third edition

FLUID MECHANICS FOR ENGINEERING TECHNOLOGY

Irving Granet, P.E.

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PREFACE

The most important input that the author of a textbook can have comes from both the students who use it as a learning tool and their instructors who teach from it. Since the publication of the second edition I have been fortunate to have the comments of students and colleagues who have used the book in the classroom, the ultimate test of any textbook. Based on these inputs and my own experiences, I have undertaken this revision. Some of the major areas of change are:

- More material has been included in the chapter on properties. Problems are more appropriate and the section on viscosity has been rewritten and expanded.
- The chapter on the Bernoulli equation has been expanded to include more applications.
- The chapter on the energy equation has been rewritten to take on a more traditional fluid mechanics approach. Also, the concept of power has been incorporated into this chapter rather than being introduced later in the book.
- Problems at the ends of the chapters have been segregated by topic and by level of difficulty. More-difficult problems are indicated by an asterisk.
- Computer problems in BASIC have been included to show some applications of this widely used computer language to fluid mechanics. Those students who have access to a simple computer can program many of the equations in the text for themselves.

- A completely new chapter on measurements has been added to consolidate material that appeared in various sections in earlier editions.
- An appendix of conversion factors has been added.

In addition to these major changes, I have added chapter objectives as learning goals at the beginning of each chapter. In this manner the student understands at the beginning of a given assignment the material that should be learned. Also, at the end of each chapter there is a comprehensive review section. The chapter is first summarized in detail. Then a list of key words is given and the words are briefly defined for ready reference. Next is a list of important equations developed in the chapter. Each equation is numbered so that it can be located readily in the body of the text. Finally, a list of questions precede the problems to make the student think about the material. It is sincerely hoped that all of these structural changes make the book more usable to both the student and the instructor.

Those teachers who have used the book in its earlier editions will find that the general approach has been retained and strengthened. There are more illustrative problems and more exercises at the end of the chapters. To make the book applicable to mechanical, aeronautical, and civil technologies, material from each discipline has been included. Since the book contains more material than can be covered in the usual one-semester course, the instructor has a choice of topics to select from, depending on the specific objectives developed for the course.

I am greatly in debt to those professionals who took the time to review and comment on the second edition of the book. My thanks go to professors Wm. Bachman of Trident Technical College, Henry Horwitz of Dutchess County Community College, Robert Rautenstrauch of Kent State University, Donald Small of Maine Maritime Academy, A. E. Blakenship of Central Missouri State University, Gilbert Borthick of Aims Community College, Adriaan Jobse of Wentworth Institute, James Hladek of the College of Staten Island, and Demetri Telionis of Virginia Polytechnic Institute and State University. Finally, I am delighted to thank my colleagues at Queensborough Community College, especially Professor Sheldon Kohen, for advice and encouragement.

In each of the earlier editions I dedicated the book to my wife Arlene for her love and forbearance in this undertaking. As time has progressed I have been indeed blessed to have her at my side and as a silent partner in these labors. Our children, Ellen, Kenny, David, Jeffrey, and now our grandchildren, Samantha and Daniel, continually show the patience, understanding, and love that she gives so unselfishly.

Irving Granet
North Bellmore, New York

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1

SYSTEMS OF UNITS AND DIMENSIONAL CONSISTENCY

LEARNING GOALS

After reading and studying this chapter you should be able to:

1. Understand the general meaning of the term *fluid* as used in this text.
2. Distinguish between a liquid and a gas.
3. Appreciate the role played by fluids in our lives.
4. Use the SI system of units, including its styling.
5. Understand the conventional English system of units used in fluid mechanics.
6. Understand and use the concept of dimensional consistency.
7. Convert from SI to English units and from English units to SI.
8. Apply dimensional consistency to units in equations.

