FLUID Mechanics

NINTH EDITION

Mc Graw Hill

Frank M. White

Henry Xue

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University of Rhode Island

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About the Authors

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At the University of Rhode Island, Frank became interested in oceanographic and coastal flow problems, and in 1966 he helped found the first Department of Ocean Engineering in the United States. His research interests have mainly been in viscous flow and convection heat transfer. Known primarily as a teacher and writer, he received the ASEE Westinghouse Teaching Excellence Award in addition to seven University of Rhode Island teaching awards. His modest research accomplishments include some 80 technical papers and reports, the ASME Lewis F. Moody Research Award in 1973, and the ASME Fluids Engineering Award in 1991. He is a Fellow of the ASME and for 12 years served as editor-in-chief of the ASME *Journal of Fluids Engineering*. He received a Distinguished Alumnus award from Georgia Tech in 1990 and was elected to the Academy of Distinguished Georgia Tech Alumni in 1994.

In addition to the present text, he has written three undergraduate textbooks: *Fluid Mechanics*; *Heat Transfer*; and *Heat and Mass Transfer*. He has served as a consulting editor of the McGraw-Hill Encyclopedia of Science and Technology from 1992 until 2006, and on the ASME Publications Committee until 2009. He continues to be inspired by his late wife, Jeanne, and lives in Narragansett, Rhode Island, with his dog Jack and his cat Kerry.

Henry Xue is Professor of Mechanical Engineering at California State Polytechnic University. He received his B.S. degree from Jiangsu University in China, and his M.S. and Ph.D. degrees from the University of Tokyo in Japan. Prior to joining California State Polytechnic University in 2000, he was on the mechanical engineering faculty of National University of Singapore.

Henry has authored and coauthored many technical papers in computational fluid mechanics and heat transfer in built environments, microscale gaseous flow modeling and simulation using DSMC, and microcombustor and thermophotovoltaic energy systems. He is a member of the American Society of Mechanical Engineers and the American Society of Heating, Refrigeration and Air-Conditioning Engineers. He lives with his wife, Sophia, in Irvine, California.

To Jeanne

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Preface

General Approach

The book is intended for an undergraduate engineering course in fluid mechanics. The principles considered in the book are fundamental and have been well established in the community of fluids engineering. However, in presenting this important subject, we have drawn on our own ideas and experience. There is plenty of material for a full year of instruction, and the content can also easily be divided into two semesters of teaching. There have been some additions and deletions in this ninth edition of *Fluid Mechanics,* but no philosophical change. There are still eleven chapters, plus appendices. The informal, student-oriented style is retained and, if it succeeds, has the flavor of an interactive lecture by the authors.

New co-author Dr. Henry Xue was brought on board for this edition.

Learning Tools

The total number of problem exercises continues to increase, from 1089 in the first edition, to 1681 in the ninth edition. Most of these are basic end-of-chapter problems, sorted according to topic. There are also Word Problems, multiple-choice Fundamentals of Engineering Problems, Comprehensive Problems, and Design Projects. Answers to Selected Problems, at the end of the book, provides the answers to approximately 700 end-of-chapter problems.

In addition, there are many example problems throughout the chapters that showcase the recommended sequence of problem-solving steps outlined in Section 1.7.

Most of the problems in this text can be solved with a hand calculator. Some can even be simply explained in words. A few problems, especially in Chapters 6, 7, 9, and 10, involve solving complicated algebraic expressions, that would be laborious for hand calculation but can be much more easily handled using licensed equation-solving software. The authors have provided examples of how to solve complicated example problems using Microsoft Excel, as illustrated in Example 6.5. Excel contains several hundred special mathematical functions for performing engineering and statistics calculations.

Content Changes

The overall content and order of presentation have not changed substantially in this edition except for the following:

Chapter 1 renames Section 1.5 “System and Control Volume.” Definitions of system and control volume, which formerly were scattered over many chapters, are now consolidated in this section. A new subheading, “Methods of Description,” has been added. The Lagrangian and Eulerian methods of description have been moved here from Chapter 4. Discussions of velocity and acceleration fields are retained as examples of using the control volume approach with the Eulerian method of description. The section “Flow Patterns: Streamlines, Streaklines, and Pathlines,” formerly Section 1.9, has been moved forward as Section 1.8 for better continuity in the introduction of fluid and flow systems. A new subsection, “Integral and Differential Approaches,” has been added to the new Section 1.9, “Basic Flow Analysis Techniques.”

