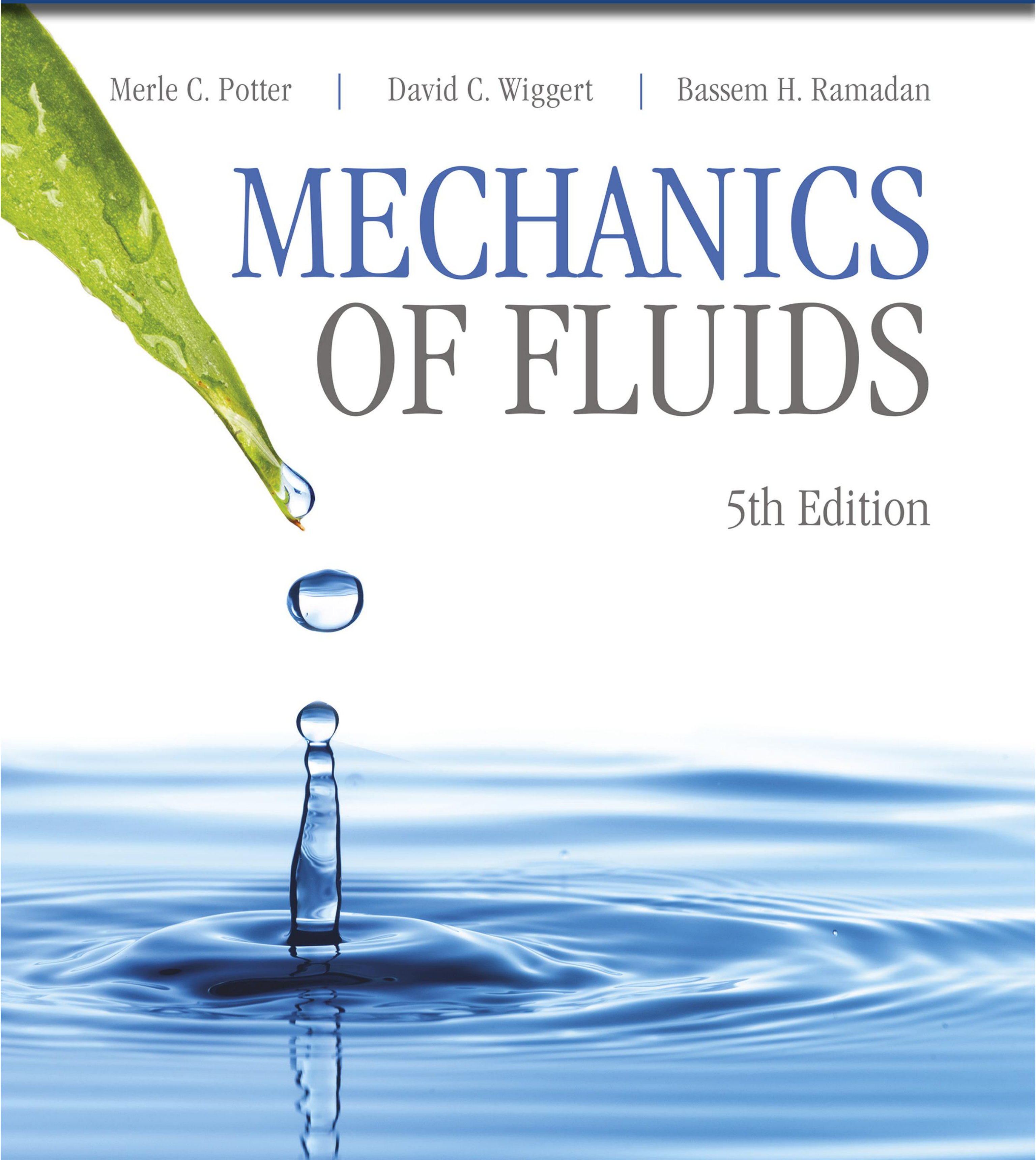
SI EDITION

Merle C. Potter | David C. Wiggert | Bassem H. Ramadan

MECHANICS OF FLUIDS

5th Edition



CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Acceleration (linear)					
foot per second squared	ft/s^2	0.3048*	0.305	meter per second squared	m/s^2
inch per second squared	$in./s^2$	0.0254*	0.0254	meter per second squared	m/s^2
Area					
circular mil	cmil	0.0005067	0.0005	square millimeter	mm^2
square foot	ft^2	0.09290304*	0.0929	square meter	m^2
square inch	$in.^2$	645.16*	645	square millimeter	mm^2
Density (mass)					
slug per cubic foot	$slug/ft^3$	515.379	515	kilogram per cubic meter	kg/m^3
Density (weight)					
pound per cubic foot	lb/ft^3	157.087	157	newton per cubic meter	N/m^3
pound per cubic inch	$lb/in.^3$	271.447	271	kilonewton per cubic meter	kN/m^3
Energy; work					
foot-pound	ft-lb	1.35582	1.36	joule (N·m)	J
inch-pound	in.-lb	0.112985	0.113	joule	J
kilowatt-hour	kWh	3.6*	3.6	megajoule	MJ
British thermal unit	Btu	1055.06	1055	joule	J
Force					
pound	lb	4.44822	4.45	newton ($kg·m/s^2$)	N
kip (1000 pounds)	k	4.44822	4.45	kilonewton	kN
Force per unit length					
pound per foot	lb/ft	14.5939	14.6	newton per meter	N/m
pound per inch	lb/in.	175.127	175	newton per meter	N/m
kip per foot	k/ft	14.5939	14.6	kilonewton per meter	kN/m
kip per inch	k/in.	175.127	175	kilonewton per meter	kN/m
Length					
foot	ft	0.3048*	0.305	meter	m
inch	in.	25.4*	25.4	millimeter	mm
mile	mi	1.609344*	1.61	kilometer	km
Mass					
slug	$lb\text{-}s^2/ft$	14.5939	14.6	kilogram	kg
Moment of a force; torque					
pound-foot	lb-ft	1.35582	1.36	newton meter	N·m
pound-inch	lb-in.	0.112985	0.113	newton meter	N·m
kip-foot	k-ft	1.35582	1.36	kilonewton meter	kN·m
kip-inch	k-in.	0.112985	0.113	kilonewton meter	kN·m

CONVERSIONS BETWEEN U.S. CUSTOMARY UNITS AND SI UNITS (Continued)

U.S. Customary unit		Times conversion factor		Equals SI unit	
		Accurate	Practical		
Moment of inertia (area)					
inch to fourth power	in.^{4}	416,231	416,000	millimeter to fourth power	mm^4
inch to fourth power	in.^{4}	0.416231×10^{-6}	0.416×10^{-6}	meter to fourth power	m^4
Moment of inertia (mass)					
slug foot squared	slug-ft^2	1.35582	1.36	kilogram meter squared	kg·m^2
Power					
foot-pound per second	ft-lb/s	1.35582	1.36	watt (J/s or N·m/s)	W
foot-pound per minute	ft-lb/min	0.0225970	0.0226	watt	W
horsepower (550 ft-lb/s)	hp	745.701	746	watt	W
Pressure; stress					
pound per square foot	psf	47.8803	47.9	pascal (N/m^2)	Pa
pound per square inch	psi	6894.76	6890	pascal	Pa
kip per square foot	ksf	47.8803	47.9	kilopascal	kPa
kip per square inch	ksi	6.89476	6.89	megapascal	MPa
Section modulus					
inch to third power	in.^{3}	16,387.1	16,400	millimeter to third power	mm^3
inch to third power	in.^{3}	16.3871×10^{-6}	16.4×10^{-6}	meter to third power	m^3
Velocity (linear)					
foot per second	ft/s	0.3048*	0.305	meter per second	m/s
inch per second	in./s	0.0254*	0.0254	meter per second	m/s
mile per hour	mph	0.44704*	0.447	meter per second	m/s
mile per hour	mph	1.609344*	1.61	kilometer per hour	km/h
Volume					
cubic foot	ft^3	0.0283168	0.0283	cubic meter	m^3
cubic inch	in.^{3}	16.3871×10^{-6}	16.4×10^{-6}	cubic meter	m^3
cubic inch	in.^{3}	16.3871	16.4	cubic centimeter (cc)	cm^3
gallon (231 in.^{3})	gal.	3.78541	3.79	liter	L
gallon (231 in.^{3})	gal.	0.00378541	0.00379	cubic meter	m^3

*An asterisk denotes an *exact* conversion factor

***Note:* To convert from SI units to USCS units, *divide* by the conversion factor**

Temperature Conversion Formulas

$$T(°\text{C}) = \frac{5}{9}[T(°\text{F}) - 32] = T(\text{K}) - 273.15$$

$$T(\text{K}) = \frac{5}{9}[T(°\text{F}) - 32] + 273.15 = T(°\text{C}) + 273.15$$

$$T(°\text{F}) = \frac{9}{5}T(°\text{C}) + 32 = \frac{9}{5}T(\text{K}) - 459.67$$

Mechanics of Fluids

FIFTH EDITION, SI

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Contents

Preface

The motivation to write a book is difficult to describe. Most often the authors suggest that the other texts on the subject have certain deficiencies that they will correct, such as an accurate description of entrance flows and flows around blunt objects, the difference between a one-dimensional flow and a uniform flow, the proper presentation of the control volume derivation, or a definition of laminar flow that makes sense. New authors, of course, introduce other deficiencies that future authors hope to correct! And life goes on. This is another fluids book that has been written in hopes of presenting an improved view of fluid mechanics so that the undergraduate can understand the physical concepts and follow the mathematics. This is not an easy task: Fluid mechanics is a subject that contains many difficult-to-understand phenomena. For example, how would you explain the hole scooped out in the snow on the upstream side of a tree? Or the higher concentration of smog contained in the Los Angeles area compared to the level in New York?

Here are several additional subtleties that are often either not discussed in most fluids texts or presented incorrectly:

1. **Laminar and turbulent flows.** The definitions of laminar and turbulent flows must be done carefully. A laminar flow of honey next to an erratically moving piston would appear to be turbulent.
2. **Entrance flow.** Both laminar and turbulent entrance flows are invariably presented incorrectly. To indicate that a parabolic profile exists when the viscous wall layers merge in a laminar pipe flow is simply incorrect.
3. **The wake and separated regions.** A separated region is contained inside the wake (see Figure 8.3), a fact that most textbooks do not present.
4. **Incompressible flow.** Incompressible flow does not require that density be constant. Flows in the ocean and atmosphere are incompressible, but the density variation creates very complicated flow patterns.

5. **High Re flows.** If Re is between 10^3 and 10^5 or greater than about 10^6 we have a high Reynolds-number flow. To perform a model study of an automobile, for example, the Reynolds numbers cannot be equated since the speed in the model study would have to be much too large.
6. **Acceleration in a rotating reference frame.** To understand the flow in a dishwasher arm, it is necessary to use a rotating reference frame, a situation often ignored in fluid texts.
7. **Boundary layers.** Texts typically do not display an actual boundary layer. It is important to realize that boundary layers are extremely thin.
8. **Inviscid (potential) flow.** The role that an inviscid flow plays in an external viscous flow, as displayed in Figure 8.21, is often not clear.

We have attempted to present fluid mechanics so that the student can understand and analyze many of the important phenomena encountered by the engineer.

The mathematical level of this book is based on previous mathematics courses required in all engineering curricula. We use solutions to differential equations and vector algebra. Some use is made of vector calculus with the use of the gradient operator, but this is kept to a minimum since it tends to obscure the physics involved.

When a fluid flows around an object, such as a building or an abutment, its velocity possesses all three components which depend on all three space variables and often, time. If we present the equations that describe such a general flow, the equations are referred to as field equations, and velocity and pressure fields become of interest. This is quite analogous to electrical and magnetic fields in electrical engineering. In order for the difficult problems of the future, such as large-scale environmental pollution, to be analyzed by engineers, it is imperative that we understand fluid fields. Thus in Chapter 5 we introduce the field equations and discuss several solutions for some relatively simple geometries. The more conventional manner of treating the flows individually is provided as an alternate route for those who wish this more standard approach. The field equations can then be included in a subsequent course.

New to the 4th and 5th Editions

- Two new subsections on wind turbines have been added, with real-life examples and problems integrated into the material to demonstrate common applications and prepare students for typical challenges.
- All of the multiple choice problems have been moved to the front of the problem set for ease of use, as these problems can be used to review the subject of Fluid Mechanics for the Fundamentals of Engineering and the GRE/Engineering exams.
- The chapter on Environmental Fluid Mechanics has been removed in order to consolidate coverage.
- The chapter on Computational Fluid Mechanics has been simplified, and additional solved examples have been added for improved student understanding.

Organization

The introductory material included in Chapters 1 through 9 has been selected carefully to introduce students to all fundamental areas of fluid mechanics. Not all of the material in each chapter can be covered in an introductory course. The instructor can fit the material to a selected course outline. Some sections may be omitted without loss of continuity in later chapters. In fact, Chapter 5 can be omitted in its entirety if it is decided to exclude field equations in the introductory course, a relatively common decision. That chapter can then be included in an intermediate fluid mechanics course. After the introductory material has been presented, there is sufficient material to present in one or two additional courses. This additional course or courses could include material that had been omitted in the introductory course and combinations of material from the more specialized Chapters 9 through 14. Much of the material is of interest to all engineers, although several of the later chapters are of interest only to particular disciplines.

Examples and Problems

We have included examples worked out in detail to illustrate each important concept presented in the text material. Numerous home problems, many having multiple parts for better homework assignments, provide the student with ample opportunity to gain experience solving problems of various levels of difficulty. To aid self-study, answers to selected home problems are presented just prior to the Index. We have also included design-type problems in several of the chapters. After studying the material, reviewing the examples, and working several of the home problems, students should gain the needed capability to work many of the problems encountered in actual engineering situations. Of course, there are numerous classes of problems that are extremely difficult to solve, even for an experienced engineer. To solve these more difficult problems, the engineer must gain considerably more information than is included in this introductory text. There are, however, many problems that can be solved successfully using the material and concepts presented herein.