1.1 INTRODUCTION

Fluid mechanics is the study of the behavior of fluids whether they are at rest or in motion; the study of fluids at rest is best known as *fluid statics* and the study of fluids in motion is termed *fluid dynamics*. In this book we use the term *fluid* to refer to both gases and liquids. To distinguish between a liquid and a gas, we note that while both will occupy the container in which they are placed, a liquid presents a free surface if it does not completely fill the container, but a gas will always fill the volume of the

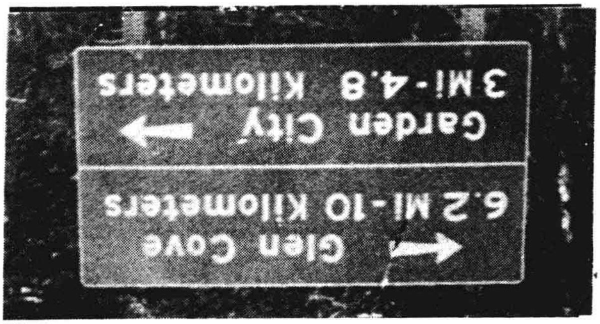

Figure 1.1 **Road sign in both SI and English units.**

container in which it is placed. For gases it is important to take into account the change in volume that occurs when either the pressure or the temperature is changed, whereas in most cases it is possible to neglect the change in volume of a liquid when there is a change in pressure.

It is apparent that almost every part of our lives and the technology of modern life involves some dependence on and knowledge of the science of fluid mechanics. Whether we consider the flow of blood in the minute blood vessels of the human body or the motion of an aircraft or missile at speeds exceeding the velocity of sound, we need to utilize some branch of fluid mechanics to describe the motion. The literature of this subject is so vast that a brief description cannot adequately reflect its scope. At one time the subject was treated from a purely mathematical approach by one group of investigators and from an entirely empirical experimental approach by another group of investigators. In this text we use the modern technique of coordinating both approaches by supplementing theory with experiment.

Since all measurements as well as theoretical developments must explicitly state the units being used, we start our study with a discussion of systems of units. As is obvious from Figure 1.1, we find that in the United States it is necessary at present to have a knowledge of both the SI (metric) and English systems of units.

1.2 THE SI SYSTEM OF UNITS

At the time of the French Revolution, the systems of weights and measures used throughout the world were an incoherent and almost hopeless jumble. International trade and the interchange of scientific information both suffered greatly because of this condition. French scientists and scholars of this era developed a rational system of weights and measures called the *metric system*, which was adopted by most countries of the world. In 1960, the General Conference of Weights and Measures extensively revised and simplified the older metric system and gave it the French title, *Système International d'Unités* (International System of Units), commonly abbreviated *SI*. The latest revisions and additions were made in an international conference in 1971, and work still continues on these standards.

For the engineer, the greatest confusion has been the units for mass and weight. The literature abounds with units such as slugs, pounds mass, pound force, poundal, kilogram force, kilogram mass, dyne, and so on. In the SI system, the base unit for *mass* (not weight or force) is the kilogram, which is equal to the mass of the international standard kilogram located at the International Bureau of Weights and Measures. It is used to specify the quantity of matter in a body. The mass of a body never varies, and it is independent of gravitational force.

The SI *derived* unit for force is the newton (N). The unit of force is defined from *Newton's second law of motion:* force is equal to mass times acceleration *($F = ma$)*. By this definition, 1 newton applied to a mass of 1 kilogram gives the mass an acceleration of 1 meter per second squared ($N = kg \cdot m/s^2$). The newton is used in all combinations of units that include force: pressure or stress (N/m^2), energy ($N \cdot m$), power ($N \cdot m/s = W$), and so on. By this procedure, the unit of force is not related to gravity as was the older kilogram force.

Weight is defined as a measure of gravitational force acting on a material object at a specified location. Thus, a constant mass has an approximate constant weight on the surface of the earth. The agreed standard value (standard acceleration) of gravity is 9.806 650 m/s^2. Figure 1.2 illustrates the difference between mass (kilogram) and force (newton).

