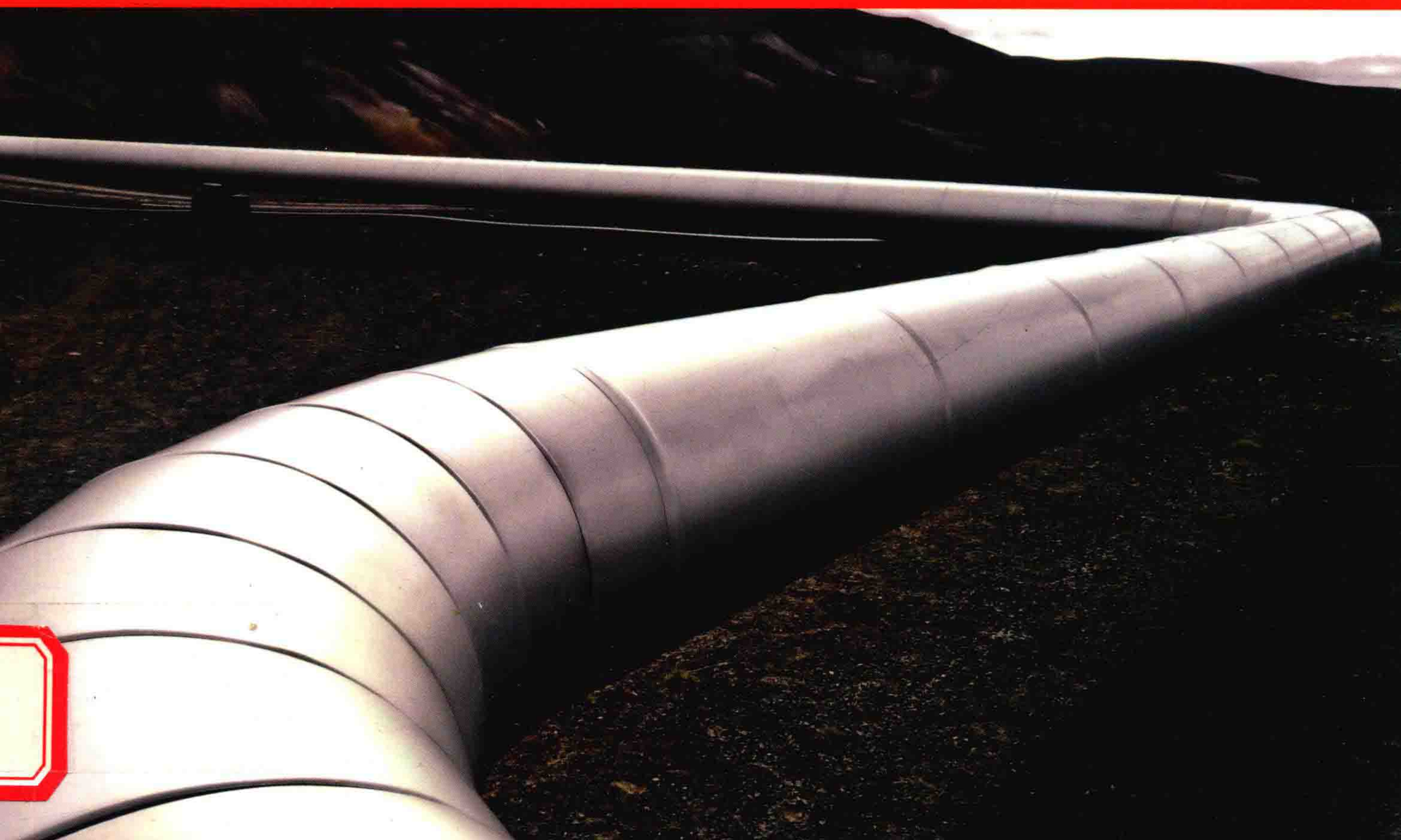
ELGER | LEBRET | CROWE | ROBERTSON

Engineering Fluid Mechanics

Eleventh Edition

EXCLUSIVE CONTENT



INTERNATIONAL STUDENT VERSION

WILEY

ELEVENTH EDITION

ENGINEERING FLUID MECHANICS

International Student Version

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WILEY

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This 11th Edition is dedicated to Dr. Clayton Crowe (1933–2012) and to our wonderful colleagues, students, friends, and families. We especially acknowledge our spouses Linda and Jim and Barbara's grandson Moses Pakootas for their patience and support.

PREFACE

Audience

This book is written for engineering students of all majors who are taking a first or second course in fluid mechanics. Students should have background knowledge in physics (mechanics), chemistry, statics, and calculus.

Why We Wrote This Book

Our mission is to equip people to do engineering skillfully. Thus, we wrote this book to explain the main ideas of fluid mechanics at a level appropriate for a first or second college course. In addition, we have included selected engineering skills (e.g., critical thinking, problem solving, and estimation) because we believe that practicing these skills will help all students learn fluid mechanics better.

