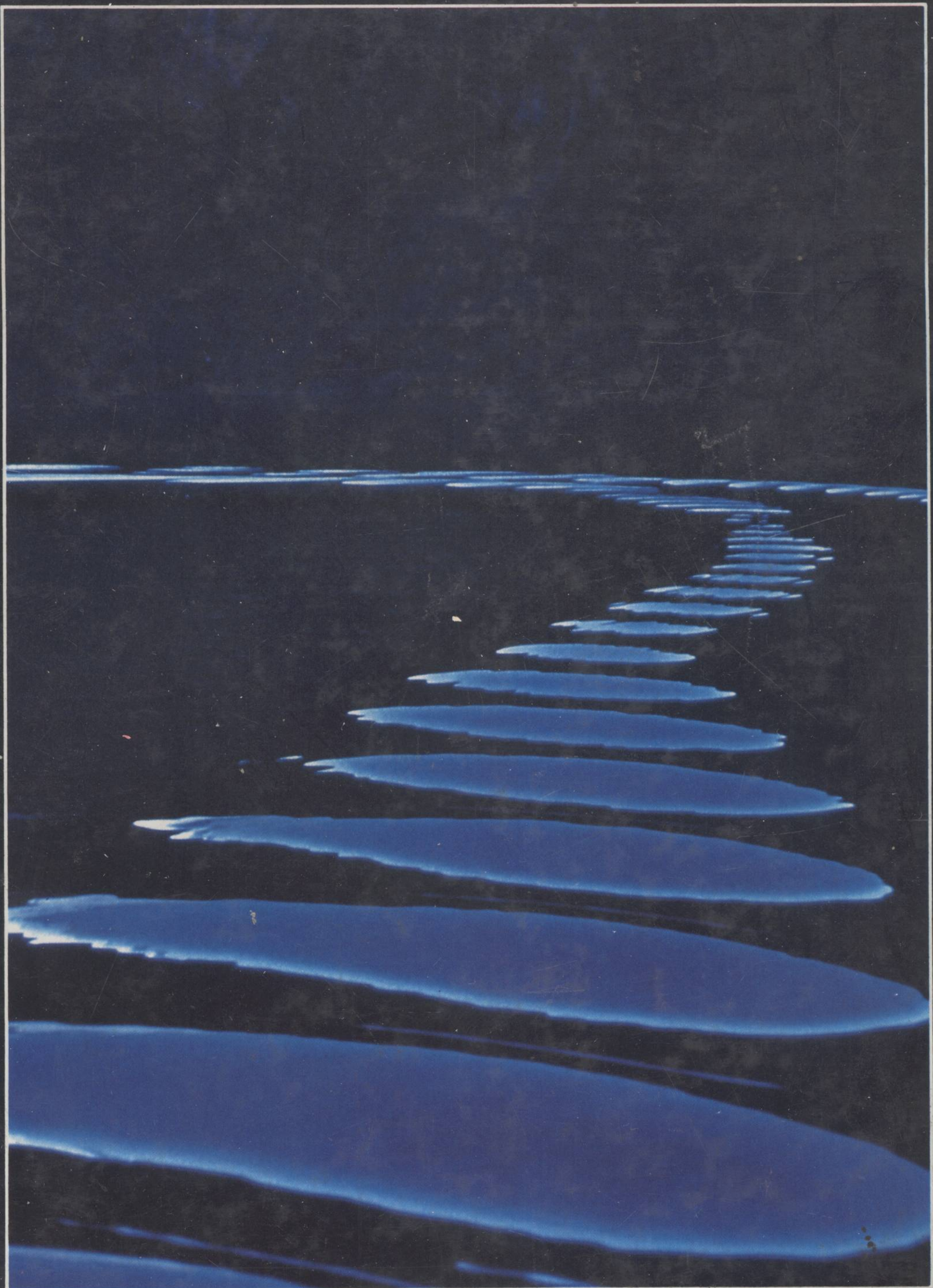
Introduction to FLUID MECHANICS



William S. Janna

Introduction to Fluid Mechanics

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Introduction to Fluid Mechanics

To Him who ordered the Universe by a word;

Whose love and glory are seen in the beauty of natural science and in the accomplishments of simple men;

And to my wife Marla who daily reflects this love and glory to me.

