GLOBAL EDITION

Fluid Mechanics

for Engineers in SI Units

David A. Chin

Pearson

FLUID MECHANICS
FOR ENGINEERS
IN SI UNITS

DAVID A. CHIN
University of Miami

Pearson

330 Hudson Street, NY, NY 10013

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Authorized adaptation from the United States edition, entitled Fluid Mechanics for Engineers, First Edition, ISBN 978-0-13-380312-9, by David A. Chin, published by Pearson Education © 2017.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

10 9 8 7 6 5 4 3 2 1

Typeset by GEX Publishing Services
Printed and bound in Malaysia

ISBN 10: 1-292-16104-3
ISBN 13: 978-1-292-16104-4

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To Stephanie and Andrew.

"Wherever there is a human being, there is an opportunity for a kindness."

Seneca

Contents

Preface

Beginning with my formative years as a graduate student at Caltech and Georgia Tech, I have applied fluid mechanics in the context of many engineering disciplines. Also, having taken all of the graduate-level fluid mechanics courses in mechanical engineering, aerospace engineering, civil engineering, and geophysics, and having taught fluid mechanics for more than 30 years, I felt well qualified and motivated to author a fluid mechanics textbook for engineering students. The unique features of this textbook are that it: (1) focuses on the basic principles of fluid mechanics that engineering students are likely to apply in their subsequent required undergraduate coursework, (2) presents the material in a rigorous fashion, and (3) provides many quantitative examples and illustrations of fluid mechanics applications. Students in all engineering disciplines where fluid mechanics is a core course should find this textbook stimulating and useful. In some chapters, the nature of the material necessitates a bias towards practical applications in certain engineering disciplines, and the disciplinary area of the author also contributes to the selection and presentation of practical examples throughout the text. In this latter respect, practical examples related to civil engineering applications are particularly prevalent. To help students learn the material, interactive instruction, tutoring, and practice questions on selected topics are provided via Pearson Mastering Engineering$^{\text{TM}}$.

The content of a first course in fluid mechanics. This is a textbook for a first course in fluid mechanics taken by engineering students. The prerequisites for a course using this textbook are courses in calculus through differential equations, and a course in engineering statics. Additional preparatory coursework in rigid-body dynamics and thermodynamics are useful, but not essential. The content of a first course in fluid mechanics for engineers depends on the the curricula of the students taking the course and the interests of the instructor. For most first courses in fluid mechanics, the following topics are deemed essential: properties of fluids (Chapter 1), fluid statics (Chapter 2), kinematics and streamline dynamics (Chapter 3), finite-control-volume analysis (Chapter 4), dimensional analysis and similitude (Chapter 6), and flow in closed conduits (Chapter 7). Additional topics that are sometimes covered include: differential analysis (Chapter 5), turbomachines (Chapter 8), flow in open channels (Chapter 9), drag and lift (Chapter 10), boundary-layer flow (Chapter 11), and compressible flow (Chapter 12). The topics covered in this textbook are sequenced such that the essential topics are covered first, followed by the elective topics. The only exception to this rule is that the chapter on differential analysis (Chapter 5) is placed within the sequence of essential material, after the chapter on control-volume analysis (Chapter 4). This is done for pedagogical reasons since, if differential analysis is to be covered, this topic should be covered immediately after control-volume analysis. If an instructor chooses to omit differential analysis and move directly from control-volume analysis to any of the other essential or elective topics, then the book is designed such that there will be no loss of continuity and students will not suffer from not having covered differential analysis. However, coverage of boundary-layer flow is facilitated by first covering differential analysis. Some of the considerations to be taken into account in selecting elective topics to be covered in a first course in fluid mechanics are given below.

Turbomachines. Coverage of turbomachines is sometimes considered as a mandatory component of a first course in fluid mechanics, and this is particularly true in civil, environmental, and mechanical engineering curricula. Pumps are an integral component of many closed-conduit systems, and turbines are widely used to extract energy from flowing fluids such as water and wind. The essentials of (turbo-)pumps and turbines are covered. Useful topics that are related to pumps include identifying the type of pump that would be most efficient for any given application, and using performance curves to determine the operating point of a pump in a pipeline system. Important topics covered that are related to turbines include identifying the type of hydraulic turbine that would be most efficient in extracting hydropower for any given site condition, and estimating the energy that could be extracted based on given turbine specifications.

Open-channel flow. Open-channel flow is an essential subject area in civil and environmental engineering curricula. However, in these curricula, the subject of open-channel flow is not always covered in a first course in fluid mechanics, being frequently covered in a subsequent course on water-resources engineering. Students in mechanical engineering and related academic programs are less likely to be exposed to open-channel flow in subsequent coursework, and so introductory coverage of this material in a first course in fluid mechanics might be desirable. A feature of this textbook is that it covers the fundamentals of open-channel flow with sufficient rigor and depth that civil and environmental engineering students taking a follow-on course in water resources engineering would have sufficient preparation that they need not be re-taught the fundamentals of open-channel flow. Students in other disciplines, particulary in mechanical engineering, would be have sufficient background to solve a variety of open-channel flow problems from first principles.

Boundary-layer flow, drag, and lift. An understanding of boundary-layer flow is a prerequisite for covering the essential topics of drag and lift. However, there are many aspects of boundary-layer flow that are not directly relevant to understanding drag and lift, and detailed coverage of boundary-layer flow in advance of drag and lift could divert attention from the practical applications of drag and lift. Consequently, the essential elements of boundary-layer flow are presented in an abbreviated form in the chapter on drag and lift (Chapter 10), with much more detailed coverage of boundary-layer flow presented in the subsequent dedicated chapter (Chapter 11). This arrangement of topics facilitates choosing to cover drag and lift, but not to cover boundary-layer flows in detail in a first course in fluid mechanics. Using such an approach, Chapter 10 would be covered, Chapter 11 would be an elective chapter, and there is no discontinuity in the presentation of the material.

Compressible flow. The treatment of compressible flow in this textbook takes a step into the modern era by ceasing reliance on compressible-flow curves and compressible-flow tables, sometimes called gas tables, which have been a staple of the treatment of compressible flow in other elementary fluid mechanics texts. The rule that one should not read a number from a graph or read a number from a table when one knows the analytic equation from which the graph or table is derived is followed in this text. The practice of reading compressible-flow variables from graphs and tables is an approximate approach originated in an earlier era when the solution of implicit equations were problematic. With modern engineering calculation software, such as Excel and MATLAB®, solution of implicit equations are more easily and accurately done numerically on a personal computer.