Approach

Knowledge. Each chapter begins with statements of what is important to learn. These learning outcomes are formulated in terms of what *students will be able to do.* Then, the chapter sections present the knowledge. Finally, the knowledge is summarized at the end of each chapter.

Practice with Feedback. The research of Dr. Anders Ericsson suggests that learning is brought about through *deliberate practice*. Deliberate practice involves doing something and then getting feedback. To provide opportunities for deliberate practice, this text contains end-of-chapter problems. The answers to selected, even-numbered problems are provided in the back of the book. Professors can gain access to the solution manual by contacting their Wiley representative.

Features of this Book

Learning Outcomes. Each chapter begins with learning outcomes so that students can identify what knowledge they should gain by studying the chapter.

Rationale. Each section describes what content is presented and why this content is relevant.

Visual Approach. This text uses sketches and photographs to help students learn more effectively by connecting images to words and equations.

Foundational Concepts. This text presents major concepts in a clear and concise format. These concepts form building blocks for higher levels of learning.

Seminal Equations. This text emphasizes technical derivations so that students can learn to do the derivations on their own, increasing their level of knowledge. Features include the following:

- Derivations of main equations are presented in a step-by-step fashion.

- The holistic meaning of main equations is explained using words.
- Main equations are named and listed in Table F.2.
- Main equations are summarized in tables in the chapters.
- A process for applying each main equation is presented in the relevant chapter.

Chapter Summaries. Each chapter concludes with a summary so that students can review the key knowledge in the chapter.

Process Approach. A process is a method for getting results. A process approach involves figuring out how experts do things and adapting this same approach. This textbook presents multiple processes.

Wales-Woods Model. The Wales-Woods Model represents how experts solve problems. This model is presented in Chapter 1 and used in example problems throughout the text.

Grid Method. This text presents a systematic process, called the grid method, for carrying and canceling units. Unit practice is emphasized because it helps engineers spot and fix mistakes and because it helps engineers put meaning on concepts and equations.

Traditional and SI Units. Examples and homework problems are presented using both SI and traditional unit systems. This presentation helps students gain familiarity with units that are used in professional practice.

Example Problems. Each chapter has examples to show how the knowledge is used in context and to present essential details needed for application.

Solutions Manual. The text includes a detailed solutions manual for instructors. Many solutions are presented with the Wales-Woods Model.

Image Gallery. The figures from the text are available in PowerPoint format, for easy inclusion in lecture presentations. This resource is available only to instructors. To request access to this and all instructor resources, please contact your local Wiley sale representative.

Interdisciplinary Approach. Historically, this text was written for the civil engineer. We are retaining this approach while adding material so that the text is also appropriate for other engineering disciplines. For example, the text presents the Bernoulli equation using both head terms (civil engineering approach) and terms with units of pressure (the approach used by chemical and mechanical engineers). We include problems that are relevant to product development as practiced by mechanical and electrical engineers. Some problems feature other disciplines, such as exercise physiology. The reason for this interdisciplinary approach is that the world of today's engineer is becoming more and more interdisciplinary.

What is New in the 11th Edition

1. Critical Thinking (CT) is introduced in Chapter 1. **Rationale**: When students apply CT, they learn fluid mechanics better. Also, they become better engineers.
2. Learn outcomes are organized into categories. **Rationale**: The grouping of outcomes increases the clarity about what is important.
3. New material was added in Chapter 1 describing force, mass, weight, Newton's law of universal gravitation, density, and specific weight. **Rationale**: We have seen many instances of student work indicating that these basic concepts are sometimes not in place. Also, introducing these topics in Chapter 1 provides a way to introduce engineering calculations earlier in the book.
4. We introduced the **Voice of the Engineer** in Chapter 1 as a way to present wisdom. **Rationale**: The **Voice of the Engineer** provides a structure for presenting an attitude that is widely shared in the professional engineering community.
5. In Chapter 1, new material was added about the ideal gas law (IGL). **Rationale**: The IGL section now has the right level of technical detail for engineering problems.
6. In Chapter 1, the material on problem solving was rewritten. Also, the Wales-Woods Model is now summarized on one page. **Rationale**: Solving problems and building math models are fundamental skills for the engineer. The ideas in Chapter 1 represent the best ideas that we have seen in the literature.

7. Chapter 2 has a new section on finding fluid properties. This new section, §2.2, contains the summary table that previously was situated at the end of the chapter. **Rationale**: Finding fluid properties is an important learning outcome for Chapter 2. The new section puts an emphasis on this outcome and organizes the ideas in one place. Previously, the knowledge needed to find fluid properties was scattered throughout Chapter 2.
8. Chapter 2 has a new section on stress, how to relate stress to force, and on common forces. **Rationale**: Stress and force are seminal ideas in mechanics. This section defines the relevant terms and shows how they are related.
9. The Chapter 2 discussions on the shear stress equation were edited to increase clarity and concision. **Rationale**: The shear stress equation is one of the seminal fluid mechanics equations.
10. The end-of-chapter problems include new or revised problems. **Rationale**: Both learning and assessment of learning are made easier by having problems available.
11. Chapter 9 was rewritten to make the chapter more suitable for students taking a first course in fluid mechanics.

