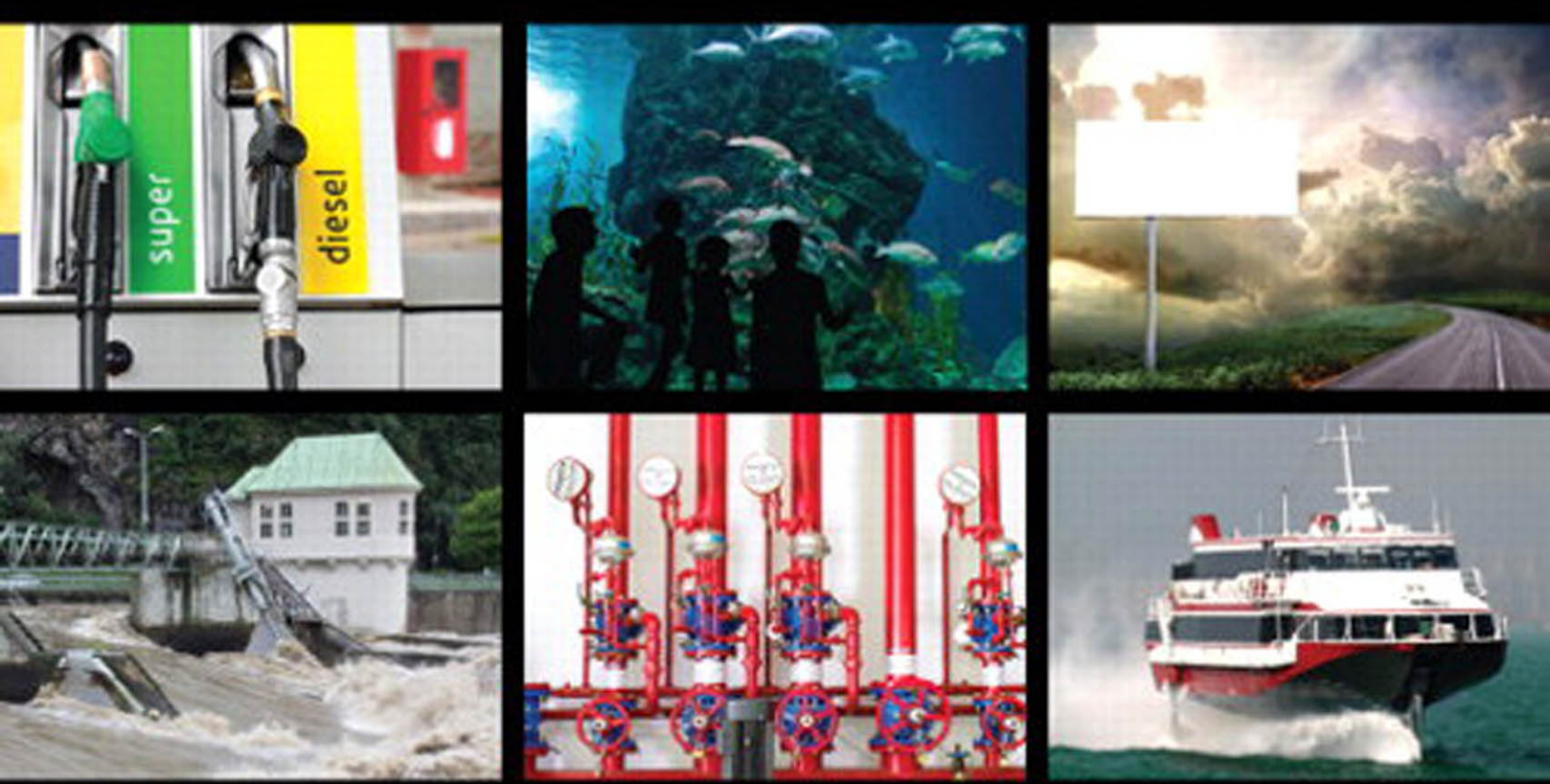
APPLIED FLUID MECHANICS

Seventh Edition



Robert L. Mott | Joseph A. Untener

KEY EQUATIONS

PRESSURE	$p = \frac{F}{A}$	(1–1)
WEIGHT-MASS RELATIONSHIP	$w = mg$	(1–2)
BULK MODULUS	$E = \frac{-\Delta p}{(\Delta V)/V}$	(1–4)
DENSITY	$\rho = m/V$	(1–5)
SPECIFIC WEIGHT	$\gamma = w/V$	(1–6)
SPECIFIC GRAVITY	$\text{sg} = \frac{\gamma_s}{\gamma_w \text{ @ } 4°\text{C}} = \frac{\rho_s}{\rho_w \text{ @ } 4°\text{C}}$	(1–7)
$\gamma - \rho$ RELATION	$\gamma = \rho g$	(1–9)
DYNAMIC VISCOSITY	$\eta = \frac{\tau}{\Delta v/\Delta y} = \tau\left(\frac{\Delta y}{\Delta v}\right)$	(2–2)
KINEMATIC VISCOSITY	$\nu = \eta/\rho$	(2–3)
ABSOLUTE AND GAGE PRESSURE	$p_{\text{abs}} = p_{\text{gage}} + p_{\text{atm}}$	(3–2)
PRESSURE-ELEVATION RELATIONSHIP	$\Delta p = \gamma h$	(3–3)
RESULTANT FORCE ON A RECTANGULAR WALL	$F_R = \gamma(h/2)A$	(4–3)
RESULTANT FORCE ON A SUBMERGED PLANE AREA	$F_R = \gamma h_c A$	(4–4)
LOCATION OF CENTER OF PRESSURE	$L_p = L_c + \frac{I_c}{L_c A}$	(4–5)
PIEZOMETRIC HEAD	$h_a = p_a/\gamma$	(4–14)
BUOYANT FORCE	$F_b = \gamma_f V_d$	(5–1)
VOLUME FLOW RATE	$Q = Av$	(6–1)
WEIGHT FLOW RATE	$W = \gamma Q$	(6–2)
MASS FLOW RATE	$M = \rho Q$	(6–3)

CONTINUITY EQUATION FOR ANY FLUID

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 \tag{6–4}$$

CONTINUITY EQUATION FOR LIQUIDS

$$A_1 v_1 = A_2 v_2 \tag{6–5}$$

BERNOULLI'S EQUATION

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g} \tag{6–9}$$

TORRICELLI'S THEOREM

$$v_2 = \sqrt{2gh} \tag{6–16}$$

TIME REQUIRED TO DRAIN A TANK

$$t_2 - t_1 = \frac{2(A_t/A_j)}{\sqrt{2g}}(h_1^{1/2} - h_2^{1/2}) \tag{6–26}$$

GENERAL ENERGY EQUATION

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} + h_A - h_R - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g} \tag{7–3}$$

POWER ADDED TO A FLUID BY A PUMP