Many students take the FE/EIT exam at the end of their senior year, the first step in becoming a professional engineer. The problems in the FE/EIT exam are all four-part, multiple choice. Consequently, we included this type of problem at the beginning of the problem sets. Multiple-choice problems are presented using SI units since the FE/EIT exam uses SI units exclusively. Additional information on the FE/EIT exam can be obtained from a website at **ppi2pass.com**.

This version of the book is written in SI units.

Instructor Resource Materials

A detailed *Instructor's Solutions Manual* and *Lecture Note PowerPoint* slides, and Mini-Exams are available for instructors through a password-protected Web site at www.cengagebrain.com.

MindTap Online Course and Reader

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap have access to the book's multimedia-rich electronic Reader and are able to complete homework and assessment material online, on their desktops, laptops, or iPads. Instructors who use a Learning Management System (such as Blackboard, Canvas, or Moodle) for tracking course content, assignments, and grading, can seamlessly access the MindTap suite of content and assessments for this course.

With MindTap, instructors can:

- Personalize the Learning Path to match the course syllabus by rearranging content or appending original material to the online content
- Connect a Learning Management System portal to the online course and Reader

- Customize online assessments and assignments
- Track student engagement, progress, and comprehension
- Promote student success through interactivity, multimedia, and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes in the digital Reader, study from or create their own Flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and automatically-graded homework.

Acknowledgments

The authors are very much indebted to both their former professors and to their present colleagues. Chapter 10 was written with inspiration from F.M. Henderson's book titled *Open Channel Flow* (1996), and D. Wood of the University of Kentucky encouraged us to incorporate comprehensive material on pipe network analysis in Chapter 11. Several illustrations in Chapter 11 relating to the water hammer phenomenon were provided by C.S. Martin of the Georgia Institute of Technology. R.D. Thorley provided some of the problems at the end of Chapter 12. Tom Shih assisted in the writing of Chapter 14 on Computational Fluid Dynamics. Thanks to Richard Prevost for writing the MATLAB® solutions. We would also like to thank our reviewers: Sajjed Ahmed, University of Nevada; Mohamed Alawardy, Louisiana State University; John R. Biddle, California State Polytechnic University; Dan Budny, University of Pittsburgh; Jay M. Khodadadi, Auburn University; Nancy Ma, North Carolina State University; Saeed Moaveni, Minnesota State University; Nikos J. Mourtos, San Jose (CA) State University; Julia Muccino, Arizona State University; Emmanuel U. Nzewi, North Carolina A&T State University; Samuel Sih, Walla Walla University; Keith Strevett, University of Oklahoma; and Yiannis Ventikos, Swiss Federal Institute of Technology.

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Preface to the SI Edition

This edition of *Mechanics of Fluids, Fifth Edition* has been adapted to incorporate the International System of Units (*Le Système International d'Unités* or SI) throughout the book.

Le Système International d'Unités

The United States Customary System (USCS) of units uses FPS (foot−pound−second) units (also called English or Imperial units). SI units are primarily the units of the MKS (meter−kilogram−second) system. However, CGS (centimeter−gram−second) units are often accepted as SI units, especially in textbooks.

Using SI Units in this Book

In this book, we have used both MKS and CGS units. USCS (U.S. Customary Units) or FPS (foot-pound-second) units used in the US Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches upon the intellectual property of the source. Some data in figures, tables, and references, therefore, remains in FPS units. For readers unfamiliar with the relationship between the USCS and the SI systems, a conversion table has been provided inside the front cover.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, readers may contact the appropriate government agencies or authorities in their regions.

Instructor Resources

The Instructors' Solution Manual in SI units is available through your Sales Representative or online through the book website at www.cengage.com. A digital version of the ISM as well as other resources are available for instructors registering on the book website.

Feedback from users of this SI Edition will be greatly appreciated and will help us improve subsequent editions.

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Nomenclature

For quick reference

A - area
A_2, A_3 - profile type
a - acceleration, speed of a pressure wave
a - acceleration vector
a_x, a_y, a_z - acceleration components
B - bulk modulus of elasticity, free surface width
b - channel bottom width
C - centroid, Chezy coefficient, Hazen-Williams coefficient
C_1, C_3 - profile type
C_D - drag coefficient
C_d - discharge coefficient
C_f - skin-friction coefficient
C_H - head coefficient
C_L - lift coefficient
C_p - pressure recovery factor, pressure coefficient
C_{NPSH} - net positive suction head coefficient
C_Q - flow-rate coefficient
C_{thrust} - thrust coefficient
C_{torque} - torque coefficient
C_V - velocity coefficient
$C_{\dot{W}}$ - power coefficient
c - specific heat, speed of sound, chord length, celerity
c_f - local skin-friction coefficient
c_p - constant pressure specific heat

c_v - constant volume specific heat
c.s. - control surface
c.v. - control volume
D - diameter
$\frac{D}{Dt}$ - substantial derivative
d - diameter
dx - differential distance
$d\theta$ - differential angle
E - energy, specific energy, coefficient
E_c - critical energy
EGL - energy grade line
Eu - Euler number
e - the exponential, specific energy, wall roughness height, pipe wall thickness
exp - the exponential e
$\mathbf{F}$ - force vector
F - force
F_B - buoyant force
F_D - drag force
F_L - lift force
F_H - horizontal force component
F_V - vertical force component
F_W - body force equal to the weight
f - friction factor, frequency
G - center of gravity
$\overline{GM}$ - metacentric height
$\mathbf{g}$ - gravity vector
g - gravity
H - enthalpy, height, total energy
H_2, H_3 - profile type
H_D - design head
H_P - pump head
H_T - turbine head
HGL - hydraulic grade line
h - distance, height, specific enthalpy
h_j - head loss across a hydraulic jump
I - second moment of an area
$\bar{I}$ - second moment about the centroidal axis
I_{xy} - product of inertia
$\hat{\mathbf{i}}$ - unit vector in the x-direction
$\hat{\mathbf{j}}$ - unit vector in the y-direction
$\hat{\mathbf{k}}$ - unit vector in the z-direction
K - thermal conductivity, flow coefficient
K_c - contraction coefficient
K_e - expansion coefficient
K_{uv} - correlation coefficient
k - ratio of specific heats
L - length
L_E - entrance length
L_e - equivalent length

l - length
l_m - mixing length
M - molar mass, momentum function
M - Mach number
M_1, M_2, M_3 - profile type
m - mass, side-wall slope, constant for curve fit
$\dot{m}$ - mass flux
$\dot{m}_r$ - relative mass flux
m_a - added mass
m_1, m_2 - side-wall slopes
$m\dot{o}m$ - momentum flux
N - general extensive property, an integer, number of jets
$NPSH$ - net positive suction head
n - normal direction, number of moles, power-law exponent, Manning number
$\hat{\mathbf{n}}$ - unit normal vector
P - power, force, wetted perimeter
p - pressure
Q - flow rate (discharge), heat transfer
Q_D - design discharge
$\dot{Q}$ - rate of heat transfer
q - source strength, specific discharge, heat flux
R - radius, gas constant, hydraulic radius, radius of curvature
Re - Reynolds number
Re_{crit} - critical Reynolds number
R_u - universal gas constant
R_x, R_y - force components
r - radius, coordinate variable
$\mathbf{r}$ - position vector
S - specific gravity, entropy, distance, slope of channel, slope of EGL
S_1, S_2, S_3 - profile type
S_c - critical slope
St - Strouhal number
$\mathbf{S}$ - position vector
S_0 - slope of channel bottom
s - specific entropy, streamline coordinate
$\hat{\mathbf{s}}$ - unit vector tangent to streamline
sys - system
T - temperature, torque, tension
t - time, tangential direction
U - average velocity
U_∞ - free-stream velocity away from a body
u - x-component velocity, circumferential blade speed
u' - velocity perturbation
$\tilde{u}$ - specific internal energy
$\overline{u}$ - time average velocity
u_τ - shear velocity
V - velocity
V_c - critical velocity
V_{ss} - steady-state velocity
$\mathbf{V}$ - velocity vector

$\overline{V}$ - spatial average velocity
$\forall$ - volume
V_B - blade velocity
V_n - normal component of velocity
V_r - relative speed
V_t - tangential velocity
v - velocity, y-component velocity
v' - velocity perturbation
$v_r, v_z, v_\theta, v_\phi$ - velocity components
W - work, weight, change in hydraulic grade line
$\dot{W}$ - work rate (power)
$\dot{W}_f$ - actual power
We - Weber number
$\dot{W}_S$ - shaft work (power)
w - z-component velocity, velocity of a hydraulic bore
X_T - distance where transition begins
x - coordinate variable
x_m - origin of moving reference frame
$\tilde{x}$ - distance relative to a moving reference frame
$\overline{x}$ - x-coordinate of centroid
Y - upstream water height above top of weir
y - coordinate variable, flow energy head
y_p - distance to center of pressure
$\overline{y}$ - y-coordinate of centroid
y_c - critical depth
z - coordinate variable
α - angle, angle of attack, lapse rate, thermal diffusivity, kinetic-energy correction factor, blade angle
β - angle, momentum correction factor, fixed jet angle, blade angle
Δ - a small increment
∇ - gradient operator
∇^2 - Laplacian
δ - boundary layer thickness
$\delta(x)$ - Dirac-delta function
δ_d - displacement thickness
δ_v - viscous wall layer thickness
ε - a small volume
$\varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{xz}$ - three rate-of-strain components
ϕ - angle, coordinate variable, velocity potential function, speed factor
Γ - circulation, vortex strength
λ - mean free path, a constant, wave length
γ - specific weight
η - a general intensive property, eddy viscosity, efficiency, a position variable
η_P - pump efficiency
η_T - turbine efficiency
μ - viscosity, doublet strength
ν - kinematic viscosity
π - a pi term
θ - angle, momentum thickness, laser beam angle

ρ - density
Ω - angular velocity
Ω_P - specific speed of a pump
Ω_T - specific speed of a turbine
$\boldsymbol{\Omega}$ - angular velocity vector
ψ - stream function
σ - surface tension, cavitation number, circumferential stress
σ_{xx} , σ_{yy} , σ_{zz} - normal stress components
$\boldsymbol{\tau}$ - stress vector
$\overline{\tau}$ - time average stress
τ_{xy} , τ_{xz} , τ_{yz} - shear stress components
ω - angular velocity, vorticity
$\boldsymbol{\omega}$ - vorticity vector
$\dfrac{\partial}{\partial x}$ - partial derivative

Left: Contemporary windmills are used to generate electricity at many locations in the United States. They are located in areas where consistent prevailing winds exist. (IRC/Shutterstock) Top right: Hurricane Bonnie, Atlantic Ocean about 800 km from Bermuda. At this stage in its development, the storm has a well-developed center, or "eye," where air currents are relatively calm. Vortex-like motion occurs away from the eye. (U.S. National Aeronautics and Space Administration) Bottom right: The Space Shuttle Discovery leaves the Kennedy Space Center on October 29, 1998. In 6 seconds the vehicle cleared the launch tower with a speed of 160 km/h, and in about two minutes it was 250 km down range from the Space Center, 47 km above the ocean with a speed of 6150 km/h. The wings and rudder on the tail are necessary for successful reentry as it enters the earth's atmosphere upon completion of its mission. (IRC/Shutterstock.com)

1 Basic Considerations

Outline

Chapter Objectives

The objectives of this chapter are to:

- Introduce many of the quantities encountered in fluid mechanics including their dimensions and units.
- Identify the liquids to be considered in this text.
- Introduce the fluid properties of interest.
- Present thermodynamic laws and associated quantities.

1.1 INTRODUCTION

A proper understanding of fluid mechanics is extremely important in many areas of engineering. In biomechanics the flow of blood and cerebral fluid are of particular interest; in meteorology and ocean engineering an understanding of the motions of air movements and ocean currents requires a knowledge of the mechanics of fluids; chemical engineers must understand fluid mechanics to design the many different kinds of chemical-processing equipment; aeronautical engineers use their knowledge of fluids to maximize lift and minimize drag on aircraft and to design fan-jet engines; mechanical engineers design pumps, turbines, internal combustion engines, air compressors, air-conditioning equipment, pollution-control equipment, and power plants using a proper understanding of fluid mechanics; and civil engineers must also utilize the results obtained from a study of the mechanics of fluids to understand the transport of river sediment and erosion, the pollution of the air and water, and to design piping systems, sewage treatment plants, irrigation channels, flood control systems, dams, and domed athletic stadiums.

KEY CONCEPT *We will present the fundamentals of fluids so that engineers are able to understand the role that fluid plays in particular applications.*

It is not possible to present fluid mechanics in such a way that all of the foregoing subjects can be treated specifically; it is possible, however, to present the fundamentals of the mechanics of fluids so that engineers are able to understand the role that the fluid plays in a particular application. This role may involve the proper sizing of a pump (the horsepower and flow rate) or the calculation of a force acting on a structure.

In this book we present the general equations, both integral and differential, that result from the conservation of mass principle, Newton's second law, and the first law of thermodynamics. From these a number of particular situations will be considered that are of special interest. After studying this book the engineer should be able to apply the basic principles of the mechanics of fluids to new and different situations.

In this chapter topics are presented that are directly or indirectly relevant to all subsequent chapters. We include a macroscopic description of fluids, fluid properties, physical laws dominating fluid mechanics, and a summary of units and dimensions of important physical quantities. Before we can discuss quantities of interest, we must present the units and dimensions that will be used in our study of fluid mechanics.