Author Team

The book was originally written by Professor John Roberson, with Professor Clayton Crowe adding the material on compressible flow. Professor Roberson retired from active authorship after the 6th edition, Professor Donald Elger joined on the 7th edition, and Professor Barbara LeBret joined on the 9th edition. Professor Crowe retired from active authorship after the 9th edition. Professor Crowe passed away on February 5, 2012.

Donald Elger, Barbara LeBret, and Clayton Crowe (Photo by Archer Photography: www.archerstudio.com)

Acknowledgments

We acknowledge our colleagues and mentors. Donald Elger acknowledges his Ph.D. mentor, Ronald Adams, who always asked why and how. He also acknowledges Ralph Budwig, fluid mechanics researcher and colleague, who has provided many hours of delightful inquiry about fluid mechanics. Barbara LeBret acknowledges Wilfried Brutsuert at Cornell University and George Bloomsburg at the University of Idaho, who inspired her passion for fluid mechanics. Last but not least, we thank technical reviewer Daniel Flick for his excellent work.

Contact Us

We welcome feedback and ideas for interesting end-of-chapter problems. Please contact us at the following email addresses:

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TABLE F.1 Formulas for Unit Conversions*

Name, Symbol, Dimensions			Conversion Formula
Length	L	L	**1 m** = 3.281 ft = 1.094 yd = 39.37 in = km/1000 = 10^6 μm **1 ft** = 0.3048 m = 12 in = mile/5280 = km/3281 **1 mm** = m/1000 = in/25.4 = 39.37 mil = 1000 μm = 10^7 Å
Speed	V	L/T	**1 m/s** = 3.600 km/hr = 3.281 ft/s = 2.237 mph = 1.944 knots **1 ft/s** = 0.3048 m/s = 0.6818 mph = 1.097 km/hr = 0.5925 knots
Mass	m	M	**1 kg** = 2.205 lbm = 1000 g = slug/14.59 = (metric ton or tonne or Mg)/1000 **1 lbm** = lbf·s^2/(32.17 ft) = kg/2.205 = slug/32.17 = 453.6 g = 16 oz = 7000 grains = short ton/2000 = metric ton (tonne)/2205
Density	ρ	M/L^3	**1000 kg/m³** = 62.43 lbm/ft³ = 1.940 slug/ft³ = 8.345 lbm/gal (US)
Force	F	ML/T^2	**1 lbf** = 4.448 N = 32.17 lbm·ft/s^2 **1 N** = kg·m/s^2 = 0.2248 lbf = 10^5 dyne
Pressure, shear stress	p, τ	M/LT^2	**1 Pa** = N/m^2 = kg/m·s^2 = 10^{-5} bar = 1.450 × 10^{-4} lbf/in² = inch H_2O/249.1 = 0.007501 torr = 10.00 dyne/cm² **1 atm** = 101.3 kPa = 2116 psf = 1.013 bar = 14.70 lbf/in² = 33.90 ft of water = 29.92 in of mercury = 10.33 m of water = 760 mm of mercury = 760 torr **1 psi** = atm/14.70 = 6.895 kPa = 27.68 in H_2O = 51.71 torr
Volume	$\forall$	L^3	**1 m³** = 35.31 ft³ = 1000 L = 264.2 U.S. gal **1 ft³** = 0.02832 m³ = 28.32 L = 7.481 U.S. gal = acre-ft/43,560 **1 U.S. gal** = 231 in³ = barrel (petroleum)/42 = 4 U.S. quarts = 8 U.S. pints = 3.785 L = 0.003785 m³
Volume flow rate (discharge)	Q	L^3/T	**1 m³/s** = 35.31 ft³/s = 2119 cfm = 264.2 gal (US)/s = 15850 gal (US)/m **1 cfs** = 1 ft³/s = 28.32 L/s = 7.481 gal (US)/s = 448.8 gal (US)/m
Mass flow rate	$\dot{m}$	M/T	**1 kg/s** = 2.205 lbm/s = 0.06852 slug/s
Energy and work	E, W	ML^2/T^2	**1 J** = kg·m²/s² = N·m = W·s = volt·coulomb = 0.7376 ft·lbf = 9.478 × 10^{-4} Btu = 0.2388 cal = 0.0002388 Cal = 10^7 erg = kWh/3.600 × 10^6
Power	P, $\dot{E}$, $\dot{W}$	ML^2/T^3	**1 W** = J/s = N·m/s = kg·m²/s³ = 1.341 × 10^{-3} hp = 0.7376 ft·lbf/s = 1.0 volt-ampere = 0.2388 cal/s = 9.478 × 10^{-4} Btu/s **1 hp** = 0.7457 kW = 550 ft·lbf/s = 33,000 ft·lbf/min = 2544 Btu/h
Angular speed	ω	T^{-1}	**1.0 rad/s** = 9.549 rpm = 0.1591 rev/s
Viscosity	μ	M/LT	**1 Pa·s** = kg/m·s = N·s/m² = 10 poise = 0.02089 lbf·s/ft² = 0.6720 lbm/ft·s
Kinematic viscosity	ν	L^2/T	**1 m²/s** = 10.76 ft²/s = 10^6 cSt
Temperature	T	Θ	**K** = °C + 273.15 = °R/1.8 **°C** = (°F − 32)/1.8 **°R** = °F + 459.67 = 1.8 K **°F** = 1.8°C + 32