Philosophy. A first course in fluid mechanics must necessarily emphasize the fundamentals of the field. These fundamentals include fluid properties, fluid statics, basic concepts of fluid flow, and the forms of the governing equations that are useful in solving practical problems. To assist students in solving practical problems, the most useful relationships are highlighted (shaded in blue) in the text, and the key equations in each chapter are listed at the end of the chapter. In engineering curricula, fluid mechanics is regarded as an engineering science that lays the foundation for more applied courses. Consequently, fundamentals of fluid mechanics that are not likely to be applied in subsequent courses taken by undergraduate engineering students are not normally covered in a first course in fluid mechanics. This philosophy has been adopted in designing the content of this textbook. For graduate students requiring more specialized knowledge of fluid mechanics, such as conformal mapping applications in ideal flow, geophysical fluid dynamics, turbulence theory, and advanced computational methods in fluid dynamics, a second course in fluid mechanics would be required. Notwithstanding the needs of graduate students specializing in areas closely related to pure fluid mechanics, this textbook provides the fundamentals of fluid mechanics with sufficient rigor that advanced courses in fluid mechanics need only build on the content of this book and need not reteach this material.

David A. Chin, Ph.D., P.E.
Professor of Civil and Environmental Engineering
University of Miami

Resources for Instructors and Students

- Pearson Mastering Engineering. This online tutorial homework program, www.masteringengineering.com, is available with *Fluid Mechanics for Engineers in SI Units*. It provides instructors customizable, easy-to-assign, and automatically graded homework and assessments, plus a powerful gradebook for tracking student and class performance. Tutorial homework problems emulate the instructor's office-hour environment. These in-depth tutorial homework problems are designed to coach students with feedback specific to their errors and optional hints that break problems down into simpler steps. This digital solution comes with Pearson eText, a complete online version of the book.

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- Presentation Resource. All figures and tables from the textbook are available in PowerPoint format.

- Video Solutions. Provided with Pearson Mastering Engineering, Video Solutions offer step-by-step solution walkthroughs of representative homework problems from sections of the textbook. Make efficient use of class time and office hours by showing students the complete and concise problem solving approaches that they can access anytime and view at their own pace. The videos are designed to be a flexible resource to be used however each instructor and student prefers.

your work...

For pressure of 47.2 kPa, $h = 6$ km

$$V_A = V_p$$

At 6 km, $\rho_a = 0.59\ \text{kg/m}^3$

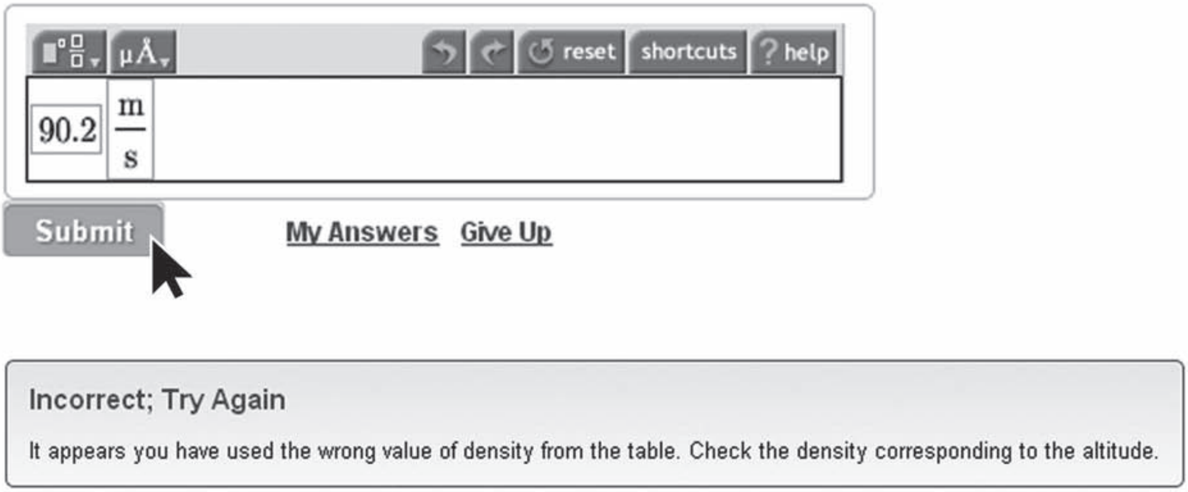
Applying the Bernoulli equation at A and B,

$$\frac{p_A}{\rho} + \frac{V_A^2}{2} + g z_A = \frac{p_B}{\rho} + \frac{V_B^2}{2} + g z_B$$

$$\frac{47.2(10^3)\ \text{N/m}^2}{0.59\ \text{kg/m}^3} + \frac{V_p^2}{2} + 0 = \frac{49.6(10^3)\ \text{N/m}^2}{0.59\ \text{kg/m}^3} + 0 + 0$$

$$V_p = \underline{90.2\ \text{m/s}}$$

your answer specific feedback



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Acknowledgements

Pearson would like to thank and acknowledge the following for their contributions to the Global Edition.

Contributors

Rakesh Kumar Dhingra, Sharda University
Basant Singh Sikarwar, Amity University

Reviewers

Kanchan Chatterjee, Dr. B. C. Roy Engineering College
Rakesh Kumar Dhingra, Sharda University
Vibha Maru
Vipin Sharma, Delhi Technological University

Chapter 1

Properties of Fluids

LEARNING OBJECTIVES

After reading this chapter and solving a representative sample of end-of-chapter problems, you will be able to:

- Identify the characteristics of a fluid and describe the fundamental differences between solids, liquids, and gases.
- Understand dimensional homogeneity, fundamental dimensions, and systems of units.
- Understand the constitutive relationships and fluid properties relevant to engineering applications.
- Identify and readily quantify the key properties of water and air.

1.1 Introduction

Fluid mechanics is the study of the behavior of liquids and gases. The study of fluids at rest is called *fluid statics*, and the study of fluids in motion is called *fluid dynamics*. Applications of fluid mechanics are found in a variety of engineering disciplines. Aerospace engineering applications include the design of aircraft, aerospace vehicles, rockets, missiles, and propulsion systems. Biomedical applications include the study of blood flow and breathing. Civil engineering applications include the design of conveyance structures, dams, water-supply systems, oil and gas pipelines, wastewater processing systems, irrigation systems, and the determination of wind loads on buildings. Mechanical engineering applications include the design of plumbing systems, heating ventilation and air conditioning systems, lubrication systems, process-control systems, pumps, fans, turbines, and engines. Naval architecture applications include the design of ships and submarines. Aside from engineering applications of fluid mechanics, the earth sciences of hydrology, meteorology, and oceanography are based largely on the principles of fluid mechanics. A wide variety of fluid mechanics applications are apparent across many disciplines. However, the fundamentals of fluid mechanics that form the bases of these applications are relatively few, and the intent of this book is to cover these fundamentals.