1.2 DIMENSIONS, UNITS, AND PHYSICAL QUANTITIES

Before we begin the more detailed studies of fluid mechanics, let us discuss the dimensions and units that will be used throughout the book. Physical quantities require quantitative descriptions when solving an engineering problem. Density is one such physical quantity. It is a measure of the mass contained in a unit volume. Density does not, however, represent a fundamental dimension. There are nine quantities that are considered to be fundamental dimensions: length, mass, time, temperature, amount of a substance, electric current, luminous intensity, plane angle, and solid angle. The dimensions of all other quantities can be expressed in terms of the fundamental dimensions. For example, the quantity "force" can be related to the fundamental dimensions of mass, length, and time. To do this, we use Newton's second law, named after Sir Isaac Newton (1642–1727), expressed in simplified form in one direction as

$$F = ma \tag{1.2.1}$$

Using brackets to denote "the dimension of," this is written dimensionally as

$$\begin{aligned} [F] &= [m][a] \\ F &= M\frac{L}{T^2} \end{aligned} \tag{1.2.2}$$

where F, M, L, and T are the dimensions of force, mass, length, and time, respectively. If force had been selected as a fundamental dimension rather than mass, a possible alternative, mass would have dimensions of

$$[m] = \frac{[F]}{[a]}$$
$$M = \frac{FT^2}{L} \tag{1.2.3}$$

where F is the dimension[1] of force.

There are also systems of dimensions in which both mass and force are selected as fundamental dimensions. In such systems conversion factors, such as a gravitational constant, are required; we do not consider these types of systems in this book, so they will not be discussed.

To give the dimensions of a quantity a numerical value, a set of units must be selected. In the United States, two primary systems of units are presently being used, the British Gravitational System, which we will refer to as English units, and the International System, which is referred to as SI (Système International) units. SI units are preferred and are used internationally; the United States is the only major country not requiring the use of SI units, but there is now a program of conversion in most industries to the predominant use of SI units. Following this trend, we have used primarily SI units. However, as English units are still in use, some examples and problems are presented in these units as well.

KEY CONCEPT *SI units are preferred and are used internationally.*

The fundamental dimensions and their units are presented in Table 1.1; some derived units appropriate to fluid mechanics are given in Table 1.2. Other units that are acceptable are the hectare (ha), which is 10 000 m^2, used for large areas; the metric ton (t), which is 1000 kg, used for large masses; and the liter (L), which is 0.001 m^3. Also, density is occasionally expressed as grams per liter (g/L).

In chemical calculations the mole is often a more convenient unit than the kilogram. In some cases it is also useful in fluid mechanics. For gases the kilogram-mole (kmol) is the quantity that fills the same volume as 32 kilograms of oxygen at the same temperature and pressure. The mass (in kilograms) of a gas filling that volume is equal to the molecular weight of the gas; for example, the mass of 1 kmol of nitrogen is 28 kilograms.

When expressing a quantity with a numerical value and a unit, prefixes have been defined so that the numerical value may be between 0.1 and 1000. These prefixes are presented in Table 1.3. Using scientific notation, however, we use powers of 10 rather than prefixes (e.g., 2×10^6 N rather than 2 MN). If larger numbers are written the comma is not used; twenty thousand would be written as 20 000 with a space and no comma.[2]

KEY CONCEPT *When using SI units, if larger numbers are written (5 digits or more), the comma is not used. The comma is replaced by a space (i.e., 20 000).*

Table 1.1 Fundamental Dimensions and Their Units

Quantity	*Dimensions*	*SI units*		*English units*	
Length ℓ	L	meter	m	foot	ft
Mass m	M	kilogram	kg	slug	slug
Time t	T	second	s	second	s
Electric current i		ampere	A	ampere	A
Temperature T	Θ	kelvin	K	Rankine	°R
Amount of substance	M	kg-mole	kmol	lb-mole	lbmol
Luminous intensity		candela	cd	candela	cd
Plane angle		radian	rad	radian	rad
Solid angle		steradian	sr	steradian	sr

[1]Unfortunately, the quantity force F and the dimension of force $[F]$ use the same symbol.

[2]In many countries, commas represent decimal points, so they are not used since confusion may occur.

Table 1.2 Derived Units

Quantity	*Dimensions*	*SI units*	*English units*
Area A	L^2	m^2	ft^2
Volume $\forall$	L^3	m^3	ft^3
		L (liter)	
Velocity V	L/T	m/s	ft/s
Acceleration a	L/T^2	m/s^2	ft/s^2
Angular velocity ω	T^{-1}	rad/s	rad/s
Force F	ML/T^2	$kg \cdot m/s^2$	$slug\text{-}ft/s^2$
		N (newton)	lb (pound)
Density ρ	M/L^3	kg/m^3	$slug/ft^3$
Specific weight γ	M/L^2T^2	N/m^3	lb/ft^3
Frequency f	T^{-1}	hertz (cycles/s)	s^{-1} (hertz)
Pressure p	M/LT^2	N/m^2	lb/ft^2
		Pa (pascal)	(psf)
Stress τ	M/LT^2	N/m^2	lb/ft^2
		Pa (pascal)	(psf)
Surface tension σ	M/T^2	N/m	lb/ft
Work W	ML^2/T^2	N · m	ft-lb
		J (joule)	
Energy E	ML^2/T^2	N · m	ft-lb
		J (joule)	
Heat rate $\dot{Q}$	ML^2/T^3	J/s	Btu/s
Torque T	ML^2/T^2	N · m	ft-lb
Power P	ML^2/T^3	J/s	ft-lb/s
$\dot{W}$		W (watt)	
Viscosity μ	M/LT	$N \cdot s/m^2$	$lb\text{-}s/ft^2$
Kinematic viscosity ν	L^2/T	m^2/s	ft^2/s
Mass flux $\dot{m}$	M/T	kg/s	slug/s
Flow rate Q	L^3/T	m^3/s	ft^3/s
Specific heat c	$L^2/T^2\Theta$	J/kg · K	Btu/slug-°R
Conductivity K	$ML/T^3\Theta$	W/m · K	lb/s-°R

Newton's second law relates a net force acting on a rigid body to its mass and acceleration. This is expressed as

$$\Sigma \mathbf{F} = m\mathbf{a} \tag{1.2.4}$$

Table 1.3 SI Prefixes

Multiplication factor	*Prefix*	*Symbol*
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi[a]	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p

[a]Permissible if used alone as cm, cm^2, or cm^3.

Consequently, the force needed to accelerate a mass of 1 kilogram at 1 meter per second squared in the direction of the net force is 1 newton; using English units, the force needed to accelerate a mass of 1 slug at 1 foot per second squared in the direction of the net force is 1 pound. This allows us to relate the units by

KEY CONCEPT *The unit lb is always a force, never mass.*

$$N = kg \cdot m/s^2 \qquad lb = slug\text{-}ft/s^2 \tag{1.2.5}$$

which are included in Table 1.2. These relationships between units are often used in the conversion of units. In the SI system, weight is always expressed in newtons, never in kilograms. In the English system, mass is usually expressed in slugs, although pounds are used in some thermodynamic relations. To relate weight to mass, we use

KEY CONCEPT *The relationship* $N = kg \cdot m/s^2$ *is often used in the conversion of units.*

$$W = mg \tag{1.2.6}$$

where g is the local gravity. The standard value for gravity is 9.80665 m/s^2 (32.174 ft/s^2) and it varies from a minimum of 9.77 m/s^2 at the top of Mt. Everest to a maximum of 9.83 m/s^2 in the deepest ocean trench. A nominal value of 9.81 m/s^2 (32.2 ft/s^2) will be used unless otherwise stated.

Finally, a note on significant figures. In engineering calculations we often do not have confidence in a calculation beyond three significant digits since the information given in the problem statement is often not known to more than three significant digits; in fact, viscosity and other fluid properties may not be known to even three significant digits. The diameter of a pipe may be stated as 2 cm; this would, in general, not be as precise as 2.000 cm would imply. If information used in the solution of a problem is known to only two significant digits, it is incorrect to express a result to more than two significant digits. In the examples and problems we will assume that all information given is known to three significant digits, and the results will be expressed accordingly, although four significant digits are usually acceptable (but never five or more).

KEY CONCEPT *We will assume that all information given is known to three significant digits.*

Example 1.1

A mass of 100 kg is acted on by a 400-N force acting vertically upward and a 600-N force acting upward at a 45° angle. Calculate the vertical component of the acceleration. The local acceleration of gravity is 9.81 m/s^2. (The rollers are frictionless.)

Solution

The first step in solving a problem involving forces is to draw a free-body diagram with all forces acting on it, as shown in Figure E1.1.

Next, apply Newton's second law (Eq. 1.2.4). It relates the net force acting on a mass to the acceleration and is expressed as

$$\Sigma F_y = ma_y$$

(Continued)

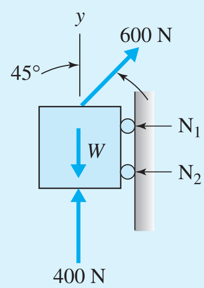

Figure E1.1

Using the appropriate components in the positive y-direction, with $W = mg$, we have

$$400 + 600 \sin 45° - 100 \times 9.81 = 100a_y$$

$$a_y = \underline{-1.57 \text{ m/s}^2}$$

The negative sign indicates that the acceleration is in the negative y-direction, i.e., down. *Note:* We have used only three significant digits in the answer since the information given in the problem is assumed known to three significant digits.

1.3 CONTINUUM VIEW OF GASES AND LIQUIDS

Liquid: *A state of matter in which the molecules are relatively free to change their positions with respect to each other but restricted by cohesive forces so as to maintain a relatively fixed volume.*[4]

Gas: *A state of matter in which the molecules are practically unrestricted by cohesive forces. A gas has neither definite shape nor volume.*

Stress vector: *The force vector divided by the area.*

Normal stress: *The normal component of force divided by the area.*

Shear stress: *The tangential force divided by the area.*

Substances referred to as fluids may be **liquids** or **gases**. In our study of fluid mechanics, we restrict the liquids that are studied. Before we state the restriction, we must define a shearing stress. A force ΔF that acts on an area ΔA can be decomposed into a normal component ΔF_n and a tangential component ΔF_t, as shown in Figure 1.1. The force divided by the area upon which it acts is called a *stress*. The force vector divided by the area is a **stress vector**,[3] the normal component of force divided by the area is a **normal stress**, and the tangential force divided by the area is a **shear stress**. In this discussion we are interested in the shear stress τ. Mathematically, it is defined as

$$\tau = \lim_{\Delta A \to 0} \frac{\Delta F_t}{\Delta A} \tag{1.3.1}$$

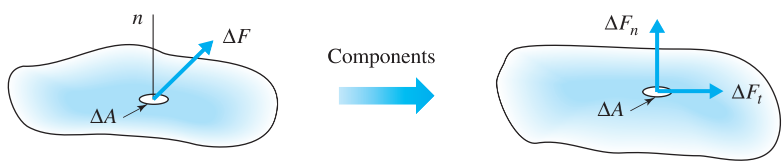

Figure 1.1 Normal and tangential components of a force.

[3] *A term that is defined in the margin is in bold face whereas a term not defined in the margin is italic.*
[4] *Handbook of Chemistry and Physics*, 40th ed. CRC Press, Boca Raton, Fla.

Our restricted family of fluids may now be identified; the fluids considered in this book are *those liquids and gases that move under the action of a shear stress, no matter how small that shear stress may be*. This means that even a very small shear stress results in motion in the fluid. Gases obviously fall within this category of fluids, but so do water and tar. Some substances, such as plastics and catsup, may resist small shear stresses without moving; a study of these substances is included in the subject of *rheology* and is not included in this book.

KEY CONCEPT *Fluids considered in this text are those that move under the action of a shear stress, no matter how small that stress may be.*

It is worthwhile to consider the microscopic behavior of fluids in more detail. Consider the molecules of a gas in a container. These molecules are not stationary but move about in space with very high velocities. They collide with each other and strike the walls of the container in which they are confined, giving rise to the pressure exerted by the gas. If the volume of the container is increased while the temperature is maintained constant, the number of molecules impacting on a given area is decreased, and as a result, the pressure decreases. If the temperature of a gas in a given volume increases (i.e., the velocities of the molecules increase), the pressure increases due to increased molecular activity.

Molecular forces in liquids are relatively high, as can be inferred from the following example. The pressure necessary to compress 20 grams of water vapor at 20°C into 20 cm^3, assuming that no molecular forces exist, can be shown by the ideal gas law to be approximately 1340 times the atmospheric pressure. Of course, this pressure is not required, because 20 g of water occupies 20 cm^3. It follows that the cohesive forces in the liquid phase must be very large.

Continuum: *Continuous distribution of a liquid or gas throughout a region of interest.*

Despite the high molecular attractive forces in a liquid, some of the molecules at the surface escape into the space above. If the liquid is contained, an equilibrium is established between outgoing and incoming molecules. The presence of molecules above the liquid surface leads to a so-called *vapor pressure*. This pressure increases with temperature. For water at 20°C this pressure is approximately 0.02 times the atmospheric pressure.

KEY CONCEPT *We use $\forall$ to represent volume and V to represent velocity.*

In our study of fluid mechanics it is convenient to assume that both gases and liquids are continuously distributed throughout a region of interest, that is, the fluid is treated as a **continuum**. The primary property used to determine if the continuum assumption is appropriate is the *density* ρ, defined by

$$\rho = \lim_{\Delta \forall \to 0} \frac{\Delta m}{\Delta \forall} \tag{1.3.2}$$

where Δm is the incremental mass contained in the incremental volume $\Delta \forall$. The density for air at **standard atmospheric conditions**, that is, at a pressure of 101.3 kPa and a temperature of 15°C, is 1.23 kg/m^3. For water, the nominal value of density is 1000 kg/m^3.

Standard atmospheric conditions: *A pressure of* 101.3 kPa *and temperature of* 15°C.