*Visit www.onlineconversion.com for a useful online reference.

TABLE F.2 Commonly Used Equations

Ideal gas law equations

$p = \rho RT$

$p\forall = mRT$

$p\forall = nR_uT$

$M = m/n;\ R = R_u/M$ (§1.6)

Specific weight

$\gamma = \rho g$ (Eq. 1.21)

Kinematic viscosity

$\nu = \mu/\rho$ (Eq. 2.1)

Specific gravity

$$S = \frac{\rho}{\rho_{\mathrm{H_2O\ at\ 4^\circ C}}} = \frac{\gamma}{\gamma_{\mathrm{H_2O\ at\ 4^\circ C}}} \quad \text{(Eq. 2.3)}$$

Definition of viscosity

$$\tau = \mu \frac{dV}{dy} \quad \text{(Eq. 2.15)}$$

Pressure equations

$p_{\text{gage}} = p_{\text{abs}} - p_{\text{atm}}$ (Eq. 3.3a)

$p_{\text{vacuum}} = p_{\text{atm}} - p_{\text{abs}}$ (Eq. 3.3b)

Hydrostatic equation

$$\frac{p_1}{\gamma} + z_1 = \frac{p_2}{\gamma} + z_2 = \text{constant} \quad \text{(Eq. 3.10a)}$$

$p_z = p_1 + \gamma z_1 = p_2 + \gamma z_2 = \text{constant}$ (Eq. 3.10b)

$\Delta p = -\gamma \Delta z$ (Eq. 3.10c)

Manometer equations

$$p_2 = p_1 + \sum_{\text{down}} \gamma_i h_i - \sum_{\text{up}} \gamma_i h_i \quad \text{(Eq. 3.21)}$$

$h_1 - h_2 = \Delta h(\gamma_B/\gamma_A - 1)$ (Eq. 3.22)

Hydrostatic force equations (flat panels)

$F_P = \bar{p}A$ (Eq. 3.28)

$$y_{\text{cp}} - \bar{y} = \frac{\bar{I}}{\bar{y}A} \quad \text{(Eq. 3.33)}$$

Buoyant force (Archimedes equation)

$F_B = \gamma \forall_D$ (Eq. 3.41a)

The Bernoulli equation

$$\left(\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2\right) \quad \text{(Eq. 4.21b)}$$

$$\left(p_1 + \frac{\rho V_1^2}{2} + \rho g z_1\right) = \left(p_2 + \frac{\rho V_2^2}{2} + \rho g z_2\right) \quad \text{(Eq. 4.21a)}$$

Volume flow rate equation

$$Q = \bar{V}A = \frac{\dot{m}}{\rho} = \int_A V\,dA = \int_A \mathbf{V} \cdot \mathbf{dA} \quad \text{(Eq. 5.10)}$$

Mass flow rate equation

$$\dot{m} = \rho A\bar{V} = \rho Q = \int_A \rho V\,dA = \int_A \rho \mathbf{V} \cdot \mathbf{dA} \quad \text{(Eq. 5.11)}$$

Continuity equation

$$\frac{d}{dt}\int_{\text{cv}} \rho\, d\forall + \int_{\text{cs}} \rho \mathbf{V} \cdot \mathbf{dA} = 0 \quad \text{(Eq. 5.28)}$$

$$\frac{d}{dt} M_{\text{cv}} + \sum_{\text{cs}} \dot{m}_o - \sum_{\text{cs}} \dot{m}_i = 0 \quad \text{(Eq. 5.29)}$$

$\rho_2 A_2 V_2 = \rho_1 A_1 V_1$ (Eq. 5.33)

Momentum equation

$$\sum \mathbf{F} = \frac{d}{dt}\int_{\text{cv}} \mathbf{v}\rho\, d\forall + \int_{\text{cs}} \mathbf{v}\rho \mathbf{V} \cdot \mathbf{dA} \quad \text{(Eq. 6.7)}$$

$$\sum \mathbf{F} = \frac{d(m_{\text{cv}}\mathbf{v}_{\text{cv}})}{dt} + \sum_{\text{cs}} \dot{m}_o \mathbf{v}_o - \sum_{\text{cs}} \dot{m}_i \mathbf{v}_i \quad \text{(Eq. 6.10)}$$