Chapter 2 edits descriptions in Section 2.4, “Application to Mamometry,” using the methods of “pressure increasing downward” and “jump across” typically. The coordinates for Figure 2.2 have been reset to be consistent with Figure 2.1. Figure 2.12 has been replaced with a new figure to better illustrate the pressure distribution on a submerged surface.

Chapter 3 adds three subheadings to elaborate areas where the linear momentum equation can be applied. Example 3.7 has been rewritten to better demonstrate how to solve the anchoring forces on a piping elbow. Brief discussions have been added to examples of the sluice gate and impinging jet with relative velocity for an inertial, moving, and nondeforming control volume.

Chapter 4 adds the constant heat flux boundary condition to the energy equation. Inlet and outlet boundary conditions are separated because the free-flow conditions are more common at the outlet. New Example 4.10 investigates the rotation of a Couette flow and a “potential vortex” flow.

Chapter 5 carries the topics of Section 5.2—the choice of variables and scaling parameters—into Section 5.3 to make it easier for students to follow the arguments. The topic “Some Peculiar Engineering Equations” has been removed from Section 5.2 because most of those equations will be introduced in Chapter 10.

In Chapter 6, Section 6.2 has been retitled “Internal Viscous Flow.” Brief discussions have been added to four types of pipe flow problems to guide students in applying appropriate strategies for designing pipe systems.

In Chapter 7, the discussion in the section “Transition to Turbulence” in Section 7.4 has been improved. The classification of external flow is elaborated. Former Section 7.6 has been split into two sections: “Drag” and “Forces on Lifting Bodies.” The methodology for solving an external flow problem is summarized.

An entire section of Chapter 8 on numerical methods, including problem exercises, has been moved to new Appendix F. The vast majority of universities do not cover numerical methods in a fundamental fluid mechanics course. Because the CFD methods are becoming a powerful tool for solving almost all problems of fluid flow, it was also inappropriate to place that topic at the end of this chapter. A new example of a free vortex has been added to Section 8.2.

Chapter 9 clarifies why we can simplify compressible flow as one-dimensional isentropic flow. Section 9.3 explains the identity of the momentum equation and the energy equation for isentropic flows. Discussions have been added regarding how to use the variables of stagnation pressure, density, and throat area after the shock wave in calculation.

Chapter 10 improves the physical interpretation of the Froude number in Section 10.1. There is a new subsection “Effects of Froude Number.” The need to maximize the hydraulic radius in order to achieve an efficient channel is elaborated in Section 10.3.

Chapter 11 elaborates further on pump performance curves. New Figure 11.18*a* illustrates the derivation for the system head. The data for worldwide wind power capacity have been updated.

Appendices A to E remain unchanged. The new Appendix F, “Numerical Methods,” presents text that formerly was in Chapter 8. This will continue to serve instructors who use this material for introducing the CFD methods to their students.

Additionally, this title is supported by SmartBook, a feature of the LearnSmart adaptive learning system that assesses student understanding of course content through a series of adaptive questions. This platform has provided feedback from thousands of students, identifying those specific portions of the text that have resulted in the greatest conceptual difficulty and comprehension among students. For the ninth edition, the entire text was reviewed and revised based on this LearnSmart student data.

Instructor Resources

A number of supplements are available to instructors through Connect. New to this edition are Lecture PowerPoints to accompany the text. Additionally, instructors may obtain the text images in PowerPoint format and the full Solutions Manual. The solutions manual provides complete and detailed solutions, including problem statements and artwork, to the end-of-chapter problems.

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Acknowledgments

We wish to express our appreciation to the many people who have helped us in recent revisions. Material help, in the form of photos, articles, and problems, came from Scott Larwood of the University of the Pacific; Sukanta Dash of the Indian Institute of Technology at Kharagpur; Mark Coffey of the Colorado School of Mines; Mac Stevens of Oregon State University; Stephen Carrington of Malvern Instruments; Carla Cioffi of NASA; Lisa Lee and Robert Pacquette of the Rhode Island Department of Environmental Management; Vanessa Blakeley and Samuel Schweighart of Terrafugia Inc.; Beric Skews of the University of the Witwatersrand, South Africa; Kelly Irene Knorr and John Merrill of the School of Oceanography at the University of Rhode Island; Adam Rein of Altaeros Energies Inc.; Dasari Abhinav of Anna University, India; Kris Allen of Transcanada Corporation; Bruce Findlayson of the University of Washington; Wendy Koch of USA Today; Liz Boardman of the South County Independent; Beth Darchi and Colin McAteer of the American Society of Mechanical Engineers; Catherine Hines of the William Beebe Web Site; Laura Garrison of York College of Pennsylvania.