Physically, we cannot let $\Delta \forall \to 0$ since, as $\Delta \forall$ gets extremely small, the mass contained in $\Delta \forall$ would vary discontinuously depending on the number of molecules in $\Delta \forall$; this is shown graphically in Figure 1.2. Actually, the zero in the definition of density should be replaced by some small volume ε, below which the continuum assumption fails. For most engineering applications, the small volume ε shown in Figure 1.2 is extremely small. For example, there are 2.7×10^{16} molecules contained in a cubic millimeter of air at standard conditions; hence, ε is much smaller than a cubic millimeter. An appropriate way to determine if the continuum model is acceptable is to compare a characteristic length ℓ (e.g., the diameter of a rocket) of the device or object of interest with the **mean free path** λ, the average distance a molecule travels before it collides with another molecule; if $\ell \gg \lambda$, the continuum model is acceptable. The mean free path derived in molecular theory, is

KEY CONCEPT *To determine if the continuum model is acceptable, compare a length ℓ with the mean free path.*

Mean free path: *The average distance a molecule travels before it collides with another molecule.*

$$\lambda = 0.225 \frac{m}{\rho d^2} \tag{1.3.3}$$

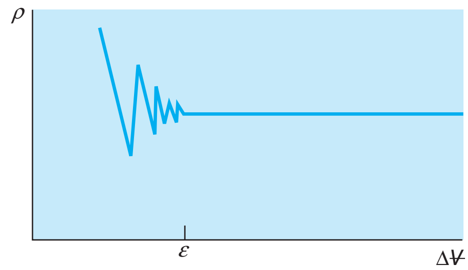

Figure 1.2 Density at a point in a continuum.

where m is the mass (kg) of a molecule, ρ the density (kg/m^3), and d the diameter (m) of a molecule. For air $m = 4.8 \times 10^{-26}$ kg and $d = 3.7 \times 10^{-10}$ m. At standard atmospheric conditions, the mean free path is approximately 6.4×10^{-8} m, at an elevation of 100 km it is 100 mm, and at 160 km it is 50 m. Obviously, at higher elevations the continuum assumption is not acceptable and the theory of rarefied gas dynamics (or free molecular flow) must be utilized. Satellites are able to orbit the earth if the primary dimension of the satellite is of the same order of magnitude as the mean free path.

With the continuum assumption, fluid properties can be assumed to exist at all points in a region at any particular instant in time. For example, the density ρ can be defined at all points in the fluid; it may vary from point to point and from instant to instant; that is, in rectangular coordinates ρ is a continuous function of x, y, z, and t, written as $\rho(x, y, z, t)$.

1.4 PRESSURE AND TEMPERATURE SCALES

In fluid mechanics pressure results from a normal compressive force acting on an area. The *pressure p* is defined as (see Figure 1.3)

$$p = \lim_{\Delta A \to 0} \frac{\Delta F_n}{\Delta A} \quad (1.4.1)$$

where ΔF_n is the incremental normal compressive force acting on the incremental area ΔA. The metric units to be used on pressure are newtons per square meter (N/m^2) or pascals (Pa). Since the pascal is a very small unit of pressure, it is more conventional to express pressure in units of kilopascals (kPa). For example, standard atmospheric pressure at sea level is 101.3 kPa. Atmospheric pressure is often expressed as millimeters (mm) of mercury as shown in Figure 1.4; such a column of fluid creates the pressure at the bottom of the column, providing the column is open to atmospheric pressure at the top.

KEY CONCEPT *In many relationships, absolute scales must be used for pressure and temperature.*

Both pressure and temperature are physical quantities that can be measured using different scales. There exist absolute scales for pressure and temperature, and there are scales that measure these quantities relative to selected reference points. In many thermodynamic relationships (see Section 1.7) absolute scales must be used for pressure and temperature. Figures 1.4 and 1.5 on pages 11 and 12 summarize the commonly used scales.

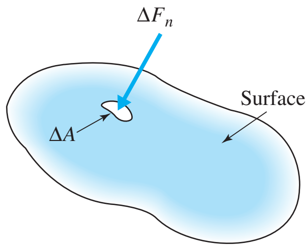

Figure 1.3 The normal force and area used in the definition of pressure.

The **absolute pressure** reaches zero when an ideal vacuum is achieved, that is, when no molecules are left in a space; consequently, a negative absolute pressure is an impossibility. A second scale is defined by measuring pressures relative to the local atmospheric pressure. This pressure is called **gage pressure**. A conversion from gage pressure to absolute pressure can be carried out using

Absolute pressure: *The scale measuring pressure, where zero is reached when an ideal vacuum is achieved.*

Gage pressure: *The scale measuring pressure relative to the local atmospheric pressure.*

$$p_{\text{absolute}} = p_{\text{atmospheric}} + p_{\text{gage}} \tag{1.4.2}$$

Note that the atmospheric pressure in Eq. 1.4.2 is the local atmospheric pressure, which may change with time, particularly when a weather "front" moves through. However, if the local atmospheric pressure is not given, we use the value given for a particular elevation, as given in Table B.3 of Appendix B, and assume zero elevation if the elevation is unknown. The gage pressure is negative whenever the absolute pressure is less than atmospheric pressure; it may then be called a *vacuum*. In this book the word "absolute" will generally follow the pressure value if the pressure is given as an absolute pressure (e.g., $p = 50$ kPa absolute). If it were stated as $p = 50$ kPa, the pressure would be taken as a gage pressure, except that atmospheric pressure is always an absolute pressure. Most often in fluid mechanics gage pressure is used.

KEY CONCEPT *Whenever the absolute pressure is less than the atmospheric pressure, it may be called a vacuum.*

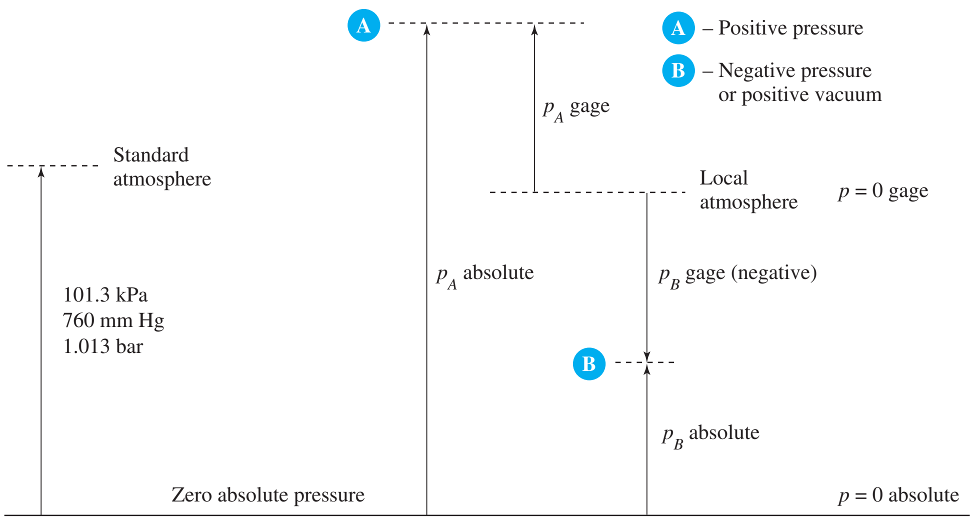

Figure 1.4 Gage pressure and absolute pressure.

	°C	K
Steam point	100°	373
Ice point	0°	273
Special point	–18°	255
Absolute zero temperature	–273°	0°

Figure 1.5 Temperatures of special points.

Two temperature scales are commonly used, the Celsius (C) and Fahrenheit (F) scales. Both scales are based on the ice point and steam point of water at an atmospheric pressure of 101.3 kPa. In this SI Edition, we do not use the Farenheit scale. Figure 1.5 shows that the ice and steam point are 0 and 100°C on the Celsius scale. There are two corresponding absolute temperature scales. The absolute scale corresponding to the Celsius scale is the kelvin (K) scale. The relation between those scales is

$$K = °C + 273.15 \tag{1.4.3}$$

The absolute scale corresponding to the Fahrenheit scale is the Rankine scale (°R). The relation between those scales is

$$°R = °F + 459.67 \tag{1.4.4}$$

KEY CONCEPT *In the SI system, we write 100 K, which is read "100 kelvins."*

Note that in the SI system we do not write 100°K but simply 100 K, which is read "100 kelvins," similar to other units.

Reference will often be made to "standard atmospheric conditions" or "standard temperature and pressure." This refers to sea-level conditions at 40° latitude, which are taken to be 101.3 kPa for pressure and 15°C for temperature. Actually, the standard pressure is usually taken as 100 kPa, sufficiently accurate for engineering calculations.

Example 1.2

A pressure gage attached to a rigid tank measures a vacuum of 42 kPa inside the tank shown in Figure E1.2, which is situated at a site in Colorado where the elevation is 2000 m. Determine the absolute pressure inside the tank.

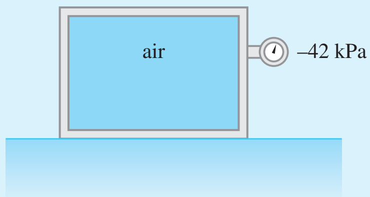

Figure E1.2

KEY CONCEPT *Gravity is essentially constant anywhere on the surface of the earth but atmospheric pressure varies significantly with elevation.*

Solution

To determine the absolute pressure, the atmospheric pressure must be known. If the elevation were not given, we would assume a standard atmospheric pressure of 100 kPa. However, with the elevation given, the atmospheric pressure is found from Table B.3 in Appendix B to be 79.5 kPa. Thus

$$p = -42 + 79.5 = \underline{37.5 \text{ kPa abs}}$$

Note: A vacuum is always a negative gage pressure.

1.5 FLUID PROPERTIES

In this section we present several of the more common fluid properties. If density variation or heat transfer is significant, several additional properties, not presented here, become important.

1.5.1 Density and Specific Weight

Fluid density was defined in Eq. 1.3.2 as mass per unit volume. A fluid property directly related to density is the **specific weight** γ or weight per unit volume. It is defined by

Specific weight: *Weight per unit volume* ($\gamma = \rho g$).

$$\gamma = \frac{W}{V\!\!\!\!-} = \frac{mg}{V\!\!\!\!-} = \rho g \tag{1.5.1}$$

where g is the local gravity. The units of specific weight are N/m^3. For water we use the nominal value of 9810 N/m^3.

The **specific gravity** S is often used to determine the specific weight or density of a fluid (usually a liquid). It is defined as the ratio of the density of a substance to the density of water at a reference temperature of 4°C:

Specific gravity: *The ratio of the density of a substance to the density of water.*

$$S = \frac{\rho}{\rho_{\text{water}}} = \frac{\gamma}{\gamma_{\text{water}}} \tag{1.5.2}$$

For example, the specific gravity of mercury is 13.6, a dimensionless number; that is, the mass of mercury is 13.6 times that of water for the same volume. The density, specific weight, and specific gravity of air and water (the two most common fluids) at standard conditions are given in Table 1.4.

KEY CONCEPT *Specific gravity is often used to determine the density of a fluid.*

The density and specific weight of water do vary slightly with temperature; the approximate relationships are, with T measured in °C,

$$\begin{aligned} \rho_{H_2O} &= 1000 - \frac{(T-4)^2}{180} \\ \gamma_{H_2O} &= 9800 - \frac{(T-4)^2}{18} \end{aligned} \tag{1.5.3}$$

For mercury the specific gravity relates to temperature by

$$S_{\text{Hg}} = 13.6 - 0.0024T \tag{1.5.4}$$

For temperatures under 50°C, using the nominal values stated earlier for water and mercury, the error is less than 1%, certainly within engineering limits for most design problems.

Table 1.4 Density, Specific Weight, and Specific Gravity of Air and Water at Standard Conditions

	Density ρ	*Specific weight* γ	*Specific gravity* S
	kg/m^3	N/m^3	
Air	1.23	12.1	0.00123
Water	1000	9810	1

Note from Eq. 1.5.3 that the density of water at 0°C is less than that at 4°C; consequently, the lighter water at 0°C rises to the top of a lake so that ice forms on the surface. For most other liquids, as for mercury, the density at freezing is greater than the density just above freezing.

1.5.2 Viscosity

Viscosity: *The internal stickiness of a fluid.*

KEY CONCEPT *Viscosity plays a primary role in the generation of turbulence.*

Viscosity can be thought of as the internal stickiness of a fluid. It is one of the properties that influences the power needed to move an airfoil through the atmosphere. It accounts for the energy losses associated with the transport of fluids in ducts, channels, and pipes. Further, viscosity plays a primary role in the generation of turbulence. Needless to say, viscosity is an extremely important fluid property in our study of fluid flows.

The rate of deformation of a fluid is directly linked to the viscosity of the fluid. For a given stress, a highly viscous fluid deforms at a slower rate than a fluid with a low viscosity. Consider the flow of Figure 1.6 in which the fluid particles move in the x-direction at different speeds, so that particle velocities u vary with the y-coordinate. Two particle positions are shown at different times; observe how the particles move relative to one another. For such a simple flow field, in which $u = u(y)$, we can define the **viscosity** μ of the fluid by the relationship

$$\tau = \mu \frac{du}{dy} \tag{1.5.5}$$

Strain rate: *The rate at which a fluid element deforms.*

where τ is the shear stress of Eq. 1.3.1 and u is the velocity in the x-direction. The units of τ are N/m^2, and of μ are $N \cdot s/m^2$. The quantity du/dy is a velocity gradient and can be interpreted as a **strain rate**. Stress velocity-gradient relationships for more complicated flow situations are presented in Chapter 5.

The concept of viscosity and velocity gradients can also be illustrated by considering a fluid within the small gap between two concentric cylinders, as shown in Figure 1.7. A torque is necessary to rotate the inner cylinder at constant rotational speed ω while the outer cylinder remains stationary. This resistance to the rotation of the cylinder is due to viscosity. The only stress that exists to resist the applied torque for this simple flow is a shear stress, which is observed to depend directly on the velocity gradient; that is,

$$\tau = \mu \left| \frac{du}{dr} \right| \tag{1.5.6}$$

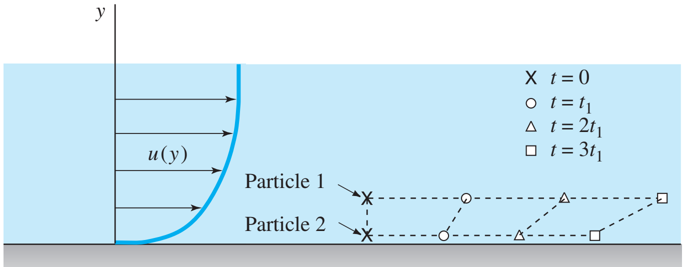

Figure 1.6 Relative movement of two fluid particles in the presence of shear stresses.