Preface

This text is intended for use at the undergraduate level in a mechanical or civil engineering or applied sciences curriculum. It is assumed that the student has a knowledge of calculus and physics so that the mathematics and physical principles in fluid mechanics can be learned without undue difficulty.

The book is arranged into thirteen chapters and is written using SI units as well as English engineering units. It is premature at this time to exclude either of these unit systems from an area of study considered fundamental. The first chapter serves as an introduction to the text and presents definitions appropriate to the study of fluid mechanics. The second chapter deals with fluid statics, specifically the forces exerted by fluids at rest, and pressure measurement. The third chapter is devoted to the basic equations of fluid mechanics. The control volume approach is explained, the continuity, momentum, and energy equations are developed, and the Bernoulli equation is derived. Dimensional analysis and modeling are presented in the fourth chapter. The concept of dimensional homogeneity and the need for dimensional analysis are discussed. Finally, mathematical techniques for modeling of prototypes are given.

Chapter 5 represents an important application of the basic concepts. Incompressible pipe flow is of significance to mechanical and civil engineers primarily. Topics covered include laminar and turbulent flow, nominal pipe and pipe sizes, the friction factor and pipe roughness, and various piping systems. Chapter 6 continues with applications to fluid flow past objects and discusses lift and drag forces. Chapter 7 on open-channel flow is of importance to civil engineers primarily, and the first few sections follow a format similar to that found in some hydraulics texts. Chapter 8 is an introduction to compressible flow. The basic concepts covered here lead to the solution of practical problems in the field.

In a one-semester course, completion of Chapter 8 might coincide with the end of the semester. Therefore, the rest of the text is intended for use at an intermediate or second level of study in fluid mechanics, although these chapters deal with applications of the basic concepts presented earlier.

Chapter 9 continues with a study of turbomachinery. Some design criteria are given as well as a description of commercially available machines. Also presented is the method by which pumps and hydraulic turbines are selected for various situations. The discussion includes a section on windmill propellers in light of recent interest in windmills as alternative energy sources. Chapter 10 surveys the measurement techniques commonly employed in fluid mechanics, including closed-conduit and open-channel flows.

Some of the more mathematically oriented topics of fluid mechanics then follow. Chapter 11 is an introduction to the equations of motion for isothermal systems (the Navier–Stokes equations). Chapter 12 presents simple solutions to the equations of inviscid flow and shows how they are combined to formulate more complex flows. Chapter 13 on boundary-layer flows derives the boundary-layer equations and discusses their application to flow over a flat plate. The momentum integral equation is derived and applied to both laminar and turbulent flows over a flat plate.

Each chapter concludes with a problems section. Problems are arranged so that they become progressively more difficult to solve. Thus they are designed systematically to improve the reader's ability to understand and apply the equations of fluid mechanics to various practical problems.

This text has been used successfully by the author in three different courses: a first course in fluid mechanics that covered the first six chapters; an intermediate course in fluid mechanics that covered Chapters 7, 8, 10, and 11; and a course in turbomachinery that covered Chapter 9.

Regardless of how many times a manuscript is perused, the occasional mistake seems to slip past even the most scrutinizing of readers. The author invites the reporting of errors to the publisher in order that misconceptions and the like do not become taught as truth. The author also invites the reader's comments; they will be accepted as advice on how to improve the book.

The author is greatly indebted to the many reviewers who read portions of the manuscript in its formative stages and made helpful suggestions for its improvement; to Ms. Michelle Aguiluz for her help in preparing appendix tables and various other secretarial tasks; to Ms. Donna Trumbach for her help in compiling the Fanno Flow Tables; to Ms. Ann Jeansonne for help in compiling the index; to Mr. Ray Kingman of Brooks/Cole who was inspirational during times of depression; to Ms. Mary Forkner for her ability in coordinating the production of this book; to Mr. Don Yoder for his expertise in making the manuscript easier to read; to Mr. Georg Klatt for his excellent drawing skills; to the University of New Orleans Audio Visual Center for their excellent photographic skills and reproduction techniques; and to the editorial staff at Brooks/Cole Engineering Division for their support and guidance.

