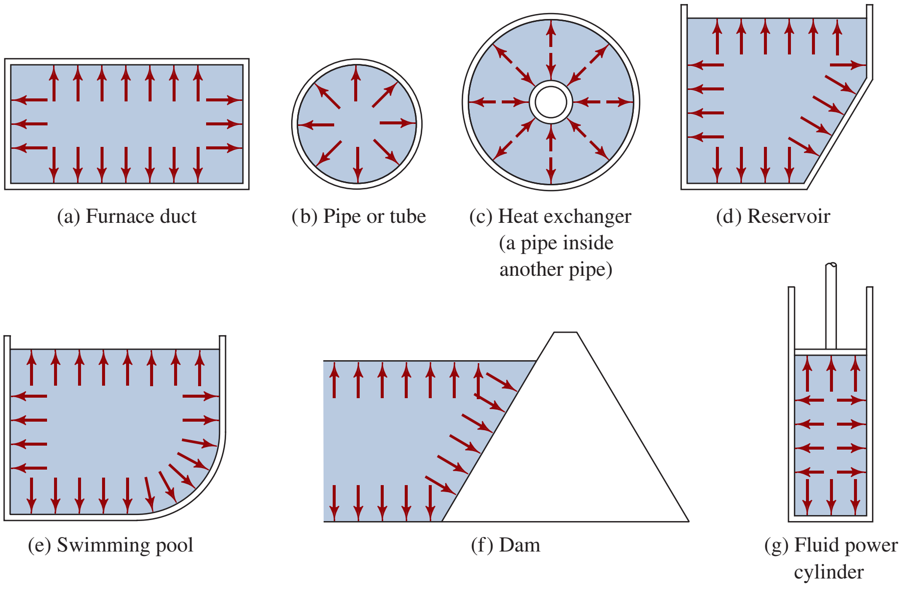


FIGURE 1.4 Direction of fluid pressure on boundaries.



Example Problem 1.2

Figure 1.5 shows a container of liquid with a movable piston supporting a load. Compute the magnitude of the pressure in the liquid under the piston if the total weight of the piston and the load is 500 N and the area of the piston is 2500 mm^2.

Solution

It is reasonable to assume that the entire surface of the fluid under the piston is sharing in the task of supporting the load. The second of Pascal's laws states that the fluid pressure acts perpendicular to the piston. Then, using Eq. (1–3), we have

$$p = \frac{F}{A} = \frac{500\ \text{N}}{2500\ \text{mm}^2} = 0.20\ \text{N/mm}^2$$

The standard unit of pressure in the SI system is the N/m^2, called the *pascal* (Pa) in honor of Blaise Pascal. The conversion can be made by using the factor 10^3 mm = 1 m. We have

$$p = \frac{0.20\ \text{N}}{\text{mm}^2} \times \frac{(10^3\ \text{mm})^2}{\text{m}^2} = 0.20 \times 10^6\ \text{N/m}^2 = 0.20\ \text{MPa}$$

Note that the pressure in N/mm^2 is numerically equal to pressure in MPa. It is not unusual to encounter pressure in the range of several megapascals (MPa) or several hundred kilopascals (kPa).

Pressure in the U.S. Customary System is illustrated in the following example problem.

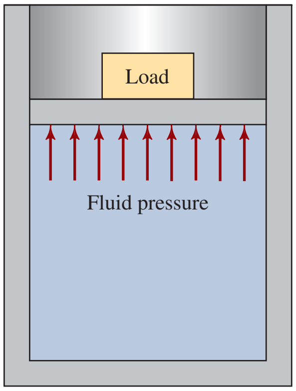


FIGURE 1.5 Illustration of fluid pressure supporting a load.

Example Problem 1.3

A load of 200 pounds (lb) is exerted on a piston confining oil in a circular cylinder with an inside diameter of 2.50 inches (in). Compute the pressure in the oil at the piston. See Fig. 1.4.

Solution

To use Eq. (1–3), we must compute the area of the piston:

$$A = \pi D^2/4 = \pi(2.50\ \text{in})^2/4 = 4.91\ \text{in}^2$$

Then,

$$p = \frac{F}{A} = \frac{200\ \text{lb}}{4.91\ \text{in}^2} = 40.7\ \text{lb/in}^2$$

Although the standard unit for pressure in the U.S. Customary System is pounds per square foot (lb/ft^2), it is not often used because it is inconvenient. Length measurements are more conveniently made in inches, and pounds per square inch (lb/in^2), abbreviated psi, is used most often for pressure in this system. The pressure in the oil is 40.7 psi. This is a fairly low pressure; it is not unusual to encounter pressures of several hundred or several thousand psi.

The *bar* is another unit used by some people working in fluid mechanics and thermodynamics. The bar is defined as 10^5 Pa or 10^5 N/m^2. Another way of expressing the bar is 1 bar = 100×10^3 N/m^2, which is equivalent to 100 kPa. Because atmospheric pressure near sea level is very nearly this value, the bar has a convenient point of physical reference. This, plus the fact that pressures expressed in bars yield smaller numbers, makes this unit attractive to some practitioners. You must realize, however, that the bar is not a part of the coherent SI system and that you must carefully convert it to N/m^2 (pascals) in problem solving.

1.9 COMPRESSIBILITY

Compressibility refers to the change in volume (V) of a substance that is subjected to a change in pressure on it. The usual quantity used to measure this phenomenon is the *bulk modulus of elasticity* or, simply, *bulk modulus*, E:

TABLE 1.3 Values for bulk modulus for selected liquids at atmospheric pressure and 68°F (20°C)

	Bulk Modulus	
Liquid	**(psi)**	**(MPa)**
Ethyl alcohol	130 000	896
Benzene	154 000	1 062
Machine oil	189 000	1 303
Water	316 000	2 179
Glycerin	654 000	4 509
Mercury	3 590 000	24 750

➭ **Bulk Modulus**

$$E = \frac{-\Delta p}{(\Delta V)/V} \qquad \textbf{(1–4)}$$

Because the quantities ΔV and V have the same units, the denominator of Eq. (1–4) is dimensionless. Therefore, the units for E are the same as those for the pressure.

As stated before, liquids are very slightly compressible, indicating that it would take a very large change in pressure to produce a small change in volume. Thus, the magnitudes of E for liquids, as shown in Table 1.3, are very high (see Reference 7). For this reason, *liquids will be considered incompressible in this book, unless stated otherwise.*

The term *bulk modulus* is not usually applied to gases. Again, gases are fluids, but they are extremely compressible relative to liquids, meaning that the volume of a gas changes significantly with a change in pressure. The principles of thermodynamics must be applied to determine the change in volume of a gas with a change in pressure.

Example Problem 1.4 Compute the change in pressure that must be applied to water to change its volume by 1.0 percent.

Solution The 1.0-percent volume change indicates that $\Delta V/V = -0.01$. Then, the required change in pressure is

$$\Delta p = -E[\Delta V/V] = [-316\ 000\ \text{psi}][-0.01] = 3160\ \text{psi}$$

1.10 DENSITY, SPECIFIC WEIGHT, AND SPECIFIC GRAVITY

Because the study of fluid mechanics typically deals with a continuously flowing fluid or with a small amount of fluid at rest, it is most convenient to relate the mass and weight of the fluid to a given volume of the fluid. Thus, the properties of density and specific weight are defined as follows:

> **Density** *is the amount of mass per unit volume of a substance.*

Therefore, using the Greek letter ρ (rho) for density, we write

➭ **Density**

$$\rho = m/V \qquad \textbf{(1–5)}$$

where V is the volume of the substance having a mass m. The units for density are kilograms per cubic meter (kg/m^3) in the SI system and slugs per cubic foot ($slugs/ft^3$) in the U.S. Customary System.

ASTM International, formerly the American Society for Testing and Materials, has published several standard test methods for measuring density that describe vessels having precisely known volumes called *pycnometers*. The proper filling, handling, temperature control, and reading of these devices are prescribed. Two types are the *Bingham pycnometer* and the *Lipkin bicapillary pycnometer*. The standards also call for the precise determination of the mass of the fluids in the pycnometers to the nearest 0.1 mg using an analytical balance. See References 3, 5, and 6.

> **Specific weight** *is the amount of weight per unit volume of a substance.*

Using the Greek letter γ (gamma) for specific weight, we write

➭ **Specific Weight**

$$\gamma = w/V \qquad \textbf{(1–6)}$$

where V is the volume of a substance having the weight w. The units for specific weight are newtons per cubic meter (N/m^3) in the SI system and pounds per cubic foot (lb/ft^3) in the U.S. Customary System.

It is often convenient to indicate the specific weight or density of a fluid in terms of its relationship to the specific weight or density of a common fluid. When the term *specific gravity* is used in this book, the reference fluid is pure water at 4°C. At that temperature water has its greatest density. Then, specific gravity can be defined in either of two ways:

a. *Specific gravity* is the ratio of the density of a substance to the density of water at 4°C.

b. *Specific gravity* is the ratio of the specific weight of a substance to the specific weight of water at 4°C.

These definitions for specific gravity (sg) can be shown mathematically as

➭ **Specific Gravity**

$$\text{sg} = \frac{\gamma_s}{\gamma_w @ 4^\circ\text{C}} = \frac{\rho_s}{\rho_w @ 4^\circ\text{C}} \qquad \textbf{(1–7)}$$

where the subscript s refers to the substance whose specific gravity is being determined and the subscript w refers to water. The properties of water at 4°C are constant, having the following values:

$$\gamma_w @ 4^\circ\text{C} = 9.81\ \text{kN/m}^3 \qquad \gamma_w @ 4^\circ\text{C} = 62.4\ \text{lb/ft}^3$$

or

$$\rho_w @ 4^\circ\text{C} = 1000\ \text{kg/m}^3 \qquad \rho_w @ 4^\circ\text{C} = 1.94\ \text{slugs/ft}^3$$

Therefore, the mathematical definition of specific gravity can be written as

$$sg = \frac{\gamma_s}{9.81 \text{ kN/m}^3} = \frac{\rho_s}{1000 \text{ kg/m}^3} \text{ or}$$

$$sg = \frac{\gamma_s}{62.4 \text{ lb/ft}^3} = \frac{\rho_s}{1.94 \text{ slugs/ft}^3} \quad \textbf{(1–8)}$$

This definition holds regardless of the temperature at which the specific gravity is being determined.

The properties of fluids do, however, vary with temperature. In general, the density (and therefore the specific weight and the specific gravity) decreases with increasing temperature. The properties of water at various temperatures are listed in Appendix A. The properties of other liquids at a few selected temperatures are listed in Appendices B and C. See Reference 9 for more such data.

You should seek other references, such as References 8 and 10, for data on specific gravity at specified temperatures if they are not reported in the appendix and if high precision is desired. One estimate that gives reasonable accuracy for petroleum oils, as presented more fully in References 8 and 9, is that the specific gravity of oils decreases approximately 0.036 for a 100°F (37.8°C) rise in temperature. This applies for nominal values of specific gravity from 0.80 to 1.00 and for temperatures in the range from approximately 32°F to 400°F (0°C to 204°C).

Some industry sectors prefer modified definitions for specific gravity. Instead of using the properties of water at 4°C (39.2°F) as the basis, the petroleum industry and others use water at 60°F (15.6°C). This makes little difference for typical design and analysis. Although the density of water at 4°C is 1000.00 kg/m^3, at 60°F it is 999.04 kg/m^3. The difference is less than 0.1 percent. References 3, 4, 6–8, and 10 contain more extensive tables of the properties of water at temperatures from 0°C to 100°C (32°F to 212°F).

Specific gravity in the Baumé and API scales is discussed in Section 1.10.2. We will use water at 4°C as the basis for specific gravity in this book.

The ASTM also refers to the property of specific gravity as *relative density*. See References 3–6.

1.10.1 Relation Between Density and Specific Weight

Quite often the specific weight of a substance must be found when its density is known and vice versa. The conversion from one to the other can be made using the following equation:

➩ γ-ρ Relation

$$\gamma = \rho g \quad \textbf{(1–9)}$$

where g is the acceleration due to gravity. This equation can be justified by referring to the definitions of density and specific gravity and by using the equation relating mass to weight, $w = mg$.

The definition of specific weight is

$$\gamma = \frac{w}{V}$$

By multiplying both the numerator and the denominator of this equation by g we obtain

$$\gamma = \frac{wg}{Vg}$$

But $m = w/g$. Therefore, we have

$$\gamma = \frac{mg}{V}$$

Because $\rho = m/V$, we get

$$\gamma = \rho g$$

The following problems illustrate the definitions of the basic fluid properties presented above and the relationships among the various properties.

Example Problem 1.5

Calculate the weight of a reservoir of oil if it has a mass of 825 kg.

Solution

Because $w = mg$, and using $g = 9.81 \text{ m/s}^2$, we have

$$w = 825 \text{ kg} \times 9.81 \text{ m/s}^2 = 8093 \text{ kg} \cdot \text{m/s}^2$$

Substituting the newton for the unit kg · m/s^2, we have

$$w = 8093 \text{ N} = 8.093 \times 10^3 \text{ N} = 8.093 \text{ kN}$$

Example Problem 1.6

If the reservoir from Example Problem 1.5 has a volume of 0.917 m^3, compute the density, the specific weight, and the specific gravity of the oil.

Solution

Density:

$$\rho_o = \frac{m}{V} = \frac{825 \text{ kg}}{0.917 \text{ m}^3} = 900 \text{ kg/m}^3$$

Specific weight:

$$\gamma_o = \frac{w}{V} = \frac{8.093 \text{ kN}}{0.917 \text{ m}^3} = 8.83 \text{ kN/m}^3$$

Specific gravity:

$$\text{sg}_0 = \frac{\rho_o}{\rho_w @ 4°\text{C}} = \frac{900 \text{ kg/m}^3}{1000 \text{ kg/m}^3} = 0.90$$

Example Problem 1.7

Glycerin at 20°C has a specific gravity of 1.263. Compute its density and specific weight.

Solution

Density:

$$\rho_g = (\text{sg})_g(1000 \text{ kg/m}^3) = (1.263)(1000 \text{ kg/m}^3) = 1263 \text{ kg/m}^3$$

Specific weight:

$$\gamma_g = (\text{sg})_g(9.81 \text{ kN/m}^3) = (1.263)(9.81 \text{ kN/m}^3) = 12.39 \text{ kN/m}^3$$

Example Problem 1.8

A pint of water weighs 1.041 lb. Find its mass.

Solution

Because $w = mg$, the mass is

$$m = \frac{w}{g} = \frac{1.041 \text{ lb}}{32.2 \text{ ft/s}^2} = \frac{1.041 \text{ lb-s}^2}{32.2 \text{ ft}}$$

$$= 0.0323 \text{ lb-s}^2/\text{ft} = 0.0323 \text{ slugs}$$

Remember that the units of slugs and lb-s^2/ft are the same.

Example Problem 1.9

One gallon of mercury has a mass of 3.51 slugs. Find its weight.

Solution

Using $g = 32.2$ ft/s^2 in Equation 1–2,

$$w = mg = 3.51 \text{ slugs} \times 32.2 \text{ ft/s}^2 = 113 \text{ slug-ft/s}^2$$

This is correct, but the units may seem confusing because weight is normally expressed in pounds. The units of mass may be rewritten as lb-s^2/ft, and we have

$$w = mg = 3.51 \frac{\text{lb-s}^2}{\text{ft}} \times \frac{32.2 \text{ ft}}{\text{s}^2} = 113 \text{ lb}$$

1.10.2 Specific Gravity in Degrees Baumé or Degrees API

The reference temperature for specific gravity measurements on the Baumé or American Petroleum Institute (API) scale is 60°F rather than 4°C as defined before. To emphasize this difference, the API or Baumé specific gravity is often reported as

$$\text{Specific gravity } \frac{60°}{60°} \text{F}$$

This notation indicates that both the reference fluid (water) and the oil are at 60°F.

