FLUID MECHANICS

R. C. HIBBELER

SECOND EDITION

Pearson

Fluid Mechanics

Second Edition

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SECOND EDITION

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R. C. HIBBELER

Kai Beng Yap

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To the Student

With the hope that this work will stimulate
an interest in Fluid Mechanics
and provide an acceptable guide to its understanding.

PREFACE

It is hoped that this book will provide the student with a clear and thorough presentation of the theory and applications of fluid mechanics. In order to achieve this objective, I have incorporated many of the suggestions and comments from the book's reviewers, university colleagues who have e-mailed me, and from my students. Some of the more important improvements are listed below.

New to This Edition

- **Rewriting of Text Material.** The purpose here is to achieve a further clarification of the material throughout the book, either with an expanded discussion, or by deleting material that seemed not relevant to a particular topic.

- **Expanded Topic Coverage.** The material in Chapters 1, 3, 5, 7, 10, and 11 have enhanced discussion on some topics, including additional data in the tables in Chapters 10, 11, and 12.

- **New Example Problems.** The addition of new examples to Chapters 7 and 10 further illustrate the applications of the theory. Many of the examples throughout the book have been expanded for clarification.

- **New Fundamental Problems.** These problems have been added to Chapter 10 to enhance the student's understanding of the theory and its applications, and to provide a review of the material that can be used to study for various engineering exams.

- **New Photos and Enhanced Art.** Many new photos and figures have been added to help the student obtain a better understanding of the subject matter.

- **New Equation Summaries.** These are found at the end of Chapters 7, 11, 12, and 13 so that students may use formula sheets when taking exams that require application of some key equations.

Besides the new features mentioned, other outstanding features that define the contents of this book include the following.

Organization and Approach. Each chapter is organized into well-defined sections that contain an explanation of specific topics, illustrative example problems, and at the end of the chapter, a set of relevant homework problems. The topics within each section are placed into subgroups defined by boldface titles. The purpose of this organization is to present a structured method for introducing each new definition or concept, and to make the book a convenient resource for later reference and review.

Procedures for Analysis. This unique feature provides the student with a logical and orderly method to follow when applying the theory that has been discussed in a particular section. The example problems are then solved using this outlined method in order to clarify its numerical application. Realize, however, that once the relevant principles have been mastered, and enough confidence and judgment has been obtained, the student can then develop his or her own procedures for solving problems.

Important Points. This feature provides a review or summary of the most important concepts in a section, and highlights the most significant points that should be remembered when applying the theory to solve problems. A further review of the material is given at the end of the chapter.

Photos. The relevance of knowing the subject matter is reflected by the realistic applications depicted in the many photos placed throughout the book. These photos are often used to show how the principles of fluid mechanics apply to real-world situations.

Fundamental Problems. These problem sets are selectively located just after the example problems. They offer students simple applications of the concepts and therefore provide them with the chance to develop their problem-solving skills before attempting to solve any of the standard problems that follow. Students may consider these problems as extended examples, since they all have complete solutions and answers given in the back of the book. Additionally, the fundamental problems offer students an excellent means of preparing for exams, and they can be used at a later time to prepare for various engineering exams.

Homework Problems. The majority of problems in the book depict realistic situations encountered in engineering practice. It is hoped that this realism will both stimulate interest in the subject, and provide a means for developing the skills to reduce any problem from its physical description to a model or symbolic representation to which the principles of fluid mechanics may then be applied.

Throughout the book, all problems use SI units. Furthermore, in any set, an attempt has been made to arrange the problems in order of increasing difficulty. Except for every fourth problem, indicated by an asterisk (*), the answers to all the other problems are given in the back of the book.

Conceptual Problems. Throughout the text, usually at the end of most chapters, there is a set of problems that involve conceptual situations related to the application of the principles contained in the chapter. These problems are intended to engage students in thinking through a real-life situation as depicted in a photo. They can be assigned after the students have developed some expertise in the subject matter and they work well either for individual or team projects.

Accuracy. Apart from my work, the accuracy of the text and problem solutions have all been thoroughly checked by other parties. Most importantly, Kai Beng Yap, Kurt Norlin of the Bittner Development Group, as well as Pavel Kolmakov and Vadim Semenenko at Competentum. The SI edition has been checked by three additional reviewers.

CONTENTS

The book is divided into 14 chapters. Chapter 1 begins with an introduction to fluid mechanics, followed by a discussion of units and some important fluid properties. The concepts of fluid statics, including constant accelerated translation of a liquid and its constant rotation, are covered in Chapter 2. In Chapter 3, the basic principles of fluid kinematics are covered. This is followed by the continuity equation in Chapter 4, the Bernoulli and energy equations in Chapter 5, and fluid momentum in Chapter 6. In Chapter 7, differential fluid flow of an ideal fluid is discussed. Chapter 8 covers dimensional analysis and similitude. Then the viscous flow between parallel plates and within pipes is treated in Chapter 9. The analysis is extended to Chapter 10 where the design of pipe systems is discussed. Boundary layer theory, including topics related to pressure drag and lift, is covered in Chapter 11. Chapter 12 discusses open channel flow, and Chapter 13 covers a variety of topics in compressible flow. Finally, turbomachines, such as axial and radial flow pumps and turbines are treated in Chapter 14.