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Frank M. White
Henry Xue

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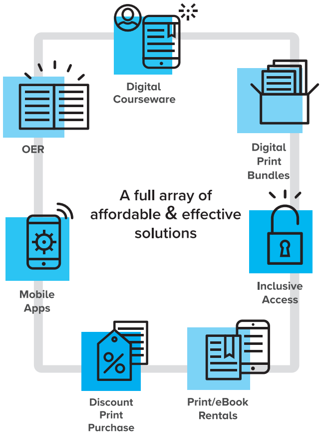

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Falls on the Nesowadnehunk Stream in Baxter State Park, Maine, which is the northern terminus of the Appalachian Trail. Such flows, open to the atmosphere, are driven simply by gravity and do not depend much upon fluid properties such as density and viscosity. They are discussed later in Chap. 10. To the writer, one of the joys of fluid mechanics is that visualization of a fluid flow process is simple and beautiful [*Robert Cable/Natural Selection/Design Pics*].

Chapter 1
Introduction

1.1 Preliminary Remarks

Fluid mechanics is the study of fluids either in motion (fluid *dynamics*) or at rest (fluid *statics*). Both gases and liquids are classified as fluids, and the number of fluid engineering applications is enormous: breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmills, pipes, missiles, icebergs, engines, filters, jets, and sprinklers, to name a few. When you think about it, almost everything on this planet either is a fluid or moves within or near a fluid.

The essence of the subject of fluid flow is a judicious compromise between theory and experiment. Since fluid flow is a branch of mechanics, it satisfies a set of well-documented basic laws, and thus a great deal of theoretical treatment is available. However, the theory is often frustrating because it applies mainly to idealized situations, which may be invalid in practical problems. The two major obstacles to a workable theory are geometry and viscosity. The basic equations of fluid motion (Chap. 4) are too difficult to enable the analyst to attack arbitrary geometric configurations. Thus most textbooks concentrate on flat plates, circular pipes, and other easy geometries. It is possible to apply numerical computer techniques to complex geometries, and specialized textbooks are now available to explain the new *computational fluid dynamics* (CFD) approximations and methods [1–4].[1] This book will present many theoretical results while keeping their limitations in mind.

The second obstacle to a workable theory is the action of viscosity, which can be neglected only in certain idealized flows (Chap. 8). First, viscosity increases the difficulty of the basic equations, although the boundary-layer approximation found by Ludwig Prandtl in 1904 (Chap. 7) has greatly simplified viscous-flow analyses. Second, viscosity has a destabilizing effect on all fluids, giving rise, at frustratingly small velocities, to a disorderly, random phenomenon called *turbulence.* The theory of turbulent flow is crude and heavily backed up by experiment (Chap. 6), yet it can be quite serviceable as an engineering estimate. This textbook only introduces the standard experimental correlations for turbulent time-mean flow. Meanwhile, there are advanced texts on both time-mean *turbulence and*

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[1] Numbered references appear at the end of each chapter.

turbulence modeling [5, 6] and on the newer, computer-intensive *direct numerical simulation* (DNS) of fluctuating turbulence [7, 8].

Thus there is theory available for fluid flow problems, but in all cases it should be backed up by experiment. Often the experimental data provide the main source of information about specific flows, such as the drag and lift of immersed bodies (Chap. 7). Fortunately, fluid mechanics is a highly visual subject, with good instrumentation [9–11], and the use of dimensional analysis and modeling concepts (Chap. 5) is widespread. Thus experimentation provides a natural and easy complement to the theory. You should keep in mind that theory and experiment should go hand in hand in all studies of fluid mechanics.