Specific gravities of crude oils vary widely depending on where they are found. Those from the western United States range from approximately 0.87 to 0.92. Eastern U.S. oil fields produce oil of about 0.82 specific gravity. Mexican crude oil is among the highest at 0.97. A few heavy asphaltic oils have sg > 1.0. (See Reference 7.)

Most oils are distilled before they are used to enhance their quality of burning. The resulting gasolines, kerosenes, and fuel oils have specific gravities ranging from about 0.67 to 0.98.

The equation used to compute specific gravity when the degrees Baumé are known is different for fluids lighter than water and fluids heavier than water. For liquids heavier than water,

$$sg = \frac{145}{145 - \text{deg Baumé}} \qquad \textbf{(1–10)}$$

Thus, to compute the degrees Baumé for a given specific gravity, use

$$\text{deg Baumé} = 145 - \frac{145}{sg} \qquad \textbf{(1–11)}$$

For liquids lighter than water,

$$sg = \frac{140}{130 + \text{deg Baumé}} \qquad \textbf{(1–12)}$$

$$\text{deg Baumé} = \frac{140}{sg} - 130 \qquad \textbf{(1–13)}$$

The API has developed a scale that is slightly different from the Baumé scale for liquids lighter than water. The formulas are

$$sg = \frac{141.5}{131.5 + \text{deg API}} \qquad \textbf{(1–14)}$$

$$\text{deg API} = \frac{141.5}{sg} - 131.5 \qquad \textbf{(1–15)}$$

Degrees API for oils may range from 10 to 80. Most fuel grades will fall in the range of API 20 to 70, corresponding to specific gravities from 0.93 to 0.70. Note that the heavier oils have the lower values of degrees API. Reference 9 contains useful tables listing specific gravity as a function of degrees API.

ASTM Standards D 287 and D 6822 (References 2 and 4, respectively) describe standard test methods for determining API gravity using a *hydrometer*. Figure 1.6 shows typical hydrometers that incorporate a weighted glass bulb with a smaller-diameter stem at the top that is designed to float upright in the test liquid. Based on the principles of buoyancy (see Chapter 5), the hydrometer rests at a position that is dependent on the density of the liquid. The stem is marked with a calibrated scale from which the direct reading of density, specific gravity, or API gravity can be made. Because of the importance of temperature to an accurate measurement of density, some hydrometers, called *thermo-hydrometers*, have a built-in precision thermometer.

1.11 SURFACE TENSION

Surface tension is evident when filling a tablespoon with liquid and noticing that the level of fluid can rise slightly above the top of edge of the spoon. Similarly, water droplets will "bead up" on the surface of a freshly waxed car or newly waterproofed deck. Further, steel is expected to sink in water, but a small needle can be placed on the surface so that it is supported by the surface tension of the water. If the needle is submerged below the surface, it will readily sink

TABLE 1.4 Surface tension of water

Temperature (°F)	Surface Tension (mlb/ft)	Temperature (°C)	Surface Tension (mN/m)
32	5.18	0	75.6
40	5.13	5	74.9
50	5.09	10	74.2
60	5.03	20	72.8
70	4.97	30	71.2
80	4.91	40	69.6
90	4.86	50	67.9
100	4.79	60	66.2
120	4.67	70	64.5
140	4.53	80	62.7
160	4.40	90	60.8
180	4.26	100	58.9
200	4.12		
212	4.04		

Source: Data from *CRC Handbook of Chemistry and Physics*, CRC Press LLC, Boca Raton, FL. (Reference 10)

Notes: Values taken at atmospheric pressure 1.0 lb = 1000 mlb; 1.0 N = 1000 mN

FIGURE 1.6 Hydrometers are carefully calibrated and then placed in fluid to accurately measure fluid density. (*Source:* YAUHENI MESHCHARAKOU/123RF and Ellirra/123RF).

TABLE 1.5 Surface tension of some common liquids

Surface Tension at Stated Temperature

Liquid	10°C (mN/m)	50°F (mlb/ft)	25°C (mN/m)	77°F (mlb/ft)	50°C (mN/m)	122°F (mlb/ft)	75°C (mN/m)	167°F (mlb/ft)	100°C (mN/m)	212°F (lb/ft)
Water	74.2	5.08	72.0	4.93	67.9	4.65	63.6	4.36	58.9	4.04
Methanol	23.2	1.59	22.1	1.51	20.1	1.38				
Ethanol	23.2	1.59	22.0	1.51	19.9	1.36				
Ethylene glycol			48.0	3.29	45.8	3.14	43.5	2.98	41.3	2.83
Acetone	24.57	1.68	22.72	1.56	19.65	1.35				
Benzene			28.2	1.93	25.0	1.71	21.8	1.49		
Mercury	488	33.4	485	33.2	480	32.9	475	32.5	470	32.2

Source: Data from *CRC Handbook of Chemistry and Physics*, CRC Press LLC, Boca Raton, FL. (Reference 10)
Notes: Values taken at atmospheric pressure. 1.0 lb = 1000 mlb; 1.0 N = 1000 mN

to the bottom. Also, if you place a very small amount of soap in the water when the needle is supported, it will almost immediately sink. The soap lowers the surface tension dramatically.

Surface tension acts somewhat like a film at the interface between the liquid water surface and the air above it. The water molecules beneath the surface are attracted to each other and to those at the surface. Quantitatively, surface tension is measured as the work per unit area required to move lower molecules to the surface of the liquid. The resulting units are force per unit length, such as N/m or lb/ft. These units can be found as follows:

$$\text{Surface tension} = \frac{\text{work}}{\text{area}} = \frac{\text{N}\cdot\text{m}}{\text{m}^2} = \text{N/m}$$

$$\text{Or: Surface tension} = \frac{\text{work}}{\text{area}} = \frac{\text{ft}\cdot\text{lb}}{\text{ft}^2} = \text{lb/ft}$$

Surface tension is also the reason that water droplets assume a nearly spherical shape. In addition, the phenomenon of capillarity depends on the surface tension. The surface of a liquid in a small-diameter tube will assume a curved shape that depends on the surface tension of the liquid. Mercury will form virtually an extended bulbous shape. The surface of water, however, will settle into a depressed cavity with the liquid seeming to climb the walls of the tube by a small amount. Adhesion of the liquid to the walls of the tube contributes to this behavior.

The movement of liquids within small spaces depends on this capillary action. *Wicking* is the term often used to describe the rise of a fluid from a liquid surface into a woven material. The movement of liquids within soils is also affected by surface tension and the corresponding capillary action.

Table 1.4 gives the surface tension of water at atmospheric pressure at various temperatures. The SI units used here are mN/m, where 1000 mN = 1.0 N. Similarly, U.S. Customary units are mlb/ft, where 1000 mlb = 1.0 lb force. Table 1.5 gives values for a variety of common liquids also at atmospheric pressure at selected temperatures.

REFERENCES

1. Taylor, Barry N., and Ambler Thompson, eds. 2008. *The International System of Units* (*SI*) (NIST Special Publication 330). Washington, DC: National Institute of Standards and Technology, U.S. Department of Commerce.
2. ASTM International. 2012. *Standard D 287-12(2012): Standard Test Method for API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)*. West Conshohocken, PA: Author.
3. ________. 2015. *Standard D 1217-15: Standard Test Method for Density and Relative Density (Specific Gravity) of Liquids by Bingham Pycnometer*. West Conshohocken, PA: Author.
4. ________. 2017. *Standard D 6822-12(2017): Standard Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Thermohydrometer Method.* West Conshohocken, PA: Author.
5. ________. 2015. *Standard D 1480-15: Standard Test Method for Density and Relative Density (Specific Gravity) of Viscous Materials by Bingham Pycnometer.* West Conshohocken, PA: Author.
6. ________. 2017. *Standard D 1481-17: Standard Test Method for Density and Relative Density (Specific Gravity) of Viscous Materials by Lipkin Bicapillary Pycnometer.* West Conshohocken, PA: Author.
7. Sadegh, Ali and William Worek. 2012. *Marks' Standard Handbook for Mechanical Engineers*, 12th ed. New York: McGraw-Hill.
8. Bolz, Ray E., 1973. *CRC Handbook of Tables for Applied Engineering Science*, 2nd ed. Boca Raton, FL: CRC Press.
9. Heald, C. C., ed. 2018. *Cameron Hydraulic Data*, 20th ed. Irving, TX: Flowserve.
10. Rumble, John, ed. 2017. *CRC Handbook of Chemistry and Physics*, 98th ed. Boca Raton, FL: CRC Press.

INTERNET RESOURCES

1. **Hydraulic Institute (HI):** HI is a nonprofit association serving the pump industry. It provides product standards in North America and worldwide.
2. **ASTM International:** ASTM establishes standards in a variety of fields, including fluid mechanics. Many ASTM standards are cited in this book for testing methods and fluid properties.
3. **Flow Control Network:** The website for *Flow Control Magazine* is a source of information on fluid flow technology, applications of fluid mechanics, and products that measure, control, and contain liquids, gases, and powders. It also includes links to standards organizations important to the fluids industry.
4. **GlobalSpec:** A searchable database of suppliers of a wide variety of technical products, including pumps, flow control, and flow measurement.

PRACTICE PROBLEMS

Conversion Factors

1.1 Convert 1750 millimeters to meters.
1.2 Convert 1800 square millimeters to square meters.
1.3 Convert 3.65×10^3 cubic millimeters to cubic meters.
1.4 Convert 2.05 square meters to square millimeters.
1.5 Convert 0.391 cubic meters to cubic millimeters.
1.6 Convert 55.0 gallons to cubic meters.
1.7 An automobile is moving at 80 kilometers per hour. Calculate its speed in meters per second.
1.8 Convert a length of 25.3 feet to meters.
1.9 Convert a distance of 1.86 miles to meters.
1.10 Convert a length of 8.65 inches to millimeters.
1.11 Convert a distance of 3570 feet to meters.
1.12 Convert a volume of 560 cubic feet to cubic meters.
1.13 Convert a volume of 6250 cubic centimeters to cubic meters.
1.14 Convert a volume of 8.45 liters to cubic meters.
1.15 Convert 6.0 feet per second to meters per second.
1.16 Convert 2500 cubic feet per minute to cubic meters per second.

Note: In all Practice Problems sections in this book, the problems will use both SI and U.S. Customary System units. In most problems, units are consistent and in the same system. It is expected that solutions are completed in the given unit system.

Consistent Units in an Equation

A body moving with constant velocity obeys the relationship $s = \upsilon t$, where s = distance, υ = velocity, and t = time.

1.17 A car travels 0.60 km in 10.6 s. Calculate its average speed in m/s.
1.18 In an attempt at a land speed record, a car travels 1.50 km in 6.2 s. Calculate its average speed in km/h.
1.19 A car travels 1000 ft in 15 s. Calculate its average speed in mi/h.
1.20 In an attempt at a land speed record, a car travels 1 mi in 5.7 s. Calculate its average speed in mi/h.

A body starting from rest with constant acceleration moves according to the relationship $s = \frac{1}{2}at^2$, where s = distance, a = acceleration, and t = time.

1.21 If a body moves 3.2 km in 4.7 min with constant acceleration, calculate the acceleration in m/s^2.
1.22 An object is dropped from a height of 13 m. Neglecting air resistance, how long would it take for the body to strike the ground? Use $a = g = 9.81$ m/s^2.
1.23 If a body moves 3.2 km in 4.7 min with constant acceleration, calculate the acceleration in ft/s^2.
1.24 An object is dropped from a height of 53 in. Neglecting air resistance, how long would it take for the body to strike the ground? Use $a = g = 32.2$ ft/s^2.

The formula for kinetic energy is $KE = \frac{1}{2}m\upsilon^2$, where m = mass and υ = velocity.

1.25 Calculate the kinetic energy in N·m of a 15-kg mass if it has a velocity of 1.20 m/s.
1.26 Calculate the kinetic energy in N·m of a 3600-kg truck moving at 16 km/h.
1.27 Calculate the kinetic energy in N·m of a 75-kg box moving on a conveyor at 6.85 m/s.
1.28 Calculate the mass of a body in kg if it has a kinetic energy of 38.6 N·m when moving at 31.5 km/h.
1.29 Calculate the mass of a body in g if it has a kinetic energy of 94.6 mN·m when moving at 2.25 m/s.
1.30 Calculate the velocity in m/s of a 12-kg object if it has a kinetic energy of 15 N·m.
1.31 Calculate the velocity in m/s of a 175-g body if it has a kinetic energy of 212 mN·m.
1.32 Calculate the kinetic energy in ft-lb of a 1-slug mass if it has a velocity of 4 ft/s.
1.33 Calculate the kinetic energy in ft-lb of an 8000-lb truck moving at 10 mi/h.
1.34 Calculate the kinetic energy in ft-lb of a 150-lb box moving on a conveyor at 20 ft/s.
1.35 Calculate the mass of a body in slugs if it has a kinetic energy of 15 ft-lb when moving at 2.2 ft/s.
1.36 Calculate the weight of a body in lb if it has a kinetic energy of 38.6 ft-lb when moving at 19.5 mi/h.
1.37 Calculate the velocity in ft/s of a 30-lb object if it has a kinetic energy of 10 ft-lb.
1.38 Calculate the velocity in ft/s of a 6-oz body if it has a kinetic energy of 30 in-oz.

One measure of a baseball pitcher's performance is earned run average or ERA. It is the average number of earned runs allowed if all the innings pitched were converted to equivalent nine-inning games. Therefore, the units for ERA are runs per game.

1.39 If a pitcher has allowed 39 runs during 141 innings, calculate the ERA.
1.40 A pitcher has an ERA of 3.12 runs/game and has pitched 150 innings. How many earned runs has the pitcher allowed?
1.41 A pitcher has an ERA of 2.79 runs/game and has allowed 40 earned runs. How many innings have been pitched?
1.42 A pitcher has allowed 49 earned runs during 123 innings. Calculate the ERA.

The Definition of Pressure

1.43 Compute the pressure produced in the oil in a closed cylinder by a piston exerting a force of 2500 lb on the enclosed oil. The piston has a diameter of 2.00 in.
1.44 A hydraulic cylinder must be able to exert a force of 6500 lb. The piston diameter is 1.50 in. Compute the required pressure in the oil.
1.45 Compute the pressure produced in the oil in a closed cylinder by a piston exerting a force of 14.0 kN on the enclosed oil. The piston has a diameter of 75 mm.

1.46 A hydraulic cylinder must be able to exert a force of 38.8 kN. The piston diameter is 50 mm. Compute the required pressure in the oil.

1.47 The hydraulic lift for an automobile service garage has a cylinder with a diameter of 8.0 in. What pressure must the oil have to be able to lift 6000 lb?

1.48 A coining press is used to produce commemorative coins with the likenesses of all the U.S. presidents. The coining process requires a force of 18 000 lb. The hydraulic cylinder has a diameter of 2.50 in. Compute the required oil pressure.

1.49 The maximum pressure that can be developed for a certain fluid power cylinder is 20.5 MPa. Compute the force it can exert if its piston diameter is 50 mm.

1.50 The maximum pressure that can be developed for a certain fluid power cylinder is 6000 psi. Compute the force it can exert if its piston diameter is 2.00 in.

1.51 The maximum pressure that can be developed for a certain fluid power cylinder is 5000 psi. Compute the required diameter for the piston if the cylinder must exert a force of 20 000 lb.

1.52 The maximum pressure that can be developed for a certain fluid power cylinder is 15.0 MPa. Compute the required diameter for the piston if the cylinder must exert a force of 30 kN.

1.53 A line of fluid power cylinders has a range of diameters in 1.00-in increments from 1.00 to 8.00 in. Compute the force that could be exerted by each cylinder with a fluid pressure of 500 psi. Draw a graph of the force versus cylinder diameter.

1.54 A line of fluid power cylinders has a range of diameters in 1.00-in increments from 1.00 to 8.00 in. Compute the pressure required by each cylinder if it must exert a force of 5000 lb. Draw a graph of the pressure versus cylinder diameter.

1.55 Determine your weight in newtons. Then, compute the pressure in pascals that would be created on the oil in a 20-mm-diameter cylinder if you stood on a piston in the cylinder. Convert the resulting pressure to psi.