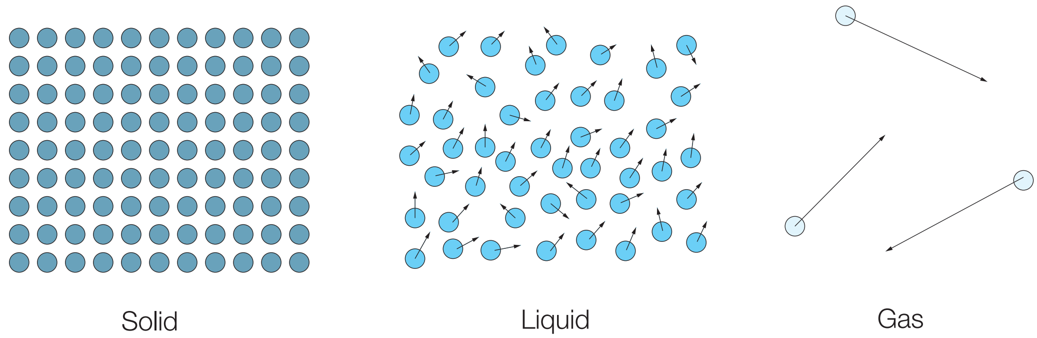

Figure 1.1: Molecular-scale views of solid, liquid, and gas

States of matter. The three states of matter commonly encountered in engineering are *solid*, *liquid*, and *gas*. Liquids and gases are both classified as fluids, and microscopic (molecular-scale) views of a solid, liquid, and gas are illustrated in Figure 1.1. Individual molecules (or atoms) in a solid are held together by relatively strong forces, and the molecules can only vibrate around an average position without any net movement. In contrast, the molecules in a liquid move relatively slowly past one another, and gas molecules move freely and at high speeds. In terms of the arrangement of molecules within the different phases of matter, in solids the molecules are closely packed in a regular pattern, in liquids the molecules are close together but do not have a fixed position relative to each other, and in gases the molecules are relatively far apart and move about independently of each other. Liquids and solids are sometimes referred to as *condensed-phase* matter because of the close spacing of their molecules.

Mechanical behavior of fluids. From a behavioral viewpoint, fluids are differentiated from solids by how they respond to applied stresses. Consider the volume of a substance acted upon by surface stresses as shown in Figure 1.2. The surface stresses can be expressed in terms of components that are normal and tangential to the surface of the specified volume; these components are called the *normal stress* and *shear stress* components, respectively. The normal stress causes the substance within the volume to compress (or expand) by a certain fixed amount, regardless of whether the substance is a fluid or a solid. However, a fluid will respond to an applied shear stress differently from a solid. A fluid will deform continuously under the action of an applied shear stress, whereas a solid will deform only

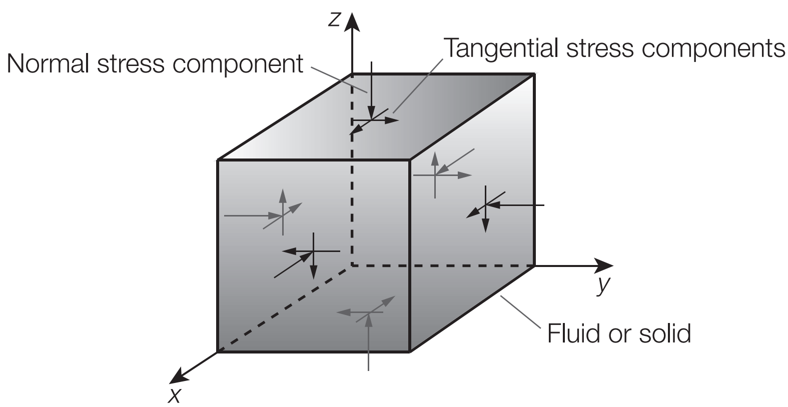

Figure 1.2: Surface stress components on a substance

by a finite fixed amount under the action of an applied shear stress. Continuous deformation under an applied shear stress is the property that differentiates a fluid from a solid. In fact, continuous deformation under the action of a shear stress is the defining behavior of a fluid.

Hybrid materials. Some materials are unusual in that they behave like a solid under some conditions and like a fluid under other conditions. Typically, these materials are solid-like when applied shear stresses are small and fluid-like when applied shear stresses are high. Examples include slurries, asphalt, and tar. The study of these types of hybrid materials is called *rheology*, which is often considered to be a field separate from fluid mechanics. In some cases, liquids and gases coexist, such as water containing air bubbles and water-steam mixtures. The flows of these mixtures are commonly called *multiphase flows*, and the study of these flows is a specialized area of fluid mechanics.

Physical differences between liquids, gases, and vapors. Liquids and gases are both fluids but with primary physical differences—a gas will expand to completely fill the volume of any closed container in which it is placed, whereas a liquid will retain a relatively constant volume within any container in which it is placed. This difference in behavior is caused by the relatively strong cohesive forces between molecules in a liquid, which tend to hold them together, compared with the weak forces between molecules in a gas, which allow them to move relatively independently of each other. Liquids will generally form a free surface in a gravitational field if unconfined from above. A *vapor* is a gas whose temperature and pressure are such that it is very near the liquid phase. Thus, steam is considered to be a vapor because its state is normally not far from that of water, whereas air is considered to be a gas because the states of its gaseous components are normally very far from the liquid phase.

Continuum approximation. Fluids as well as solids are made up of discrete molecules, and yet it is commonplace to disregard the discrete molecular nature of a fluid and view it as a continuum. The *continuum idealization* allows us to treat fluid properties as varying continually in space with no discontinuities. This idealization is valid as long as the size of the fluid volume is large compared to the space between molecules in the fluid. Under normal temperatures and pressures, the spacing of molecules in a fluid is on the order of 10^{-6} mm for gases and 10^{-7} mm for liquids. Hence, the continuum model is applicable as long as the characteristic length scale of the fluid volume is much larger than the characteristic spacing between molecules. The continuum approximation is sometimes considered applicable for volumes as small as 10^{-9} mm^3. It is interesting to note that the spacing between molecules in a liquid is not much different from the spacing between molecules in a solid. However, the molecules in liquids are less restrained in their ability to move relative to each other. In the case of gases, the characteristic spacing between molecules is sometimes measured by the *mean free path* of the molecules, which is the average distance traveled by a molecule between collisions. Under standard atmospheric conditions, the mean free path of molecules in air is on the order of 6.4×10^{-5} mm. At very high vacuums or at very high elevations, the mean free path may become large; for example, it is about 10 cm for atmospheric air at an elevation of 100 km and about 50 m at an elevation of 160 km. Under these circumstances, *rarefied gas flow theory* should be used and the impact of individual molecules should be considered.