1.2 The Concept of a Fluid

From the point of view of fluid mechanics, all matter consists of only two states, fluid and solid. The difference between the two is perfectly obvious to the layperson, and it is an interesting exercise to ask a layperson to put this difference into words. The technical distinction lies with the reaction of the two to an applied shear or tangential stress. *A solid can resist a shear stress by a static deflection; a fluid cannot*. Any shear stress applied to a fluid, no matter how small, will result in motion of that fluid. The fluid moves and deforms continuously as long as the shear stress is applied. As a corollary, we can say that a fluid at rest must be in a state of zero shear stress, a state often called the hydrostatic stress condition in structural analysis. In this condition, Mohr's circle for stress reduces to a point, and there is no shear stress on any plane cut through the element under stress.

Given this definition of a fluid, every layperson also knows that there are two classes of fluids, *liquids* and *gases.* Again the distinction is a technical one concerning the effect of cohesive forces. A liquid, being composed of relatively close-packed molecules with strong cohesive forces, tends to retain its volume and will form a free surface in a gravitational field if unconfined from above. Free-surface flows are dominated by gravitational effects and are studied in Chaps. 5 and 10. Since gas molecules are widely spaced with negligible cohesive forces, a gas is free to expand until it encounters confining walls. A gas has no definite volume, and when left to itself without confinement, a gas forms an atmosphere that is essentially hydrostatic. The hydrostatic behavior of liquids and gases is taken up in Chap. 2. Gases cannot form a free surface, and thus gas flows are rarely concerned with gravitational effects other than buoyancy.

Figure 1.1 illustrates a solid block resting on a rigid plane and stressed by its own weight. The solid sags into a static deflection, shown as a highly exaggerated dashed line, resisting shear without flow. A free-body diagram of element A on the side of the block shows that there is shear in the block along a plane cut at an angle θ through A. Since the block sides are unsupported, element A has zero stress on the left and right sides and compression stress $\sigma = -p$ on the top and bottom. Mohr's circle does not reduce to a point, and there is nonzero shear stress in the block.

By contrast, the liquid and gas at rest in Fig. 1.1 require the supporting walls in order to eliminate shear stress. The walls exert a compression stress of $-p$ and reduce Mohr's circle to a point with zero shear everywhere—that is, the hydrostatic condition. The liquid retains its volume and forms a free surface in the

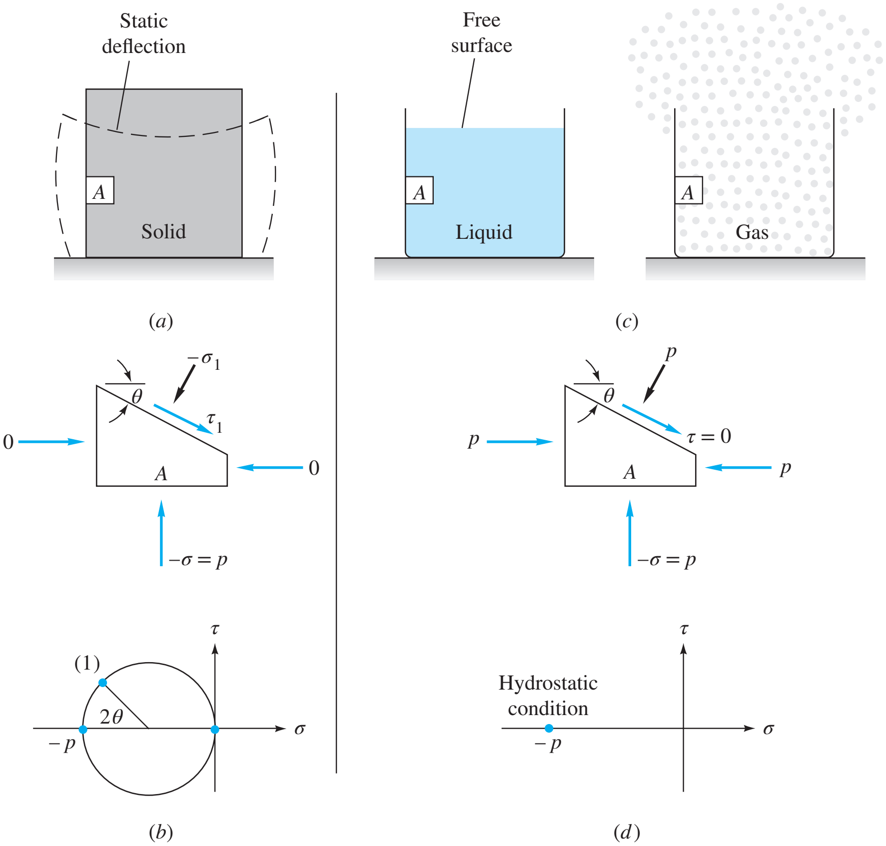

Fig. 1.1 A solid at rest can resist shear. (*a*) Static deflection of the solid; (*b*) equilibrium and Mohr's circle for solid element *A*. A fluid cannot resist shear. (*c*) Containing walls are needed; (*d*) equilibrium and Mohr's circle for fluid element *A*.