1.56 For the pressure you computed in Problem 1.55, compute the force in newtons that could be exerted on a piston with 250-mm diameter. Then, convert the resulting force to pounds.

Bulk Modulus

1.57 Compute the pressure change required to cause a decrease in the volume of ethyl alcohol by 1.00 percent. Express the result in both psi and MPa.

1.58 Compute the pressure change required to cause a decrease in the volume of mercury by 1.00 percent. Express the result in both psi and MPa.

1.59 Compute the pressure change required to cause a decrease in the volume of machine oil by 1.00 percent. Express the result in both psi and MPa.

1.60 For the conditions described in Problem 1.59, assume that the 1.00-percent volume change occurred in a cylinder with an inside diameter of 1.00 in and a length of 12.00 in. Compute the axial distance the piston would travel as the volume change occurs.

1.61 A certain hydraulic system operates at 3000 psi. Compute the percentage change in the volume of the oil in the system as the pressure is increased from zero to 3000 psi if the oil is similar to the machine oil listed in Table 1.4.

1.62 A certain hydraulic system operates at 20.0 MPa. Compute the percentage change in the volume of the oil in the system if the oil is similar to the machine oil listed in Table 1.4.

1.63 A measure of the stiffness of a linear actuator system is the amount of force required to cause a certain linear deflection. For an actuator that has an inside diameter of 0.50 in and a length of 42.0 in and that is filled with machine oil, compute the stiffness in lb/in.

1.64 Repeat Problem 1.63 but change the length of the cylinder to 10.0 in. Compare the results.

1.65 Repeat Problem 1.63 but change the cylinder diameter to 2.00 in. Compare the results.

1.66 Using the results of Problems 1.63–1.65, generate a statement about the general design approach to achieving a very stiff system.

Force and Mass

1.67 Calculate the mass of a can of oil if it weighs 810 N.

1.68 Calculate the mass of a tank of gasoline if it weighs 1.85 kN.

1.69 Calculate the weight of 1 m^3 of kerosene if it has a mass of 825 kg.

1.70 Calculate the weight of a jar of castor oil if it has a mass of 450 g.

1.71 Calculate the mass of 1 gal of oil if it weighs 7.8 lb.

1.72 Calculate the mass of 1 ft^3 of gasoline if it weighs 42.0 lb.

1.73 Calculate the weight of 1 ft^3 of kerosene if it has a mass of 1.58 slugs.

1.74 Calculate the weight of 1 gal of water if it has a mass of 0.258 slug.

1.75 Assume that a man weighs 160 lb (force).

a. Compute his mass in slugs.
b. Compute his weight in N.
c. Compute his mass in kg.

1.76 In the United States, hamburger and other meats are sold by the pound. Assuming that this is 1.00-lb force, compute the mass in slugs, the mass in kg, and the weight in N.

1.77 The metric ton is 1000 kg (mass). Compute the force in newtons required to lift it.

1.78 Convert the force found in Problem 1.77 to lb.

1.79 Determine your weight in lb and N and your mass in slugs and kg.

Density, Specific Weight, and Specific Gravity

1.80 The specific gravity of benzene is 0.876. Calculate its specific weight and its density in SI units.

1.81 Air at 16°C and standard atmospheric pressure has a specific weight of 12.02 N/m^3. Calculate its density.

1.82 Carbon dioxide has a density of 1.964 kg/m^3 at 0°C. Calculate its specific weight.

1.83 A certain medium lubricating oil has a specific weight of 8.860 kN/m^3 at 5°C and 8.483 kN/m^3 at 50°C. Calculate its specific gravity at each temperature.

1.84 At 100°C mercury has a specific weight of 130.4 kN/m^3. What volume of the mercury would weigh 3.50 kN?

1.85 A cylindrical can 150 mm in diameter is filled to a depth of 100 mm with a fuel oil. The oil has a mass of 1.56 kg. Calculate its density, specific weight, and specific gravity.

1.86 Glycerin has a specific gravity of 1.258. How much would 0.50 m^3 of glycerin weigh? What would be its mass?

1.87 The fuel tank of an automobile holds 0.095 m^3. If it is full of gasoline having a specific gravity of 0.68, calculate the weight of the gasoline.

1.88 The density of muriatic acid is 1200 kg/m^3. Calculate its specific weight and its specific gravity.

1.89 Liquid ammonia has a specific gravity of 0.826. Calculate the volume of ammonia that would weigh 32.0 N.

1.90 Vinegar has a density of 1080 kg/m^3. Calculate its specific weight and its specific gravity.

1.91 Methyl alcohol has a specific gravity of 0.789. Calculate its density and its specific weight.

1.92 A cylindrical container is 150 mm in diameter and weighs 2.25 N when empty. When filled to a depth of 200 mm with a certain oil, it weighs 35.4 N. Calculate the specific gravity of the oil.

1.93 A storage vessel for gasoline (sg = 0.68) is a vertical cylinder 10 m in diameter. If it is filled to a depth of 6.75 m, calculate the weight and mass of the gasoline.

1.94 What volume of mercury (sg = 13.54) would weigh the same as 0.030 m^3 of castor oil, which has a specific weight of 9.42 kN/m^3?

1.95 A rock has a specific gravity of 2.32 and a volume of $1.42 \times 10^{-4} m^3$. How much does it weigh?

1.96 The specific gravity of benzene is 0.876. Calculate its specific weight and its density in U.S. Customary System units.

1.97 Air at 59°F and standard atmospheric pressure has a specific weight of 0.0765 lb/ft^3. Calculate its density.

1.98 Carbon dioxide has a density of 0.003 81 $slug/ft^3$ at 32°F. Calculate its specific weight.

1.99 A certain medium lubricating oil has a specific weight of 56.4 lb/ft^3 at 40°F and 54.0 lb/ft^3 at 120°F. Calculate its specific gravity at each temperature.

1.100 At 212°F mercury has a specific weight of 834 lb/ft^3. What volume of the mercury would weigh 500 lb?

1.101 One gallon of a certain fuel oil weighs 7.50 lb. Calculate its specific weight, its density, and its specific gravity.

1.102 Glycerin has a specific gravity of 1.258. How much would 50 gal of glycerin weigh?

1.103 The fuel tank of an automobile holds 25.0 gal. If it is full of gasoline having a density of 1.32 $slugs/ft^3$, calculate the weight of the gasoline.

1.104 The density of muriatic acid is 1.20 g/cm^3. Calculate its density in $slugs/ft^3$, its specific weight in lb/ft^3, and its specific gravity. (Note that specific gravity and density in g/cm^3 are numerically equal.)

1.105 Liquid ammonia has a specific gravity of 0.826. Calculate the volume in cm^3 that would weigh 5.0 lb.

1.106 Vinegar has a density of 1.08 g/cm^3. Calculate its specific weight in lb/ft^3.

1.107 Alcohol has a specific gravity of 0.79. Calculate its density both in $slugs/ft^3$ and g/cm^3.

1.108 A cylindrical container has a 6.0-in diameter and weighs 0.50 lb when empty. When filled to a depth of 8.0 in with a certain oil, it weighs 7.95 lb. Calculate the specific gravity of the oil.

1.109 A storage vessel for gasoline (sg = 0.68) is a vertical cylinder 30 ft in diameter. If it is filled to a depth of 22 ft, calculate the number of gallons in the tank and the weight of the gasoline.

1.110 How many gallons of mercury (sg = 13.54) would weigh the same as 5 gal of castor oil, which has a specific weight of 59.69 lb/ft^3?

1.111 A rock has a specific gravity of 2.32 and a volume of 8.64 in^3. How much does it weigh?

Supplemental Problems

Use explicit and careful unit analysis to set up and solve the fluid problems below:

1.112 A village of 75 people desires a tank to store a 3-day supply of water. If the average daily usage per person is 1.7 gal, determine the required size of the tank in cubic feet.

1.113 A cylindrical tank has a diameter of 38 in with its axis vertical. Determine the depth of fluid in the tank when it is holding 85 gal of fluid.

1.114 What is the required rate, in N/min, to empty a tank containing 80 N of fluid in 5 s?

1.115 An empty tank measuring 1.5 m by 2.5 m on the bottom is filled at a rate of 60 L/min. Determine the time required for the fluid to reach a depth of 25 cm.

1.116 A tank that is 2 ft in diameter and 18 in tall is to be filled with a fluid in 90 s. Determine the required fill rate in gal/min.

1.117 A standard pump design can be upgraded to higher efficiency for an additional capital investment of $17,000. What is the period for payback if the upgrade saves 7500 $/year?

1.118 What is the annual cost to run a 2 HP system if it is to run continuously and the cost for energy is 0.10 $/kW-h?

For Problems 1.119 to 1.121: A piston/cylinder arrangement like the one shown in Fig. P1.119 is used to pump liquid. It moves a volume of liquid equal to its displacement, which is the area of the piston face times the length of the stroke, for each revolution of the crank. Perform the following calculations.

1.119 Determine the displacement, in liters, for one revolution of a pump with a 75-mm diameter piston and 100 mm-stroke.

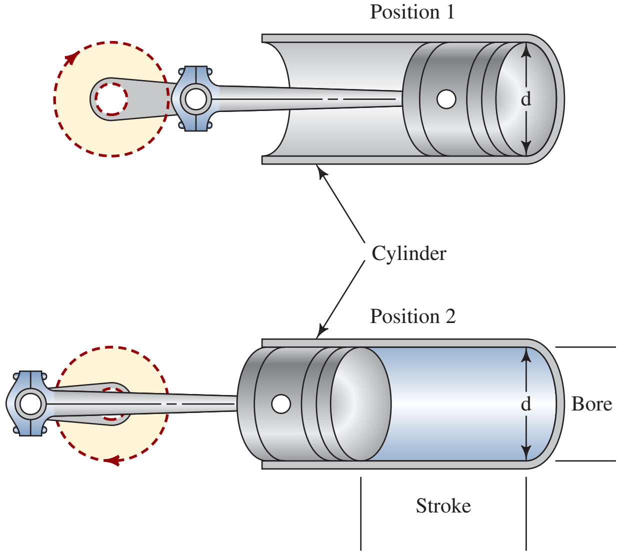


FIGURE P1.119

1.120 Determine the flow rate, in m^3/h, for another pump that has a displacement of 2.2 L/revolution is run at 80 revolutions/min (rpm).

1.121 At what speed, in rpm, does a single cylinder pump with a 1.0-in diameter piston and a 2.5-in stroke need to be run to provide 20 gal/min of flow?

COMPUTER APPLICATION ASSIGNMENTS

1. Generate a computer application that computes the specific weight of water for a given temperature using the data from Appendix A. Such an application could be part of more comprehensive software to be developed later. The following options could be used:

a. Enter the table data for specific weight as a function of temperature into an array. Then, for a specified temperature, search the array for the corresponding specific weight. Interpolate temperatures between values given in the table.

b. Include data in both SI units and U.S. Customary System units.

c. Include density.

d. Include checks in the software to ensure that the specified temperature is within the range given in the tables (i.e., above the freezing point and below the boiling point).

e. Instead of using the table look-up approach, use a curve-fit technique to obtain equations of the properties of water versus temperature. Then compute the desired property value for any specified temperature.

2. Use a spreadsheet or other application to display the values of specific weight and density of water from Appendix A. Then create curve-fit equations for specific weight versus temperature and density versus temperature using the *Trendlines* feature of the spreadsheet chart. Add this equation to the spreadsheet to produce computed values of specific weight and density for any given temperature. Compute the percent difference between the table values and the computed values. Display graphs for specific weight versus temperature and density versus temperature on the spreadsheet showing the equations used.

VISCOSITY OF FLUIDS

THE BIG PICTURE

The ease with which a fluid flows through pipes or pours from a container is an indication of its viscosity. Fluids that flow and pour easily have relatively low viscosity, while those that pour or flow more slowly have high viscosity. Think about some of the fluids you encounter frequently and recall how easily or slowly they pour:

- **Liquids:** Water, milk, juices, sodas, vinegar, syrup for waffles and pancakes, cooking oil, chocolate syrup for ice cream sundaes, mouthwash, shampoo, hair conditioner, liquid soap or detergent, jams and jellies, paint, varnish, sunscreen, insect repellants, gasoline, kerosene, motor oil, household and shop lubricants, cleaning fluids in spray bottles or those that are poured out, windshield washer fluids, weed control liquids, refrigerants in the liquid state, liquid chemicals and mixtures in a factory, oil-hydraulic fluids used in fluid power systems for automated machinery, and many others.
- **Gases:** The air you breathe; air flow through a forced air heating, ventilating and air conditioning (HVAC) system in your home, office, or school; air flow drawn over a car's radiator to keep the coolant at an effective temperature; refrigerants in a gaseous state; natural gas used for home heating, cooking, or hot water heating; compressed air used in pneumatic actuation and control systems in a factory; steam, chemical vapors, atomized spray cleaners, and non-stick spray cooking oils.
- **High Viscosity Fluids and Semi-solids:** Catsup, mustard, salad dressing, peanut butter, apple butter, mayonnaise, face cream, ointments, tooth paste, artist paint, adhesives, sealants, grease, tar, wax, and liquid polymers.

Considering the *liquids*, you likely noticed that water pours easily and rapidly from a faucet, garden hose, or a bucket. However, oils, syrups, and shampoos pour much more slowly as illustrated in Fig. 2.1, which shows oil and honey being poured. Water has a relatively low viscosity, while oil has a relatively high viscosity. We also say that *oil is more viscous than water.* A good exercise is to add any other liquid you can think of to the list above and then arrange the complete list in the approximate order of how easily they flow, that is, put them in the order from the less viscous to the more viscous.

FIGURE 2.1 Engine oil and honey are both used as examples of viscous fluids, but *all* fluids, even gases, have viscosity and this property greatly affects their behavior in engineering systems, and hence our calculations and designs. (*Source*: Ellirra/123RF; Elisanth/123RF)

Gases are also fluids, although they behave much differently from liquids as explained in general in Chapter 1. We don't often think of *pouring* a gas because it moves freely unless confined into a container. However, there are many situations in which gases are *flowing* through pipes, tubing, ductwork, or conduits of other shapes. Consider the high-pressure air you put in the tires of your car, bicycle, or motorcycle; the heated or cooled air delivered by an HVAC system; the compressed air delivered throughout a factory to drive automation devices; the movement of refrigerants in their gaseous state through the tubing in a refrigeration or air conditioning system; or the flow of chemical vapors in a distillation process of a petroleum refining plant. You must consider the viscosity of these gases when designing the flow systems.

High viscosity fluids and semi-solids are those which do not readily pour at all. Think about trying to pour catsup and mustard onto your sandwich. You typically have to shake the bottle, beat on the bottom, or squeeze it to get it on the bread. Other such fluids listed above behave similarly although, given enough time, all of them conform to their containers. These fluids behave very differently as compared with the more normal liquids described earlier and their behavior is described later in this chapter.

You have likely noticed that cold viscous fluids pour more slowly than when they are warm. Examples are motor oil, lubricating oil, and syrups. This phenomenon is due to the fact that a liquid's viscosity typically increases as the temperature drops. You will see data to support this observation in this chapter.

Internet resource 9 states the definition of viscosity as follows:

> *Viscosity is the internal friction of a fluid, caused by molecular attraction, which makes it resist a tendency to flow.*

The internal friction, in turn, causes energy losses to occur as the fluid flows through pipes or other conduits. You will use the property of viscosity in Chapters 8 and 9 when we predict the energy lost from a fluid as it flows in a pipe, a tube, or a conduit of some other shape. Then in Chapters 10–13, it continues to be an important factor in designing and analyzing fluid flow systems. Also, in Chapter 13 on Pump Selection and Application, we show that the performance of a pump is affected by the fluid's viscosity. On a more general basis, viscosity measurement is often used as a measure of product quality and consistency. It can be sensed by the customer when the viscosity of a food product such as syrup is either too high (thick) or too low (thin). In materials processing, viscosity can often affect the mixing of constituents or chemical reactions.