Alternative Coverage. After covering the basic principles of Chapters 1 through 6, at the discretion of the instructor, the remaining chapters may be presented in *any sequence*, without the loss of continuity. If time permits, sections involving more advanced topics, may be included in the course. Most of these topics are placed in the later chapters of the book. In addition, this material also provides a suitable reference for basic principles when it is discussed in more advanced courses.

ACKNOWLEDGMENTS

I have endeavored to write this book so that it will appeal to both the student and instructor. Through the years many people have helped in its development, and I will always be grateful for their valued suggestions and comments. In particular, along with R. Sultana, California State University, Long Beach, J. Karl, University of South Florida, and C. Dreyer, Colorado School of Mines, the following individuals have contributed important reviewer comments relative to preparing this work:

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Lastly, many thanks are extended to all my students and colleagues that have e-mailed me their suggestions and comments. Since this list is too long to mention, it is hoped that those who have helped in this manner will accept this anonymous recognition.

I value your judgment as well, and would greatly appreciate hearing from you if at any time you have any comments or suggestions that may help to improve the contents of this book.

Russell Charles Hibbeler
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GLOBAL EDITION

The publishers would like to thank the following for their contribution to the Global Edition:

Contributor for the Second Edition in SI Units
Kai Beng Yap is currently a registered professional engineer who works in Malaysia. He has BS and MS degrees in civil engineering from the University of Louisiana, Lafayette, Louisiana; and has done further graduate work at Virginia Tech in Blacksburg, Virginia. He has taught at the University of Louisiana and worked as an engineering consultant in the areas of structural analysis and design, as well as the associated infrastructure.