1.1.1 Nomenclature

Fluid mechanics can be divided into three branches: statics, kinematics, and dynamics. *Fluid statics* is the study of the mechanics of fluids at rest, *kinematics* is the study of the geometry of fluid motion, and *fluid dynamics* is the study of the relationship between fluid motion and the forces acting on the fluid. Fluid dynamics is further divided into several specialty areas.

The study of fluid dynamics when the fluid is incompressible and frictionless is called *hydrodynamics*. Fluids that are incompressible and frictionless are called *ideal fluids*. In contrast to ideal fluids, real fluids have some degree of compressibility and internal friction. The study of liquid flows in pipes and open channels is sometimes called *hydraulics*, a term that some civil engineers associate with the description of flow based on empirical relationships rather than the fundamental physical laws on which fluid mechanics is based. *Gas dynamics* deals with the flow of fluids that undergo significant density changes, such as the flow of gases through nozzles at high speeds, and *aerodynamics* deals with the flow of gases (especially air) over bodies such as aircraft, rockets, and automobiles at high or low speeds.

Computational fluid mechanics. In many cases, the governing equations of fluid mechanics cannot be solved analytically, and numerical methods are used to determine the flow conditions at selected locations in the flow domain. The application of numerical methods to solve the governing equations of fluid mechanics is called *computational fluid mechanics*. Such applications are endemic to the field of aerospace engineering, although these techniques are also used for advanced applications in other engineering disciplines.

1.1.2 Dimensions and Units

Dimensions are physical measures by which variables are expressed, and examples of dimensions are mass, length, and time. *Units* are names assigned to dimensions, and examples of units are the kilogram (a unit of mass) and the meter (a unit of length). The seven fundamental dimensions in nature and their base units in the *Système International d'Unités (SI system)* are listed in Table 1.1. Additional units that are sometimes taken as fundamental are the unit of a plane angle (radian, rad), and the unit of a solid angle (steradian, sr). However, these units are properly classified as derived units in the SI system. The SI system of units is an *absolute system of units*, because it does not involve a fundamental dimension of force, which is a gravity effect.

Gravitational units. A *gravitational system of units* uses force as a fundamental dimension. The dimensions of force, mass, length, and time are related by Newton's law, which states that

$$F = ma \tag{1.1}$$

where a force F causes a mass m to accelerate at a rate a. In a gravitational system, F and m are not independent dimensions and the relationship between F and m is fixed by specifying the numerical value of a, which is commonly taken as unity in defining fundamental dimensions. A gravitational system in common use in the United States is the *U.S. Customary*

Table 1.1: Fundamental Dimensions and Units

Dimension	SI Unit	Symbol	USCS Unit	Symbol
Mass	kilogram	kg	–	–
Force	–	–	pound	lb
Length	meter[1]	m	foot	ft
Time	second	s	second	sec
Temperature	kelvin	K	rankine	°R
Electric current	ampere	A	ampere	A
Luminous intensity	candela	cd	candela	cd
Amount of substance	mole	mol	mole	mol

[1]The official spelling is "metre." In the United States, "meter" is used.

System (USCS) in which the fundamental dimension of force has a unit of pound (lb). The fundamental dimensions of the USCS are listed in Table 1.1 along with those of the SI system.

Dimensions in fluid mechanics applications. In fluid mechanics applications, the SI fundamental dimensions that are generally used include mass [M], length [L], time [T], temperature [Θ], and amount of substance [mol]. In the USCS system, force [F] replaces mass [M] as a fundamental dimension. Fundamental dimensions are sometimes referred to as *primary dimensions*, with dimensions derived from combinations of primary dimensions being referred to as *secondary dimensions*. In this text, square brackets are used to illustrate the dimensions of a given variable. For example, the statement "v is the velocity [LT^{-1}]" means that the velocity denoted by v has dimensions of length divided by time.

Dimensional homogeneity. All equations derived from fundamental physical laws must be *dimensionally homogeneous*. If an equation is dimensionally homogeneous, then all terms in a summation must have the same dimensions, which also means that terms on both sides of an equal sign must have the same dimensions.

EXAMPLE 1.1

Application of Newton's second law to the settling of a spherical particle in a stagnant fluid yields the theoretical relationship

$$mg - \frac{\pi}{8}C_\text{D}\rho V^2 D^2 = m\frac{\text{d}V}{\text{d}t}$$

where m is the mass of the particle [M], g is the acceleration due to gravity [LT^{-2}], C_D is a (dimensionless) drag coefficient [-], ρ is the density of the fluid [ML^{-3}], V is the settling velocity [LT^{-1}], and t is time [T]. Determine whether the given equation is dimensionally homogeneous.

SOLUTION

Expressing the variables in the given equation in terms of their dimensions yields

$$mg - \frac{\pi}{8}C_\text{D}\rho V^2 D^2 = m\frac{\text{d}V}{\text{d}t} \quad \rightarrow \quad [\text{M}]\left[\frac{\text{L}}{\text{T}^2}\right] - [\text{-}]\left[\frac{\text{M}}{\text{L}^3}\right]\left[\frac{\text{L}}{\text{T}}\right]^2[\text{L}]^2 = [\text{M}]\frac{\left[\frac{\text{L}}{\text{T}}\right]}{[\text{T}]}$$

$$\rightarrow \quad \frac{\text{ML}}{\text{T}^2} + \frac{\text{ML}}{\text{T}^2} = \frac{\text{ML}}{\text{T}^2}$$

Because each term in the given equation has the same dimensions, the equation is dimensionally homogeneous.

The requirement of dimensional homogeneity is particularly useful in checking the derivation of equations obtained by algebraic manipulation of other dimensionally homogeneous equations. This is because any equation derived from a set of dimensionally homogeneous equations must itself be dimensionally homogeneous.