Finally, I would like to acknowledge the encouragement and support of my wife, Marla, who made many sacrifices during this book's preparation.

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CHAPTER 1

Fundamental Concepts

Fluid mechanics is the branch of engineering that deals with the study of fluids—liquids and gases alike. Such a study is important because of the prevalence of fluids and our dependence on them. The air we breathe, the water transported through pipes, and the blood in our veins are examples of common fluids. Further, fluids in motion are potential sources of energy that can be converted into useful work—for example by a waterwheel or a windmill. Clearly fluids are important and a study of them is essential to the engineer. The objectives of this chapter are to define a fluid, to describe the unit systems used in the text, to discuss common properties of fluids, to establish features that distinguish liquids from gases, and to present the concept of a continuum.

1.1 / Definition of a Fluid

A fluid is a substance that deforms continuously under the action of an applied shear stress. This definition can be easily illustrated if a fluid is compared to a solid. Recall from strength of materials how a solid material deforms when a shear stress is applied (see Figure 1.1). A planar element Δx by Δy is acted upon by a shear stress τ. The element will deflect a finite amount until an equilibrium position is reached. The final position depends on the magnitude of the shear stress.

Consider next a fluid-filled space formed by two horizontal parallel plates a distance Δy apart (see Figure 1.2). The upper plate has an area A in contact with the fluid. The upper plate is moved to the right when pulled

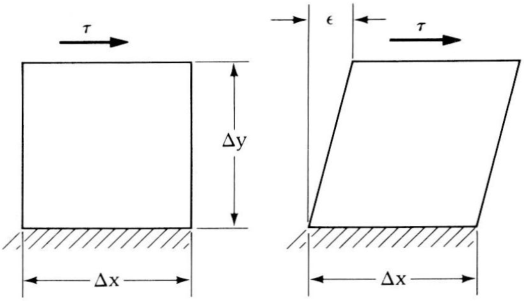

Figure 1.1. Deformation of a planar element.

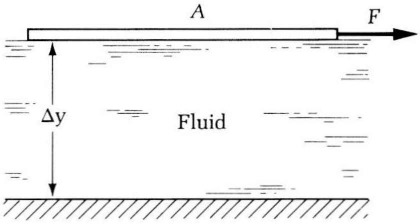

Figure 1.2. A fluid acted upon by an applied shear stress.

with a force F; the lower plate is stationary. The applied shear stress then is $\tau = F/A$. As soon as the plate is pulled, it continues to move but, unlike the solid, never reaches a final equilibrium position. The fluid deforms continuously.

1.2 / Dimensions and Units

In this text we will use two unit systems: the English engineering system and the international system (SI). Whatever the unit system, dimensions can be considered as either fundamental or derived. In the English system, the fundamental dimensions are mass, length, time, and force. The unit for each dimension is:

English Engineering System

Dimension	Abbreviation	Unit
Mass	M	pound-mass (lbm)
Length	L	foot (ft)
Time	T	second (s)
Force	F	pound-force (lbf)

These units are related by Newton's law, which states that force is proportional to the product of mass and acceleration:

$$F \propto ma$$

By introducing a constant of proportionality k:

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

Next let us define 1 pound-force as the force required to accelerate a mass of 1 pound-mass at a rate of acceleration 32.2 ft/s^2. By substitution into Equation 1.1, we get

$$1 \text{ lbf} = k(1 \text{ lbm})(32.2 \text{ ft/s}^2)$$

Solving for the reciprocal of the constant yields

$$g_c = \frac{1}{k} = 32.2 \text{ lbm-ft/lbf-s}^2 \tag{1.2}$$

where g_c is a constant that arises in equations in the English system to make them dimensionally correct.