It is important for you to learn how to define fluid viscosity, the units used for it, what industry standards apply to viscosity measurement of fluids such as engine oils and lubricants, and to become familiar with some of the commercially available instruments used to measure it.

Exploration

Now perform some experiments to demonstrate the wide range of viscosities for different kinds of fluids at different temperatures.

- Obtain samples of three different fluids with noticeably different viscosities. Examples are water, oil (cooking or lubricating), liquid detergent or other kinds of cleaning fluid, and foods that are fluids (e.g., tomato juice or catsup).
- Put some of each kind of fluid in the refrigerator and keep some at room temperature.
- Obtain a small, disposable container to use for a test cup and make a small hole in its bottom.
- For each fluid at both room and refrigerated temperature, pour the same amount into the test cup while holding your finger over the hole to keep the fluid in.
- Uncover the hole and allow the fluid to drain out while measuring the time to empty the cup.
- Compare the times for the different fluids at each temperature and the amount of change in time between the two temperatures.

Discuss your results with your fellow students and your instructor.

This chapter describes the physical nature of viscosity, defines both dynamic viscosity and kinematic viscosity, discusses the units for viscosity, and describes several methods for measuring the viscosity of fluids. Standards for testing and classifying viscosities for lubricants, developed by SAE International, ASTM International, International Standards Organization (ISO), and the Coordinating European Council (CEC), are also discussed.

2.1 LEARNING OBJECTIVES

After completing this chapter, you should be able to:

1. Define *dynamic viscosity*.
2. Define *kinematic viscosity*.
3. Identify the units of viscosity in both the SI system and the U.S. Customary System.
4. Describe the difference between a *Newtonian fluid* and a *non-Newtonian fluid*.

5. Describe the methods of viscosity measurement using the *rotating-drum viscometer*, the *capillary-tube viscometer*, the *falling-ball viscometer*, and the *Saybolt Universal viscometer*.
6. Describe the variation of viscosity with temperature for both liquids and gases and define *viscosity index*.
7. Identify several types of commercially available viscometers.
8. Describe the viscosity of lubricants using the SAE viscosity grades and the ISO viscosity grades.

2.2 DYNAMIC VISCOSITY

As a fluid moves, a shear stress develops in it, the magnitude of which depends on the viscosity of the fluid. *Shear stress*, denoted by the Greek letter τ (tau), can be defined as *the force required to slide one unit-area layer of a substance over another*. Thus, τ is a force divided by an area and can be measured in the units of N/m^2 (Pa) or lb/ft^2. In fluids such as water, oil, alcohol, or other common liquids, the magnitude of the shearing stress is directly proportional to the change of velocity between different positions in the fluid.

Figure 2.2 illustrates the concept of velocity change in a fluid by showing a thin layer of fluid between two surfaces, one of which is stationary, while the other is moving. A fundamental condition that exists when a real fluid is in contact with a boundary surface is that the fluid has the same velocity as the boundary. In Fig. 2.2, then, the fluid in contact with the lower surface has a zero velocity and that in contact with the upper surface has the velocity v. If the distance between the two surfaces is small, then the rate of change of velocity with position y is linear. That is, it varies in a straight-line manner. The *velocity gradient* is a measure of the velocity change and is defined as $\Delta v/\Delta y$. This is also called the *shear rate*.

The fact that the shear stress in the fluid is directly proportional to the velocity gradient can be stated mathematically as

$$\tau = \eta\,(\Delta v/\Delta y) \qquad \textbf{(2–1)}$$

where the constant of proportionality η (the Greek letter eta) is called the *dynamic viscosity* of the fluid. The term *absolute viscosity* is sometimes used.

You can gain a physical feel for the relationship expressed in Equation (2–1) by stirring a fluid with a rod. The action of stirring causes a velocity gradient to be created in the fluid. A greater force is required to stir cold oil having a high viscosity (a high value of η) than is required to stir water, which has a low viscosity. This is an indication of the higher shear stress in the cold oil. The direct application of Equation (2–1) is used in some types of viscosity measuring devices as will be explained later.

2.2.1 Units for Dynamic Viscosity

Many different unit systems are used to express viscosity. The systems used most frequently are described here for dynamic viscosity and in the next section for kinematic viscosity.

The definition of dynamic viscosity can be derived from Equation (2–1) by solving for η:

Dynamic Viscosity

$$\eta = \frac{\tau}{\Delta v/\Delta y} = \tau\left(\frac{\Delta y}{\Delta v}\right) \qquad \textbf{(2–2)}$$

The units for η can be derived by substituting the SI units into Eq. (2–2) as follows:

$$\eta = \frac{\mathrm{N}}{\mathrm{m}^2} \times \frac{\mathrm{m}}{\mathrm{m/s}} = \frac{\mathrm{N \cdot s}}{\mathrm{m}^2}$$

Because Pa is another name for N/m^2, we can also express η as

$$\eta = \mathrm{Pa \cdot s}$$

This is the standard unit for dynamic viscosity as stated in official documents of the National Institute for Standards and Technology (NIST), ASTM International, SAE International, ISO, and the Coordinating European Council (CEC). See Internet resources 1–4 of this chapter and Reference 1 from Chapter 1.

Sometimes, when units for η are being combined with other terms—especially density—it is convenient to express η in terms of kg rather than N. Because 1 N = 1 kg · m/s^2, η can be expressed as

$$\eta = \mathrm{N} \times \frac{\mathrm{s}}{\mathrm{m}^2} = \frac{\mathrm{kg \cdot m}}{\mathrm{s}^2} \times \frac{\mathrm{s}}{\mathrm{m}^2} = \frac{\mathrm{kg}}{\mathrm{m \cdot s}}$$

Thus, N · s/m^2, Pa · s, or kg/m · s may all be used for η in the SI system.

Table 2.1 lists the dynamic viscosity units in the three most widely used systems. The dimensions of force multiplied by time divided by length squared are evident in each system. The units of poise and centipoise are listed here because much published data are given in these units. They are part of the obsolete metric system called cgs, derived from its base units of centimeter, dyne, gram, and second. Summary tables listing

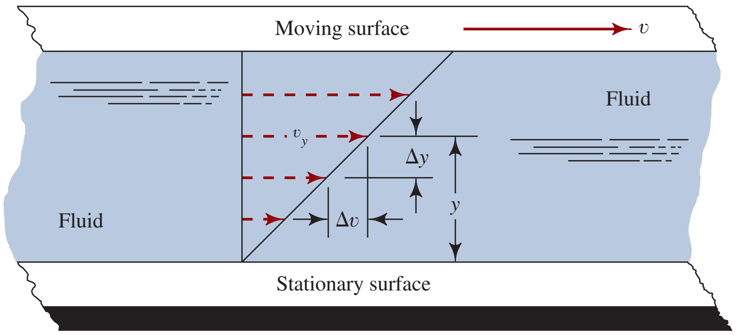


FIGURE 2.2 Velocity gradient in a moving fluid.

TABLE 2.1 Units for dynamic viscosity, η (Greek letter eta)

Unit System	Dynamic Viscosity (η) Units
International System (SI)	$N \cdot s/m^2$, $Pa \cdot s$, or $kg/(m \cdot s)$
U.S. Customary System	$lb \cdot s/ft^2$ or $slug/(ft \cdot s)$
cgs system (obsolete)	poise = $dyne \cdot s/cm^2 = g/(cm \cdot s) = 0.1\ Pa \cdot s$ centipoise = poise/100 = $0.001\ Pa \cdot s = 1.0\ mPa \cdot s$

many conversion factors are included in Appendix K. Also, Internet resource 14 contains online conversion calculators for units of both dynamic and kinematic viscosity along with large lists of viscosity conversion factors.

Dynamic viscosities of common industrial liquids, such as those listed in Appendices A–D and in Section 2.7, range from approximately $1.0 \times 10^{-4}\ Pa \cdot s$ to $60.0\ Pa \cdot s$. Because of this common range, many sources of fluid property data and the scales of viscosity-measurement instruments are listed in a more convenient unit of $mPa \cdot s$, where

$$1.0\ mPa \cdot s = 1.0 \times 10^{-3}\ Pa \cdot s$$

Note that the older unit of centipoise is numerically equivalent to $mPa \cdot s$. Then the range given above expressed in $mPa \cdot s$ is

$$1.0 \times 10^{-4}\ Pa \cdot s = 0.10 \times 10^{-3}\ Pa \cdot s = 0.10\ mPa \cdot s$$

to

$$60.0\ Pa \cdot s = 60\,000 \times 10^{-3}\ Pa \cdot s = 60\,000\ mPa \cdot s$$

Note that the value of $60\,000\ mPa \cdot s$ is for engine-lubricating oil at extremely low temperatures as indicated in Section 2.7 in the discussion of SAE viscosity ratings for engine oils. This is the maximum dynamic viscosity accepted under cold starting conditions to ensure that the oil is able to flow into the engine's oil pump.

2.3 KINEMATIC VISCOSITY

Many calculations in fluid mechanics involve the ratio of the dynamic viscosity to the density of the fluid. As a matter of convenience, the kinematic viscosity ν (the Greek letter nu) is defined as

Kinematic Viscosity

$$\nu = \eta/\rho \tag{2–3}$$

Because η and ρ are both properties of the fluid, ν is also a property. It is an unfortunate inconvenience that the Greek letter ν and the lower case υ ("vee") in this text look very similar. Use care with these terms.

2.3.1 Units for Kinematic Viscosity

We can derive the SI units for kinematic viscosity by substituting the previously developed units for η and ρ:

$$\nu = \frac{\eta}{\rho} = \eta\left(\frac{1}{\rho}\right)$$

$$\nu = \frac{kg}{m \cdot s} \times \frac{m^3}{kg}$$

$$\nu = m^2/s$$

Table 2.2 lists the kinematic viscosity units in the three most widely used systems. The basic dimensions of length squared divided by time are evident in each system. The obsolete units of stoke and centistoke are listed because published data often employ these units. Appendix K lists conversion factors.

Kinematic viscosities of common industrial liquids, such as those listed in Appendices A–D and in Section 2.7, range from approximately $1.0 \times 10^{-7}\ m^2/s$ to $7.0 \times 10^{-2}\ m^2/s$. More convenient values are often reported in mm^2/s, where

$$1.0 \times 10^6\ mm^2/s = 1.0\ m^2/s$$

Note that the older unit of centistoke is numerically equivalent to mm^2/s. Then the range expressed in mm^2/s is

$$1.0 \times 10^{-7}\ m^2/s = (0.10 \times 10^{-6}\ m^2/s)(10^6\ mm^2/1.0\ m^2) = 0.10\ mm^2/s$$

to

$$7.0 \times 10^{-2}\ m^2/s = (70\,000 \times 10^{-6}\ m^2/s)(mm^2/1.0\ m^2) = 70\,000\ mm^2/s$$

Again, the very large value is for extremely cold engine oil.

TABLE 2.2 Units for kinematic viscosity, ν (Greek letter nu)

Unit System	Kinematic Viscosity (ν) Units
International System (SI)	m^2/s
U.S. Customary System	ft^2/s
cgs system (obsolete)	stoke = $cm^2/s = 1 \times 10^{-4}\ m^2/s$ centistoke = stoke/100 = $1 \times 10^{-6}\ m^2/s = 1\ mm^2/s$

2.4 NEWTONIAN FLUIDS AND NON-NEWTONIAN FLUIDS

The study of the deformation and flow characteristics of substances is called *rheology*, which is the field from which we learn about the viscosity of fluids. One important distinction is between a *Newtonian fluid* and a *non-Newtonian fluid*. Any fluid that behaves in accordance with Fig. 2.2 and Equation (2–1) is called a *Newtonian fluid*. The viscosity η is a function only of the condition of the fluid, particularly its temperature. The magnitude of the velocity gradient $\Delta v/\Delta y$ has no effect on the magnitude of η. Most common fluids such as water, oil, gasoline, alcohol, kerosene, benzene, and glycerin are classified as Newtonian fluids. See Appendices A–E for viscosity data for water, several other Newtonian fluids, air, and other gases. See also Reference 12 that contains numerous tables and charts of viscosity data for petroleum oil and other common fluids. Internet resource 19 also lists many useful values for viscosities for oils. Most fluids considered in later chapters of this book are Newtonian.

In contrast to the behavior of Newtonian fluids, a fluid that does not behave in accordance with Equation (2–1) is called a *non-Newtonian fluid*. The difference between the two is shown in Fig. 2.3. The viscosity of the non-Newtonian fluid is dependent on the velocity gradient in addition to the condition of the fluid.

Note that in Fig. 2.3(a), the slope of the curve for shear stress versus the velocity gradient is a measure of the *apparent viscosity* of the fluid. The steeper the slope, the higher is the apparent viscosity. Because Newtonian fluids have a linear relationship between shear stress and velocity gradient, the slope is constant and, therefore, the viscosity is constant. The slopes of the curves for non-Newtonian fluids vary and Fig. 2.3(b) shows how viscosity changes with velocity gradient.

Two major classifications of non-Newtonian fluids are *time-independent* and *time-dependent* fluids. As their name implies, time-independent fluids have a viscosity at any given shear stress that does not vary with time. The viscosity of time-dependent fluids, however, changes with time.

Three types of time-independent fluids can be defined as follows:

- ***Pseudoplastic*** The plot of shear stress versus velocity gradient lies above the straight, constant sloped line for Newtonian fluids, as shown in Fig. 2.3. The curve begins steeply, indicating a high apparent viscosity. Then the slope decreases with increasing velocity gradient. Examples of such fluids are blood plasma, molten polyethylene, latexes, syrups, adhesives, molasses, and inks.
- ***Dilatant Fluids*** Again referring to Fig. 2.3, the plot of shear stress versus velocity gradient or dilatant fluids lies below the straight line for Newtonian fluids. The curve begins with a low slope, indicating a low apparent viscosity. Then, the slope increases with increasing velocity gradient. Examples of dilatant fluids are slurries with high concentrations of solids such as corn starch in ethylene glycol, starch in water, and titanium dioxide, an ingredient in paint.
- ***Bingham Fluids*** Sometimes called *plug-flow fluids*, Bingham fluids require the development of a significant level of shear stress before flow will begin, as illustrated in Fig. 2.3. Once flow starts, there is an essentially linear slope to the curve indicating a constant apparent viscosity. Examples of Bingham fluids are chocolate, catsup, mustard, mayonnaise, toothpaste, paint, asphalt, some greases, and water suspensions of fly ash or sewage sludge.

2.4.1 Time-Dependent Fluids

Time-dependent fluids are very difficult to analyze because apparent viscosity varies with time as well as with velocity gradient and temperature. Examples of time-dependent fluids are some crude oils at low temperatures, printer's ink, liquid nylon and other polymer solutions, some jellies, flour dough, some kinds of greases, and paints. Figure 2.4 shows two types of time-dependent fluids where in each case the temperature is held constant. The vertical axis is the apparent dynamic viscosity, η, and the horizontal axis is time.

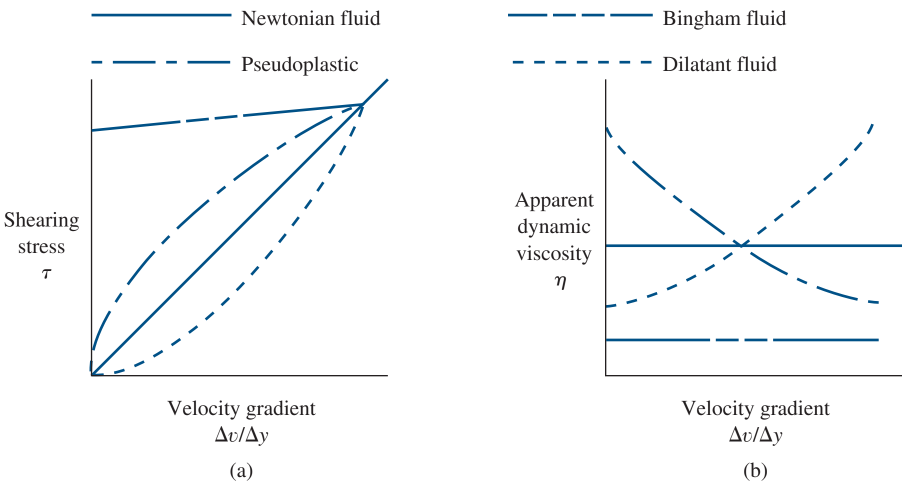


FIGURE 2.3 Newtonian and non-Newtonian fluids.