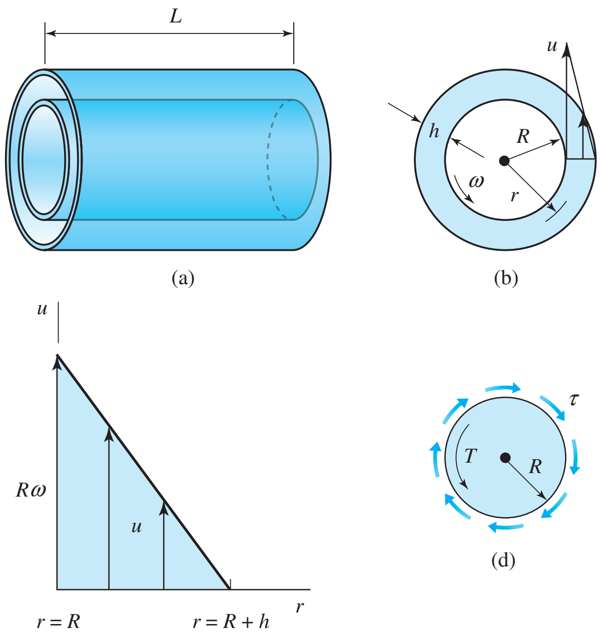

Figure 1.7 Fluid being sheared between cylinders with a small gap: (a) the two cylinders; (b) rotating inner cylinder; (c) velocity distribution; (d) the inner cylinder. The outer cylinder is fixed and the inner cylinder is rotating.

where du/dr is the velocity gradient and u is the tangential velocity component, which depends only on r. For a small gap ($h \ll R$), this gradient can be approximated by assuming a linear velocity distribution[5] in the gap. Thus

$$\left|\frac{du}{dr}\right| = \frac{\omega R}{h} \tag{1.5.7}$$

where h is the gap width. We can thus relate the applied torque T to the viscosity and other parameters by the equation

$$\begin{aligned} T &= \text{stress} \times \text{area} \times \text{moment arm} \\ &= \tau \times 2\pi RL \times R \\ &= \mu\frac{\omega R}{h} \times 2\pi RL \times R = \frac{2\pi R^3 \omega L \mu}{h} \end{aligned} \tag{1.5.8}$$

where the shearing stress acting on the ends of the cylinder is assumed to be negligible; L represents the length of the rotating cylinder. Note that the torque depends directly on the viscosity; thus the cylinders could be used as a *viscometer*, a device that measures the viscosity of a fluid.

[5]If the gap is not small relative to R, the velocity distribution will not be linear (see Section 7.5). The distribution will also not be linear for relatively small values of ω.

[6]To view a file on a specified page, simply open any of the eight major headings, then enter a page number in the box at the top and click on "go to page." The numbers after the descriptors refer to the pages on the DVD.

Newtonian fluid: *The shear stress of the fluid is directly proportional to the velocity gradient.*

If the shear stress of a fluid is directly proportional to the velocity gradient, as was assumed in Eqs. 1.5.5 and 1.5.6, the fluid is said to be a **Newtonian fluid**. Fortunately, many common fluids, such as air, water, and oil, are Newtonian. *Non-Newtonian fluids*, with shear stress versus strain rate relationships as shown in Figure 1.8, often have a complex molecular composition.

Dilatants (quicksand, slurries) become more resistant to motion as the strain rate increases, and *pseudoplastics* (paint and catsup) become less resistant to motion with increased strain rate. *Ideal plastics* (or *Bingham fluids*) require a minimum shear stress to cause motion. Clay suspensions and toothpaste are examples that also require a minimum shear to cause motion, but they do not have a linear stress-strain rate relationship.

KEY CONCEPT *Viscosity causes fluid to adhere to a surface.*

No-slip condition: *Condition where viscosity causes fluid to adhere to the surface.*

An extremely important effect of viscosity is to cause the fluid to adhere to the surface; this is known as the **no-slip condition**. This was assumed in the example of Figure 1.7. The velocity of the fluid at the rotating cylinder was taken to be ωR, and the velocity of the fluid at the stationary cylinder was set equal to zero, as shown in Figure 1.7b. When a space vehicle reenters the atmosphere, the high speed creates very large velocity gradients at the surface of the vehicle, resulting in large stresses that heat up the surface; the high temperatures can cause the vehicle to disintegrate if not properly protected.

The viscosity is very dependent on temperature in liquids in which cohesive forces play a dominant role; note that the viscosity of a liquid decreases with increased temperature, as shown in Figure B.1 in Appendix B. The curves are often approximated by the equation

$$\mu = Ae^{Bt} \tag{1.5.9}$$

known as *Andrade's equation*; the constants A and B would be determined from measured data. For a gas it is molecular collisions that provide the internal stresses, so that as the temperature increases, resulting in increased molecular activity, the viscosity increases. This can be observed in the bottom curves for the gases of Figure B.1 in Appendix B. Note, however, that the percentage change of viscosity in a liquid is much greater than in a gas for the same temperature difference. Also, it is known that cohesive forces and molecular activity are quite insensitive to pressure, so that $\mu = \mu(T)$ only for both liquids and gases.

Since the viscosity is often divided by the density in the derivation of equations, it has become useful and customary to define *kinematic viscosity* v to be

$$v = \frac{\mu}{\rho} \tag{1.5.10}$$

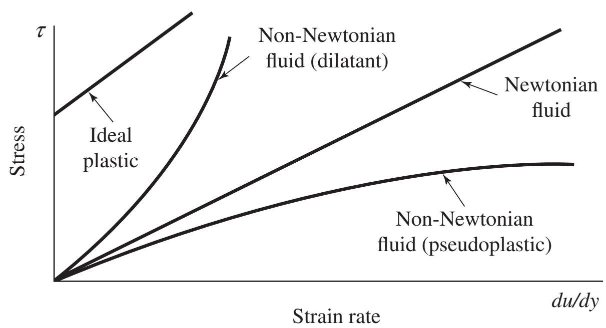

Figure 1.8 Newtonian and non-Newtonian fluids.

where the units of ν are m^2/s (ft^2/s). Note that for a gas, the kinematic viscosity will also depend on the pressure since density is pressure sensitive. The kinematic viscosity is shown, at atmospheric pressure, in Figure B.2 in Appendix B.

Example 1.3

A viscometer is constructed with two 300 mm-long concentric cylinders, one 200 mm in diameter and the other 202 mm in diameter. A torque of 0.13 N·m is required to rotate the inner cylinder at 400 rpm (revolutions per minute). Calculate the viscosity.

Solution

The applied torque is just balanced by a resisting torque due to the shear stresses (see Figure 1.7c). This is expressed by the small gap equation, Eq. 1.5.8.

The radius is $R = d/2 = 100$ mm; the gap $h = (d_2 - d_1)/2 = 1$ mm; the rotational speed, expressed as rad/s, is $\omega = 400 \times 2\pi/60 = 41.89$ rad/s.

Equation 1.5.8 provides:

$$\begin{aligned}\mu &= \frac{Th}{2\pi R^3 \omega L} \\ &= \frac{0.13(0.001)}{2\pi(0.1)^3(41.89)(0.3)} = \underline{0.001646\ \text{N}\cdot\text{s/m}^2}\end{aligned}$$

Note: All lengths are in meters so that the desired units on μ are obtained. The units can be checked by substitution:

$$[\mu] = \frac{(\text{N}\cdot\text{m})\text{m}}{\text{m}^3(\text{rad/s})\text{m}} = \frac{\text{N}\cdot\text{s}}{\text{m}^2}$$

1.5.3 Compressibility

In the preceding section we discussed the deformation of fluids that results from shear stresses. In this section we discuss the deformation that results from pressure changes. All fluids compress if the pressure increases, resulting in a decrease in volume or an increase in density. A common way to describe the compressibility of a fluid is by the following definition of the **bulk modulus of elasticity** B:

Bulk modulus of elasticity: *The ratio of change in pressure to relative change in density.*

$$\begin{aligned}B &= \lim_{\Delta V \to 0}\left[-\frac{\Delta p}{\Delta V/V}\right]_T = \lim_{\Delta\rho\to 0}\frac{\Delta p}{\Delta\rho/\rho}\bigg|_T \\ &= -V\frac{\partial p}{\partial V}\bigg|_T = \rho\frac{\partial p}{\partial\rho}\bigg|_T\end{aligned} \qquad (1.5.11)$$

In words, the bulk modulus, also called the *coefficient of compressibility*, is defined as the ratio of the change in pressure (Δp) to relative change in density ($\Delta\rho/\rho$) while the temperature remains constant. The bulk modulus has the same units as pressure.

The bulk modulus for water at standard conditions is approximately 2100 MPa, or 21 000 times the atmospheric pressure. For air at standard conditions, B is equal to 1 atm. In general, B for a gas is equal to the pressure of the gas. To cause a 1% change in the density of water, a pressure of 21 MPa (210 atm) is required. This is an extremely large pressure needed to cause such a small change; thus liquids are often assumed to be incompressible. For gases, if significant changes in density occur, say 4%, they should be considered as compressible; for small density changes under 3% they may also be treated as incompressible. This occurs for atmospheric airspeeds under about 100 m/s, which includes many airflows of engineering interest: air flow around automobiles, landing and take-off of aircraft, and air flow in and around buildings.

KEY CONCEPT *Gases with small density changes under 3% may be treated as incompressible.*

Small density changes in liquids can be very significant when large pressure changes are present. For example, they account for "water hammer," which can be heard shortly after the sudden closing of a valve in a pipeline; when the valve is closed, an internal pressure wave propagates down the pipe, producing a hammering sound due to pipe motion when the wave reflects from the closed valve or pipe elbows. Water hammer is considered in detail in Section 11.5.

The bulk modulus can also be used to calculate the speed of sound in a liquid; in Section 9.2 it will be shown to be given by

$$c = \sqrt{\left.\frac{\partial p}{\partial \rho}\right|_T} \cong \sqrt{\left.\frac{\Delta p}{\Delta \rho}\right|_T} = \sqrt{\frac{B}{\rho}} \tag{1.5.12}$$

This yields approximately 1450 m/s for the speed of sound in water using $B = 2100$ MPa at standard conditions. The speed of sound in a gas will be presented in Section 1.7.3.

1.5.4 Surface Tension

Surface tension: *A property resulting from the attractive forces between molecules.*

Surface tension is a property that results from the attractive forces between molecules. As such, it manifests itself only in liquids at an interface, usually a liquid-gas interface. The forces between molecules in the bulk of a liquid are equal in all directions, and as a result, no net force is exerted on the molecules. However, at an interface the molecules exert a force that has a resultant in the interface layer. This force holds a drop of water suspended on a rod and limits the size of the drop that may be held. It also causes the small drops from a sprayer or atomizer to assume spherical shapes. It may also play a significant role when two immiscible liquids (e.g., oil and water) are in contact with each other.

KEY CONCEPT *Force due to surface tension results from a length multiplied by the surface tension.*

Surface tension has units of force per unit length, N/m. The force due to surface tension results from a length multiplied by the surface tension; the length to use is the length of fluid in contact with a solid, or the circumference in the case of a bubble. A surface tension effect can be illustrated by considering the free-body diagrams of half a droplet in Figure 1.9a and half a bubble in Figure 1.9b. The droplet has one surface, and the bubble is composed of a thin film of liquid with an inside surface and an outside surface. An expression for the pressure inside the droplet and bubble can now be derived.

The pressure force $p\pi R^2$ in the droplet balances the surface tension force around the circumference. Hence

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

$$\therefore p = \frac{2\sigma}{R} \tag{1.5.13}$$

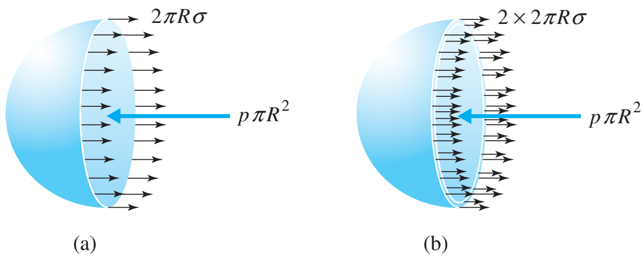

Figure 1.9 Internal forces in (a) a droplet and (b) a bubble.

Similarly, the pressure force in the bubble is balanced by the surface tension forces on the two circumferences assuming the bubble's surface thickness is small. Therefore,

$$p\pi R^2 = 2 \times (2\pi R\sigma)$$

$$\therefore p = \frac{4\sigma}{R} \tag{1.5.14}$$

From Eqs. 1.5.13 and 1.5.14 we can conclude that the internal pressure in a bubble is twice as large as that in a droplet of the same size.

Figure 1.10 shows the rise of a liquid in a clean glass capillary tube due to surface tension. The liquid makes a contact angle β with the glass tube. Experiments have shown that this angle for water and most liquids in a clean glass tube is zero. There are also cases for which this angle is greater than 90° (e.g., mercury); such liquids have a capillary drop. If h is the capillary rise, D the diameter, ρ the density, and σ the surface tension, h can be determined from equating the vertical component of the surface tension force to the weight of the liquid column:

$$\sigma\pi D\cos\beta = \gamma\frac{\pi D^2}{4}h \tag{1.5.15}$$

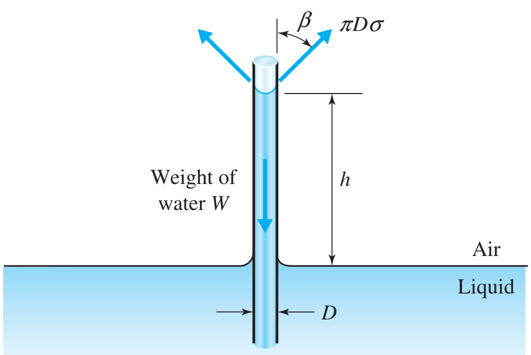

Figure 1.10 Rise in a capillary tube.

or, rearranged,

$$h = \frac{4\sigma \cos\beta}{\gamma D} \tag{1.5.16}$$

Surface tension may influence engineering problems when, for example, laboratory modeling of waves is conducted at a scale that surface tension forces are of the same order of magnitude as gravitational forces.