Reviewers for the Second Edition in SI Units
Haluk Aksel, *Middle East Technical University*
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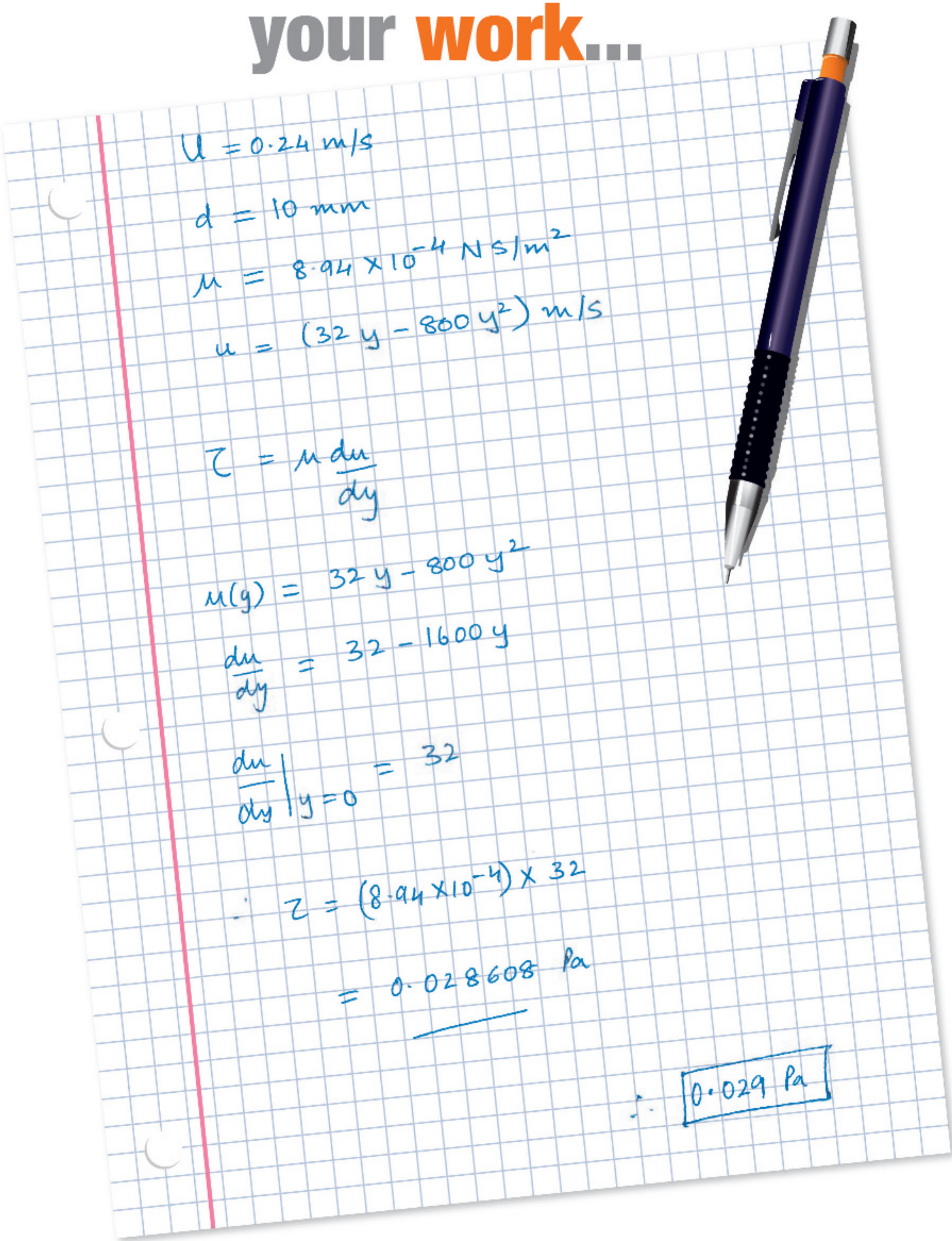
U = 0.24 m/s
d = 10 mm
μ = 8.94 x 10^-4 N s/m^2
u = (32 y − 800 y^2) m/s
τ = μ du/dy
u(y) = 32 y − 800 y^2
du/dy = 32 − 1600 y
du/dy |y=0 = 32
∴ τ = (8.94 x 10^-4) x 32
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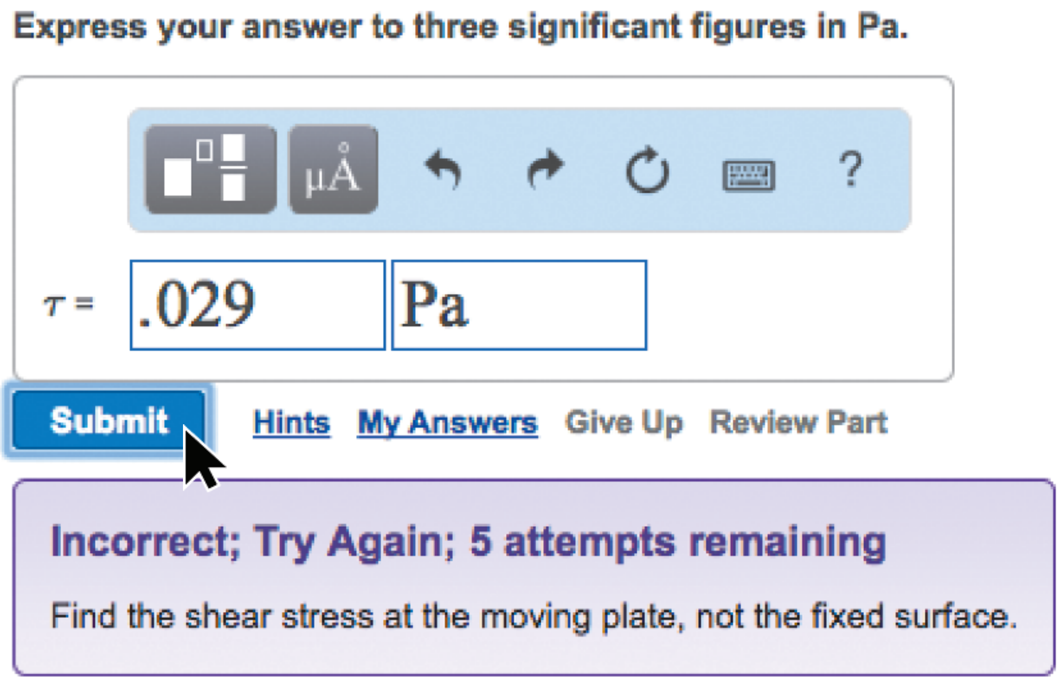


RESOURCES FOR INSTRUCTORS

- **Mastering Engineering.** This online Tutorial Homework program allows you to integrate dynamic homework with automatic grading. Mastering Engineering allows you to easily track the performance of your entire class on an assignment-by-assignment basis, or the detailed work of an individual student.

- **Instructor's Solutions Manual.** An instructor's solutions manual was prepared by the author. The manual includes homework assignment lists and was also checked as part of the accuracy checking program. The Instructor Solutions Manual is available at www.pearsonglobaleditions.com.

- **Presentation Resource.** All art from the text is available in PowerPoint slide and JPEG format. These files are available for download from the Instructor Resource Center at www.pearsonglobaleditions.com. If you are in need of a login and password for this site, please contact your local Pearson representative.

- **Video Solutions.** Developed by Professor Garret Nicodemus, video solutions which are located on the companion website offer step-by-step solution walkthroughs of homework problems from each section of the text. Make efficient use of class time and office hours by showing students the complete and concise problem solving approaches that they can access anytime and view at their own pace. The videos are designed to be a flexible resource to be used however each instructor and student prefers. A valuable tutorial resource, the videos are also helpful for student self-evaluation as students can pause the videos to check their understanding and work alongside the video. Access the videos at www.pearsonglobaleditions.com and follow the links for the *Fluid Mechanics* text.