container. If the walls are removed, shear develops in the liquid and a big splash results. If the container is tilted, shear again develops, waves form, and the free surface seeks a horizontal configuration, pouring out over the lip if necessary. Meanwhile, the gas is unrestrained and expands out of the container, filling all available space. Element *A* in the gas is also hydrostatic and exerts a compression stress $-p$ on the walls.

In the previous discussion, clear decisions could be made about solids, liquids, and gases. Most engineering fluid mechanics problems deal with these clear cases—that is, the common liquids, such as water, oil, mercury, gasoline, and alcohol, and the common gases, such as air, helium, hydrogen, and steam, in their common temperature and pressure ranges. There are many borderline cases, however, of which you should be aware. Some apparently "solid" substances such as asphalt and lead resist shear stress for short periods but actually deform slowly and exhibit definite fluid behavior over long periods. Other substances, notably colloid and slurry mixtures, resist small shear stresses but "yield" at large stress and begin to flow as fluids do. Specialized textbooks are devoted to this study of more general deformation and flow, a field called *rheology* [16]. Also, liquids and gases can coexist in two-phase mixtures, such as steam–water mixtures or water with entrapped air bubbles. Specialized textbooks present the analysis of such *multiphase flows* [17]. Finally, in some situations the distinction between a liquid and a gas blurs. This is the case at temperatures and pressures above the so-called *critical point* of a substance, where only a single phase exists, primarily resembling a gas. As pressure increases far above the critical point, the gaslike substance becomes so dense that there is some resemblance to a liquid, and the usual thermodynamic approximations like the perfect-gas law become inaccurate. The critical temperature and pressure of water are $T_c = 647$ K and $p_c = 219$ atm (atmosphere)[2] so that typical problems involving water and steam are below the critical point. Air, being a mixture of gases, has no distinct critical point, but its principal component, nitrogen, has $T_c = 126$ K and $p_c = 34$ atm. Thus typical problems involving air are in the range of high temperature and low pressure where air is distinctly and definitely a gas. This text will be concerned solely with clearly identifiable liquids and gases, and the borderline cases just discussed will be beyond our scope.

1.3 The Fluid as a Continuum

We have already used technical terms such as *fluid pressure* and *density* without a rigorous discussion of their definition. As far as we know, fluids are aggregations of molecules, widely spaced for a gas, closely spaced for a liquid. The distance between molecules is very large compared with the molecular diameter. The molecules are not fixed in a lattice but move about freely relative to each other. Thus fluid density, or mass per unit volume, has no precise meaning because the number of molecules occupying a given volume continually changes. This effect becomes unimportant if the unit volume is large compared with, say, the cube of the molecular spacing, when the number of molecules within the volume will remain nearly constant in spite of the enormous interchange of particles across the boundaries. If, however, the chosen unit volume is too large, there could be a noticeable variation in the bulk aggregation of the particles. This situation is illustrated in Fig. 1.2, where the "density" as calculated from molecular mass δm within a given volume $\delta\mathcal{V}$ is plotted versus the size of the unit volume. There is a limiting volume $\delta\mathcal{V}^*$ below which molecular variations may be important and above which aggregate variations may be important. The *density* ρ of a fluid is best defined as

$$\rho = \lim_{\delta\mathcal{V}\to\delta\mathcal{V}^*} \frac{\delta m}{\delta\mathcal{V}} \tag{1.1}$$

The limiting volume $\delta\mathcal{V}^*$ is about 10^{-9} mm^3 for all liquids and for gases at atmospheric pressure. For example, 10^{-9} mm^3 of air at standard conditions contains approximately 3×10^7 molecules, which is sufficient to define a nearly constant density according to Eq. (1.1). Most engineering problems are concerned

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[2] One atmosphere equals 2116 lbf/ft^2 = 101,300 Pa.