Example 1.4

A 2-mm-diameter clean glass tube is inserted in water at 15°C (Figure E1.4). Determine the height that the water will climb up the tube. The water makes a contact angle of 0° with the clean glass.

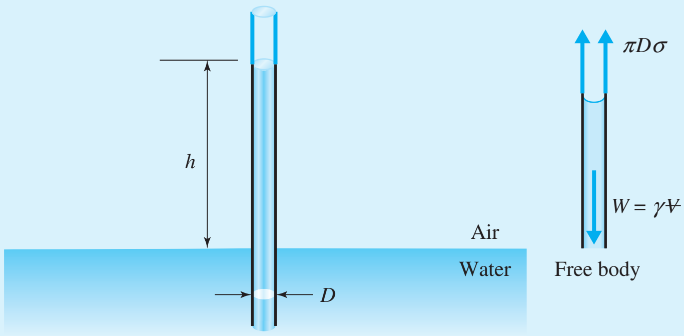

Figure E1.4

Solution

Comment: *Sap climbs far up the small capillary tubes in a tree.*

A free-body diagram of the water shows that the upward surface-tension force is equal and opposite to the weight. Writing the surface-tension force as surface tension times distance, we have

$$\sigma\pi D = \gamma\frac{\pi D^2}{4}h$$

or

$$h = \frac{4\sigma}{\gamma D} = \frac{4 \times 0.0741\ \text{N/m}}{9810\ \text{N/m}^3 \times 0.002\ \text{m}} = 0.01512\ \text{m} \quad \text{or} \quad \underline{15.12\ \text{mm}}$$

The numerical values for σ and ρ were obtained from Table B.1 in Appendix B. *Note:* If temperature is not given, the nominal value used for the specific weight of water is $\gamma = \rho g = 9810\ \text{N/m}^3$.

Figure 1.11 Cooking food in boiling water takes longer at a high altitude. It would take significantly longer to boil eggs in Denver than in New York City. (Chad Zuber/Shutterstock.com)

1.5.5 Vapor Pressure

When a small quantity of liquid is placed in a closed container, a certain fraction of the liquid will vaporize. Vaporization will terminate when equilibrium is reached between the liquid and gaseous states of the substance in the container—in other words, when the number of molecules escaping from the water surface is equal to the number of incoming molecules. The pressure resulting from molecules in the gaseous state is the **vapor pressure**.

Vapor pressure: *The pressure resulting from molecules in a gaseous state.*

The vapor pressure is different from one liquid to another. For example, the vapor pressure of water at 15°C is 1.70 kPa absolute, and for ammonia it is 33.8 kPa absolute.

The vapor pressure is highly dependent on temperature; it increases significantly when the temperature increases. For example, the vapor pressure of water increases to 100 kPa if the temperature reaches 100°C. Water vapor pressures for other temperatures are given in Appendix B.

It is, of course, no coincidence that the water vapor pressure at 100°C is equal to the standard atmospheric pressure. At that temperature the water is **boiling**; that is, the liquid state of the water can no longer be sustained because the attractive forces are not sufficient to contain the molecules in a liquid phase. In general, a transition from the liquid state to the gaseous state occurs if the local absolute pressure is less than the vapor pressure of the liquid. At high elevations where the atmospheric pressure is relatively low, boiling occurs at temperatures less than 100°C; see Figure 1.11. At an elevation of 3000 m where $p_{atm} \cong 70$ kPa, boiling would occur at approximately 90°C; see Tables B.3 and B.1.

Boiling: *The point where vapor pressure is equal to the atmospheric pressure.*

In liquid flows, conditions can be created that lead to a pressure below the vapor pressure of the liquid. When this happens, bubbles are formed locally. This phenomenon, called **cavitation**, can be very damaging when these bubbles are transported by the flow to higher-pressure regions. What happens is that the bubbles collapse upon entering the higher-pressure region,

Cavitation: *Bubbles form in a liquid when the local pressure falls below the vapor pressure of the liquid.*

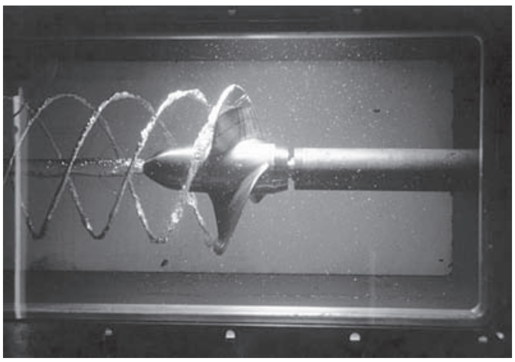

Figure 1.12 A photograph of a cavitating propeller inside MIT's water tunnel. (Courtesy of Prof. S. A. Kinnas, Ocean Engineering Group, University of Texas—Austin.)

KEY CONCEPT
Cavitation can be very damaging.

and this collapse produces local pressure spikes which have the potential of damaging a pipe wall or a ship's propeller. Cavitation on a propeller is shown in Figure 1.12 on previous page. Additional information on cavitation is included in Section 8.3.4.

KEY CONCEPT *We always use a straight-line interpolation in tables, hence the 3 significant digits.*

Example 1.5

Calculate the vacuum necessary to cause cavitation in a water flow at a temperature of 80°C in Colorado where the elevation is 2500 m.

Solution

The vapor pressure of water at 80°C is given in Table B.1. It is 47.3 kPa absolute. The atmospheric pressure is found by interpolation using Table B.3 to be $79.48 - (79.48 - 61.64)500/2000 \cong 75.0$. The required pressure is then

$$p = 47.3 - 75.0 = -27.7\,\text{kPa} \quad \text{or} \quad \underline{27.7\ \text{kPa vacuum}}$$

1.6 CONSERVATION LAWS

Conservation of mass: *Matter is indestructible.*

From experience it has been found that fundamental laws exist that appear exact; that is, if experiments are conducted with the utmost precision and care, deviations from these laws are very small and in fact, the deviations would be even smaller if improved experimental techniques were employed. Three such laws form the basis for our study of fluid mechanics. The first is the **conservation of mass**, which states that matter is indestructible. Even though Einstein's theory of relativity postulates that under certain conditions, matter is convertible into energy and leads to the statement that the extraordinary quantities of radiation from the sun are associated with a conversion of 3.3×10^{14} kg of matter per day into energy, the destructibility of matter under typical engineering conditions is not measurable and does not violate the conservation of mass principle.

System: *A fixed quantity of matter.*

For the second and third fundamental laws, it is necessary to introduce the concept of a system. A **system** is defined as a fixed quantity of matter upon which attention is focused. Everything external to the system is separated by the system boundaries.

Newton's second law: *The sum of all external forces acting on a system is equal to the time rate of change of linear momentum of the system.*

These boundaries may be fixed or movable, real, or imagined. With this definition we can now present our second fundamental law, the *conservation of momentum*: The momentum of a system remains constant if no external forces are acting on the system. A more specific law based on this principle is **Newton's second law**: The sum of all external forces acting on a system is equal to the time rate of change of linear momentum of the system. A parallel law exists for the moment of momentum: The rate of change of angular momentum is equal to the sum of all torques acting on the system.

Conservation of energy: *The total energy of an isolated system remains constant; it is also known as the first law of thermodynamics.*

The third fundamental law is the **conservation of energy**, which is also known as the *first law of thermodynamics*: The total energy of an isolated system remains constant. If a system is in contact with the surroundings, its energy increases only if the energy of the surroundings experiences a corresponding decrease. It is noted that the total energy consists of potential, kinetic, and internal energy, the latter being the energy content due to the temperature of the system. Other forms of energy[7] are not considered in fluid mechanics. The first law of thermodynamics and other thermodynamic relationships are presented in the following section.

[7]Other forms of energy include electric and magnetic field energy, the energy associated with atoms, and energy released during combustion.

1.7 THERMODYNAMIC PROPERTIES AND RELATIONSHIPS

For incompressible fluids, the three laws mentioned in the preceding section suffice. This is usually true for liquids but also for gases if relatively small pressure, density, and temperature changes occur. However, for a compressible fluid, it may be necessary to introduce other relationships, so that density, temperature, and pressure changes are properly taken into account. An example is the prediction of changes in density, pressure, and temperature when compressed gas is released from a rocket through a nozzle.

Thermodynamic properties, quantities that define the state of a system, either depend on the system's mass or are independent of the mass. The former is called an **extensive property**, and the latter is called an **intensive property**. An intensive property can be obtained by dividing the extensive property by the mass of the system. Temperature and pressure are intensive properties; momentum and energy are extensive properties.

Extensive property: *A property that depends on the system's mass.*

Intensive property: *A property that is independent of the system's mass.*

1.7.1 Properties of an Ideal Gas

The behavior of gases in most engineering applications can be described by the ideal gas law, also called the perfect-gas law. When the temperature is relatively low and/or the pressure relatively high, caution should be exercised and real-gas laws should be applied. For air with temperatures higher than $-50°C$ the ideal gas law approximates the behavior of air to an acceptable degree provided that the pressure is not extremely high.

The *ideal gas law* is given by

$$p = \rho RT \tag{1.7.1}$$

where p is the absolute pressure, ρ the density, T the absolute temperature, and R the gas constant. The gas constant is related to the universal gas constant R_u by the relationship

$$R = \frac{R_u}{M} \tag{1.7.2}$$

where M is the molar mass. Values of M and R are tabulated in Table B.4 in Appendix B. The value of R_u is

$$R_u = 8.314\,\text{kJ/kmol}\cdot\text{K} \tag{1.7.3}$$

For air $M = 28.97$ kg/kmol, so that for air $R = 0.287$ kJ/kg·K, a value used extensively in calculations involving air.

Other forms that the ideal gas law takes are

$$p\mathcal{V} = mRT \tag{1.7.4}$$

and

$$p\mathcal{V} = nR_uT \tag{1.7.5}$$

where n is the number of moles.

Example 1.6

A tank with a volume of $0.2\ \text{m}^3$ contains 0.5 kg of nitrogen. The temperature is 20°C. What is the pressure?

Solution

Assume this is an ideal gas. Apply Eq. 1.7.1 (R can be found in Table B.4). Solving the equation, $p = \rho RT$, we obtain, using $\rho = m/\mathcal{V}$,

$$p = \frac{0.5\ \text{kg}}{0.2\ \text{m}^3} \times 0.2968 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}(20 + 273)\,\text{K} = \underline{218\ \text{kPa abs}}$$

Note: The resulting units are $\text{kJ/m}^3 = \text{kN}\cdot\text{m/m}^3 = \text{kN/m}^2 = \text{kPa}$. The ideal gas law requires that pressure and temperature be in absolute units.

1.7.2 First Law of Thermodynamics

KEY CONCEPT *Energy exchange with surroundings is heat transfer or work.*

In the study of incompressible fluids, the first law of thermodynamics is particularly important. The *first law of thermodynamics* states that when a system, which is a fixed quantity of fluid, changes from state 1 to state 2, its energy content changes from E_1 to E_2 by energy exchange with its surroundings. The energy exchange is in the form of heat transfer or work. If we define heat transfer to the system as positive and work done by the system as positive,[8] the first law of thermodynamics can be expressed as

$$Q_{1-2} - W_{1-2} = E_2 - E_1 \tag{1.7.6}$$

where Q_{1-2} is the amount of heat transfer to the system and W_{1-2} is the amount of work done by the system. The energy E represents the total energy, which consists of kinetic energy ($mV^2/2$), potential energy (mgz), and internal energy ($m\tilde{u}$), where $\tilde{u}$ is the internal energy per unit mass; hence

$$E = m\left(\frac{V^2}{2} + gz + \tilde{u}\right) \tag{1.7.7}$$

Note that $V^2/2$, gz, and $\tilde{u}$ are all intensive properties and E is an extensive property.

For an isolated system, one that is thermodynamically disconnected from the surroundings (i.e., $Q_{1-2} = W_{1-2} = 0$), Eq. 1.7.6 becomes

$$E_1 = E_2 \tag{1.7.8}$$

This equation represents the conservation of energy.

[8]In some presentations the work done on the system is positive, so that Eq. 1.7.6 would appear as $Q + W = \Delta E$. Either choice is acceptable.

The work term in Eq. 1.7.6 results from a force F moving through a distance as it acts on the system's boundary; if the force is due to pressure, it is given by

KEY CONCEPT
Work results from a force moving through a distance.

$$\begin{aligned} W_{1-2} &= \int_{l_1}^{l_2} F\,dl \\ &= \int_{l_1}^{l_2} pA\,dl = \int_{V_1}^{V_2} p\,dV \end{aligned} \qquad (1.7.9)$$

where $A\,dl = dV$. An example that demonstrates an application of the first law of thermodynamics follows.

Example 1.7

A cart with a mass of 29.2 kg is pushed up a ramp with an initial force of 445 N (Figure E1.7). The force decreases according to

$$F = 72.95(6.1 - l)\ \text{N}$$

If the cart starts from rest at $l = 0$, determine its velocity after it has traveled 6.1 m up the ramp. Neglect friction.

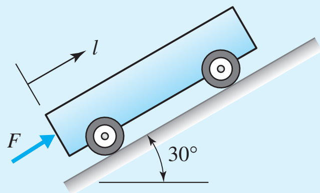

Figure E1.7

Solution

The energy equation (Eq. 1.7.6) allows us to relate the quantities of interest. Since there is no heat transfer, we have

$$-W_{1-2} = E_2 - E_1$$

Recognizing that the force is doing work on the system, the work is negative. Hence the energy equation becomes, using $W = \int F\,dl$,

$$-\left[-\int_0^{6.1} 72.95(6.1 - l)\,dl\right] = m\left(\frac{V_2^2}{2} + gz_2\right) - m\left(\cancelto{0}{\frac{V_1^2}{2}} + \cancelto{0}{gz_1}\right)$$

Units:
$[F\,dl] = \text{N} \cdot \text{m}$
See Eq. 1.2.5.