RESOURCES FOR STUDENTS

- **Mastering Engineering.** Tutorial homework problems emulate the instructor's office-hour environment.

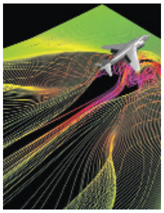
- **Companion Website.** The companion website, located at www.pearsonglobaleditions.com, includes opportunities for practice and review, including access to animations and video solutions offering complete, step-by-step solution walkthroughs of representative homework problems from various sections of the text.

CONTENTS

1 Fundamental Concepts 19

2 Fluid Statics 61

3 Kinematics of Fluid Motion 153

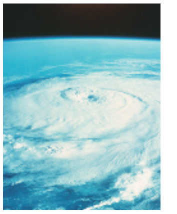


4 Conservation of Mass 189

5 Work and Energy of Moving Fluids 231

6 Fluid Momentum 301

7 Differential Fluid Flow 359

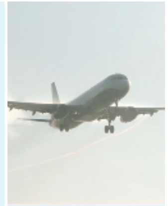


8 Dimensional Analysis and Similitude 435

9 Viscous Flow within Enclosed Conduits 475

10 Analysis and Design for Pipe Flow 521

11 Viscous Flow over External Surfaces 575



12 Open-Channel Flow 655

13 Compressible Flow 715

14 Turbomachines 807

FLUID MECHANICS

SECOND EDITION IN SI UNITS

CHAPTER 1

Eric Middelkoop/Fotolia

Fluid mechanics plays an important role in the design and analysis of pressure vessels, pipe systems, and pumps used in chemical processing plants.

FUNDAMENTAL CONCEPTS

CHAPTER OBJECTIVES

- To define fluid mechanics and indicate its various branches.
- To discuss the system of units for measuring fluid quantities, and establish proper calculation techniques.
- To define some important fluid properties.
- To describe some of the behavior characteristics of fluids.

1.1 INTRODUCTION

Fluid mechanics is a study of the behavior of a gas or liquid that is either at rest or in motion. Because fluids are so common, this subject has important applications in many engineering disciplines. For example, aeronautical and aerospace engineers use fluid mechanics to study flight and to design propulsion systems. Civil engineers use it to design channels, water networks, sewer systems, and water-resisting structures such as dams and levees. Fluid mechanics is used by mechanical engineers to design pumps, compressors, control systems, heating and air conditioning equipment, wind turbines, and solar heating devices. Chemical and petroleum engineers apply this subject to design equipment used for filtering, pumping, and mixing fluids. And finally, engineers in the electronics and computer industry use fluid mechanics principles to design switches, screen displays, and data storage equipment. Apart from the engineering profession, the principles of fluid mechanics are also used in the field of biomechanics, where they play a vital role in the understanding of the circulatory, digestive, and respiratory systems; and in meteorology to study the motion and effects of tornadoes and hurricanes.

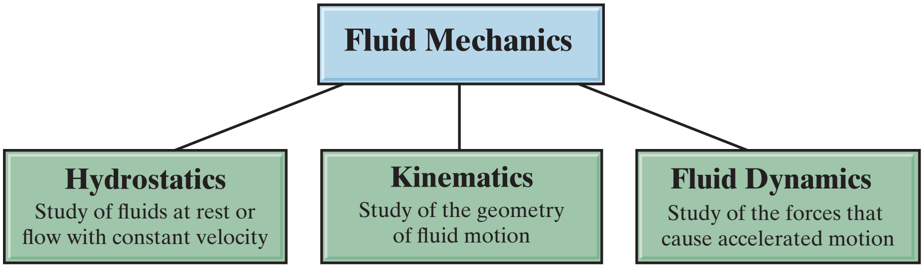


Fig. 1–1

Branches of Fluid Mechanics. The principles of fluid mechanics are based on Newton's laws of motion, the conservation of mass, the first and second laws of thermodynamics, and laws related to the physical properties of a fluid. The subject is divided into three main categories, as shown in Fig. 1–1. In this book, hydrostatics is presented in Chapter 2, kinematics is introduced in Chapter 3, and the study of fluid dynamics is presented throughout the rest of the book.

Historical Development. A fundamental knowledge of the principles of fluid mechanics has been of considerable importance throughout the development of human civilization. Historical records show that through the process of trial and error, early societies, such as the Roman Empire, used fluid mechanics in the construction of their irrigation and water supply systems. In the middle of the 3rd century B.C., Archimedes discovered the principle of buoyancy, and then much later, in the 15th century, Leonardo Da Vinci developed principles for the design of canal locks and other devices used for water transport. However, many important discoveries of basic fluid mechanics principles occurred in the 17th century. It was then that Evangelista Torricelli designed the barometer, Blaise Pascal formulated the law of static pressure, and Isaac Newton developed his law of viscosity to describe the nature of fluid resistance to flow.