The term "mass" or "unit mass" should be used only to indicate the quantity of matter in an object. The old practice of using weight in such cases should be avoided in engineering and scientific practice. The general relation that ties together mass *(m)* and weight *(w)* is found from Newton's second law of motion,

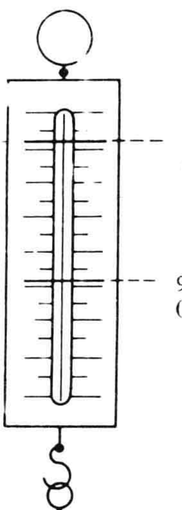

Figure 1.2 Mass and force.

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

If we now perform a simple experiment on earth that consists of dropping a weight (in a vacuum to eliminate the effects of the air on the body) and measuring its acceleration, we would obtain from equation (1.1) that the unbalanced force acting on the body is its weight, w, and its acceleration is the acceleration of gravity, g. Thus we can write equation (1.1) as

$$\boxed{w = mg} \tag{1.2}$$

where w is the weight of the body in newtons, m is its mass in kilograms, and g is the local acceleration of gravity in meters per second squared. For the surface of the earth we will use $g = 9.81 \text{ m/s}^2$.

ILLUSTRATIVE PROBLEM 1.1

One kilogram of lead is taken to the moon, where the local acceleration of gravity is one-sixth that of earth's gravity. What is its mass on the moon, and how much does it weigh on the moon?

Solution As shown in Figure 1.2, the body weighs 9.81 N on the earth. On the moon the mass will still be 1 kg, since the amount of matter in the body stays constant. However, since the local acceleration of gravity on the moon is one-sixth of the earth's gravity, it will weigh one-sixth of its earth's weight on the moon, since

$$w = mg$$

$$\text{weight (moon)} = 1 \text{ kg} \times \frac{9.81}{6} \text{ m/s}^2 = 1.635 \text{ N}$$

The SI system consists of three classes of units:

1. Base units
2. Supplementary units
3. Derived units
   (a) With special names
   (b) Without special names

Table 1.1 gives the seven base units of the SI system. Several observations concerning this table should be noted. The unit of length is the meter, and the kilogram is a unit of mass, not weight. Also, symbols are never pluralized; never written with a period; and the use of upper- and lowercase symbols *must* be used as shown *without exception*.

TABLE 1.1 BASE SI UNITS

Quantity	Base SI unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

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Table 1.2 gives the supplementary units of the SI system. These units can be regarded as either base units or as derived units.

Table 1.3 gives the derived units (with and without symbols) often used in fluid mechanics. These derived units are formed by the algebraic combination of base and supplementary units. It is noted that where the name is named for a person, the first letter of the symbol appears as a capital (e.g., newton is N). Otherwise, the convention is to make the symbol lowercase.

In order for the SI system to be universally understood, it is most important that the symbols for the SI units and the conventions governing their use be strictly adhered to. Care should be taken to use the correct case for symbols, units, and their multiples (e.g., K for kelvin, k for kilo; m for milli, M for mega). As noted earlier, unit *names* are never capitalized except at the beginning of a sentence. SI unit *symbols* derived from proper names are written with the first letter in uppercase; all other symbols are written in lowercase. For example, m (meter), s (second), K (kelvin), Wb (weber). Also, unit names form their plurals in the usual manner. Unit symbols are always written in singular form: for example, 350 megapascals, or 350 MPa; 50 milligrams, or 50 mg. Since the unit symbols are standardized, the symbols should always be used in preference to the unit names. An exception is made when a number written out in words

TABLE 1.2 SUPPLEMENTARY SI UNITS

Quantity	Supplementary SI unit	Symbol
Plane angle	radian	rad
Solid angle	steradian	sr