Energy equation

$$\left(\frac{p_1}{\gamma} + \alpha_1 \frac{\bar{V}_1^2}{2g} + z_1\right) + h_p = \left(\frac{p_2}{\gamma} + \alpha_2 \frac{\bar{V}_2^2}{2g} + z_2\right) + h_t + h_L \quad \text{(Eq. 7.29)}$$

The power equation

$P = FV = T\omega$ (Eq. 7.3)

$P = \dot{m}gh = \gamma Q h$ (Eq. 7.31)

Efficiency of a machine

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} \quad \text{(Eq. 7.32)}$$

Reynolds number (pipe)

$$\mathrm{Re}_D = \frac{VD}{\nu} = \frac{\rho VD}{\mu} = \frac{4Q}{\pi D \nu} = \frac{4\dot{m}}{\pi D \mu} \quad \text{(Eq. 10.1)}$$

Combined head loss equation

$$h_L = \sum_{\text{pipes}} f \frac{L}{D}\frac{V^2}{2g} + \sum_{\text{components}} K \frac{V^2}{2g} \quad \text{(Eq. 10.45)}$$

Friction factor *f* (Resistance coefficient)

$$f = \frac{64}{\mathrm{Re}_D} \quad \mathrm{Re}_D \le 2000 \quad \text{(Eq. 10.34)}$$

$$f = \frac{0.25}{\left[\log_{10}\left(\frac{k_s}{3.7D} + \frac{5.74}{\mathrm{Re}_D^{0.9}}\right)\right]^2} \quad (\mathrm{Re}_D \ge 3000) \quad \text{(Eq. 10.39)}$$

Drag force equation

$$F_D = C_D A\left(\frac{\rho V_0^2}{2}\right) \quad \text{(Eq. 11.5)}$$

Lift force equation

$$F_L = C_L A\left(\frac{\rho V_0^2}{2}\right) \quad \text{(Eq. 11.17)}$$

TABLE F.3 Useful Constants

Name of Constant	Value
Acceleration of gravity	$g = 9.81\ \mathrm{m/s^2} = 32.2\ \mathrm{ft/s^2}$
Universal gas constant	$R_u = 8.314\ \mathrm{kJ/kmol\cdot K} = 1545\ \mathrm{ft\cdot lbf/lbmol\cdot {}^\circ R}$
Standard atmospheric pressure	$p_{\mathrm{atm}} = 1.0$ atm $= 101.3$ kPa $= 14.70$ psi $= 2116$ psf $= 33.90$ ft of water $p_{\mathrm{atm}} = 10.33$ m of water $= 760$ mm of Hg $= 29.92$ in of Hg $= 760$ torr $= 1.013$ bar

TABLE F.4 Properties of Air [$T = 20°\mathrm{C}$ (68°F), $p = 1$ atm]

Property	SI Units	Traditional Units
Specific gas constant	$R_{\mathrm{air}} = 287.0\ \mathrm{J/kg\cdot K}$	$R_{\mathrm{air}} = 1716\ \mathrm{ft\cdot lbf/slug\cdot {}^\circ R}$
Density	$\rho = 1.20\ \mathrm{kg/m^3}$	$\rho = 0.0752\ \mathrm{lbm/ft^3} = 0.00234\ \mathrm{slug/ft^3}$
Specific weight	$\gamma = 11.8\ \mathrm{N/m^3}$	$\gamma = 0.0752\ \mathrm{lbf/ft^3}$
Viscosity	$\mu = 1.81 \times 10^{-5}\ \mathrm{N\cdot s/m^2}$	$\mu = 3.81 \times 10^{-7}\ \mathrm{lbf\cdot s/ft^2}$
Kinematic viscosity	$\nu = 1.51 \times 10^{-5}\ \mathrm{m^2/s}$	$\nu = 1.63 \times 10^{-4}\ \mathrm{ft^2/s}$
Specific heat ratio	$k = c_p/c_v = 1.40$	$k = c_p/c_v = 1.40$
Specific heat	$c_p = 1004\ \mathrm{J/kg\cdot K}$	$c_p = 0.241\ \mathrm{Btu/lbm\cdot {}^\circ R}$
Speed of sound	$c = 343\ \mathrm{m/s}$	$c = 1130\ \mathrm{ft/s}$

TABLE F.5 Properties of Water [$T = 15°\mathrm{C}$ (59°F), $p = 1$ atm]