In the 18th century, Leonhard Euler and Daniel Bernoulli pioneered the field of ***hydrodynamics***, which deals with the motion of an idealized fluid, that is, one having a constant density and providing no internal frictional resistance. Unfortunately, this study has limited application since not all physical properties of the fluid are taken into account. The need for a more realistic approach led to the development of ***hydraulics***. This field uses empirical equations found from fitting curves to data determined from experiments, primarily for applications involving water. In the 19th century, contributors included Gustave de Coriolis, who developed water turbines, and Gotthilf Hagen and Jean Poiseuille, who studied the resistance to water flowing through pipes. In the early 20th century, hydrodynamics and hydraulics were essentially *combined* through the work of Ludwig Prandtl, who introduced the concept of the boundary layer while studying aerodynamics. Through the years, many others have also made important contributions to this subject, and we will discuss many of these throughout the book.*

*References [1] and [2] provide a more complete description of the historical development of this subject.

1.2 CHARACTERISTICS OF MATTER

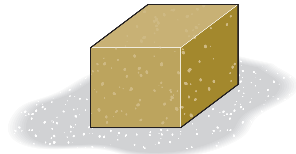
In general, matter can be classified by the state it is in—as a solid, a liquid, or a gas.

Solid. A ***solid***, such as steel, aluminum, or wood, maintains a definite shape and volume, Fig. 1–2*a*. It maintains its shape because the molecules or atoms of a solid are densely packed and are held tightly together, generally in the form of a lattice or geometric structure. The spacing of atoms within this structure is due in part to large cohesive forces that exist between molecules. These forces prevent any relative movement, except for any slight vibration of the molecules themselves. As a result, when a solid is subjected to a load it will not easily deform, but once in its deformed state, it will continue to support the load.

Liquid. A ***liquid***, such as water, alcohol, or oil, is a fluid that is composed of molecules that are more mobile than those in a solid. Their intermolecular forces are weaker, so liquids do not hold their shape. Instead, they flow and take the shape of their container, forming a horizontal free surface at the top, Fig. 1–2*b*. Although liquids can easily deform, their molecular spacing allows them to resist compressive forces when they are confined.

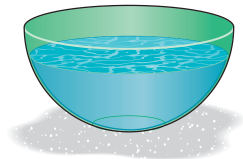
Gas. A ***gas***, such as helium, nitrogen, or air, is a fluid that flows until it fills the entire volume of its container, Fig. 1–2*c*. Gases are composed of molecules that are much farther apart than those of a liquid. As a result, the molecules of a gas are free to travel away from one another until a force of repulsion pushes them away from other gas molecules, or from the molecules on the surface of a container.

Continuum. Studying the behavior of a fluid as in Fig. 1–3*a* by analyzing the motion of all its many molecules would be an impossible task. Fortunately, however, almost all engineering applications involve a volume of fluid that is much greater than the very small distance between adjacent molecules of the fluid, and so it is reasonable to assume that the fluid is uniformly dispersed throughout this volume. Under these circumstances, we can then consider the fluid to be a ***continuum***, that is, a continuous distribution of matter leaving no empty space, Fig. 1–3*b*. This assumption allows us to use *average properties* of the fluid at any point throughout its volume. For those special situations where the molecular distance does become important, which is on the order of a billionth of a meter, the continuum model does not apply, and it is necessary to employ statistical techniques to study the fluid flow, a topic that will not be considered here. See Ref. [3].



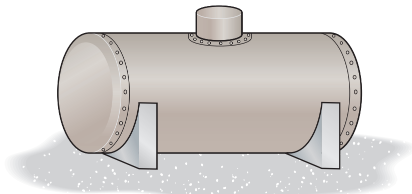
Solids maintain a constant shape

(a)



Liquids take the shape of their container

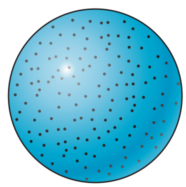
(b)



Gases fill the entire volume of their container

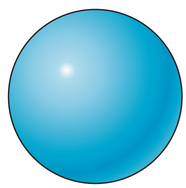
(c)

Fig. 1–2



Actual fluid

(a)



Continuum model

(b)

Fig. 1–3

1

1.3 THE INTERNATIONAL SYSTEM OF UNITS

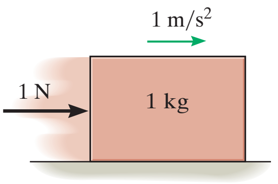
We can describe a fluid and its flow characteristics using combinations of units based on five basic quantities, namely, length, time, mass, force, and temperature. However, because length, time, mass, and force are all related by Newton's second law of motion, $F = ma$, the units used to define the size of each of these quantities cannot all be selected arbitrarily. The equality $F = ma$ is maintained when three of these units are *arbitrarily defined*, and the fourth unit is then derived from the equation.