EXAMPLE 1.1

On the earth 1 ft^3 of water weighs 62.4 lbf. **(a)** What is the mass of 1 ft^3 of water on the earth where acceleration due to gravity is 32.2 ft/s^2? **(b)** What is the weight of 1 ft^3 of water on the moon where the acceleration due to gravity is one-sixth that of earth's?

SOLUTION

(a) Applying Newton's law,

$$F = \frac{ma}{g_c}$$

we have

$$62.4 \text{ lbf} = \frac{m(32.2 \text{ ft/s}^2)}{32.2 \text{ lbm-ft/lbf-s}^2}$$

Solving, we get

$$\underline{m = 62.4 \text{ lbm}}$$

(b) Again we apply Newton's law,

$$F = \frac{ma}{g_c}$$

where in this case $m = 62.4$ lbm because mass is the same and

$$a = \tfrac{1}{6}(32.2) = 5.37 \text{ ft/s}^2$$

By substitution,

$$F = \frac{62.4 \text{ lbm}(5.37 \text{ ft/s}^2)}{32.2 \text{ lbm-ft/lbf-s}^2}$$

$$\underline{F = 10.4 \text{ lbf}}$$

The second unit system we will use is the international system (SI). In the SI system there are only three fundamental dimensions:

SI Unit System

Dimension	Abbreviation	Unit
Mass	M	kilogram (kg)
Length	L	meter (m)
Time	T	second (s)

In this system force is a derived dimension and is given in newtons (abbreviated N). The newton is defined in terms of the other units as

$$1 \text{ N} = 1 \frac{\text{kg-m}}{\text{s}^2} \tag{1.3}$$

When one is using the SI system with equations of fluid mechanics the conversion factor g_c is not necessary nor is it used. In this text, however, because we are working with both systems, the equations will include g_c. Merely ignore g_c if SI units are used, because SI units already incorporate the effect.

EXAMPLE 1.2

(a) What is the weight of 1 m^3 of water on the earth's surface if the water has a mass of 1 000 kg? **(b)** What is its weight on Mars where the acceleration due to gravity is about two-fifths that of earth's?

SOLUTION

(a) Using Newton's law,

$$F = \frac{ma}{g_c}$$

where $m = 1\ 000$ kg and $a = 9.81 \text{ m/s}^2$, we have

$$F = 1\ 000 \text{ kg} \frac{9.81 \text{ m}}{\text{s}^2} = 9\ 810 \text{ kg-m/s}^2$$

or

$$\underline{F = 9\ 810\ \text{N}}$$

(b) On Mars, $a = \frac{2}{5}(9.81) = 3.92\ \text{m/s}^2$ and $m = 1\ 000$ kg. Hence we obtain

$$F = 1\ 000\ \text{kg}\ (3.92)\ \text{m/s}^2 = 3\ 920\ \text{kg-m/s}^2$$

or

$$\underline{F = 3\ 920\ \text{N}}$$

There are certain conventions to be followed when using SI. For instance, in the preceding example four-digit numbers were written with a space where one might normally place a comma. Other conventions and definitions will be pointed out as we encounter them. (See "Standards for Metric Practice," ASTM E380-76.)

It is permissible in SI to use prefixes with the units for convenience. Appendix Table A–1 gives a complete listing of the names of multiples and submultiples of SI units. As an example of the usage of prefixes consider the answer to Example 1.2*b*:

$$F = 3\ 920\ \text{N} = 3.920\ \text{kN}$$

where, by definition, 10^3 is a factor by which the unit is multiplied and is represented by the lowercase letter "k."

Mention has been made of derived dimensions. An example is area A, which has dimensions of L^2—units of square feet in the English system and square meters in SI. In general all derived dimensions are made up of fundamental dimensions.

For purposes of illustration let us briefly examine the British gravitational system of units. In this system force, length, and time are primary dimensions with units of pound-force, foot, and second respectively:

British Gravitational System

Dimension	Abbreviation	Unit
Force	F	pound-force (lbf)
Length	L	foot (ft)
Time	T	second (s)

Mass is a derived dimension with units of slug and defined in terms of the primary dimensions as

$$1\ \text{slug} = 1\ \frac{\text{lbf-s}^2}{\text{ft}}$$