Table 1.2: SI Derived Units

Unit Name	Quantity	Symbol	In Terms of Base Units
degree Celsius	temperature	°C	K
hectare	area	ha	10^4 m^2
hertz	frequency	Hz	s^{-1}
joule	energy, work, quantity of heat	J	N·m
liter	volume	L	10^{-3} m^3
watt	power	W	J/s
newton	force	N	kg·m/s^2
pascal	pressure, stress	Pa	N/m^2

SI Units. Some key conventions in the SI systems that are relevant to fluid mechanics applications are given below.

- In addition to the base SI units, a wide variety of units derived from the base SI units are also used. A few commonly used derived units are listed in Table 1.2.

- When units are named after people, such as the newton (N), joule (J), and pascal (Pa), they are capitalized when abbreviated but not capitalized when spelled out. The abbreviation capital L for liter is a special case, used to avoid confusion with one (1).

- In accordance with Newton's law (Equation 1.1), 1 N is defined as the force required to accelerate a mass of 1 kg at 1 m/s^2; hence,

$$1\ \text{N} = 1\ \text{kg} \times 1\ \text{m/s}^2$$

- A nonstandard derived unit of force that is commonly used in Europe is the *kilogram force* (kgf), where 1 kgf is the gravitational force on a 1 kg mass, where the gravitational acceleration is equal to the standard value of 9.80665 m/s^2; therefore, 1 kgf = 9.80665 N. It is not uncommon in Europe to see tire pressures quoted in the nonstandard unit of kgf/cm^2. It is also common in Europe to express weights in *kilos*, where 1 kilo = 1 kgf.

- The unit of absolute temperature is the kelvin,[1] which is abbreviated K without the degree symbol. In engineering practice, the degree Celsius (°C) is widely used in lieu of the kelvin and the relationship between these temperature scales is given by

$$T_\text{K} = T_\text{C} + 273.15 \tag{1.2}$$

  where T_K and T_C are the temperatures in kelvins and degrees Celsius, respectively. Note that 1 K = 1°C, and an ideal gas theoretically has zero energy when the temperature is equal to 0 K. The reference quantity 273.15 K in Equation 1.2 is exactly 0.01 K below the triple point of water.

- The units of second, minute, hour, day, and year are correctly abbreviated as s, min, h, d, and y, respectively.

[1]Named in honor of the Irish and British physicist and engineer William Thomson (also known as The Lord Kelvin) (1824–1907).

Table 1.3: Prefixes to SI Units

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p

- In using prefixes with SI units, multiples of 10^3 are preferred in engineering usage, with other multiples avoided if possible. Standard prefixes and their associated symbols are given in Table 1.3. Note that the prefix "centi," as in *centimeter*, is not a preferred prefix because it does not involve a multiple of 10^3. Unit prefixes are typically utilized when the magnitude of a quantity is more than 1000 or less than 0.1. For example, 2100 Pa can be expressed as 2.1 kPa and 0.005 m as 5 mm.

USCS Units. USCS units are sometimes called *English units*, *Imperial units*, or *British Gravitational units*. Some key conventions in the USCS system that are relevant to fluid mechanics applications are given below.

- The USCS system is a gravitational system of units in which the unit of length is the foot (ft), the unit of force is the pound (lb), the unit of time is the second (s), and the unit of temperature is the degree Rankine[2] (°R). In engineering practice, the degree Fahrenheit (°F) is widely used in lieu of the degree Rankine and the relationship between these temperature scales is given by

$$T_\mathrm{R} = T_\mathrm{F} + 459.67 \tag{1.3}$$

  where T_R and T_F are the temperatures in degrees Rankine and degrees Fahrenheit, respectively. Note that $1°\mathrm{R} = 1°\mathrm{F}$, and an ideal gas theoretically has zero energy when the temperature is equal to $0°\mathrm{R}$.

- Other fundamental units that are not usually encountered in fluid mechanics applications are the same for the USCS and SI systems, specifically the units of electric current (ampere, A), luminous intensity (candela, cd), and amount of substance (mole, mol).

- In the USCS system, the unit of mass is the slug, which is a derived unit from the fundamental unit of force, which is the pound. The slug is defined as the mass that accelerates at 1 ft/sec^2 when acted upon by a force of 1 pound; hence,

$$1 \text{ slug} = \frac{1 \text{ lb}}{1 \text{ ft/sec}^2}$$

- The abbreviation for pound is sometimes equivalently expressed as "lbf" rather than "lb" to emphasize that the pound is a unit of force (1 lb = 1 lbf). The pound force (lbf) in the USCS system is a comparable quantity to the newton (N) in the SI system, where 1 lbf $\approx$ 4.448 N.

- The USCS units of second, minute, hour, day, and year are correctly abbreviated as sec, min, hr, day, and yr, respectively. However, it is not uncommon to use the SI abbreviations (s, min, h, d, and y, respectively) when otherwise using USCS units.

[2]Named in honor of the Scottish physicist and engineer William John Macquorn Rankine (1820–1872).

English Engineering units. The English Engineering system of units is almost identical to the USCS, with the main differences being that both force and mass are taken as fundamental dimensions in the English Engineering system and the pound mass (lbm) is used as the unit of mass. The relationship between the pound mass (lbm) and the slug is

$$1 \text{ lbm} = 1 \text{ slug} \times 32.174 \text{ ft/sec}^2$$

This relationship is derived from the basic definition that a gravity force of 1 lbf will accelerate a mass of 1 lbm at a rate of 32.174 ft/sec^2, which is the acceleration due to gravity. A mass of 1.0000 slug is equivalent to 32.174 lbm.

Conversion between units. It is generally recommended that engineers have a sense of the conversion factors from one system of units to another, especially for the most commonly encountered dimensions and units. Such conversion factors can be found in Appendix A.2. Some fields of engineering commonly use mixed units, where some quantities are traditionally expressed in USCS units and other quantities are traditionally expressed in SI units. A case in point is in applications related to the analysis and design of air-handling units, where airflow rates are commonly expressed in CFM (= ft^3/min) and power requirements are expressed in kW. When mixed units are encountered in a problem, it is generally recommended to convert all variables to a single system of units before beginning to solve the problem. This text uses SI units.