The International System of units is a modern version of the metric system that has received worldwide recognition. The SI system specifies length in meters (m), time in seconds (s), and mass in kilograms (kg). The unit of force, called a *newton* (N), is *derived* from $F = ma$, where 1 newton is equal to the force required to give 1 kilogram of mass an acceleration of 1 m/s^2 $\left(\text{N} = \text{kg}\cdot\text{m/s}^2\right)$, Fig. 1–4*a*.

To determine the weight of a fluid in newtons at the "standard location," where the acceleration due to gravity is $g = 9.81\ \text{m/s}^2$, and the mass of the fluid is m (kg), we have

$$W\ (\text{N}) = [m\ (\text{kg})](9.81\ \text{m/s}^2) \qquad (1\text{–}1)$$

And so a fluid having a mass of 1 kg has a weight of 9.81 N, 2 kg of fluid has a weight of 19.62 N, and so on.



The newton is a unit of force

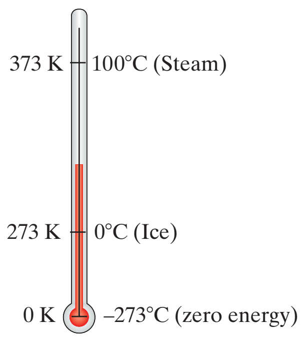
(a)

Fig. 1–4

Temperature. The ***absolute temperature*** is the temperature measured from a point at which the molecules of a substance have so-called "zero energy" or no motion.* Its unit in the SI system is the kelvin (K). This unit is expressed *without* reference to degrees, so 7 K is stated as "seven kelvins." Although not officially an SI unit, an equivalent-size unit measured in degrees Celsius (°C) is often used. This measurement is referenced from the freezing and boiling points of pure water, where the freezing point is 0°C (273 K) and the boiling point is 100°C (373 K), Fig. 1–4*b*. For conversion,

$$T_K = T_C + 273 \quad (1\text{–}2)$$

We will use Eqs. 1–1 and 1–2 in this book, since they are suitable for most engineering applications. However, for more accurate work, use the exact value of 273.15 in Eq. 1–2. Also, at the "standard location," the more exact value $g = 9.807\ \text{m/s}^2$ or the *local* acceleration due to gravity should be used in Eq. 1–1.



The Kelvin and Celsius scales

(b)

Fig. 1–4 (cont.)

*This is actually an unreachable point according to the law of quantum mechanics.

Prefixes. In the SI system, when a numerical quantity is either very large or very small, the units used to define its size should be modified by using a prefix. The range of prefixes used for problems in this book is shown in Table 1–1. Each represents a multiple or submultiple of a unit that moves the decimal point of a numerical quantity either forward or backward by three, six, or nine places. For example, 5 000 000 g = 5000 kg (kilogram) = 5 Mg (Megagram), and 0.000 006 s = 0.006 ms (millisecond) = 6 μs (microsecond).

As a general rule, the units of quantities that are multiplied together are separated by a dot to avoid confusion with prefix notation. Thus, m · s is a meter-second, whereas ms is a millisecond. And finally, the exponential power applied to a unit having a prefix refers to *both the unit and its prefix*. For example, $\text{ms}^2 = (\text{ms})^2 = (\text{ms})(\text{ms}) = \left(10^{-3}\ \text{s}\right)\left(10^{-3}\ \text{s}\right) = 10^{-6}\ \text{s}^2$.

TABLE 1–1 Prefixes

	Exponential Form	Prefix	SI Symbol
Submultiple			
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ
0.000 000 001	10^{-9}	nano	n
Multiple			
1 000 000 000	10^{9}	Giga	G
1 000 000	10^{6}	Mega	M
1 000	10^{3}	kilo	k

1.4 CALCULATIONS

Application of fluid mechanics principles often requires algebraic manipulations of a formula followed by numerical calculations. For this reason it is important to keep the following concepts in mind.

Dimensional Homogeneity. The terms of an equation used to describe a physical process must be ***dimensionally homogeneous***, that is, each term must be expressed in the *same units*. Provided this is the case, then all the terms of the equation can be *combined* when numerical values are substituted for the variables. For example, consider the Bernoulli equation, which is a specialized application of the principle of work and energy. We will study this equation in Chapter 5, but it can be expressed as

$$\frac{p}{\gamma} + \frac{V^2}{2g} + z = \text{constant}$$

Using SI units, the pressure p is expressed in N/m^2, the specific weight γ is in N/m^3, the velocity V is in m/s, the acceleration due to gravity g is in m/s^2, and the elevation z is in meters, m. In the form stated, each of the three terms is in meters, as noted if you cancel the units in each fraction.

$$\frac{\text{N/m}^2}{\text{N/m}^3} + \frac{(\text{m/s})^2}{\text{m/s}^2} + \text{m}$$

Regardless of how the equation is algebraically arranged, it will maintain its dimensional homogeneity, and as a result, a partial check of the algebraic manipulation of any equation can be made by checking to be sure all the terms have the same units.