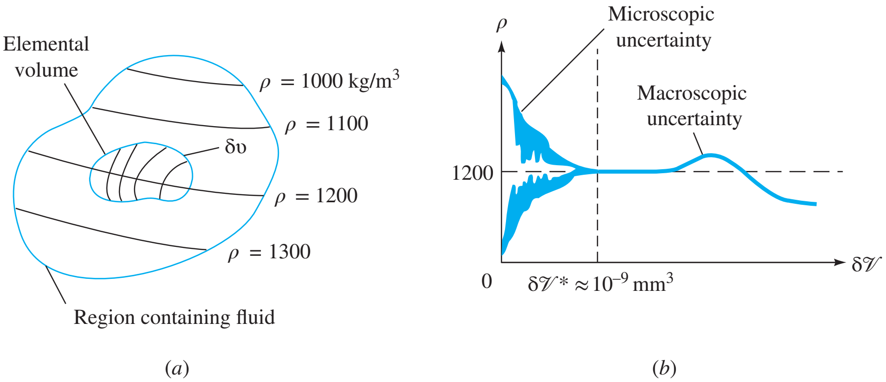

Fig. 1.2 The limit definition of continuum fluid density: (*a*) an elemental volume in a fluid region of variable continuum density; (*b*) calculated density versus size of the elemental volume.

with physical dimensions much larger than this limiting volume, so that density is essentially a point function and fluid properties can be thought of as varying continually in space, as sketched in Fig. 1.2a. Such a fluid is called a *continuum*, which simply means that its variation in properties is so smooth that differential calculus can be used to analyze the substance. We shall assume that continuum calculus is valid for all the analyses in this book. Again there are two borderline cases for gases. One is at such low pressures that molecular spacing and mean free path[3] are comparable to, or larger than, the physical size of the system. Applications include vacuum engineering, aero-thermal analysis and design of spacecrafts, satellites, missiles, etc., flying at high altitudes. The non-continuum effects also become significant when system length scales reduce to microscopically small. Applications with microscopic length scales are becoming increasingly common since the advent of Micro-Electro-Mechanical Systems (MEMS) and nano devices, where the characteristic length of the system decreases to a magnitude of sub-micron or nanometer. Both cases require that the continuum approximation be dropped in favor of a molecular theory of rarefied gas flow [18]. In principle, all fluid mechanics problems can be attacked from the molecular viewpoint, but no such attempt will be made here. Note that the use of continuum calculus does not preclude the possibility of discontinuous jumps in fluid properties across a free surface or fluid interface or across a shock wave in a compressible fluid (Chap. 9). Our calculus in analyzing fluid flow must be flexible enough to handle discontinuous boundary conditions.

1.4 Dimensions and Units

A *dimension* is the measure by which a physical variable is expressed quantitatively. A *unit* is a particular way of attaching a number to the quantitative dimension. Thus length is a dimension associated with such variables as distance, displacement, width, deflection, and height, while centimeters and inches are both numerical units for expressing length. Dimension is a powerful concept about which a splendid tool called *dimensional analysis* has been developed (Chap. 5), while units are the numerical quantity that the customer wants as the final answer.

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[3] The mean distance traveled by molecules between collisions (see Prob. P1.5).

Table 1.1 Primary Dimensions in SI and BG Systems

Primary dimension	SI unit	BG unit	Conversion factor
Mass $\{M\}$	Kilogram (kg)	Slug	1 slug = 14.5939 kg
Length $\{L\}$	Meter (m)	Foot (ft)	1 ft = 0.3048 m
Time $\{T\}$	Second (s)	Second (s)	1 s = 1 s
Temperature $\{\Theta\}$	Kelvin (K)	Rankine (°R)	1 K = 1.8°R

In 1872 an international meeting in France proposed a treaty called the Metric Convention, which was signed in 1875 by 17 countries including the United States. It was an improvement over British systems because its use of base 10 is the foundation of our number system, learned from childhood by all. Problems still remained because even the metric countries differed in their use of kiloponds instead of dynes or newtons, kilograms instead of grams, or calories instead of joules. To standardize the metric system, a General Conference of Weights and Measures, attended in 1960 by 40 countries, proposed the *International System of Units* (SI). We are now undergoing a painful period of transition to SI, an adjustment that may take many more years to complete. The professional societies have led the way. Since July 1, 1974, SI units have been required by all papers published by the American Society of Mechanical Engineers, and there is a textbook explaining the SI [19]. The present text will use SI units together with British gravitational (BG) units.