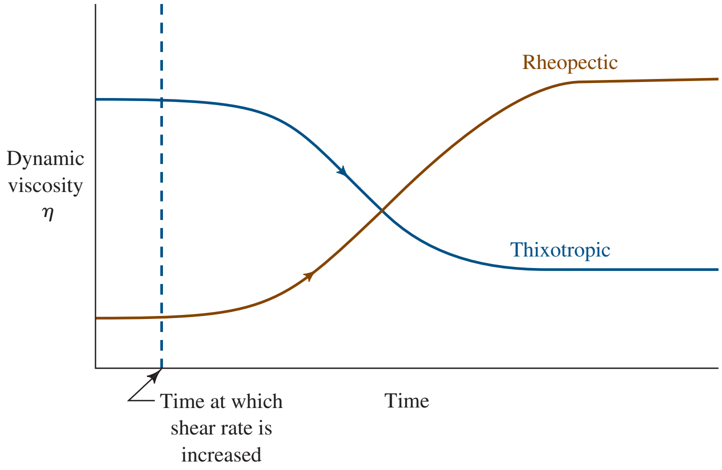


FIGURE 2.4 Behavior of time-dependent fluids.

The left part of the curves shows stable viscosity when the shear rate is not changing. Then, when the shear rate changes, the apparent viscosity changes, either increasing or decreasing depending on the type of fluid described here.

- ***Thixotropic Fluids.*** A fluid that exhibits *thixotropy* whereby the apparent viscosity decreases with time as shear rate remains constant. This is the most common type of time-dependent fluid.
- ***Rheopectic Fluids.*** A fluid that exhibits *rheopexy* whereby the viscosity increases with time. *Rheopectic fluids* are quite rare.

2.4.2 Actively Adjustable Fluids

Other types of fluids of more recent development are those for which the rheological properties, particularly the viscosity and stiffness, can be changed actively by varying an electric current or by changing the magnetic field around the material. Adjustments can be made manually or by computer control rapidly and they are reversible. Applications include shock absorbers for vehicles where harder or softer rides can be selected, to adjust for varying loads on the vehicle, or when increased damping is used to reduce bounce and jounce when operating on rough, off-road locations; adjusting the motion of truck drivers' seats; active control of clutches; tuning of engine mounts to minimize vibration; providing adjustable damping in buildings and bridges to resist earthquakes; in various prosthetic devices for handicapped people; and computer-controlled Braille displays. Two types are described here. Refer to Internet resource 5 for more details.

- ***Electrorheological Fluids (ERF)*** These are suspensions of fine particles, such as starch, polymers, and ceramics, in a nonconducting oil, such as mineral oil or silicone oil. Fluid properties are controllable by the application of an electric current. When no current is applied, they behave like other liquids. But when a current is applied, they turn into a gel and behave more like a solid. The change can occur in less than $^1/_{1000}$ s.
- ***Magnetorheological Fluids (MRF)*** Similar to ER fluids, MR fluids contain suspended particles in a base fluid. However, in this case, the particles are fine iron powders. The base fluid can be a petroleum oil, silicone oil, or water. When there is no magnetic field present, the MRF behaves much like other fluids, with a viscosity that ranges from 0.2 Pa·s to 0.3 Pa·s at 25°C. The presence of a magnetic field can cause the MRF to become virtually solid such that it can withstand a shear stress of up to 100 kPa. The change can be controlled electronically quite rapidly.

2.4.3 Nanofluids

Nanofluids are those that contain extremely small, nanoscale particles (less than 100 nm in diameter) in base fluids such as water, ethylene glycol coolants, oil and synthetic lubricants, biological fluids, and polymer solutions. The nanoparticle materials can be metals such as aluminum and copper, silicon carbide, aluminum dioxide, copper oxide, graphite, carbon nanotubes and several others. The nanoparticles have far higher surface to volume ratios than conventional fluids, mixtures, or suspensions, leading to enhanced thermal conductivity and other physical properties. One major use of nanofluids is to enhance the overall performance of fluids used to cool electronic devices. Used in lubrication applications, improved flow characteristics can be obtained while maintaining lubricity and carrying heat away from critical surfaces. Bio-medical, drug delivery, and environmental control applications are also being researched and developed. See Reference 16.

2.4.4 Viscosity of Liquid Polymers

Liquid polymers are the subject of much industrial study and research because of their importance in product design, manufacturing, lubrication, and health care. They are decidedly non-Newtonian, and we need a variety of additional viscosity terminology to describe their behavior. See Internet resources 6, 7, and 9–12 for commercial equipment used to characterize liquid polymers, either in the laboratory or during production; some are designed to sample the polymer melt just before extrusion or injection into a die.

Five additional viscosity factors are typically measured or computed for polymers:

1. *Relative viscosity*
2. *Inherent viscosity*
3. *Reduced viscosity*
4. *Specific viscosity*
5. *Intrinsic viscosity* (also called *limiting viscosity number*)

A solvent is added to the liquid polymer prior to performing some of these tests and making the final calculations. Examples of polymer/solvent combinations are as follows:

1. Nylon in formic acid
2. Nylon in sulfuric acid
3. Epoxy resins in methanol
4. Cellulose acetate in acetone and methylene chloride
5. Polycarbonate in methylene chloride

The concentration (C) of polymer, measured in grams per 100 mL, must be known. The following calculations are then completed:

Relative Viscosity, η_{rel}. The ratio of the viscosities of the polymer solution and of the pure solvent at the same temperature

Inherent Viscosity, η_{inh}. The ratio of the natural logarithm of the relative viscosity and the concentration C

Specific Viscosity, η_{spec}. The relative viscosity of the polymer solution minus 1

Reduced Viscosity, η_{red}. The specific viscosity divided by the concentration

Intrinsic Viscosity, η_{intr}. The ratio of the specific viscosity to the concentration, extrapolated to zero concentration. The relative viscosity is measured at several concentrations and the resulting trend line of specific viscosities is extrapolated to zero concentration. Intrinsic viscosity is a measure of the molecular weight of the polymer or the degree of polymerization.

Testing procedures for liquid polymers must be carefully chosen because of their non-Newtonian nature. Figure 2.3(a) shows that the apparent viscosity changes as the velocity gradient changes, and the rate of shearing within the fluid also changes as the velocity gradient changes. Therefore, it is important to control the shear rate, also called the strain rate, in the fluid during testing. Reference 13 includes an extensive discussion of the importance of controlling the shear rate and the types of rheometers that are recommended for different types of fluids.

Many liquid polymers and other non-Newtonian fluids exhibit time-dependent viscoelastic characteristics in addition to basic viscosity. Examples are extruded plastics, adhesives, paints, coatings, and emulsions. For these materials, it is helpful to measure their elongational behavior to control manufacturing processes or application procedures. This type of testing is called *extensional rheometry*. See Internet resource 11.

2.5 VARIATION OF VISCOSITY WITH TEMPERATURE

You are probably familiar with some examples of the variation of fluid viscosity with temperature. Engine oil is generally quite difficult to pour when it is cold, indicating that it has a high viscosity. As the temperature of the oil is increased, its viscosity decreases noticeably.

All fluids exhibit this behavior to some extent. Appendix D gives two graphs of dynamic viscosity versus temperature for many common liquids. Notice that viscosity is plotted on a logarithmic scale because of the large range of numerical values. To check your ability to interpret these graphs, a few examples are listed in Table 2.3.

Gases behave differently from liquids in that the viscosity increases as the temperature increases. Also, the general magnitude of the viscosities and the amount of change is generally smaller than that for liquids.

2.5.1 Viscosity Index

A measure of how greatly the viscosity of a fluid changes with temperature is given by its viscosity index, sometimes referred to as *VI*. This is especially important for lubricating oils and hydraulic fluids used in equipment that must operate at wide extremes of temperature.

A fluid with a high viscosity index exhibits a small change in viscosity with temperature. A fluid with a low viscosity index exhibits a large change in viscosity with temperature.

Typical curves for oils with *VI* values of 50, 100, 150, 200, 250, and 300 are shown in Fig. 2.5 on chart paper created especially for viscosity index that results in the curves being straight lines. Viscosity index is determined by measuring the kinematic viscosity of the sample fluid at 40°C and 100°C (104°F and 212°F) and comparing these values with those of certain reference fluids that were assigned *VI* values of 0 and 100. Standard ASTM D 2270 gives the complete method. See Reference 3.

TABLE 2.3 Selected values of viscosity read from Appendix D

Fluid	Temperature (°C)	Dynamic Viscosity ($N \cdot s/m^2$ or $Pa \cdot s$)
Water	20	1.0×10^{-3}
Water	70	4.0×10^{-4}
Gasoline	20	3.1×10^{-4}
Gasoline	62	2.0×10^{-4}
SAE 30 oil	20	3.5×10^{-1}
SAE 30 oil	80	1.9×10^{-2}

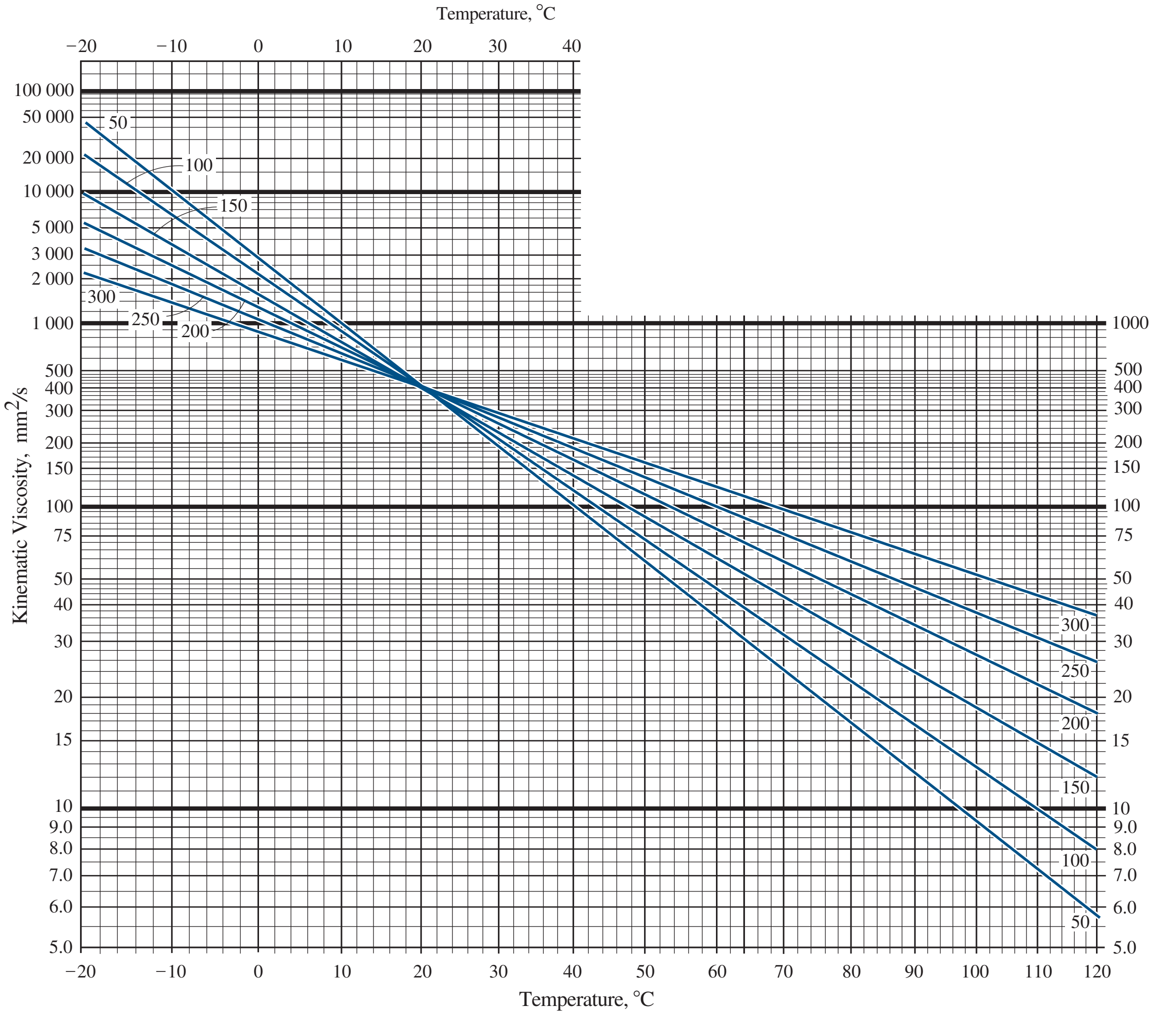


FIGURE 2.5 Typical viscosity index curves.

The general form of the equation for calculating the viscosity index for a type of oil that has a *VI* value up to and including 100 is given by the following formula. All kinematic viscosity values are in the unit of mm^2/s:

$$VI = \frac{L - U}{L - H} \times 100 \tag{2–4}$$

where

$U =$ Kinematic viscosity at 40°C of the test oil
$L =$ Kinematic viscosity at 40°C of a standard oil of 0 *VI* having the same viscosity at 100°C as the test oil
$H =$ Kinematic viscosity at 40°C of a standard oil of 100 *VI* having the same viscosity at 100°C as the test oil

The values of L and H can be found from a table in ASTM Standard D 2270 for oils with kinematic viscosities between 2.0 mm^2/s and 70.0 mm^2/s at 100°C. This range encompasses most of the practical oils used as fuels or for lubrication.

For oils with $VI > 100$, ASTM Standard D 2270 gives an alternate method of computing *VI* that also depends on obtaining values from the table in the standard.

Look closer at the *VI* curves in Fig. 2.5. They are plotted for the special case where each type of oil has the same value of kinematic viscosity of 400 mm^2/s at 20°C (68°F), approximately at room temperature. Table 2.4 gives the kinematic viscosity for six types of oil having different values of viscosity index (*VI*) at −20°C (−4°F), 20°C (68°F), and 100°C (212°F).

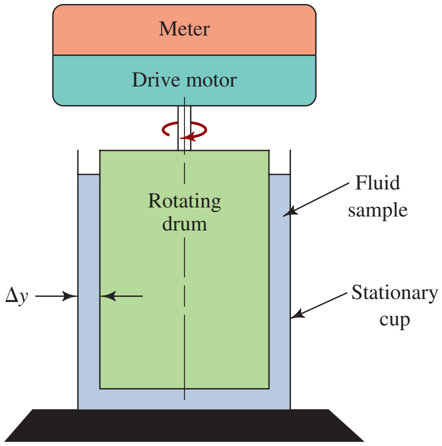
Notice the huge range of the values. The *VI* 50 oil has a very high viscosity at the cold temperature, and it may be difficult to make it flow to critical surfaces for lubrication. Conversely, at the hot temperature, the viscosity has decreased to such a low value that it may not have adequate lubricating ability. The amount of variation is much less for the types of oil with high viscosity indexes.

Lubricants and hydraulic fluids with a high *VI* should be used in engines, machinery, and construction equipment used outdoors where temperatures vary over wide ranges. In a given day the oil could experience the −20°C to +100°C range illustrated.

The higher values of *VI* are obtained by blending selected oils with high paraffin content or by adding special polymers that increase *VI* while maintaining good lubricating properties, and good performance in engines, pumps, valves, and actuators.