Taking the datum as $z_1 = 0$, we have $z_2 = 6.1 \sin 30° = 3.05$ m. Thus

$$72.95 \times 6.1^2 - 72.95 \times \frac{6.1^2}{2} = 29.2\left(\frac{V_2^2}{2} + 9.81 \times 3.05\right)$$

$$\therefore V_2 = \underline{5.76\ \text{m}}$$

Note: We have assumed no internal energy change and no heat transfer.

1.7.3 Other Thermodynamic Quantities

Enthalpy: *A property created to aid in thermodynamic calculations.*

In compressible fluids it is sometimes useful to define thermodynamic quantities that are combinations of other thermodynamic quantities. One such combination is the sum ($m\tilde{u} + p\forall$), which can be considered a system property; it is encountered in numerous thermodynamic processes. This property is defined as **enthalpy** H:

$$H = m\tilde{u} + p\forall \tag{1.7.10}$$

The corresponding intensive property (H/m) is

$$h = \tilde{u} + \frac{p}{\rho} \tag{1.7.11}$$

KEY CONCEPT *Constant-pressure specific heat and constant-volume specific heat are used to calculate the enthalpy and internal energy changes.*

Other useful thermodynamic quantities are the *constant-pressure specific heat* c_p and the *constant-volume specific heat* c_v; they are used to calculate the enthalpy and the internal energy changes in an ideal gas as follows:

$$\Delta h = \int c_p\, dT \qquad dh = c_p dT \tag{1.7.12}$$

and

$$\Delta \tilde{u} = \int c_v\, dT \qquad d\tilde{u} = c_v dT \tag{1.7.13}$$

For many situations we can assume constant specific heats in the foregoing relationships. Specific heats for common gases are listed in Table B.4. For an ideal gas c_p is related to c_v by using Eq. 1.7.11 in differential form:

$$dh = d\tilde{u} + R dT \qquad c_p = c_v + R \tag{1.7.14}$$

Ratio of specific heats: *The ratio of c_p to c_v.*

where we used $p/\rho = RT$ The **ratio of specific heats** k is often of use for an ideal gas; it is expressed as

$$k = \frac{c_p}{c_v} \tag{1.7.15}$$

For liquids and solids we use $\Delta u = c\Delta T$ where c is the specific heat of the substance. For water $c \cong 4.18$ kJ/kg·°C(1 Btu/lb-°F).

Quasi-equilibrium process: *A process in which properties are essentially constant at any instant throughout a system.*

A process in which pressure, temperature, and other properties are essentially constant at any instant throughout the system is called a **quasi-equilibrium** or *quasi-static* **process.** An example of such a process is the compression and expansion in the cylinder of an internal combustion engine.[9] If, in addition, no heat is transferred ($Q_{1-2} = 0$), the process is called an

[9]Even though these processes may seem fast, they are thermodynamically slow. Molecules move very fast.

adiabatic, quasi-equilibrium process or an isentropic process. For such an isentropic[10] process the following relationships may be used:

$$\frac{p_1}{p_2} = \left(\frac{\rho_1}{\rho_2}\right)^k \qquad \frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{(k-1)/k} \qquad \frac{T_1}{T_2} = \left(\frac{\rho_1}{\rho_2}\right)^{k-1} \tag{1.7.16}$$

For a small pressure wave traveling in a gas at relatively low frequency (the speed of sound), the wave speed is given by an isentropic process so that

$$c = \sqrt{\left.\frac{dp}{d\rho}\right|_s} = \sqrt{kRT} \tag{1.7.17}$$

If the frequency is relatively high, entropy is not constant and we use

$$c = \sqrt{\left.\frac{dp}{d\rho}\right|_T} = \sqrt{RT} \tag{1.7.18}$$

These are the primary thermodynamic relationships that will be used when considering compressible fluids.

Example 1.8

A cylinder fitted with a piston has an initial volume of 0.5 m^3. It contains 2.0 kg of air at 400 kPa absolute. Heat is transferred to the air while the pressure remains constant until the temperature is 300°C. Calculate the heat transfer and the work done. Assume constant specific heats.

Solution

Using the first law (Eq. 1.7.6), and the definition of enthalpy, we see that, with no kinetic or internal energy changes, there results

$$\begin{aligned} Q_{1-2} &= p_2 V_2 - p_1 V_1 + m\tilde{u}_2 - m\tilde{u}_1 \\ &= m\tilde{u}_2 + p_2 V_2 - (m\tilde{u}_1 + p_1 V_1) \\ &= H_2 - H_1 = m(h_2 - h_1) = mc_p(T_2 - T_1) \end{aligned}$$

where Eq. 1.7.12 is used assuming c_p to be constant. The initial temperature is

$$T_1 = \frac{p_1 V_1}{mR} = \frac{400 \text{ kN/m}^2 \times 0.5 \text{ m}^3}{2.0 \text{ kg} \times 0.287 \text{ kJ/kg}\cdot\text{K}} = 348.4 \text{ K}$$

(*Continued*)

[10]An isentropic process occurs when the entropy is constant. We will not define or calculate entropy here; it is discussed in Section 9.1.

(Use kJ = kN·m to check the units.) Thus the heat transfer is (c_p is found in Table B.4)

Units: $\text{kg}\dfrac{\text{kJ}}{\text{kg}\cdot\text{K}}\text{K} = \text{kJ}$

$$Q_{1-2} = 2.0 \times 1.0[(300 + 273) - 348.4] = \underline{449 \text{ kJ}}$$

The final volume is found using the ideal gas law:

$$\forall_2 = \frac{mRT_2}{p_2} = \frac{2 \text{ kg} \times (0.287 \text{ kJ/kg}\cdot\text{K}) \times 573 \text{ K}}{400 \text{ kN/m}^2} = 0.822 \text{ m}^3$$

The work done for the constant-pressure process is, using Eq. 1.7.9 with p = const,

$$\begin{aligned} W_{1-2} &= p(\forall_2 - \forall_1) \\ &= 400 \text{ kN/m}^2(0.822 - 0.5) \text{ m}^3 = 129 \text{ kN}\cdot\text{m or } \underline{129 \text{ kJ}} \end{aligned}$$

Example 1.9

The temperature on a cold winter day in the mountains of Wyoming is −30°C at an elevation of 4 km. Calculate the density of the air assuming the same pressure as in the local atmosphere; also find the speed of sound.

Solution

From Table B.3 we find the atmospheric pressure at an elevation of 4 km to be 61.64 kPa. The absolute temperature is found to be

$$T = -30 + 273 = 243 \text{ K}$$

Using the ideal gas law, the mass density is calculated as

Comment: *The gas constants are found in Table B.4.*

$$\begin{aligned} \rho &= \frac{p}{RT} \\ &= \frac{61.64}{0.287 \times 243} = \underline{0.884 \text{ kg/m}^3} \end{aligned}$$

The speed of sound, using Eq. 1.7.17, is determined to be

$$\begin{aligned} c &= \sqrt{kRT} \\ &= \sqrt{1.4 \times 287 \times 243} = \underline{312 \text{ m/s}} \end{aligned}$$

Note: The gas constant in the foregoing equations has units of J/kg·K so that the appropriate units result.

1.8 SUMMARY

To relate units we often use Newton's second law, which allows us to write

$$\text{N} = \text{kg}\cdot\text{m/s}^2 \tag{1.8.1}$$

When making engineering calculations, an answer should have the same number of significant digits as the least accurate number used in the calculations. Most fluid properties are known to at most four significant digits. Hence, answers should be expressed to at most four significant digits, and often to only three significant digits.

In fluid mechanics pressure is expressed as gage pressure unless stated otherwise. This is unlike thermodynamics, in which pressure is assumed to be absolute. If absolute pressure is needed, add 100 kPa if the atmospheric pressure is not given in the problem statement.

The density, or specific weight, of a fluid is known if the specific gravity is known:

$$\rho_x = S_x \rho_{\text{water}} \qquad \gamma_x = S_x \gamma_{\text{water}} \tag{1.8.2}$$

The shear stress due to viscous effects in a simple flow where $u = u(y)$ is given by

$$\tau = \mu \frac{du}{dy} \tag{1.8.3}$$

This stress can be used to calculate the torque needed to rotate a shaft in a bearing.

Many air flows, and other gases too, are assumed to be incompressible at low speeds, speeds under about 100 m/s for atmospheric air.

The three fundamental laws used in our study of fluid mechanics are the conservation of mass, Newton's second law, and the first law of thermodynamics. These will take on various forms depending on the problem being studied. Much of our study of fluid mechanics will be expressing these laws in mathematical forms so that quantities of interest can be calculated.

FUNDAMENTALS OF ENGINEERING EXAM REVIEW PROBLEMS[11]

1.1 If force, length, and time are selected as the three fundamental dimensions, the units of mass in the SI system could be written as:
(A) FT^2/L **(B)** FL/T
(C) $\text{N}\cdot\text{s}^2/\text{m}$ **(D)** $\text{N}\cdot\text{m/s}^2$

1.2 Select the dimensions of viscosity using the F-L-T system:
(A) FT^2/L **(B)** FT/L^2
(C) $\text{N}\cdot\text{s/m}^2$ **(D)** $\text{N}\cdot\text{s}^2/\text{m}$

1.3 The quantity 2.36×10^{-8} Pa can be written as:
(A) 23.6 nPa **(B)** 236 μPa
(C) 236×10^{-3} mPa **(D)** 236 nPa

1.4 A body that weighs 250 N on earth would weigh how much on the moon where $g \cong 1.6\ \text{m/s}^2$?
(A) 5030 N **(B)** 250 N
(C) 40.77 N **(D)** 6.2 N

1.5 A 4200-N force acts on a 250-cm area at an angle of 30° to the normal. The shear stress acting on the area is:
(A) 84 Pa **(B)** 84 mPa
(C) 84 kPa **(D)** 84 MPa

1.6 The temperature at 11 000 m in the standard atmosphere, using a parabolic interpolation of the entries in Table B.3, is nearest:
(A) −62.4°C **(B)** −53.6°C
(C) −32.8°C **(D)** −17.3°C

1.7 Using an equation, estimate the density of water at 80°C:
(A) $980\ \text{kg/m}^3$ **(B)** $972\ \text{kg/m}^3$
(C) $976\ \text{kg/m}^3$ **(D)** $968\ \text{kg/m}^3$

1.8 The velocity distribution in a 4-cm-diameter pipe transporting 20°C water is given by $u(r) = 10(1 - 2500r^2)$ m/s. The shearing stress at the wall is nearest:
(A) 1.0 Pa **(B)** 0.1 Pa
(C) 0.01 Pa **(D)** 0.001 Pa

1.9 The distance 20°C water would climb in a long 10-μm-diameter, clean glass tube is nearest:
(A) 50 cm **(B)** 100 cm
(C) 200 cm **(D)** 300 cm

[11]Select the correct answer from the four choices.

1.10 Which of the following is an intensive property?
(A) Kinetic energy (B) Enthalpy
(C) Density (D) Momentum

1.11 The mass of propane contained in a 4-m^3 tank maintained at 800 kPa and 10°C is nearest:
(A) 100 kg (B) 80 kg
(C) 60 kg (D) 20 kg

1.12 Five 40-cm^3 ice cubes completely melt in 2 liters of warm water (it takes 320 kJ to melt a kilogram of ice). The temperature drop in the water is nearest:
(A) 10°C (B) 8°C
(C) 6°C (D) 4°C

1.13 The speed of sound of a dog whistle in the atmosphere at a location where the temperature is 50°C is nearest:
(A) 396 m/s (B) 360 m/s
(C) 332 m/s (D) 304 m/s

PROBLEMS

Dimensions, Units, and Physical Quantities

1.14 State the three basic laws that are used in the study of the mechanics of fluids. State at least one global (integral) quantity that occurs in each. State at least one quantity that may be defined at a point that occurs in each.

1.15 Verify the dimensions given in Table 1.2 for each of the following quantities:
(a) Density (b) Pressure
(c) Power (d) Energy
(e) Mass (f) Flow rate

1.16 Express the dimensions of each of the following quantities using the F-L-T system:
(a) Density (b) Pressure
(c) Power (d) Energy
(e) Mass flux (f) Flow rate

1.17 Recognizing that all terms in an equation must have the same dimensions, determine the dimensions on the constants in the following equations:
(a) $d = 4.9\,t^2$ where d is distance and t is time.
(b) $F = 9.8\,m$ where F is a force and m is mass.
(c) $Q = 80\,AR^{2/3}\,S_0^{\;1/2}$ where A is area, R is a radius, S_0 is a slope and Q is a flow rate with dimensions of L^3/T.

1.18 Determine the units on each of the constants in the following equations, recognizing that all terms in an equation have the same units:
(a) $d = 4.9\,t^2$ where d is in meters and t is in seconds.
(b) $F = 9.8\,m$ where F is in newtons and m is in kilograms.
(c) $Q = 80\,AR^{2/3}S_0^{\;1/2}$ where A is in meters squared, R is in meters, S_0 is the slope, and Q has units of meters cubed per second.

1.19 State the SI units of Table 1.1 on each of the following:
(a) Pressure (b) Energy
(c) Power (d) Viscosity
(e) Heat flux (f) Specific heat

1.20 Determine the units on c, k and $f(t)$ in $m\dfrac{d^2y}{dt^2} + c\dfrac{dy}{dt} + ky = f(t)$ if m is in kilograms, y is in meters, and t is in seconds.