Property	SI Units	Traditional Units
Density	$\rho = 999\ \mathrm{kg/m^3}$	$\rho = 62.4\ \mathrm{lbm/ft^3} = 1.94\ \mathrm{slug/ft^3}$
Specific weight	$\gamma = 9800\ \mathrm{N/m^3}$	$\gamma = 62.4\ \mathrm{lbf/ft^3}$
Viscosity	$\mu = 1.14 \times 10^{-3}\ \mathrm{N\cdot s/m^2}$	$\mu = 2.38 \times 10^{-5}\ \mathrm{lbf\cdot s/ft^2}$
Kinematic viscosity	$\nu = 1.14 \times 10^{-6}\ \mathrm{m^2/s}$	$\nu = 1.23 \times 10^{-5}\ \mathrm{ft^2/s}$
Surface tension (water–air)	$\sigma = 0.073\ \mathrm{N/m}$	$\sigma = 0.0050\ \mathrm{lbf/ft}$
Bulk modulus of elasticity	$E_v = 2.14 \times 10^9\ \mathrm{Pa}$	$E_v = 3.10 \times 10^5\ \mathrm{psi}$

TABLE F.6 Properties of Water [$T = 4°\mathrm{C}$ (39°F), $p = 1$ atm]

Property	SI Units	Traditional Units
Density	$\rho = 1000\ \mathrm{kg/m^3}$	$\rho = 62.4\ \mathrm{lbm/ft^3} = 1.94\ \mathrm{slug/ft^3}$
Specific weight	$\gamma = 9810\ \mathrm{N/m^3}$	$\gamma = 62.4\ \mathrm{lbf/ft^3}$

CONTENTS

CHAPTER**ONE**

Introduction

CHAPTER ROAD MAP Our purpose is to equip you for success. Success means that you can do engineering skillfully. This chapter presents (a) fluid mechanics topics and (b) engineering skills. The engineering skills are optional. We included these skills because we believe that applying these skills while you are learning fluid mechanics will strengthen your fluid mechanics knowledge while also making you a better engineer.

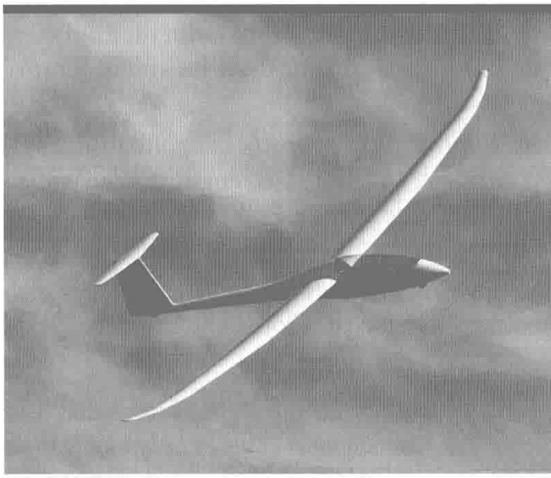


FIGURE 1.1
As engineers, we get to design fascinating systems like this glider. This is exciting! (© Ben Blankenburg/Corbis RF/Age Fotostock America, Inc.)

LEARNING OUTCOMES

ENGINEERING FLUID MECHANICS (§1.1*).

- Define engineering.
- Define fluid mechanics.

MATERIAL SCIENCE TOPICS (§1.2).

- Explain material behaviors using either a microscopic or a macroscopic approach or both.
- Know the main characteristics of liquids, gases, and fluids.
- Understand the concepts of body, material particle, body-as-a-particle, and the continuum assumption.

DENSITY AND SPECIFIC WEIGHT (§1.5).

- Know the main ideas about $W = mg$.
- Know the main ideas about density and specific weight.

THE IDEAL GAS LAW (IGL) (§1.6).

- Describe an ideal gas and a real gas.
- Convert temperature, pressure, and mole/mass units.
- Apply the IGL equations.

OPTIONAL ENGINEERING SKILLS (§1.1, §1.3, §1.4, §1.7, §1.8).

- Apply critical thinking to fluid mechanics problems.
- Make estimates when solving fluid mechanics problems.
- Apply ideas from calculus to fluid mechanics.
- Carry and cancel units when doing calculations.
- Check that an equation is DH (dimensionally homogeneous).
- Apply problem solving methods to fluid mechanics problems.

*The symbol § means "section"; e.g., the notation "§1.1" means Section 1.1.

1.1 Engineering Fluid Mechanics

In this section, we explain what engineering fluid mechanics means, and then we introduce *critical thinking* (CT), a method that is at the heart of doing engineering well.

About Engineering Fluid Mechanics

Why study engineering fluid mechanics? To answer this question, we'll start with some examples:

- When people started living in cities, they faced problems involving water. Those people who solved these problems were the engineers. For example, engineers designed aqueducts to bring water to the people. Engineers innovated technologies to remove waste water from the cities, thereby keeping the towns clean and free from effluent. Engineers developed technologies for treating water to remove waterborne diseases and to remove hazards such as arsenic.
- At one time, people had no flying machines. So, the Wright Brothers applied the engineering method to develop the world's first airplane. In the 1940s, engineers developed practical jet engines. More recently, the engineers at The Boeing Company developed the 787 Dreamliner.
- People have access to electrical power because engineers have developed technologies such as the water turbine, the wind turbine, the electric generator, the motor, and the electric grid system.