Conventions and constants. In cases where large numbers are given, it is common practice not to use commas, because in some countries, a comma is interpreted as a decimal point. A recommended practice is to leave a space where the comma would be; for example, use 25 000 instead of 25,000. Acceleration due to gravity, g, is used in the analysis of many fluid flows, and by international agreement, standard gravity, g, at sea level is 9.80665 m/s^2. Actual variation in g on Earth's surface is relatively small and is usually neglected. To illustrate the variability, g is approximately equal to 9.77 m/s^2 on the top of Mount Everest and is approximately 9.83 m/s^2 at the deepest point in Earth's oceans; hence, the deviation is less than 0.4% from standard gravity. It is sometimes convenient to represent the units of g as N/kg rather than m/s^2, particularly in dimensional analysis applications. In analyzing fluid behavior, reference is commonly made to *standard temperature and pressure*. By convention, standard temperature is 15°C and standard pressure is 101.3 kPa. These standard conditions roughly represent average atmospheric conditions at sea level at 40° latitude.

Physical appreciation of magnitudes. In engineering applications, it is important to have a physical appreciation of the magnitudes of quantities, at least to make an assessment of whether calculated results and designs are physically realistic. With this in mind, the following approximate relationships between SI units and USCS units might be helpful.

- FORCE: A force of 1 N is roughly equal to $\frac{1}{4}$ lb, which is approximately the weight of a small apple. A weight of 1 lb is roughly equal to 4 N. In many cases, force units of kilonewtons are more appropriate.

- PRESSURE: A pressure of 1 Pa is roughly equal to 10^{-4} lb/in^2. The pressure unit of pascal (Pa) is too small for most pressures encountered in engineering applications. Units of kilopascal or megapascal are usually more appropriate, where 1 kPa $\approx$ 0.1 lb/in^2 and 1 MPa $\approx$ 100 lb/in^2. The pressure unit of "atmosphere" (atm) is a convenient unit in many applications, because 1 atm is equal to standard atmospheric pressure at sea level (= 101.3 kPa). Pressure units of atm, bar, and kgf/cm^2 are approximately equal because 1 atm $\approx$ 1.01 bar $\approx$ 1.03 kgf/cm^2.

- VOLUME: A volume of 1 m^3 is roughly equal to 35 ft^3. The unit of m^3 is quite large for some applications. Units of liters (L), where 1 L = 0.001 m^3, are frequently used when dealing with smaller volumes. A volume of 1 L is roughly equal to $\frac{1}{4}$ gal, and 1 L is approximately equal to 1 quart.

- VOLUME FLOW RATE: The conventional SI unit of (volume) flow rate is m^3/s, the conventional USCS unit of flow rate is ft^3/s (cfs), and 1 m^3/s $\approx$ 35 cfs. These conventional units are used to represent fairly large flows such as those found in rivers and streams. Smaller flow rates such as airflow rates in building ventilation systems are typically expressed in ft^3/min (CFM) or m^3/min, and liquid flow rates in pipelines are commonly expressed in L/min, L/s, or gallons per minute (gpm). Note that 1 m^3/s = 60 000 L/min = 1000 L/s $\approx$ 2120 CFM $\approx$ 15 850 gpm.

Consideration of significant digits. The number of significant digits in a number reflects the accuracy of the number. Because the last significant digit in a number is regarded as uncertain (± 1), numbers with one significant digit can have a maximum error of 100%, numbers with two significant digits can have a maximum error of 10%, numbers with three significant digits can have a maximum error of 1%, and so on. In engineering applications, measured numbers seldom have accuracies greater than 0.1%, and such numbers are represented by no more than four significant digits. In performing calculations, one cannot arrive at a result that is more accurate (in terms of percentage error) than the numbers used in calculations to arrive at that number; hence, the final result of calculations cannot have more significant digits than the numbers used in calculating that result. The following three rules are useful: (1) For multiplication and division, the number of significant digits in the calculated result is equal to the number of significant digits in the least accurate number used in the calculation; (2) for addition and subtraction, the number of significant decimal places in the result equal that of the least number of significant decimal places in the added/subtracted numbers; and (3) where multiple operations are involved, extra (nonsignificant) digits in the intermediate calculations are retained and the final result is rounded to the appropriate number of significant digits based on the accuracy of the numbers used in the calculations. Because the solution of most problems in fluid mechanics involves multiple operations, retaining nonsignificant digits in intermediate quantities and rounding the final result to the appropriate number of significant digits is the most common practice.

EXAMPLE 1.2

(a) In the analysis of building ventilation, airflows are commonly expressed in units of ft^3/min or CFM. If the fresh airflow into a particular building space is 800 CFM, what is the airflow rate in m^3/s? (b) A relationship between the energy per unit weight, h_p, added by a pump and the flow rate, Q, through the pump is given by

$$h_\mathrm{p} = 22.3 + 7.54 \times 10^5 Q^2 \tag{1.4}$$

where h_p is in N·m/N or m and Q is in m^3/s. What is the equivalent relationship if h_p is expressed in ft and Q in gallons per minute (gpm)?

SOLUTION

Commonly used conversion factors are found in Appendix A.2. The basic conversion factors to be used here are 1 ft = 0.3048 m, 1 min = 60 s, and 1 (US) gal = 3.785 L = 3.785×10^{-3} m^3.

(a) Using the basic conversion factors,

$$800 \text{ ft}^3/\text{min} = 800\frac{\text{ft}^3}{\text{min}} \times 0.3048^3\frac{\text{m}^3}{\text{ft}^3} \times \frac{1}{60}\frac{\text{min}}{\text{s}} = 0.3775 \text{ m}^3/\text{s} \approx \mathbf{0.378 \text{ m}^3/\text{s}}$$

In general, a converted quantity should have approximately the same accuracy as that of the original quantity. Therefore, the number of significant digits in the converted quantity should be the same in the converted and original quantities. Intermediate conversion calculations and conversion factors must be at least as accurate as the quantity being converted.

(b) Using the basic conversion factors,

$$1.00 \text{ m}^3/\text{s} = 1.00\frac{\text{m}^3}{\text{s}} \times \frac{1}{3.785 \times 10^{-3}}\frac{\text{gal}}{\text{m}^3} \times 60\frac{\text{s}}{\text{min}} = 1.585 \times 10^4 \text{ gpm}$$

This gives the conversion factor for m^3/s to gpm. Applying this conversion factor along with 1 ft = 0.3048 m to the given empirical equation, where h_p is in ft and Q is in gpm, gives the following equivalent equation in the modified units:

$$(0.3048\,h_\text{p}) = 22.3 + 7.54 \times 10^5\left(\frac{Q}{1.585 \times 10^4}\right)^2 \quad \rightarrow \quad \boldsymbol{h_\text{p} = 73.2 + 9.85 \times 10^{-3}Q^2} \tag{1.5}$$

Therefore, Equations 1.4 and 1.5 are equivalent, with the exception that h_p and Q in Equation 1.4 are in m and m^3/s, respectively, whereas in Equation 1.5, h_p and Q are in ft and gpm, respectively. The coefficients in both equations have the same number of significant digits and therefore yield results of comparable accuracy.