TABLE 2.4 Viscosity readings of types of oil with a variety of viscosity index (*VI*) values at three different temperatures

Viscosity Index *VI*	Kinematic Viscosity ν (mm^2/s) At –20°C	At 20°C	At 100°C
50	47 900	400	9.11
100	21 572	400	12.6
150	9985	400	18.5
200	5514	400	26.4
250	3378	400	37.1
300	2256	400	51.3



(a) Sketch of system components

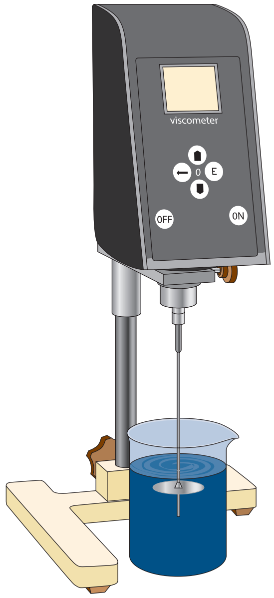


FIGURE 2.6 Rotating-drum viscometer with torque indicating viscosity.

2.6 VISCOSITY MEASUREMENT

Procedures and equipment for measuring viscosity are numerous. Some employ fundamental principles of fluid mechanics to indicate viscosity in its basic units. Others indicate only relative values for viscosity, which can be used to compare different fluids. In this section, we will describe several common methods used for viscosity measurement. Devices for characterizing the flow behavior of liquids are called *viscometers* or *rheometers*. You should become familiar with the numerous suppliers of viscosity measurement instruments and systems. Some are designed for laboratory use, while others are designed to be integral with production processes to maintain quality control and to record data for historical documentation of product characteristics. Internet resources 6–14 are examples of such suppliers.

ASTM International, ISO, and CEC generate standards for viscosity measurement and reporting. See Internet resources 1, 3, and 4 along with References 1–11 for ASTM standards pertinent to the discussion in this section. Specific standards are cited in the sections that follow. Another important standards-setting organization is SAE International that defines and publishes many standards for fuels and lubricants. See Internet resource 2 and References 14 and 15. More discussion of SAE standards is included in Section 2.7. The German standards organization, DIN, also develops and publishes standards that are cited by some manufacturers of viscometers. (See www.din.de.)

2.6.1 Rotating-Drum Viscometer

The apparatus shown in Fig. 2.6(a) measures dynamic viscosity, η, by its definition given in Eq. (2–2), which we can write in the form

$$\eta = \tau/(\Delta v/\Delta y)$$

The outer cup is held stationary while the motor in the meter drives the rotating drum. The space Δy between the rotating drum and the cup is small. The part of the fluid in contact with the outer cup is stationary, whereas the fluid in contact with the surface of the inner drum is moving with a velocity equal to the surface speed of the drum. Therefore, a known velocity gradient, $\Delta v/\Delta y$, is set up in the fluid. The fluid viscosity causes a shearing stress τ in the fluid that exerts a drag torque on the rotating drum. The meter senses the drag torque and indicates viscosity directly on the display. Special consideration is given to the fluid in contact with the bottom of the drum because its velocity varies from zero at the center to the higher value at the outer diameter. Different models for the style of tester shown in Fig. 2.6(b), and different rotors for each tester allow measurement of a wide range of viscosity levels. This kind of tester can be used for a variety of fluids such as paint, ink, food, petroleum products, cosmetics, and adhesives. The tester is battery operated and can be either mounted on a stand as shown or hand held for in-plant operation. See Internet resources 5–14.

A variant of the rotating-drum viscometer, called a *cold-cranking simulator,* is described in Reference 5 and is often used in testing engine oils for their ability to start in cold temperatures. In this apparatus, a universal motor drives a rotor, which is closely fitted inside a stator. The rotor speed is related to the viscosity of the test oil that fills the space between the stator and the rotor because of the viscous drag produced by the oil. Speed measurement is correlated to viscosity in mPa · s by reference to a calibration chart prepared by running a set of at least five standard calibration oils of known viscosity on the particular apparatus being used. The resulting data are used by engine designers and users to ensure the proper operation of the engine at cold temperatures.

SAE International specifies that the pumpability viscosity requirements for engine oils be determined using the methods described in Reference 9. A small rotary viscometer is used, and the oil is cooled to very low temperatures as described later in Section 2.7. It is also recommended that Reference 7 be used to determine the borderline pumping temperature of engine oils when specifying new oil formulations.

A novel design called the Stabinger viscometer employs a variation on the rotating-drum principle. The apparatus includes a small tube with a light cylindrical rotor suspended inside. Magnetic forces are used to maintain the rotor in position. The outer tube is rotated at a constant, specified speed, and viscous drag causes the internal rotor to rotate at a speed that is dependent on the fluid viscosity. A small magnet on the rotor creates a rotating magnetic field that is sensed outside the outer tube. The dynamic viscosity of the fluid can be computed from the simple equation

$$\eta = \frac{K}{(n_2/n_1 - 1)}$$

where n_2 is the speed of the outer tube and n_1 is the speed of the internal rotor. K is a calibration constant provided by the instrument manufacturer. See Internet resource 13.

Other designs for rotary viscometers employ a paddle-type rotor mounted to a small-diameter shaft that is submerged in the test fluid. As with other rotary styles of viscometers, the measurement is based on the torque required to drive the paddle at a fixed speed while submerged in the test fluid. See Internet resources 6 and 9.

2.6.2 Capillary Tube Viscometer

Figure 2.7 shows two reservoirs connected by a long, small-diameter tube called a *capillary tube*. As the fluid flows through the tube with a constant velocity, some energy is lost from the system, causing a pressure drop that can be measured by using manometers. The magnitude of the pressure drop is related to the fluid viscosity by the following equation, which is developed in Chapter 8:

$$\eta = \frac{(p_1 - p_2)D^2}{32 v L} \qquad \textbf{(2–5)}$$

In Eq. (2–5), D is the inside diameter of the tube, v is the fluid velocity, and L is the length of the tube between points 1 and 2 where the pressure difference is measured.

2.6.3 Standard Calibrated Glass Capillary Viscometers

References 1 and 2 describe the use of standard glass capillary viscometers to measure the kinematic viscosity of transparent and opaque liquids. Figures 2.8 and 2.9 show two of the 17 types of viscometers discussed in the standards. Other capillary viscometers are available that are integrated units having temperature control and automatic sequencing of small samples of fluid through the device. See Fig. 2.10 and Internet resource 12.

In preparation for the viscosity test, the viscometer tube is charged with a specified quantity of test fluid. After stabilizing the test temperature, suction is used to draw fluid through the bulb and slightly above the upper timing mark. The suction is removed and the fluid is allowed to flow by gravity. The working section of the tube is the capillary below the lower timing mark indicated in the figures. The time required for the leading edge of the meniscus to pass from the upper timing mark to the lower timing mark is recorded. The kinematic viscosity is computed by multiplying the flow time by the calibration constant of the viscometer supplied by the vendor. The viscosity unit used in these tests is the centistoke (cSt), which is equivalent to mm^2/s. This value must be multiplied by 10^{-6} to obtain the SI standard unit of m^2/s, which is used for calculations in this book.

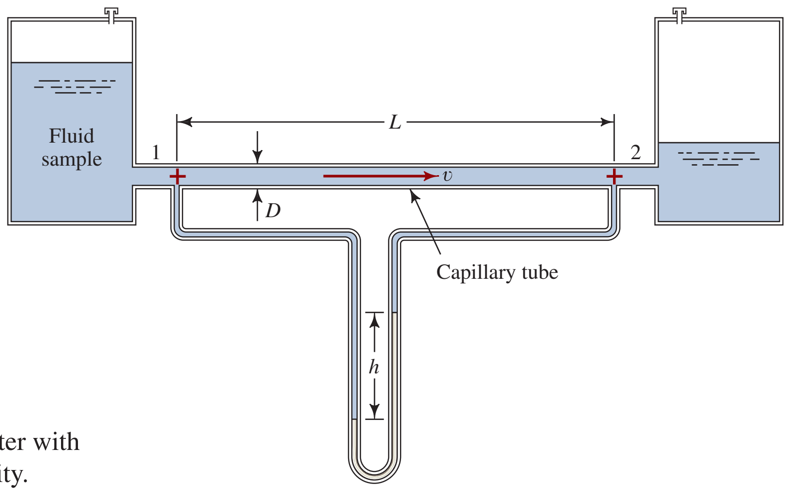


FIGURE 2.7 Capillary-tube viscometer with pressure difference indicating viscosity.

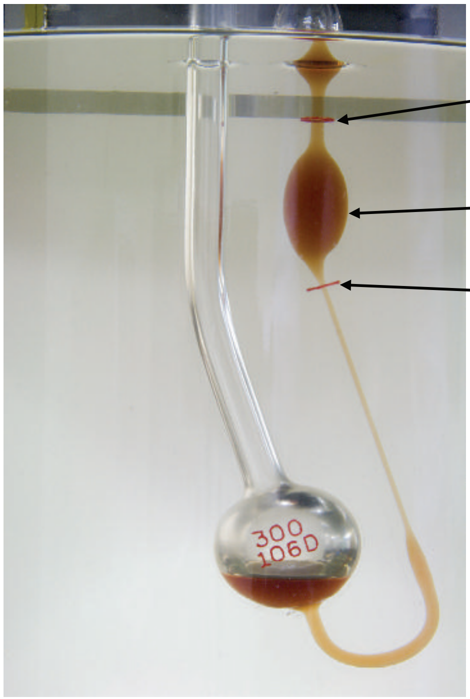


FIGURE 2.8 Cannon–Fenske routine viscometer with flow time indicating viscosity. (*Source:* Alexey Stiop/Shutterstock)

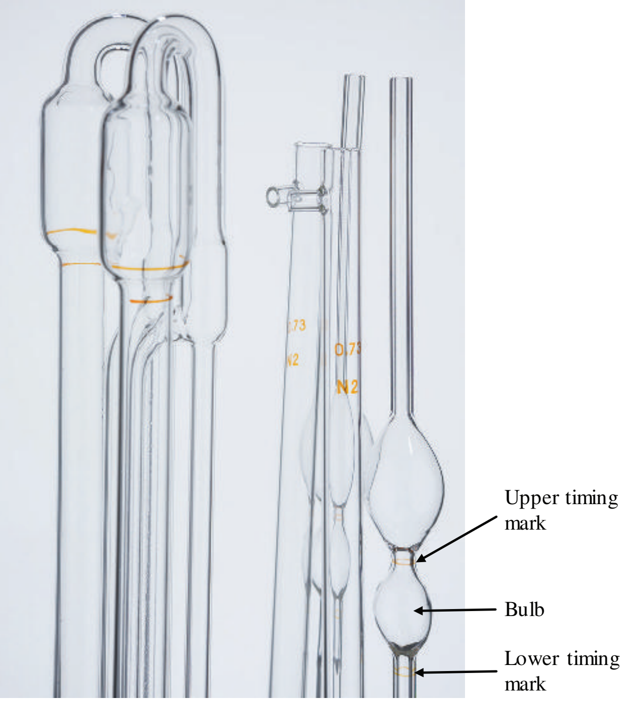


FIGURE 2.9 Ubbelohde viscometer with flow time indicating viscosity. (*Source:* Igor Tsarev/123RF)

FIGURE 2.10 Automated multi-range capillary viscometer. (*Source:* Precision Scientific Petroleum Instruments Company)

2.6.4 Falling-Ball Viscometer

As a body falls in a fluid under the influence of gravity only, it will accelerate until the downward force (its weight) is just balanced by the buoyant force and the viscous drag force acting upward. Its velocity at that time is called the *terminal velocity, v*. The falling-ball viscometer sketched in Fig. 2.11 uses this principle by causing a spherical ball to fall freely through the fluid and measuring the time required for the ball to drop a known distance. Thus, the velocity can be calculated. Figure 2.12 shows a free-body diagram of the ball, where w is the weight of the ball, F_b is the buoyant force, and F_d is the viscous drag force on the ball, discussed more fully in Chapter 17. When the ball has reached its terminal velocity, it is in equilibrium. Therefore, we have

$$w - F_b - F_d = 0 \qquad \textbf{(2–6)}$$

If γ_s is the specific weight of the sphere, γ_f is the specific weight of the fluid, V is the volume of the sphere, and D is the diameter of the sphere, we have

$$w = \gamma_s V = \gamma_s \pi D^3/6 \qquad \textbf{(2–7)}$$

$$F_b = \gamma_f V = \gamma_f \pi D^3/6 \qquad \textbf{(2–8)}$$

For very viscous fluids and a small velocity, the drag force on the sphere is

$$F_d = 3\pi\eta v D \qquad \textbf{(2–9)}$$

Equation (2–6) then becomes

$$\eta = \frac{(\gamma_s - \gamma_f)D^2}{18v} \qquad \textbf{(2–10)}$$

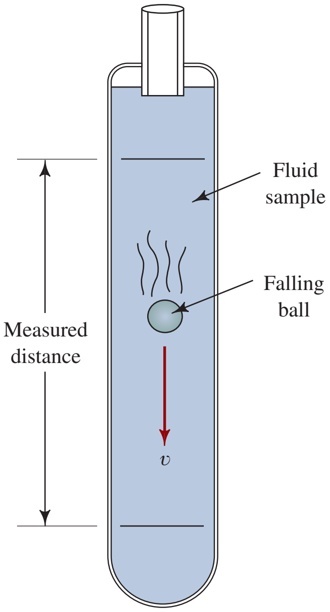


FIGURE 2.11 Falling-ball viscometer with the speed of the ball indicating viscosity.

For visual timing of the descent of the ball, the fluid must be transparent so we can observe the falling ball and time its travel. However, some commercially available falling-ball viscometers have automatic sensing of the position of the ball, so that opaque fluids can be used. Some falling-ball viscometers employ a tube that is slightly inclined to the vertical so that the motion is a combination of rolling and sliding. Calibration between time of travel and viscosity is provided by the manufacturer. Several types and sizes of balls are available to enable the viscometer to be used for fluids with a wide range of viscosities, typically 0.5 mPa·s to 10^5 mPa·s. Balls are made from stainless steel, nickel–iron alloy, and glass. See Internet resources 9 and 12.

2.6.5 Saybolt Universal Viscometer

The ease with which a fluid flows through a small-diameter orifice is an indication of its viscosity. This is the principle on which the Saybolt viscometer is based. The fluid sample is placed in an apparatus similar to that sketched in Fig. 2.13, in which the external vessel maintains a constant temperature of the test fluid. After steady flow from the orifice is established, the time required to collect 60 mL of the fluid is measured. The resulting time is reported as the viscosity of the fluid in Saybolt Universal seconds (SUS). Because the measurement is not based on the basic definition of viscosity, the results are only relative. However, they do serve to compare the viscosities of different fluids. The advantage of this procedure is that it is simple and requires relatively unsophisticated equipment. See Internet resources 8, 10, and 11.

The use of the Saybolt viscometer is covered by ASTM Standard D 88 (Reference 10). However, this standard recommends that other methods be used for viscosity measurement, such as those listed in References 1 and 2 describing the use of glass capillary viscometers. Furthermore, it is recommended that kinematic viscosity data be reported in the proper SI unit, mm^2/s.

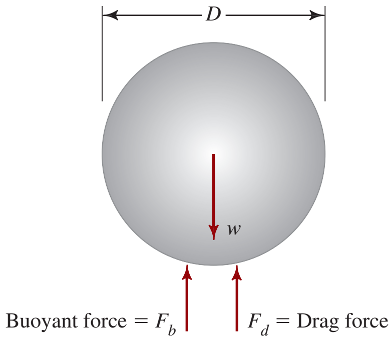


FIGURE 2.12 Free-body diagram of a ball in a falling-ball viscometer.