The preceding examples reveal that engineers solve problems and innovate in ways that lead to the development or improvement of technology. *How are engineers able to accomplish these difficult feats*? Why were the Wright Brothers able to succeed? What was the secret sauce that Edison had? The answer is that engineers have developed a method for success that is called the **engineering method**, which is actually a collection of submethods such as building math models, designing and conducting experiments, and designing and building physical systems.

Based on the ideas just presented, **engineering** is the body of knowledge that is concerned with solving problems by creating, designing, applying, and improving technology. **Engineering fluid mechanics** is engineering when a project involves substantial knowledge from the discipline of fluid mechanics.

Defining Mechanics

Mechanics is the branch of science that deals with motion and the forces that produce this motion. Mechanics is organized into two main categories: **solid mechanics** (materials in the solid state) and **fluid mechanics** (materials in the gas or liquid state). Note that many of the concepts of mechanics apply to both fluid mechanics and solid mechanics.

Critical Thinking (CT)

This section introduces critical thinking. Rationale. (1) The heart of the engineering method is critical thinking (CT); thus, skill with CT will give you the ability to do engineering well. (2) Applying CT while you are learning fluid mechanics will result in better learning.

Examples of CT are common. One example is seen when a police detective uses physical evidence and deductive reasoning to reach a conclusion about who committed a crime. A second example occurs when a medical doctor uses diagnostic test data and evidence from a physical examination to reach a conclusion about why a patient is ill. A third example exists when an engineering researcher gathers experimental data about groundwater flow, then reaches some conclusions and publishes these conclusions in a scientific journal. A fourth

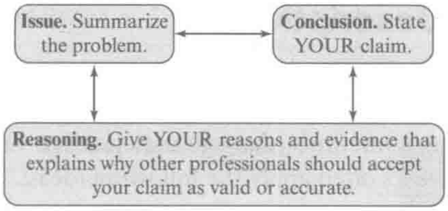


FIGURE 1.2

The Standard Structure of Critical Thinking (SSCT).

example arises when a practicing engineer uses experimental data and engineering calculations to conclude that Site ABC is a good choice for a wind turbine. These examples reveal some facts about critical thinking:

- CT is used by professionals in most fields (e.g., detectives, medical doctors, scientists, and engineers).
- Professionals apply CT to avoid major mistakes. No competent detective wants an innocent person convicted of a crime. No competent physician wants to make an incorrect diagnosis. No competent engineer wants a bridge to fail.
- CT involves methods that are agreed upon by a professional community. For example, the method of fingerprinting is accepted within the law enforcement community. Similarly, engineering has many agreed-upon methods (you can learn some of these methods in this book).

In summary, **critical thinking** is a collection of beliefs and methods that are accepted by a professional community for reaching a sound or strong conclusion. Some examples of the beliefs associated with CT are as follows:

- I want to find out the best idea or what is most correct (I have no interest in *being right*; I want to find out *what is right*).
- I want to make sure that my technical work is valid or correct (I don't want major mistakes or flaws; I bend over backwards to validate my findings).
- I am open to new beliefs and ideas, especially when these ideas are aligned with the knowledge and the beliefs of the professional community (I don't get stuck thinking that I am always right, my ideas are best, or that I know everything; by being open to new ideas, I open myself up to learning).

Regarding "how to do critical thinking," we teach and we apply the **Standard Structure of CT** (Fig. 1.2), which involves three methods:

1. **Issue**. Define the problem you are trying to solve so that is clear and unambiguous. Note that you will often need to rewrite or paraphrase the issue or question.
2. **Reasoning**. List the reasons that explain why professionals should accept your claim (i.e., your answer, your explanation, your conclusion, or your recommendation). To create your reasoning, take actions such as stating facts, citing references, defining terms, applying deductive logic, applying inductive logic, and building subconclusions.
3. **Conclusions**. State your claim. Make sure your claim addresses the issue. Recognize that a claim can be presented in multiple ways, such as an answer, a recommendation, or your stance on a controversial issue.

1.2 How Materials are Idealized

To understand the behavior of materials, engineers apply a few simple ideas. This section presents some of these ideas.

The Microscopic and Macroscopic Descriptions

Engineers strive to understand things. For example, an engineer might ask, why does Steel Alloy #1 fail given that Steel Alloy #2 does not fail in the same application? Or, an engineer might ask, why does water boil? Why does this boiling sometimes damage materials, as in cavitation*? To address questions about materials, engineers often apply the following ideas:

- **Microscopic Description**. Explain something about a material by describing what is happening at the atomic level (i.e., describing the atoms, molecules, electrons, etc.).
- **Macroscopic Description**. Explain something about a material without resorting to descriptions at the atomic level.