Primary Dimensions

In fluid mechanics there are only four *primary dimensions* from which all other dimensions can be derived: mass, length, time, and temperature.[4] These dimensions and their units in both systems are given in Table 1.1. Note that the Kelvin unit uses no degree symbol. The braces around a symbol like $\{M\}$ mean "the dimension" of mass. All other variables in fluid mechanics can be expressed in terms of $\{M\}$, $\{L\}$, $\{T\}$, and $\{\Theta\}$. For example, acceleration has the dimensions $\{LT^{-2}\}$. The most crucial of these secondary dimensions is force, which is directly related to mass, length, and time by Newton's second law. Force equals the time rate of change of momentum or, for constant mass,

$$\mathbf{F} = m\mathbf{a} \tag{1.2}$$

From this we see that, dimensionally, $\{F\} = \{MLT^{-2}\}$.

The International System (SI)

The use of a constant of proportionality in Newton's law, Eq. (1.2), is avoided by defining the force unit exactly in terms of the basic units. In the SI system, the basic units are kilograms $\{M\}$, meters $\{L\}$, and seconds $\{T\}$. We define

$$1 \text{ newton of force} = 1 \text{ N} = 1 \text{ kg} \cdot 1 \text{ m/s}^2$$

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[4] If electromagnetic effects are important, a fifth primary dimension must be included, electric current $\{I\}$, whose SI unit is the ampere (A).

The newton is a relatively small force, about the weight of an apple (0.225 lbf). In addition, the basic unit of temperature $\{\Theta\}$ in the SI system is the degree Kelvin, K. They are referred to as the MLTΘ system of dimension. Use of these SI units (kg, m, s, K) will require no conversion factors in our equations.

The British Gravitational (BG) System

In the BG system also, a constant of proportionality in Eq. (1.2) is avoided by defining the force unit exactly in terms of the basic units. In the BG system, the basic units are pound-force $\{F\}$, feet $\{L\}$, and seconds $\{T\}$. We define

$$1 \text{ pound of force} = 1 \text{ lbf} = 1 \text{ slug} \cdot 1 \text{ ft/s}^2$$

One lbf ≈ 4.4482 N and approximates the weight of four apples. We will use the abbreviation *lbf* for pound-force and *lbm* for pound mass. The slug is a rather hefty mass, equal to 32.174 lbm. The basic unit of temperature $\{\Theta\}$ in the BG system is the degree Rankine, °R. Recall that a temperature difference 1 K = 1.8°R. They are referred to as the FLTΘ system of dimension. Use of these BG units (lbf, ft, s, °R) will require no conversion factors in our equations.

Other Unit Systems

There are other unit systems still in use. At least one needs no proportionality constant: the CGS system (dyne, gram, cm, s, K). However, CGS units are too small for most applications ($1 \text{ dyne} = 10^{-5}$ N) and will not be used here.

In the USA, some still use the English Engineering system (lbf, lbm, ft, s, °R), where the basic mass unit is the *pound of mass*. Newton's law (1.2) must be rewritten:

$$\mathbf{F} = \frac{m\mathbf{a}}{g_c}, \quad \text{where} \quad g_c = 32.174 \frac{\text{ft} \cdot \text{lbm}}{\text{lbf} \cdot \text{s}^2} \tag{1.3}$$

The constant of proportionality, g_c, has both dimensions and a numerical value not equal to 1.0. The present text uses only the SI and BG systems and will not solve problems or examples in the English Engineering system. Because Americans still use them, a few problems in the text will be stated in truly awkward units: acres, gallons, ounces, or miles. Your assignment will be to convert these and solve in the SI or BG systems.

The Principle of Dimensional Homogeneity

In engineering and science, *all* equations must be *dimensionally homogeneous,* that is, each additive term in an equation must have the same dimensions. For example, take Bernoulli's incompressible equation, to be studied and used throughout this text:

$$p + \frac{1}{2}\rho V^2 + \rho g Z = \text{constant}$$

Each and every term in this equation *must* have dimensions of pressure $\{ML^{-1}T^{-2}\}$. We will examine the dimensional homogeneity of this equation in detail in Example 1.3.