$$P_A = h_A W = h_A \gamma Q \tag{7–5}$$

PUMP EFFICIENCY

$$e_M = \frac{\text{Power delivered to fluid}}{\text{Power put into pump}} = \frac{P_A}{P_I} \tag{7–6}$$

POWER REMOVED FROM A FLUID BY A MOTOR

$$P_R = h_R W = h_R \gamma Q \tag{7–8}$$

MOTOR EFFICIENCY

$$e_M = \frac{\text{Power output from motor}}{\text{Power delivered by fluid}} = \frac{P_O}{P_R} \tag{7–9}$$

REYNOLDS NUMBER—CIRCULAR SECTIONS

$$N_R = \frac{vD\rho}{\eta} = \frac{vD}{\nu} \tag{8–1}$$

DARCY'S EQUATION FOR ENERGY LOSS

$$h_L = f \times \frac{L}{D} \times \frac{v^2}{2g} \tag{8–3}$$

HAGEN-POISEUILLE EQUATION

$$h_L = \frac{32\eta L v}{\gamma D^2} \tag{8–4}$$

FRICTION FACTOR FOR LAMINAR FLOW

$$f = \frac{64}{N_R} \tag{8–5}$$

FRICTION FACTOR FOR TURBULENT FLOW

$$f = \frac{0.25}{\left[\log\left(\frac{1}{3.7(D/\epsilon)} + \frac{5.74}{N_R^{0.9}}\right)\right]^2} \tag{8–7}$$

HAZEN-WILLIAMS FORMULA – U.S. CUSTOMARY UNITS

$$v = 1.32\, C_h R^{0.63} s^{0.54} \tag{8–8}$$

APPLIED FLUID MECHANICS

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Seventh Edition

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PREFACE

INTRODUCTION

The objective of this book is to present the principles of fluid mechanics and the application of these principles to practical, applied problems. 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 are expected to have an understanding of algebra, trigonometry, and mechanics. After completing the book, the student should have the ability to design and analyze practical fluid flow systems and to continue learning in the field. Students could take other applied courses, such as those on fluid power, HVAC, and civil hydraulics, following this course. Alternatively, this book could be used to teach selected fluid mechanics topics within such courses.