Forces between Molecules

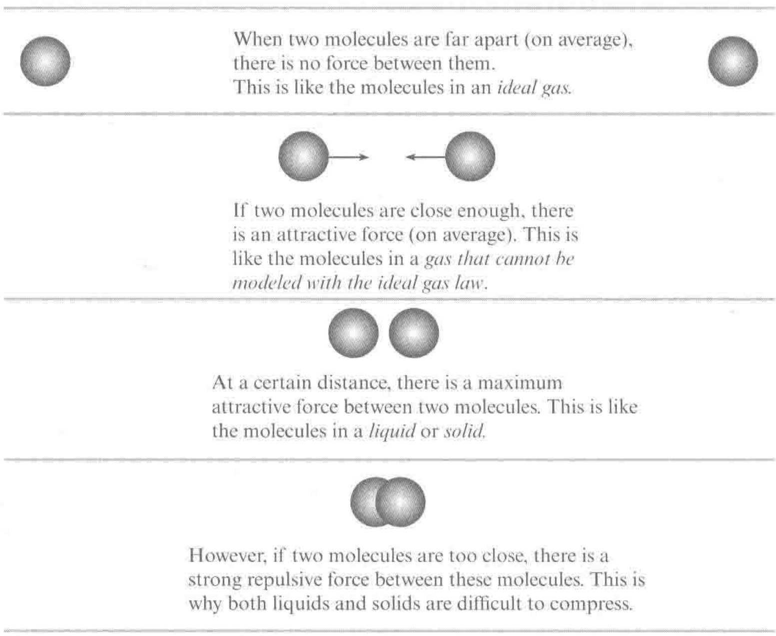
One of the best ways to understand materials is to apply the idea that molecules attract one another if they are close together and repel if they are too close[†] (Fig. 1.3).

Defining the Liquid, Gas, and Fluid

In science, there are four states of matter: gas, liquid, solid, and plasma. A **gas** is a state of matter in which the molecules are on average far apart so that the forces between molecules (or atoms) is typically very small or zero. Consequently, a gas lacks a fixed shape, and it also lacks a fixed volume, because a gas will expand to fill its container.

A **liquid** is a state of matter in which the molecules are on average close together so that the forces between molecules (or atoms) are strong. In addition, the molecules are relatively

FIGURE 1.3
A description[‡] of the forces between molecules.

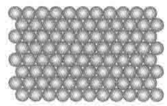
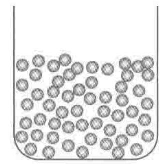
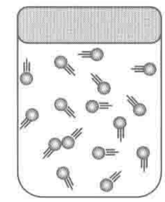


Cavitation is explained in §5.5.

[†]Dr. Richard Feynman, who won the Nobel Prize in Physics, calls this the *single most important idea in science*. See the *Feynman Lectures on Physics*, Vol. 1, p. 2.

[‡]For additional details about forces between molecules, consult an expert source, such as a chemistry text or a professor who teaches material science.

TABLE 1.1 Comparison of Solids, Liquids, and Gases

Attribute	Solid	Liquid	Gas
Typical Visualization			
Description	Solids hold their shape; no need for a container	Liquids take the shape of the container and will stay in an open container	Gases expand to fill a closed container
Mobility of Molecules	Molecules have low mobility because they are bound in a structure by strong intermolecular forces	Molecules move around freely even though there are strong intermolecular forces between the molecules	Molecules move around freely with little interaction except during collisions; this is why gases expand to fill their container
Typical Density	Often high; e.g., the density of steel is 7700 kg/m^3	Medium; e.g., the density of water is 1000 kg/m^3	Small; e.g., the density of air at sea level is 1.2 kg/m^3
Molecular Spacing	Small—molecules are close together	Small—molecules are held close together by intermolecular forces	Large—on average, molecules are far apart
Effect of Shear Stress	Produces deformation	Produces flow	Produces flow
Effect of Normal Stress	Produces deformation that may associate with volume change; can cause failure	Produces deformation associated with volume change	Produces deformation associated with volume change
Viscosity	NA	High; decreases as temperature increases	Low; increases as temperature increases
Compressibility	Difficult to compress; bulk modulus of steel is 160×10^9 Pa	Difficult to compress; bulk modulus of liquid water is 2.2×10^9 Pa	Easy to compress; bulk modulus of a gas at room conditions is about 1.0×10^5 Pa

free to move around. In comparison, when a material is in the solid state, atoms tend to be fixed in place—for example, in a crystalline lattice. Thus, a liquid flows easily as compared to a solid. Due to the strong forces between molecules, a liquid has a fixed volume but not a fixed shape.

The term **fluid** refers to both a liquid and a gas and is generally defined as a state of matter in which the material flows freely under the action of a shear stress.*

Table 1.1 provides additional facts about solids, liquids, and gases. Notice that many features in this table can be explained by applying the ideas in Fig. 1.3. **Example**. The density of a liquid or a solid is much higher than the density of a gas because the strong attractive forces in a liquid or solid act to bring the molecules closer together. **Example**. A liquid is difficult to compress because the molecules will have strong repulsive forces if they are brought close together. In contrast, a gas is easy to compress because there are no forces (on average) between the molecules.

*Shear stress is explained in §2.4.