1.1.3 Basic Concepts of Fluid Flow

Fluid flows are influenced by a variety of forces, with the dominant forces usually including pressure forces, gravity forces, and drag forces caused by fluid motion relative to solid boundaries. Whenever a moving fluid is in contact with a solid surface, the velocity of the fluid in contact with the solid surface must necessarily be equal to the velocity at which the solid surface is moving. This is called the *no-slip condition*, and the region within the fluid close to a solid surface where the velocity of the fluid is affected by the no-slip condition is called the *boundary layer*. Viscosity is the fluid property that causes the formation of a boundary layer. Although all fluid flows bounded by solid surfaces have boundary layers, in some cases, there are (outer) regions of the flow field where the viscosity of the fluid exerts a negligible influence on the fluid motion. Such flows are called *inviscid flows*, where the word “inviscid" means “without viscosity." In addition to the no-slip condition at a solid boundary, there also exists a *no-temperature-jump condition*. This requires the temperature of the fluid in contact with a solid boundary to be equal to the temperature of the boundary itself.

Classification of fluid flows. Classification of fluid flows is the conventional approach to simplifying the analysis fluid flows. Flows within various classifications are typically characterized by the unimportance of some forces, which leads to simplifications in the governing equations. A variety of flow classifications are of importance in engineering analyses. A fluid flow can be classified as a *viscous flow* when the viscosity of the fluid exerts a significant influence on the flow and as *inviscid flow* when the viscosity has a negligible influence on the flow. A fluid flow can be classified as *laminar flow* when random perturbations in velocity do not occur and as *turbulent flow* when random perturbations in the velocity field do occur. A fluid flow can be classified as an *internal flow* when the flow is confined within solid boundaries and as an *external flow* when the flow is unconfined around a solid object. Examples of internal flows are flows in pipes and ducts, and examples of external flows are flows around buildings and the wings of airplanes (i.e., airfoils). Internal flows are dominated by the influence of viscosity throughout the flow field, whereas in external flows, the viscous effects are limited to boundary layers near solid surfaces and to wake regions downstream of bodies. A fluid flow is classified as *incompressible flow* when the density of the fluid remains approximately constant throughout the flow field. The fluid flow is classified as *compressible flow* when the density of the fluid within the flow field varies significantly in response to pressure variations. Liquid flows and gas flows at speeds much less than the speed of sound are typically taken as incompressible flows. The classification of fluid flows, implementation of simplifications, and derivation of consequent relationships that are useful in analysis and design is the tact followed in this text on applied fluid mechanics.

Role of fluid properties. The behavior of a fluid depends on its properties, and in a fluid mechanical sense, fluids only differ from each other to the extent their properties are different. The physical properties of fluids that are important in most engineering applications include density, viscosity, compressibility, surface tension, saturation vapor pressure, and latent heat of vaporization. These properties as well as others are commonly referred to as *thermodynamic properties*, because they are used in quantifying the heat content of fluids and the conversion of energy between different forms. Fluids can be either liquids or gases, and fluid properties are sometimes given under conditions referred to as *standard temperature and pressure* (STP). For air, STP is generally taken as 15°C and 101.3 kPa. The definitions of commonly used fluid properties, along with their utilization in various engineering applications, are presented in the following sections.

1.2 Density

The *density* (or *mass density*) of a fluid, ρ, is defined as the mass of fluid per unit volume [ML^{-3}]; hence,

$$\text{density, } \rho = \frac{\text{mass of substance}}{\text{volume of substance}} \tag{1.6}$$

The densities of most gases are directly proportional to pressure and inversely proportional to temperature, whereas the densities of most liquids are relatively insensitive to pressure but depend on temperature. In comparison to gases, liquids are commonly regarded as incompressible. A 1% change in density of water at 101.3 kPa requires a change in pressure of about 21.28 MPa. In contrast, a 1% change in the density of air at 101.3 kPa requires a change in pressure of only 1.01 kPa. Liquids are about three orders of magnitude more dense than gases, with mercury being one of the denser liquids (ρ = 13 580 kg/m^3) and hydrogen being the least dense gas (ρ = 0.0838 kg/m^3).

Density of water and other liquids. At temperatures in the range of 0–100°C and at a standard atmospheric pressure of 101.3 kPa, water exists in the liquid state. The densities of pure water at temperatures between 0°C and 100°C are given in Appendix B.1, and the densities of several other commonly encountered liquids are given in Appendix

B.4. For most liquids, the density decreases monotonically as the temperature increases. However, pure water has the unusual property of the density increasing with temperatures between 0°C and 4°C and then decreasing with temperature higher than 4°C; hence, water has its maximum density at 4°C. This unique property of water explains why when temperatures drop to near freezing (i.e., near 0°C) over a lake or another water body, the colder, less dense water "floats" to the top, causing ice to form from the top down rather than the bottom up as would occur if water had the monotonic density properties of most other liquids, which would lead to the denser, colder water being on the bottom. The density of water as a function of temperature in the ranges of 0–100°C and 0–10°C is illustrated in Figures 1.3(a) and 1.3(b), respectively. It is apparent from these figures that the peak in the density of water is not noticeable on the scale of density variations over the temperature range of 0–100°C, but is readily apparent on the scale of density variations over the temperature range of 0–10°C. An approximate analytic expression (within ±0.2%) for the density of water, ρ_w, at a temperature, T, in the range of 0–100°C is

$$\rho_\mathrm{w} = 1000 - 0.0178\,|T-4|^{1.7} \tag{1.7}$$

where ρ_w is in kg/m^3 and T is in °C. The addition of salt to water increases the density of the water, suppresses the temperature at which the maximum density occurs, and suppresses the freezing point of the water. The effect of salt on suppressing the freezing point of water is utilized when "road salt" is applied to prevent the formation of ice on roads. The effect of salt on increasing the density of water explains why seawater intrudes below fresh water in coastal areas. Seawater is a mixture of pure water and various salts, and the salt content of seawater is commonly measured by the salinity, S, which is defined by

$$\text{salinity, } S = \frac{\text{weight of dissolved salt}}{\text{weight of mixture}} \tag{1.8}$$

The average salinity of seawater is typically taken as 0.035, which is commonly expressed as 35‰, the symbol ‰ meaning "parts per thousand." At this salinity, the average density of seawater is 1030 kg/m^3. The effect of salt content on density is vividly illustrated in Figure 1.4, which shows water with different salt concentrations that have been carefully poured in layers on top of each other. The different layers are identified using a different dye color in each layer. Of course, the salt concentration is lowest in the top layer and highest in the bottom layer.