Rounding off Numbers. Rounding off a number is necessary so that the accuracy of the result will be the same as that of the problem data. As a general rule, any numerical figure ending in a number greater than five is rounded up and a number less than five is rounded down. For example, if 3.558 is to be rounded off to *three* significant figures, then because the fourth digit (8) is *greater than* 5, the third number is rounded up to 6, so the number becomes 3.56. Likewise 0.5896 becomes 0.590 and 9.387 becomes 9.39. If we round off 1.341 to three significant figures, because the fourth digit (1) is *less than* 5, then we get 1.34. Likewise 0.3762 becomes 0.376 and 9.873 becomes 9.87. There is a special case for any number that ends in exactly 5. If the digit preceding the 5 is an *even number*, than this digit is *not* rounded up. If the digit preceding the 5 is an *odd number*, then it is rounded up. For example, 75.25 rounded off to three significant figures becomes 75.2, 0.1275 becomes 0.128, and 0.2555 becomes 0.256.

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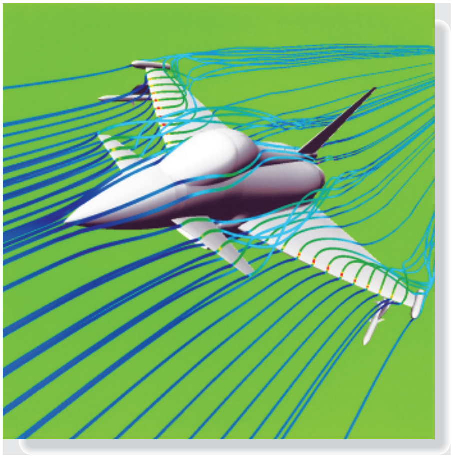
Calculation Procedure. When performing numerical calculations, it is best to store the intermediate results in the calculator. In other words, do not round off calculations until reporting the final result. This procedure maintains precision throughout the series of steps to the final solution. In this text we will generally round off the answers to *three significant figures,* since most of the data in fluid mechanics, such as geometry and fluid properties, may be reliably measured to this accuracy.

Also, when using SI units, *first* represent all the quantities in terms of their base or derived units by converting any prefixes to powers of 10. Then do the calculation, and finally express the result using a *single prefix*. For example, $[3\text{ MN}](2\text{ mm}) = \left[3\left(10^6\right)\text{ N}\right]\left[2\left(10^{-3}\right)\text{ m}\right] = 6\left(10^3\right)\text{ N}\cdot\text{m} = 6\text{ kN}\cdot\text{m}$. In the case of fractional units, with the exception of the kilogram, the prefix should always be in the numerator, as in MN/s or mm/kg.



Complex flows are often studied using a computer analysis; however, it is important to have a good grasp of the principles of fluid mechanics to be sure reasonable predictions have been made. (© CHRIS SATTLBERGER/Science Source)

1.5 PROBLEM SOLVING

At first glance, the study of fluid mechanics can be rather daunting, because there are many aspects of this field that must be understood. Success at solving problems, however, will depend on your attitude and your willingness to both focus on class lectures and to carefully read the material in the book. Aristotle once said, "What we have to learn to do, ***we learn by doing***," and indeed your ability to solve problems in fluid mechanics depends upon a thoughtful preparation and neat presentation.

In any engineering subject, it is very important that you follow a logical and orderly procedure when solving problems. In the case of fluid mechanics this should include the sequence of steps outlined below.

GENERAL PROCEDURE FOR ANALYSIS

Fluid Description.

Fluids can behave in many different ways, and so at the outset it is important to *identify the type of fluid flow* and specify the fluid's *physical properties*. Knowing this provides a means for the proper selection of equations used for an analysis.

Analysis.

This generally involves the following steps:

- Tabulate the problem data and draw any necessary diagrams.
- Apply the relevant principles, generally in mathematical form. When substituting numerical data into any equations, be sure to include their units, and check to be sure the terms are dimensionally homogeneous.
- Solve the equations, and report any numerical answers to three significant figures.
- Study the answer with technical judgment and common sense to determine whether or not it seems reasonable.

When applying this procedure, do the work as neatly as possible. Being neat generally stimulates clear and orderly thinking.

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IMPORTANT POINTS

- Solids have a definite shape and volume, liquids take the shape of their container, and gases fill the entire volume of their container.
- For most engineering applications, we can consider a fluid to be a continuum, and therefore use its average properties to model its behavior.
- Weight is measured in newtons in the SI system and is determined from $W\,(\text{N}) = m\,(\text{kg})(9.81\ \text{m/s}^2)$.
- Certain rules must be followed when performing calculations and using prefixes in the SI system of units. First convert all numerical quantities with prefixes to their base units, then perform the calculations, and finally choose an appropriate prefix for the result.
- The derived equations of fluid mechanics are all dimensionally homogeneous, and thus each term in an equation has the same units. Careful attention should therefore be paid to the units when entering data and then solving an equation.
- As a general rule, perform calculations with sufficient numerical accuracy, and then round off the final answer to three significant figures.