ASTM Standard 2161 (Reference 11) describes the preferred conversion methods between viscosity measured in SUS and kinematic viscosity in mm^2/s. However, the introduction to the standard states that the use of the Saybolt viscometer is now obsolete in the petroleum industry. Other industries may continue to use it because of historical data and because it is an easy method to use. Figure 2.14 shows a graph of SUS versus kinematic viscosity ν in mm^2/s for a fluid temperature of 100°F. The curve is straight above $\nu = 75\ mm^2/s$, following the equation

$$SUS = 4.632\nu \qquad \textbf{(2–11)}$$

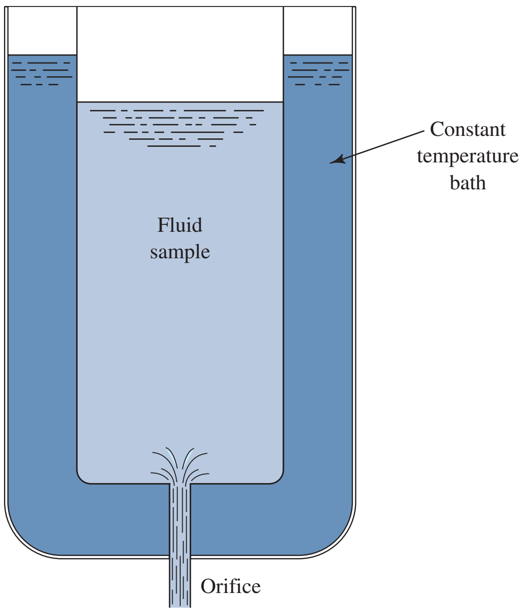


FIGURE 2.13 Basic elements of a Saybolt viscometer with time required to drain indicating viscosity

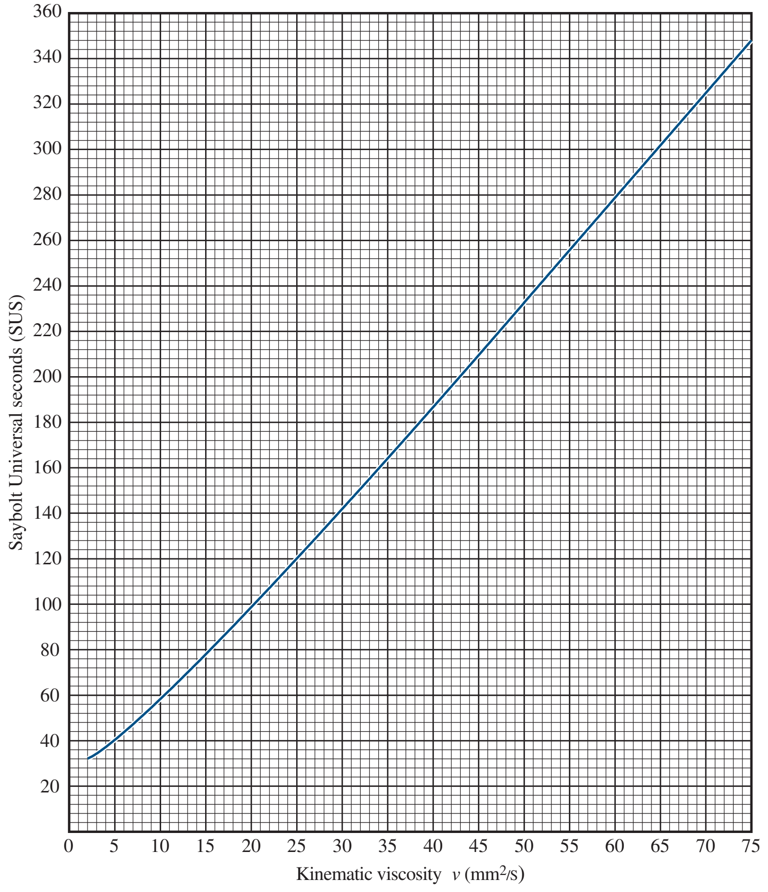


FIGURE 2.14 Kinematic viscosity ν in SUS versus ν in mm^2/s at 100°F.

For a fluid temperature of 210°F, the equation for the straight-line portion is

$$SUS = 4.664\nu \quad \textbf{(2–12)}$$

These equations can be used down to approximately $\nu = 50\ mm^2/s$ with an error of less than 0.5 percent and down to approximately $\nu = 38\ mm^2/s$ with an error of less than 1.0 percent $(<1.0\ SUS)$.

The SUS value for any other temperature t in degrees Fahrenheit can be found by multiplying the SUS value for 100°F by the factor A shown in Fig. 2.15. The factor A can be computed from

$$A = 6.061 \times 10^{-5}t + 0.994$$

$$\text{(rounded to three decimal places)} \quad \textbf{(2–13)}$$

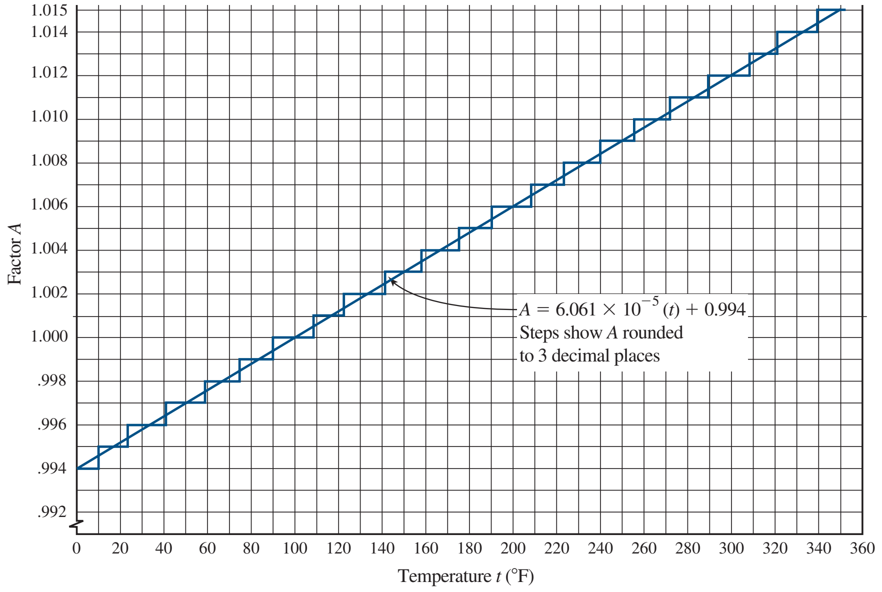


FIGURE 2.15 Factor A versus temperature t in degrees Fahrenheit used to determine the kinematic viscosity in SUS for any temperature.

Example Problem 2.1 Given that a fluid at 100°F has a kinematic viscosity of 30.0 mm^2/s, determine the equivalent SUS value at 100°F.

Solution Because $\nu < 75\ mm^2/s$, use Fig. 2.14 to find $\nu = 141.5$ SUS.

Example Problem 2.2 Given that a fluid at 100°F has a kinematic viscosity of 220 mm^2/s, determine the equivalent SUS value at 100°F.

Solution Because $\nu > 75\ mm^2/s$, use Equation (2–11):

$$\text{SUS} = 4.632\nu = 4.632(220) = 1019\ \text{SUS}$$

Example Problem 2.3 Given that a fluid at 260°F has a kinematic viscosity of 145 mm^2/s, determine its kinematic viscosity in SUS at 260°F.

Solution Use Equation (2–13) to compute the factor A:

$$A = 6.061 \times 10^{-5}t + 0.994 = 6.061 \times 10^{-5}(260) + 0.994 = 1.010$$

Now find the kinematic viscosity at 100°F using Equation (2–11):

$$\text{SUS} = 4.632\nu = 4.632(145) = 671.6\ \text{SUS}$$

Finally, multiply this value by A to get the SUS value at 260°F:

$$\text{SUS} = A(671.6) = 1.010(671.6) = 678\ \text{SUS}$$

2.7 SAE VISCOSITY GRADES

SAE International has developed rating systems for engine oils (Reference 14) and automotive gear lubricants (Reference 15) which indicate the viscosity of the oils at specified temperatures. Note the ASTM testing standards listed as References 1–11. Internet resources 15–18 are representative of the many producers of automotive engine oils and gear lubricants. Internet resource 19 offers tables of data for viscosities of oils from several standards-setting organizations.

Popular viscosity grades for engine oils used for crankcase lubrication are as follows:

0W, 5W, 10W, 15W, 20W, 25W

20, 30, 40, 50, 60

Grades often used for lubricating automotive gear transmissions are as follows:

70W, 75W, 80W, 85W

80, 85, 90, 110, 140, 190, 250

Oils with a suffix W are based on maximum dynamic viscosity at specified cold temperatures from −10°C to −40°C under conditions that simulate both the cranking of an engine and the pumping of the oil by the oil pump. Applicable ASTM testing standards are described in References 5 and 9. They must also exhibit a kinematic viscosity above a specified minimum at 100°C using a glass capillary viscometer as described in Reference 1. Those without the suffix W are rated for viscosity at high temperatures by two different methods described in Reference 14, the kinematic viscosity under low-shear-rate conditions at 100°C and the dynamic viscosity under high-shear-rate conditions at 150°F as described in References 1 and 8. The ratings simulate the conditions in journal bearings and for sliding surfaces. Internet resource 6 offers the Ravenfield Tapered Plug HTHS viscometer for making such measurements. Multiviscosity-grade oils, such as SAE 10W-40, must meet the standards at both the low- and high-temperature conditions.

The specification of maximum low-temperature viscosity values for oils is related to the ability of the oil to flow to the surfaces needing lubrication at the engine speeds encountered during starting at cold temperatures. The pumping viscosity indicates the ability of the oil to flow into the oil pump inlet of an engine. The high-temperature viscosity range specifications relate to the ability of the oil to provide a satisfactory oil film to carry expected loads while not having an excessively high viscosity that would increase friction and energy losses generated by moving parts.

Note that oils designed to operate at wide ranges of temperature have special additives to increase the viscosity index. An example is multiviscosity engine oil (e.g., 5W-40) that must meet stringent low-temperature viscosity limits while maintaining a sufficiently high viscosity at higher engine operating temperatures for effective lubrication. In addition, automotive hydraulic system oils that must operate with similar performance in cold and warm climates and machine-tool hydraulic system oils that must operate outdoors as well as indoors must have high viscosity indexes. Achieving a high viscosity index in oil often calls for the blending of polymeric materials with the petroleum. The resulting blend may exhibit non-Newtonian characteristics, particularly at the lower temperatures.

See also Appendix C for typical properties of petroleum lubricating oils used in engines, gear drives, hydraulic systems, and machine tool applications.

2.8 ISO VISCOSITY GRADES

Lubricants used in industrial applications must be available in a wide range of viscosities to meet the needs of production machinery, bearings, gear drives, electrical machines, fans and blowers, fluid power systems, mobile equipment, and many other devices. The designers of such systems must ensure that the lubricant can withstand the temperatures to be experienced while providing sufficient load-carrying ability. The result is a need for a wide range of viscosities.

To meet these requirements and still have an economical and manageable number of options, ASTM Standard D 2422 (Reference 4) defines a set of 20 ISO viscosity grades. The standard designation includes the prefix ISO VG followed by a number representing the nominal kinematic viscosity in mm^2/s (cSt) for a temperature of 40°C. Table 2.5 gives the data. The maximum and minimum values are ±10 percent from the nominal. Although the standard is voluntary, the intent is to encourage producers and users of lubricants to agree on the specification of viscosities from the list. This system is gaining favor throughout world markets. The CEC develops lubricant performance standards for many European countries and that have been adopted by others throughout the world. See Internet resource 3. Internet resources 15–18 include examples of the many companies that provide oils and lubricants for the automotive and industrial markets. Internet resource 19 provides comparisons between ISO grades and some others.

TABLE 2.5 ISO viscosity grades

Grade	Kinematic Viscosity at 40°C (cSt) or (mm^2/s)		
ISO VG	Nominal	Minimum	Maximum
2	2.2	1.98	2.40
3	3.2	2.88	3.52
5	4.6	4.14	5.06
7	6.8	6.12	7.48
10	10	9.00	11.0
15	15	13.5	16.5
22	22	19.8	24.2
32	32	28.8	35.2
46	46	41.4	50.6
68	68	61.2	74.8
100	100	90.0	110
150	150	135	165
220	220	198	242
320	320	288	352
460	460	414	506
680	680	612	748
1000	1000	900	1100
1500	1500	1350	1650
2200	2200	1980	2420
3200	3200	2880	3520

Source: ASTM Standard 2422. Copyright ASTM. 2013. D2422-13: Standard Classification of Industrial Lubricants by Viscosity System. West Conshohocken, PA:Author. DOI: 10.1520/D2422-13, www.astm.org. (See Reference 4.)

2.9 HYDRAULIC FLUIDS FOR FLUID POWER SYSTEMS

Fluid power systems use fluids under pressure to actuate linear or rotary devices used in construction equipment, industrial automation systems, agricultural equipment, aircraft hydraulic systems, automotive braking systems, and many others. Fluid power includes both air-type systems, commonly called *pneumatics*, and liquid-type systems, usually referred to as hydraulic systems. This section will deal with liquid-type systems.

There are several types of hydraulic fluids in common use, including the following:

- Petroleum oils
- Water–glycol fluids
- High water-based fluids (HWBF)
- Silicone fluids
- Synthetic oils

The primary characteristics of such fluids for operation in fluid power systems are as follows:

- Adequate viscosity for the purpose
- High lubricating capability, sometimes called lubricity
- Cleanliness
- Chemical stability at operating temperatures
- Noncorrosiveness with the materials used in fluid power systems
- Inability to support bacteria growth
- Ecologically acceptable
- High bulk modulus (low compressibility)

You should examine carefully the environment in which the fluid power system is to be used and select a fluid that is optimal for the application. Trade-offs will typically be required so that the combination of properties is acceptable. Suppliers of components, particularly pumps and valves, should be consulted for appropriate fluids to use with their products. Internet resources 15–18 provide information and data from representative suppliers of hydraulic fluids in automotive, construction, and general industrial machinery applications.

Viscosity is one of the most important properties because it relates to lubricity and the ability of the fluid to be pumped and to flow through the tubing, piping, actuators, valves, and other control devices found in fluid power systems.

Common industrial fluid power systems require fluids with viscosities in the range of ISO grades 32, 46, or 68. See Table 2.5 for the kinematic viscosity ranges for such fluids. In general, the ISO grade number is the nominal kinematic viscosity in the unit of mm^2/s.

Special care is needed when extreme temperatures are encountered. Consider the case of the fluid power system on a piece of construction equipment that is kept outdoors throughout the year. In winter, the temperature may range to −20°F (−29°C). When starting the system at that temperature you must consider the ability of the fluid to flow into the intake ports of the pumps, through the piping systems, and through the control valves. The fluid viscosity may be greater than 800 mm^2/s. Then, when the system has warmed to approximately 150°F (66°C), the fluid viscosity may be as low as 15 mm^2/s. The performance of the pumps and valves is likely to be remarkably different under this range of conditions. Also, as you will learn in Chapter 8, the very nature of the flow may change as the viscosities change. At the cold temperatures the fluid flow will likely be laminar, whereas at the higher temperatures with the decreased viscosities the flow may be turbulent. Hydraulic fluids for operation at these ranges of temperatures should have a high viscosity index, as described earlier in this chapter.

Petroleum oils may be very similar to the automotive engine oils discussed earlier in this chapter. SAE 10W and SAE 20W-20 are appropriate. However, several additives are required to inhibit the growth of bacteria, to ensure compatibility with seals and other parts of fluid power components, to improve its antiwear performance in pumps, and to improve the viscosity index. Suppliers of hydraulic fluids should be consulted for recommendations of specific formulations. Some of the additives used to improve viscosity are polymeric materials, and they may change the flow characteristics dramatically under certain high-pressure conditions that may occur within valves and pumps. The oils may behave as non-Newtonian fluids.

Silicone fluids are desirable when high temperatures are to be encountered, as in work near furnaces, hot processes, and some vehicle braking systems. These fluids exhibit very high thermal stability. Compatibility with the pumps and valves of the system must be checked.

High water-based fluids (HWBF) are desirable where fire resistance is needed. Water-in-oil emulsions contain approximately 40 percent oil blended in water with a significant variety and quantity of additives to tailor the fluid properties to the application. A different class of fluids, called oil-in-water emulsions, contains 90–95 percent water with the balance being oil and additives. Such emulsions typically appear to be milky white because the oil is dispersed in the form of very small droplets.