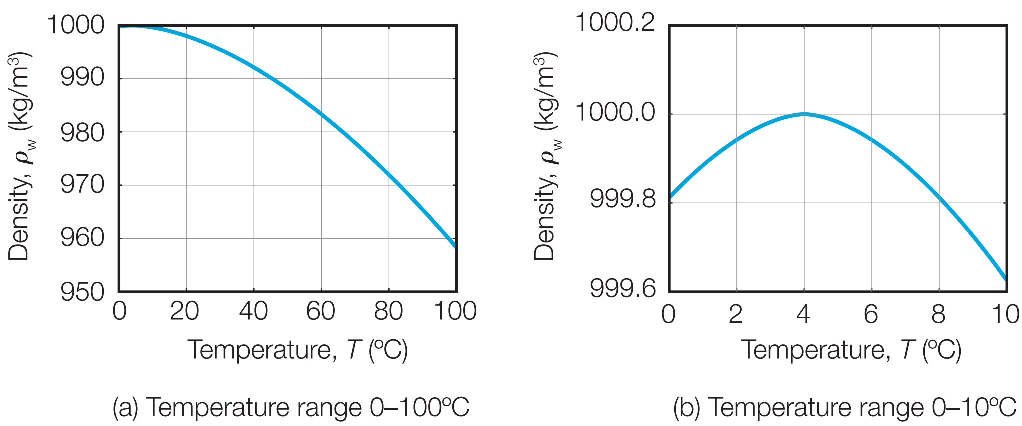

Figure 1.3: Density of water as a function of temperature

Figure 1.4: Layers of water with different salt content
Source: ginton/Fotolia.

Density of air and other gases. Standardized properties of air are commonly used in engineering analyses. By volume, standard (dry) air contains approximately 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide, and small amounts of other gases. Atmospheric air also contains a variable amount of water vapor, with an average volumetric content of around 1%. At the standard atmospheric pressure of 101.3 kPa, the density of standard air at a temperature of 15°C is 1.225 kg/m^3. The density of standard air as a function of temperature at a pressure of 101.3 kPa is given in Appendix B.2. Standard atmospheric pressure (101.3 kPa) is typically used to approximate conditions at sea level. The density of air at elevations above sea level typically decrease with increasing altitude, which is the net result of decreasing pressure and decreasing temperature with altitude. Although the variation of air density with altitude varies with location, the *standard atmosphere* is used in engineering analyses to approximate the variation of air density with altitude. The variation of air density with altitude in a standard atmosphere is given in Appendix B.3. Gases at states far removed from their liquid states are commonly approximated as ideal gases, and the variation of density with temperature and pressure is commonly approximated by the ideal gas law, which is discussed in more detail in Section 1.4. For ready reference, the densities of several gases that are commonly encountered in engineering applications are given in Appendix B.5, where these densities correspond to standard atmospheric pressure and a temperature of 20°C.

Specific weight. The *specific weight* (or *weight density*) of a fluid, γ, is defined as the weight per unit volume and is related to the density by

$$\text{specific weight, } \gamma = \rho g = \frac{\text{weight of substance}}{\text{volume of substance}} \tag{1.9}$$

where g is the acceleration due to gravity, which can be taken as its standard value of 9.80665 m/s^2. As a reference point, at a temperature of 20°C and a pressure of 101.3 kPa, the specific weight of water is 9790 N/m^3 and the specific weight of air is 11.8 N/m^3. Referring to γ as the weight density and ρ as the mass density can be helpful in characterizing the relationship between these two closely related fluid properties.

Specific gravity. The *specific gravity*, SG, of a liquid is defined as the ratio of the density of the liquid to the density of pure water at some specified temperature, usually 4°C. The *specific gravity* is also called the *relative density*, with the latter term being more widely used in the United Kingdom and the former term more widely used in the United States. The definition of the specific gravity (= relative density) is given by

$$\text{specific gravity, SG} = \frac{\rho}{\rho_{\mathrm{H_2O@4^\circ C}}} = \frac{\text{density of liquid}}{\text{density of water at 4°C}} \tag{1.10}$$

where the density of pure water at 4°C is equal to 1000 kg/m^3. In some specialized applications, a reference temperature of 15.56°C is used instead of 4°C, a practice that is particularly common in the petroleum industry. However, because the density of water is 1000 kg/m^3 at 4°C and 999.04 kg/m^3 at 15.56°C, the adjusted reference temperature changes the specific gravity by less than 0.1%. The specific gravity of a gas is the ratio of its density to that of either hydrogen or air at some specified temperature and pressure; there is no general agreement on these standards, and the specific gravity of a gas is a seldom-used quantity. Note that the specific gravity of a substance is a dimensionless quantity. The specific gravities of several substances used in engineering applications are listed in Table 1.4 in decreasing order of magnitude. Not shown in Table 1.4 are the specific gravities of various crude oils, which vary depending on the source. Crude oils in the western United States typically have specific gravities in the range of 0.87–0.92, those in the eastern United States have specific gravities around 0.82, and Mexican crude oil has specific gravities around 0.97. Distillates of oil such as gasolines, kerosenes, and fuel oils have specific gravities in the range of 0.67–0.98.

Specific volume. The *specific volume*, v, is the volume occupied by a unit mass of fluid. It is commonly applied to gases and expressed in m^3/kg. The specific volume is related to the density by

$$\text{specific volume, } v = \frac{1}{\rho} = \frac{\text{volume of substance}}{\text{mass of substance}} \tag{1.11}$$

The specific volume is not a commonly used property in fluid mechanics; it is more commonly used in the field of thermodynamics.

Table 1.4: Typical Specific Gravities of Selected Engineering Materials

Substance*	Specific Gravity (SG)	Substance*	Specific Gravity (SG)
Gold	19.3	Seawater	1.025
Uranium	18.7	**Water**	**0.998**
Mercury	13.6	SAE 10-W motor oil	0.92
Lead	11.4	Dense oak wood	0.93
Copper	8.91	Ice (at 0°C)	0.916
Steel	7.83	Benzene	0.879
Cast iron	7.08	Crude oil	0.87
Aluminum	2.64	Ethyl alcohol	0.790
Concrete (cured)	2.4	Gasoline	0.72
Blood (at 37°C)	1.06	Balsa wood	0.17

*Liquids are at 20°C unless otherwise stated.