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TABLE 1.3 DERIVED SI UNITS

Quantity	Derived SI unit	Symbol	Formula	Expressed in terms of base units
Acceleration	—	m/s^2	m/s^2	m/s^2
Area	square meter	m^2	m^2	m^2
Density	kilogram per cubic meter	—	kg/m^3	$kg \cdot m^{-3}$
Energy or work	joule	J	N·m	$m^2 \cdot kg \cdot s^{-2}$
Force	newton	N	$m \cdot kg \cdot s^{-2}$	$m \cdot kg \cdot s^{-2}$
Length	meter	m	m	m
Mass	kilogram	kg	kg	kg
Moment	newton-meter	N·m	N·m	$m^2 \cdot kg \cdot s^{-2}$
Moment of inertia of area	—	m^4	m^4	m^4
Plane angle	radian	rad	rad	rad
Power	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
Pressure or stress	pascal	Pa	N/m^2	$N \cdot m^{-2}$
Rotational frequency	revolutions per second	rev/sec	s^{-1}	s^{-1}
Temperature	degree celsius	°C	°C	1 °C = 1 K
Time	second	s	s	s
Torque (*see* Moment)	newton-meter	N·m	N·m	$m^2 \cdot kg \cdot s^{-2}$
Velocity (speed)	meter per second	m/s	m/s	$m \cdot s^{-1}$
Volume	cubic meter	—	m^3	m^3

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precedes the unit (e.g., seven meters, not seven m). Unit symbols are not followed by a period unless they occur at the end of a sentence and the numerical value associated with a symbol should be separated from that symbol by a space (e.g., 1.81mm, *not* 1.81mm). The period is only to be used as a decimal marker. Since the comma is used by some countries as a decimal marker, the SI system does not use the comma. A space is used to separate large numbers in groups of threes starting from the decimal in either direction. Thus, 3 807 747.0 and 0.030 704 254 indicate this type of grouping. Notice that for numerical values of less than 1, the decimal point is preceded by a zero. For a number of four digits, the space can be omitted.

In addition, certain style rules should also be adhered to:

1. When a product is to be indicated, use a space between unit names (e.g., newton meter).
2. When a quotient is indicated, use the word "per" (e.g., meter per second).

3. When a product is indicated, use the word "square," "cubic," and so on (e.g., square meter).
4. In designating the product of units, use a centered dot (e.g., N·s, kg·m).
5. For quotients, use a solidus (/) or a negative exponent (e.g., m/s or $m \cdot s^{-1}$). The solidus (/) should not be repeated in the same expression unless ambiguity is avoided by using parentheses. Thus, one should use m/s^2 or $m \cdot s^{-2}$ but *not* m/s/s; also, use $m \cdot kg/(s^3 \cdot A)$ or $m \cdot kg \cdot s^{-3} \cdot A^{-1}$ but *not* $m \cdot kg/s^3/A$.

One of the features of the older metric system and the current SI system that is most useful is the fact that multiples and submultiples of the units are in terms of factors of 10. Thus, the prefixes given in Table 1.4 are used in conjunction with SI units to

TABLE 1.4 FACTORS OF TEN FOR SI UNITS

Prefix	Symbol	Factor	
tera	T	10^{12}	1 000 000 000 000
giga	G	10^{9}	1 000 000 000
mega	M	10^{6}	1 000 000
kilo	k	10^{3}	1 000
hecto	h	10^{2}	100
deka	da	10^{1}	10
deci	d	10^{-1}	0.1
centi	c	10^{-2}	0.01
milli	m	10^{-3}	0.001
micro	μ	10^{-6}	0.000 001
nano	n	10^{-9}	0.000 000 001
pico	p	10^{-12}	0.000 000 000 001
femto	f	10^{-15}	0.000 000 000 000 001
atto	a	10^{-18}	0.000 000 000 000 000 001

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form names and symbols of multiples of SI units. Certain general rules apply to the use of these prefixes:

1. The prefix becomes part of the name or symbol with no separation (e.g., kilometer, megagram, etc.).
2. Compound prefixes should not be used: use GPa, not kMPa.
3. In calculations, use powers of 10 in place of prefixes.
4. Try to select a prefix where the numerical value will fall between 0.1 and 1000. This rule may be disregarded when it is better to use the same multiple for all items. It is also recommended that prefixes representing 10 raised to a power that is a multiple of 3 be used (e.g., 100 mg, not 10 cg).