APPROACH

The approach used in this book encourages the student 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-assisted approaches, 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 as well as a mathematical basis is 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 2008 publication *The International System of Units* (*SI*) (NIST Special Publication 330), edited by Barry N. Taylor and Ambler Thompson.

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.

New, powerful, commercially available software: A new feature of this 7th edition is the integration of the use of a major, internationally renowned software package for piping system analysis and design, called PIPE-FLO®, produced and marketed by Engineered Software, Inc. (often called ESI) in Lacey, Washington. As stated by ESI's CEO and president, along with several staff members, the methodology used in this textbook for analyzing pumped fluid flow systems is highly compatible with that used in their software. Students who learn well 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.

Students using this book in classes will be informed about a unique link to the ESI website where a specially adapted version of the industry-scale software can be used. Virtually all of the piping analysis and design problems in this book can be set up and solved using this special version. 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. New 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.

Students and instructors can access the special version of PIPE-FLO® at this site:

http://www.eng-software.com/appliedflluidmechanics

FEATURES NEW TO THE SEVENTH EDITION

The seventh 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 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 and several have been updated or expanded.

The following list highlights some of the changes in this edition:

- A large percentage of the illustrations have been upgraded in terms of realism, consistency, and graphic quality. Full color has been introduced enhancing 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.
- Most chapters include an extensive list of Internet resources that provide useful supplemental 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. The resources have been updated and many have been added to those in previous editions.
- The end-of-chapter references have been extensively revised, updated, and extended.
- Use of metric units has been expanded in several parts of the book. Two new Appendix tables have been added that feature purely metric sizes for steel, copper, and plastic tubing. Use of the metric DN-designations for standard Schedules 40 and 80 steel pipes have been more completely integrated into the discussions, example problems, and end-of chapter problems. Almost all metric-based problems use these new 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 new, creative supplemental problems have been added to the end-of-chapter set of problems 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 refined in Chapter 6 and used in later chapters and design projects.
- The discussion of computational fluid mechanics included in Chapter 9 has been revised with attractive new graphics that are highly relevant to the study of pipe flow.
- The use of *K*-factors (resistance coefficients) based on the equivalent-length approach has been updated, expanded, and refined 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 has been expanded in Chapter 10 with new equations for use with metric units. It is also included in new parts of Chapter 13 that emphasize the use of valves as control elements.
- The section General Principles of Pipeline System Design has been refined in Chapter 11.
- Several sections in Chapter 13 on pump selection and application have been updated and revised to provide more depth, greater consistency with TP 410, a smoother development of relevant topics, and use of the PIPE-FLO® software.

INTRODUCING PROFESSOR JOSEPH A. UNTENER—NEW CO-AUTHOR OF THIS BOOK

We are pleased to announce that the seventh edition of *Applied Fluid Mechanics* has been co-authored by:

Robert L. Mott and Joseph A. Untener

Professor Untener has been an outstanding member of the faculty 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. A gifted instructor, a strong leader, a valued colleague, and a wise counselor of students, Joe is a great choice for the task of preparing this book. He brings fresh ideas, a keen sense of style and methodology, and an eye for effective and attractive graphics. He initiated the major move toward integrating the PIPE-FLO® software into the book and managed the process of working with the leadership and staff of Engineered Software, Inc. His contributions should prove to be of great value to users of this book, both students and instructors.

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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.

On a larger scale, consider the chemical processing plant shown in Fig. 1.1. Complex piping systems use pumps to transfer fluids from tanks and move them through various processing systems. The finished products may be stored in other tanks and then transferred to trucks or railroad cars to be delivered to customers.

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.
- 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

FIGURE 1.1 Industrial and commercial fluid piping systems, like this one used in a chemical processing plant, involve complex arrangements requiring careful design and analysis. (*Source:* Nikolay Kazachok/Fotolia)

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.

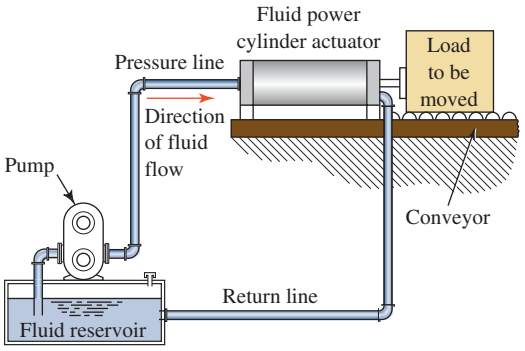

FIGURE 1.2 Typical piping system for fluid power.

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 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? Describe the cooling system and the nature of the coolant. 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 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.