EXAMPLE 1.1

Evaluate $(80\ \text{MN/s})(5\ \text{mm})^2$, and express the result with SI units having an appropriate prefix.

SOLUTION

We first convert all the quantities with prefixes to powers of 10, perform the calculation, and then choose an appropriate prefix for the result.

$$(80\ \text{MN/s})(5\ \text{mm})^2 = [80(10^6)\ \text{N/s}][5(10^{-3})\ \text{m}]^2$$
$$= [80(10^6)\ \text{N/s}]\,[25(10^{-6})\ \text{m}^2]$$
$$= 2(10^3)\ \text{N}\cdot\text{m}^2/\text{s} = 2\ \text{kN}\cdot\text{m}^2/\text{s} \qquad \textit{Ans.}$$

EXAMPLE 1.2

Convert a fluid flow of 24 000 liters/h to m^3/s.

SOLUTION

Using 1 m^3 = 1000 liters and 1 h = 3600 s, the factors of conversion are arranged in the following order so that cancellation of units occurs.

$$\left(24\,000\ \frac{\text{liters}}{\text{h}}\right)\left(\frac{1\ \text{m}^3}{1000\ \text{liters}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right)$$

$$= 6.67(10^{-3})\,\text{m}^3/\text{s} \qquad \textit{Ans.}$$

Notice here that the result is rounded off to three significant figures. For engineering work, the results are expressed as a multiple of 10, having an exponential power in multiples of three as in (10^3), (10^6), (10^{-9}), etc.

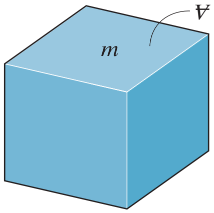
1.6 SOME BASIC FLUID PROPERTIES

A fluid has several important physical properties used to describe its behavior. In this section, we will define its density, specific weight, specific gravity, and bulk modulus. Then at the end of this section, we will use the ideal gas law to discuss how an ideal gas behaves.

Density. The ***density*** ρ (rho) refers to the mass of the fluid that is contained in a unit of volume, Fig. 1–5. It is measured in kg/m^3 and is determined from

$$\rho = \frac{m}{V\!\!\!\!-} \tag{1–3}$$

Here m is the mass of the fluid, and $V\!\!\!\!-$ is its volume.



Density is mass/volume

Fig. 1–5

Liquid. Through experiment it has been found that a liquid is practically incompressible, that is, the density of a liquid varies little with pressure. It does, however, have a slight but greater variation with temperature. For example, water at 4°C has a density of $\rho_w = 1000\ \text{kg/m}^3$, whereas at 100°C its volume will expand, and so $\rho_w = 958.1\ \text{kg/m}^3$. If the temperature range is small, we can, for most practical applications, consider the density of a liquid to be essentially constant, meaning its volume does not change, and the fluid is then referred to as ***incompressible***.

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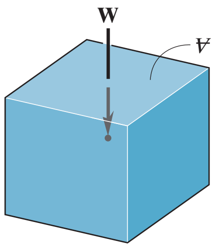
Gas. Unlike a liquid, temperature and pressure can markedly affect the density of a gas, since it has a higher degree of compressibility. For example, air has a density of $\rho = 1.23 \text{ kg/m}^3$ when the temperature is 15°C and the atmospheric pressure is 101.3 kPa [1 Pa (pascal) = 1 N/m²]. But at this same temperature, and at twice the pressure, the density of air will *double* and become $\rho = 2.46 \text{ kg/m}^3$.

Appendix A lists typical values for the densities of common liquids and gases. Included are tables of specific values for water at different temperatures, and air at different temperatures and atmospheric elevations.



Specific weight is weight/volume

Fig. 1–6

Specific Weight.

The ***specific weight*** γ (gamma) of a fluid is its weight per unit volume, Fig. 1–6. It is measured in N/m³. Thus,

$$\gamma = \frac{W}{V} \tag{1–4}$$

Here W is the weight of the fluid, and V is its volume.

Since weight is related to mass by $W = mg$, then substituting this into Eq. 1–4, and comparing this result with Eq. 1–3, the specific weight is related to the density by

$$\gamma = \rho g \tag{1–5}$$

Specific Gravity.

The ***specific gravity*** S of a substance is a dimensionless quantity that is defined as the ratio of its density or specific weight to that of some other substance that is taken as a "standard." It is most often used for liquids, and water at an atmospheric pressure of 101.3 kPa and a temperature of 4°C is taken as the standard. Thus,

$$S = \frac{\rho}{\rho_w} = \frac{\gamma}{\gamma_w} \tag{1–6}$$

The density of water for this case is $\rho_w = 1000 \text{ kg/m}^3$. So, for example, if an oil has a density of $\rho_o = 880 \text{ kg/m}^3$, then its specific gravity will be $S_o = 0.880$.