1.21 Write the following with the use of prefixes:
(a) 2.5×10^5 N (b) 5.72×10^{11} Pa
(c) 4.2×10^{-8} Pa (d) $1.76 \times 10^{-5}\ m^3$
(e) $1.2 \times 10^{-4}\ m^2$ (f) $7.6 \times 10^{-8}\ m^3$

1.22 Write the following with the use of powers; do not use a prefix:
(a) 125 MN (b) 32.1 μs
(c) 0.67 GPa (d) 0.0056 mm^3
(e) 520 cm^2 (f) 7.8 km^3

1.23 Rewrite Eq. 1.3.3 using the English units of Table 1.1.

1.24 Using the table of conversions on the inside front cover, express each of the following in the SI units of Table 1.2:
(a) 20 cm/hr (b) 2000 rpm
(c) 500 hp (d) 1000 cm^3/min
(e) 2000 kN/cm^2 (f) 300 g/min
(g) 500 g/L (h) 500 kWh

1.25 What net force is needed to accelerate a 10-kg mass at the rate of 40 m/s^2 (neglect all friction):
(a) Horizontally?
(b) Vertically upward?
(c) On an upward slope of 30°?

1.26 A particular body weighs 27 kg on earth. Calculate its weight on the moon, where $g \simeq 1.63\ m/s^2$.

1.27 Calculate the mean free path in the atmosphere using Eq. 1.3.3 and Table B.3 in the Appendix at an elevation of:
(a) 30 000 m
(b) 50 000 m
(c) 80 000 m

Pressure and Temperature

1.28 A gage pressure of 52.3 kPa is read on a gage. Find the absolute pressure if the elevation is:
(a) At sea level **(b)** 1000 m
(c) 5000 m **(d)** 10 000 m
(e) 30 000 m

1.29 A vacuum of 31 kPa is measured in an airflow at sea level. Find the absolute pressure in:
(a) kPa **(b)** mm Hg
(c) mN/cm^2 **(d)** N/mm^2
(e) cm Hg

1.30 For a constant-temperature atmosphere, the pressure as a function of elevation is given by $p(z) = p_0 e^{-gz/RT}$, where g is gravity, $R = 287\ J/kg \cdot K$, and T is the absolute temperature. Use this equation and estimate the pressure at 4000 m assuming that $p_0 = 101\,kPa$ and $T = 15°C$. What is the error?

1.31 Estimate the pressure and temperature at an elevation of 6.88 km using Table B.3. Employ:
(a) A linear interpolation:
$f \simeq f_0 + n(f_1 - f_0)$.
(b) A parabolic interpolation:
$f \simeq f_0 + n(f_1 - f_0) + (n/2)(n-1)\ (f_2 - 2f_1 + f_0)$.

1.32 Estimate the temperature in °C at 10 km, an elevation at which many commercial airplanes fly. Use Table B.3.

1.33 An applied force of 26.5 MN is distributed uniformly over a 152-cm^2 area; however, it acts at an angle of 42° with respect to a normal vector (see Figure P1.33). If it produces a compressive stress, calculate the resulting pressure.

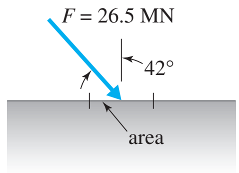

Figure P1.33

1.34 The force on an area of 0.2 cm^2 is due to a pressure of 120 kPa and a shear stress of 20 Pa, as shown in Figure P1.34. Calculate the magnitude of the force acting on the area and the angle of the force with respect to a normal coordinate.

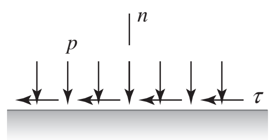

Figure P1.34

Density and Specific Weight

1.35 Calculate the density and specific weight of water if 3 kg occupies $3 \times 10^6\ mm^3$.

1.36 Use Eq. 1.5.3 to determine the density and specific gravity of water at 70°C. What is the error in the calculation for density? Use Table B.1.

1.37 The specific gravity of mercury is usually taken as 13.6. What is the percent error in using a value of 13.6 at 50°C?

1.38 The specific weight of an unknown liquid is 12 400 N/m^3. What mass of the liquid is contained in a volume of 500 cm^3? Use:
(a) The standard value of gravity.
(b) The minimum value of gravity on the earth.
(c) The maximum value of gravity on the earth.

1.39 A liquid with a specific gravity of 1.2 fills a volume. If the mass in the volume is 150 kg, what is the magnitude of the volume?

Viscosity

1.40 In combustion systems that burn hydrocarbon fuels, the carbon dioxide gas that is produced eventually escapes to the atmosphere thereby contributing to global warming. Calculate the density, specific weight, viscosity, and kinematic viscosity of carbon dioxide at a pressure of 200 kPa absolute and 90°C.

1.41 In a single cylinder engine a piston without rings is designed to slide freely inside the vertical cylinder. Lubrication between the piston and cylinder is maintained by a thin oil film. Determine the velocity with which the 120-mm-diameter piston will fall inside the 120.5-mm-diameter cylinder. The 350-g piston is 10 cm long. The lubricant is SAE 10W-30 oil at 60°C.

1.42 Consider a fluid flow between two parallel fixed plates 5 cm apart, as shown in Figure P1.42. The velocity distribution for the flow is given by $u(y) = 120(0.05y - y^2)$ m/s where y is in meters. The fluid is water at 10°C. Calculate the magnitude of the shear stress acting on each of the plates.

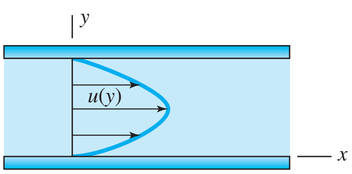

Figure P1.42

1.43 A velocity distribution in a 5-cm-diameter pipe is measured to be $u(r) = 9(1 - r^2/r_0^2)$ m/s, where r_0 is the radius of the pipe. Calculate the shear stress at the wall if water at 24°C is flowing.

1.44 The velocity distribution in a 10 mm-diameter pipe is given by $u(r) = 16(1 - r^2/r_0^2)$ m/s, where r_0 is the pipe radius. Calculate the shearing stress at the centerline, at $r = 2.5$ mm, and at the wall if water at 20°C is flowing.

1.45 For two 0.2-m-long rotating concentric cylinders, the velocity distribution is given by $u(r) = 0.4/r - 1000r$ m/s. If the diameters of the cylinders are 20 mm and 40 mm, respectively, calculate the fluid viscosity if the torque on the inner cylinder is measured to be 0.0026 N·m.

1.46 A 1.5-m-long, 24-mm-diameter shaft rotates inside an equally long cylinder that is 24.6 mm in diameter. Calculate the torque required to rotate the inner shaft at 2000 rpm if SAE-30 oil at 20°C fills the gap. Also, calculate the horsepower required. Assume concentric cylinders.

1.47 A 60 cm-wide belt moves at 10 m/s, as shown in Figure P1.47. Calculate the horsepower requirement assuming a linear velocity profile in the 10°C water.

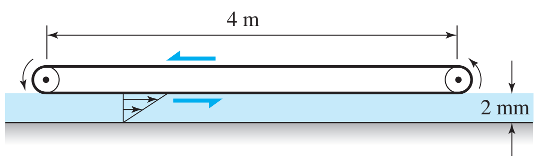

Figure P1.47

1.48 A 15-cm-diameter horizontal disk rotates a distance of 2 mm above a solid surface. Water at 16°C fills the gap. Estimate the torque required to rotate the disk at 400 rpm.

1.49 Calculate the torque needed to rotate the cone shown in Figure P1.49 at 2000 rpm if SAE-30 oil at 40°C fills the gap. Assume a linear velocity profile between the cone and the fixed wall.

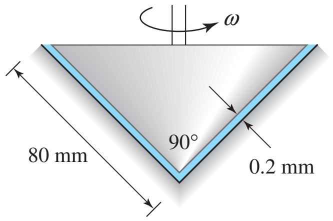

Figure P1.49

1.50 A free-body diagram of the liquid between a moving belt and a fixed wall shows that the shear stress in the liquid is constant. If the temperature varies according to $T(y) = K/y$, where y is measured from the wall (the temperature at the wall is very large), what would be the shape of the velocity profile if the viscosity varies according to Andrade's equation $\mu = Ae^{B/T}$?

1.51 The viscosity of water at 20°C is $0.001\ \text{N}\cdot\text{s/m}^2$ and at 80°C it is $3.57 \times 10^{-4}\ \text{N}\cdot\text{s/m}^2$. Using Andrade's equation $\mu = Ae^{B/T}$ estimate the viscosity of water at 40°C. Determine the percent error.

Compressibility

1.52 Show that $d\rho/\rho = -d\forall/\forall$, as was assumed in Eq 1.5.11

1.53 What is the volume change of $2\ \text{m}^3$ of water at 20°C due to an applied pressure of 10 MPa?

1.54 Two engineers wish to estimate the distance across a lake. One pounds two rocks together under water on one side of the lake and the other submerges his head and hears a small sound 0.62 s later, as indicated by a very accurate stopwatch. What is the distance between the two engineers?

1.55 A pressure is applied to 20 L of water. The volume is observed to decrease to 18.7 L. Calculate the applied pressure.

1.56 Calculate the speed of propagation of a small-amplitude wave through water at:

(a) 4°C
(b) 37°C
(c) 97°C

1.57 The change in volume of a liquid with temperature is given by $\Delta\forall = \alpha_T \forall \Delta T$, where α_T is the *coefficient of thermal expansion*. For water at 40°C, $\alpha_T = 3.8 \times 10^{-4}\ \text{K}^{-1}$. What is the volume change of $1\ \text{m}^3$ of 40°C water if $\Delta T = -20$°C? What pressure change would be needed to cause that same volume change?

Surface Tension

1.58 Calculate the pressure in the small 10-μm-diameter droplets that are formed by spray machines. Assume the properties to be the same as water at 15°C. Calculate the pressure for bubbles of the same size.

1.59 A small 1.5-mm-diameter bubble is formed by a stream of 16°C water. Estimate the pressure inside the bubble.

1.60 In diesel engines diesel fuel is injected directly into the engine cylinder during the compression stroke where the average air pressure could reach 8000 kPa. Assuming that liquid fuel droplets are formed as the fuel flows from the injector, determine the interior pressure in a 5-μm diameter spherical droplet. The surface tension for diesel fuel in air is 0.025 N/m.

1.61 Determine the height that 20°C water would climb in a vertical 0.02-cm-diameter tube if it attaches to the wall with an angle β of 30° to the vertical.

1.62 Mercury makes an angle of 130° (β in Figure 1.10) when in contact with clean glass. What distance will mercury depress in a vertical 2-cm-diameter glass tube? Use $\sigma = 0.47$ N/m.

1.63 Find an expression for the rise of liquid between two parallel plates a distance t apart. Use a contact angle β and surface tension σ.

1.64 Write an expression for the maximum diameter d of a needle of length L that can float in a liquid with surface tension σ. The density of the needle is ρ.

1.65 Would a 70-mm-long 4-mm-diameter steel needle be able to float in 15°C water? Use $\rho_{steel} = 7850 \text{ kg/m}^3$.

1.66 Find an expression for the maximum vertical force F needed to lift a thin wire ring of diameter D slowly from a liquid with surface tension σ.

1.67 Two flat plates are positioned as shown in Figure P1.67 with a small angle α in an open container with a small amount of liquid. The plates are vertical, and the liquid rises between the plates. Find an expression for the location $h(x)$ of the surface of the liquid assuming that $\beta = 0$.

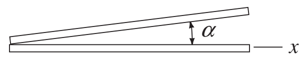

Figure P1.67

Vapor Pressure

1.68 Water is transported through the pipe of Figure P1.68 such that a vacuum of 80 kPa exists at a particular location. What is the maximum possible temperature of the water? Use $p_{atm} = 92 \text{ kPa}$.

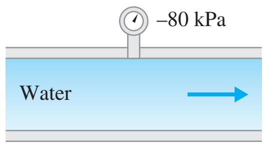

Figure P1.68

1.69 A group of explorers desired their elevation. An engineer boiled water and measured the temperature to be 82°C. They found a fluid mechanics book in a backpack, and the engineering explorer told the group their elevation! What elevation should the engineer have quoted?

1.70 A tank half-filled with 40°C water is to be evacuated. What is the minimum pressure that can be expected in the space above the water?

1.71 Water is forced through a contraction causing low pressure. The water is observed to "boil" at a pressure of −80 kPa (gage). If atmospheric pressure is 100 kPa, what is the temperature of the water?

1.72 Oil is transported through a pipeline by a series of pumps that can produce a pressure of 10 MPa in the oil leaving each pump. The losses in the pipeline cause a pressure drop of 600 kPa each kilometer. What is the maximum possible spacing of the pumps?

Ideal Gas

1.73 Determine the density and the specific gravity of air at standard conditions (i.e., 15°C and 101 kPa absolute).

1.74 Calculate the density of air inside a house and outside a house using 20°C inside and −25°C outside. Use an atmospheric pressure of 85 kPa. Do you think there would be a movement of air from the inside to the outside (infiltration), even without a wind? Explain.

1.75 A 0.41-m^3 air tank is pressurized to 5.17 mPa. When the temperature reaches −13°C, calculate the density and the air mass.

1.76 Estimate the weight of air contained in a classroom that measures $10 \text{ m} \times 20 \text{ m} \times 4 \text{ m}$. Assume reasonable values for the variables.

1.77 A car tire is pressurized to 240 kPa in Michigan when the temperature is −13°C. The car is driven to Arizona, where the temperature on the highway, and in the tire, reaches 66°C. Estimate the maximum pressure in the tire.

1.78 The mass of all the air in the atmosphere contained above a 1-m^2 area is to be contained in a spherical volume. Estimate the diameter of the sphere if the air is at standard conditions.

First Law

1.79 A body falls from rest. Determine its velocity after 3 m and 6 m, using the energy equation.

1.80 Determine the maximum final velocity of the 15-kg mass of Figure P1.80 moving horizontally if it starts at 10 m/s and moves a distance of 10 m while the following net force acts in the direction of motion (where s is the distance in the direction of motion):

(a) 200 N **(b)** $20s$ N
(c) $200 \cos (s\pi/20)$ N