In addition to these familiar differences between gases and liquids, another difference 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 can compress the air fairly easily by pushing on the piston. Perhaps you have used a hand-operated pump to inflate a bicycle tire, a beach ball, an air mattress, or a basketball. As you move the piston, the volume of the gas is reduced appreciably as the pressure increases. But what would happen if the cylinder contained water rather than air? 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.

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

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

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

$$F = ma$$

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

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

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 $F = ma$:

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

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

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	$10^{3} = 1\,000$
milli	m	$10^{-3} = 0.001$
micro	μ	$10^{-6} = 0.000\,001$
nano	n	$10^{-9} = 0.000\,000\,001$
pico	p	$10^{-12} = 0.000\,000\,000\,001$

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.

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

Sometimes called the *English gravitational unit system* or the *pound-foot-second* system, the U.S. Customary System defines the basic quantities as follows:

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

Probably the most difficult of these units to understand is the slug because we are more familiar with measuring in

*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.

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

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

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

$$w = mg$$

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

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

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

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,

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

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 below.

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

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·m or Joule (J)	$kg \cdot m^2/s^2$	lb·ft	lb·in
Power (P)	Energy/time	watt (W) or N·m/s or J/s	kilowatt (kW)	lb·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/hr	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 $N \cdot s^2/m^4$		$slugs/ft^3$	

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.

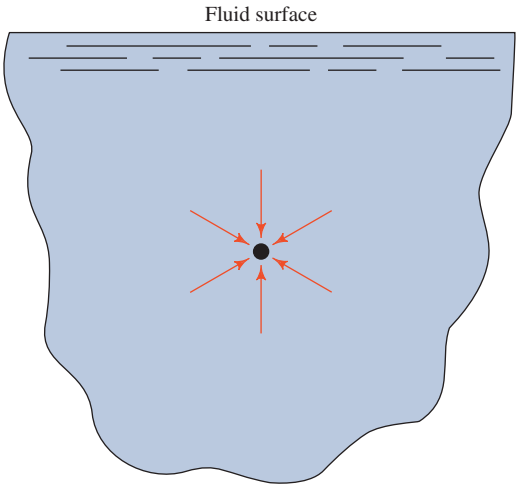

FIGURE 1.3 Pressure acting uniformly in all directions on a small volume of fluid.

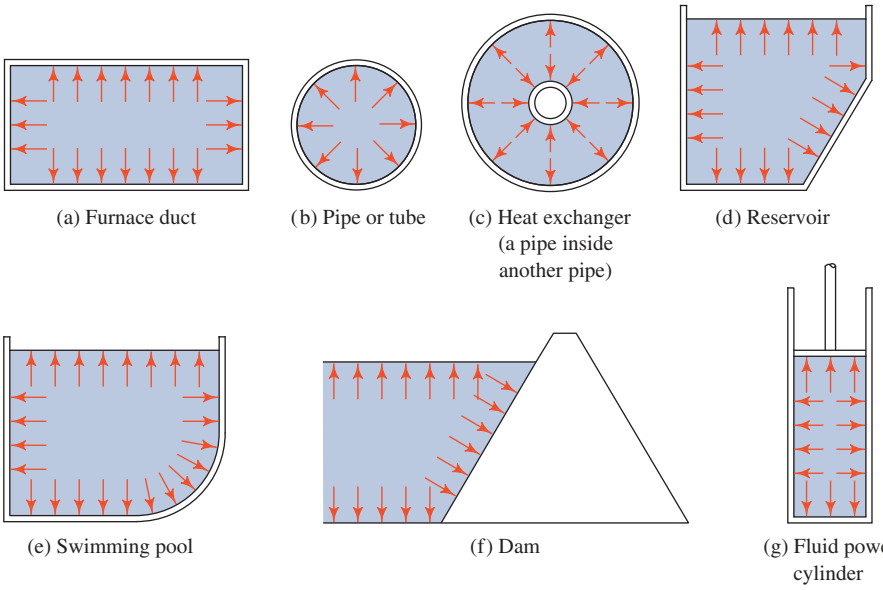

FIGURE 1.4 Direction of fluid pressure on boundaries.

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

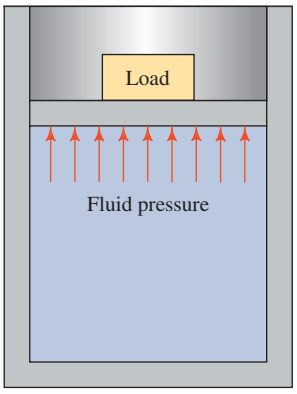

FIGURE 1.5 Illustration of fluid pressure supporting a load.

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.