Water–glycol fluids are also fire resistant, containing approximately 35–50 percent water, with the balance being any of several glycols along with additives suitable for the environment in which the system is to be operated.

REFERENCES

1. ASTM International. 2017. D445-17A: *Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids*, West Conshohocken, PA: Author. DOI: 10.1520/D445-17A, www.astm.org.
2. ________. 2017. D446-17: *Standard Specifications for Glass Capillary Kinematic Viscometers.* West Conshohocken, PA: Author. DOI: 10.1520/D446-17, www.astm.org.
3. ________. 2016. D2270-16: *Standard Practice for Calculating Viscosity Index from Kinematic Viscosity at 40 and 100°C.* West Conshohocken, PA: Author. DOI: 10.1520/D2270-16, www.astm.org.
4. ________. 2013. D2422-13: *Standard Classification of Industrial Lubricants by Viscosity System*. West Conshohocken, PA: Author. DOI: 10.1520/D2422-13, www.astm.org.
5. ________. 2017. D5293-17A: *Standard Test Method for Apparent Viscosity of Engine Oils and Base Stocks Between –10 and –35°C Using the Cold-Cranking Simulator.* West Conshohocken, PA: Author. DOI: 10.1520/D5293-17, www.astm.org.
6. ________. 2017. D2983-17: *Standard Test Method for Low-Temperature Viscosity of Automatic Transmission Fluids, Hydraulic Fluids, and Lubricants Using a Rotational Viscometer.* West Conshohocken, PA: Author. DOI: 10.1520/D2983-17, www.astm.org.
7. ________. 2018. D3829-18: *Standard Test Method for Predicting the Borderline Pumping Temperature of Engine Oil*. West Conshohocken, PA: Author. DOI: 10.1520/D3829-18, www.astm.org.
8. ________. 2017. D4683-17: *Standard Test Method for Measuring Viscosity of New and Used Engine Oils at High-Shear Rate and High Temperature by Tapered Bearing Simulator Viscometer at 150°C*. West Conshohocken, PA: Author. DOI: 10.1520/D4683-17, www.astm.org.
9. ________. 2018. D4684-18: *Standard Test Method for Determination of Yield Stress and Apparent Viscosity of Engine Oils at Low Temperature.* West Conshohocken, PA: Author. DOI: 10.1520/D4684-18, www.astm.org.
10. ________. 2013. D88-13: *Standard Test Method for Saybolt Viscosity*. West Conshohocken, PA: Author. DOI: 10.1520/D88-13, www.astm.org.
11. ________. 2017. D2161-17: *Standard Practice for Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Furol Viscosity.* West Conshohocken, PA: Author. DOI: 10.1520/D2161-17, www.astm.org.
12. Heald, C. C., ed. 2018. *Cameron Hydraulic Data*, 20th ed. Irving, TX: Flowserve.
13. Schramm, Gebhard. 2000. *A Practical Approach to Rheology and Rheometry,* 2nd ed. Karlsruhe, Germany: Thermo Haake.
14. SAE International (SAE). 2015. *SAE Standard J300*: *Engine Oil Viscosity Classification.* Warrendale, PA: Author.
15. ________. 2017. *SAE Standard J306*: *Automotive Gear Lubricant Viscosity Classification.* Warrendale, PA: Author.

16. 16. Votz, Sebastian. 2009. *Thermal Nanosystems and Nanomaterials*. New York: Springer Publishing.

INTERNET RESOURCES

1. **ASTM International:** Develops and publishes standards for testing procedures and properties of numerous kinds of materials, including fluids.
2. **SAE International:** The engineering society for advancing mobility—land, sea, air, and space. Publisher of numerous industry standards including viscosity of lubricants and fuels.
3. **ISO (International Organization for Standardization):** ISO is the world's largest developer of voluntary International Standards.
4. **The Coordinating European Council (CEC):** Developer of fluid performance test methods used extensively in Europe and widely throughout the world. Represents the motor, oil, petroleum additive, and allied industries in performance evaluation of transportation fuels, lubricants, and other fluids.
5. **Lord Corporation:** Producer of a wide variety of vibration mounts and damping devices, including magneto-rheological fluids and their applications. From the home page, select *Products & Solutions* and then *Magneto-Rheological (MR).*
6. **Cannon Instrument Company:** Producer of many types of viscometers and other instruments for measuring fluid properties.
7. **Fisher Scientific:** Supplier of numerous instruments and materials for laboratory and scientific uses, including viscometers under the Fisher brand and many others.
8. **Kohler Instrument Company:** A leading producer and supplier of petroleum and petrochemical instrumentation worldwide, including manual and automated petroleum ASTM testing equipment for viscosity, density, and tribology friction and wear properties.
9. **AMETEK Brookfield Engineering Laboratories:** The world's leading manufacturer of viscosity-measuring equipment for laboratory and process control applications.
10. **Malvern Panalytical Ltd.:** The company designs, manufactures, and sells materials-characterization instruments, including rheometers, viscometers, and particle analysis devices. A Spectris company.
11. **Thermo Scientific Corporation:** Producer of many types of measurement equipment for industry and scientific laboratories and production operations. The Haake Division produces several types of viscometers and rheometers including the falling ball and rotary types. Part of ThermoFisher Scientific Inc.
12. **PAC L.P.:** PAC is a leading global provider of advanced analytical instruments for laboratories and online process applications in industries such as refinery, petrochemical, biofuels, environmental, food & beverage, and pharmaceutical. Search on *paclp*. PAC consists of several product lines featuring viscosity measurement and testing of other fluid properties, such as Cambridge Viscosity, ISL, PetroSpec, Herzog, Antek, Alcor, and PetroSpec.
13. **Anton Paar:** Manufacturer of instruments for measuring viscosity, density, and other properties of fluids.
14. **Cole-Parmer Company:** Cole-Parmer is a leading global source of laboratory and industrial fluid handling products, instrumentation, equipment, and supplies, including viscometers, pumps, flowmeters, and other fluid mechanics related products. The site includes viscosity conversion calculators for both dynamic and kinematic viscosity along with lists of viscosity conversion factors.
15. **Wynn's USA:** Wynn's is a producer and distributor of automotive lubricant products including engine oil, transmission fluid, brake fluid, and general-purpose lubricants. Part of the Performance Polymers division of Illinois Tool Works, Inc.
16. **Mobil Industrial Lubricants:** Producer of a wide range of industrial hydraulic oils and other industrial lubricants. The site includes a product search feature related to specific applications such as bearings, air compressors, gears, and wind turbines. A discussion of synthetic versus conventional oil is also included.
17. **Castrol Limited:** Producer of industrial and automotive oils and lubricants for construction, machinery, and general industrial hydraulic systems. The site includes an oil selector.
18. **CITGO Petroleum Corporation:** Producer of a full range of engine oils, hydraulic fluids, lubricants, and greases for the automotive, construction, petrochemicals, and general industrial markets.
19. **Tribology-ABC:** Part of *Engineering-ABC,* a website with a huge set of data helpful in many kinds of engineering calculations. From the home page, select the letter *V*, then select *Viscosity* to connect to the page listing basic definitions of viscosity terms, ISO viscosity grades, AGMA viscosity classifications for gear oils, SAE viscosity grades for engine and automotive gear oils and a comparison of all of these classifications.

PRACTICE PROBLEMS

2.1 Define *shear stress* as it applies to a moving fluid.
2.2 Define *velocity gradient*.
2.3 State the mathematical definition for *dynamic viscosity*.
2.4 Which would have the greater dynamic viscosity, a cold lubricating oil or fresh water? Why?
2.5 State the standard units for dynamic viscosity in the SI system.
2.6 State the standard units for dynamic viscosity in the U.S. Customary System.
2.7 State the equivalent units for *poise* in terms of the basic quantities in the cgs system.
2.8 Why are the units of poise and centipoise considered obsolete?
2.9 State the mathematical definition for *kinematic viscosity*.
2.10 State the standard units for kinematic viscosity in the SI system.
2.11 State the standard units for kinematic viscosity in the U.S. Customary System.
2.12 State the equivalent units for *stoke* in terms of the basic quantities in the cgs system.
2.13 Why are the units of stoke and centistoke considered obsolete?
2.14 Define a *Newtonian fluid*.
2.15 Define a *non-Newtonian fluid*.
2.16 Give five examples of Newtonian fluids.
2.17 Give four examples of the types of fluids that are non-Newtonian.

Appendix D gives dynamic viscosity for a variety of fluids as a function of temperature. Using this appendix, give the value of the viscosity for the following fluids:

2.18 Water at 40°C.
2.19 Water at 5°C.
2.20 Air at 40°C.
2.21 Hydrogen at 40°C.
2.22 Glycerin at 40°C.
2.23 Glycerin at 20°C.
2.24 Water at 40°F.
2.25 Water at 150°F.
2.26 Air at 40°F.
2.27 Hydrogen at 40°F.
2.28 Glycerin at 60°F.
2.29 Glycerin at 110°F.
2.30 Mercury at 60°F.
2.31 Mercury at 210°F.
2.32 SAE 10 oil at 60°F.
2.33 SAE 10 oil at 210°F.
2.34 SAE 30 oil at 60°F.
2.35 SAE 30 oil at 210°F.
2.36 Define *viscosity index* (*VI*). Is this the same as viscosity? Explain.
2.37 If you want to choose a fluid that exhibits a small change in viscosity as the temperature changes, would you choose one with a high *VI* or a low *VI*?
2.38 Which type of viscosity measurement method uses the basic definition of dynamic viscosity for direct computation?
2.39 In the *rotating-drum viscometer*, describe how the velocity gradient is created in the fluid to be measured.
2.40 In the *rotating-drum viscometer*, describe how the magnitude of the shear stress is measured.
2.41 What measurements must be taken to determine dynamic viscosity when using a *capillary tube viscometer*?
2.42 Define the term *terminal velocity* as it applies to *a falling-ball viscometer*.
2.43 What measurements must be taken to determine dynamic viscosity when using the *falling-ball viscometer*?
2.44 Describe the basic features of the *Saybolt Universal viscometer*.
2.45 Are the results of the Saybolt viscometer tests considered to be direct measurements of viscosity?
2.46 Does the Saybolt viscometer produce data related to a fluid's dynamic viscosity or kinematic viscosity?
2.47 Which type of viscometer is prescribed by SAE for measurements of viscosity of oils at 100°C?
2.48 Describe the difference between an SAE 20 oil and an SAE 20W oil.
2.49 What grades of SAE oil are suitable for lubricating the crankcases of engines?
2.50 What grades of SAE oil are suitable for lubricating gear-type transmissions?
2.51 If you were asked to check the viscosity of an oil that is described as SAE 40, at what temperatures would you make the measurements?
2.52 If you were asked to check the viscosity of an oil that is described as SAE 10W, at what temperatures would you make the measurements?
2.53 How would you determine the viscosity of an oil labeled SAE 5W-40 for comparison with SAE standards?
2.54 The viscosity of a lubricating oil is given as 500 SUS at 100°F. Calculate the viscosity in m^2/s and ft^2/s.
2.55 Using the data from Table 2.5, report the minimum, nominal, and maximum values for viscosity for ISO grades VG 10, VG 65, VG 220, and VG 1000.
2.56 Convert a dynamic viscosity measurement of 4500 cP into $Pa \cdot s$ and $lb \cdot s/ft^2$.
2.57 Convert a kinematic viscosity measurement of 5.6 cSt into m^2/s and ft^2/s.
2.58 The viscosity of an oil is given as 80 SUS at 100°F. Determine the viscosity in m^2/s.
2.59 Convert a viscosity measurement of 6.5×10^{-3} $Pa \cdot s$ into the units of $lb \cdot s/ft^2$.
2.60 An oil container indicates that it has a viscosity of 0.12 poise at 60°C. Which oil in Appendix D has a similar viscosity?
2.61 In a falling-ball viscometer, a steel ball 1.6 mm in diameter is allowed to fall freely in a heavy fuel oil having a specific gravity of 0.94. Steel weighs 77 kN/m^3. If the ball is observed to fall 250 mm in 10.4 s, calculate the viscosity of the oil.
2.62 A capillary tube viscometer similar to that shown in Fig. 2.7 is being used to measure the viscosity of an oil having a specific gravity of 0.90. The following data apply:
Tube inside diameter = 2.5 mm = D
Length between manometer taps = 300 mm = L
Manometer fluid = mercury
Manometer deflection = 177 mm = h
Velocity of flow = 1.58 m/s = v
Determine the viscosity of the oil.
2.63 In a falling-ball viscometer, a steel ball with a diameter of 0.063 in is allowed to fall freely in a heavy fuel oil having a specific gravity of 0.94. Steel weighs 0.283 lb/in^3. If the ball is observed to fall 10.0 in in 10.4 s, calculate the dynamic viscosity of the oil in $lb \cdot s/ft^2$.
2.64 A capillary type viscometer similar to that shown in Fig. 2.7 is being used to measure the viscosity of an oil having a specific gravity of 0.90. The following data apply:
Tube inside diameter = 0.100 in = D
Length between manometer taps = 12.0 in = L
Manometer fluid = mercury
Manometer deflection = 7.00 in = h
Velocity of flow = 4.82 ft/s = v
Determine the dynamic viscosity of the oil in $lb \cdot s/ft^2$.
2.65 A fluid has a kinematic viscosity of 15.0 mm^2/s at 100°F. Determine its equivalent viscosity in SUS at that temperature.
2.66 A fluid has a kinematic viscosity of 55.3 mm^2/s at 100°F. Determine its equivalent viscosity in SUS at that temperature.
2.67 A fluid has a kinematic viscosity of 188 mm^2/s at 100°F. Determine its equivalent viscosity in SUS at that temperature.
2.68 A fluid has a kinematic viscosity of 244 mm^2/s at 100°F. Determine its equivalent viscosity in SUS at that temperature.
2.69 A fluid has a kinematic viscosity of 153 mm^2/s at 40°F. Determine its equivalent viscosity in SUS at that temperature.
2.70 A fluid has a kinematic viscosity of 205 mm^2/s at 190°F. Determine its equivalent viscosity in SUS at that temperature.
2.71 An oil is tested using a Saybolt viscometer and its viscosity is 6250 SUS at 100°F. Determine the kinematic viscosity of the oil in mm^2/s at that temperature.
2.72 An oil is tested using a Saybolt viscometer and its viscosity is 438 SUS at 100°F. Determine the kinematic viscosity of the oil in mm^2/s at that temperature.

2.73 An oil is tested using a Saybolt viscometer and its viscosity is 68 SUS at 100°F. Determine the kinematic viscosity of the oil in mm^2/s at that temperature.

2.74 An oil is tested using a Saybolt viscometer and its viscosity is 176 SUS at 100°F. Determine the kinematic viscosity of the oil in mm^2/s at that temperature.

2.75 An oil is tested using a Saybolt viscometer and its viscosity is 4690 SUS at 80°C. Determine the kinematic viscosity of the oil in mm^2/s at that temperature.

2.76 An oil is tested using a Saybolt viscometer and its viscosity is 526 SUS at 40°C. Determine the kinematic viscosity of the oil in mm^2/s at that temperature.

2.77 Convert all of the kinematic viscosity data in Table 2.5 for ISO viscosity grades from mm^2/s (cSt) to SUS.

COMPUTER APPLICATION ASSIGNMENTS

1. Generate software to convert viscosity units from any given system to another system using the conversion factors and techniques from Appendix K. Write this application for your programmable calculator, your phone, or some other device.
2. Write code to calculate the viscosity of water at a given temperature using data from Appendix A. This software could be joined with what you wrote in Chapter 1, which used other properties of water. Use the same options described in Chapter 1.
3. Use a spreadsheet or other application to display the values of kinematic viscosity and dynamic viscosity of water from Appendix A. Then create curve-fit equations for both types of viscosity versus temperature using the *Trendlines* feature of the spreadsheet chart. Display graphs for both viscosities versus temperature on the spreadsheet showing the equations used.