VENNARD & STREET

ELEMENTARY FLUID MECHANICS

SIXTH EDITION

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PREFACE

Fluid mechanics is the study of fluids under all conditions of rest and motion. Its approach is analytical and mathematical rather than empirical; it is concerned with basic principles that provide the solution to numerous and diverse problems encountered in many fields of engineering, regardless of the physical properties of the fluids involved.

This textbook is intended for beginners who have completed differential and integral calculus and engineering courses in statics and dynamics, but who have not yet encountered a course in thermodynamics and have no prior experience with fluid phenomena except for that obtained in basic physics courses. The limited experience of the beginner and the broad scope of fluid mechanics have led us to define *elementary fluid mechanics* as that portion of the subject that may be feasibly studied in an introductory course; with more extensive training in mathematics and thermodynamics, the beginner in fluid mechanics could be expected to cover considerably more subject matter, especially in flowfields and compressible fluid motion.

In view of our considerable experience in teaching fluid mechanics to American undergraduates, we believe the difficulties are more of a conceptual than a mathematical nature; for this reason, the emphasis here is on physical concepts rather than mathematical manipulation. Because this book is written for the beginning student, rather than the mature professional, we hope that by itself the text will prove to be an understandable introduction to the various topics, allowing precious classroom time to be spent on amplification and extension of the material. It is our conviction that the use of a textbook in this manner provides vital training for later professional life when new subjects must be assimilated without teachers to introduce them.

Presentation of the subject begins with a discussion of fundamentals and fluid properties, followed by fluid statics, at which point students first encounter a fluid field and the use of partial derivatives. A chapter on kinetics discusses velocity, acceleration, vorticity, circulation, and the conservation of mass (the equation of continuity). Here the key concept of the control volume is first introduced. After this, we move to chapters that discuss the flow of the incompressible and compressible ideal fluid, which include a brief treatment of two-dimensional flowfields; the impulse-momentum principle is then developed in a separate chapter, including applications to incompressible and compressible flow. Discussion of frictional processes and a chapter on similitude and dimensional analysis complete the presentation of the primary tools and lead to applications to pipes, open channels, and measuring devices. Chapter 12, on elementary hydrodynamics, precedes the final chapter on flow about immersed objects.

References to written and visual materials have been provided to guide the inquiring reader to more exhaustive treatment of the various topics. The relevant films listed at the ends of the chapters may be quite useful to the beginner by filling in background and providing visual experience with various fluid phenomena. More than a thousand problems are included at the ends of the chapters, and most quantitative articles in the text are accompanied by Illustrative Problems which show how to achieve useful engineering answers from the derived concepts and procedures.

The traditional American units are derived from the English FSS (foot-slug-second) system. However, most of the world uses the Système International d'Unités (SI). Although SI units are coming into use in the United States, both types of units will be used for many years. To assist in the transition and provide users in the metric countries access to this textbook, this edition uses both SI and FSS unit systems. The emphasis is on SI units, however, and they account for approximately 70% of the usage. In many problems at the ends of the chapters, both sets of units are quoted, and the Solution Manual, which is available to instructors, contains solutions in both sets of units for these problems. Accordingly, instructors may choose the appropriate sets of units to be used at their option.

The revision over the years of a textbook produces an evolution in its content. Such is the case with this book and this edition. Thus, I have maintained the level, style, and basic organization of the original book which made it appealing to many generations of students and their teachers. However, a major effort has been made to improve the clarity of the Illustrative Problems so that they may effectively lead the student from concept to successful solution of engineering problems. In addition, significant changes have been made in several chapters. The role and meaning of control volumes have been emphasized further and they are now more tightly integrated into the text. But there has not been an increase in the complexity or sophistication of presentation. The work-energy principle has been more clearly delineated in Chapter 4. The general quality and depth of the discussion of real fluid flow has been upgraded by a moderate revision of Chapter 7 and by a virtually complete revision and reorganization of Chapter 9, which now leads the student from concrete physical principles and observations on laminar, turbulent, and smooth or rough flows, to their synthesis in the Moody diagram, and then to applications. Finally, the material on similitude and dimensional analysis has been reorganized to stress the key similitude principles, to incorporate the modern approach to the Buckingham Π-theorem, and to raise the practical applicability and scope of the material on turbomachines.

I am deeply indebted to my friend and Stanford colleague, Professor En Yun Hsu, who provided the framework for the revision of Chapters 7 and 9, and who has critically reviewed the entire manuscript. The efforts of Mr. Jeffrey Koseff, who read the manuscript from the student's point of view, are greatly appreciated by me and, without doubt, will be by the readers.

Stanford, California
December 1980

Robert L. Street

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1 FUNDAMENTALS

1.1 Development and Scope of Fluid Mechanics

The human desire for knowledge of fluid phenomena began with problems of water supply, irrigation, navigation,and water power. With only a rudimentary appreciation for the physics of fluid flow, we dug wells, constructed canals, operated crude water wheels and pumping devices and, as our cities increased in size, constructed ever larger aqueducts, which reached their greatest size and grandeur in the city of Rome. However, with the exception of the thoughts of Archimedes (287–212 B.C.) on the principles of buoyancy, little of the scant knowledge of the ancients appears in modern fluid mechanics. After the fall of the Roman Empire (A.D. 476) there is no record of progress in fluid mechanics until the time of Leonardo da Vinci (1425–1519). This great genius designed and built the first chambered canal lock near Milan and ushered in a new era in hydraulic engineering; he also studied the flight of birds and developed some ideas on the origin of the forces that support them. However, down through da Vinci's time, concepts of fluid motion must be considered to be more art than science.

After the time of da Vinci, the accumulation of hydraulic knowledge rapidly gained momentum, with the contributions of Galileo, Torricelli, Mariotte, Pascal, Newton, Pitot, Bernoulli, Euler, and d'Alembert to the fundamentals of the science being outstanding. Although the theories proposed by these scientists were in general confirmed by crude experiments, divergences between theory and fact led d'Alembert to observe in 1744, "The theory of fluids must necessarily be based upon experiment." He showed that there is no resistance to motion when a body moves through an ideal (nonviscous or *inviscid*) fluid; yet obviously this conclusion is not valid for bodies moving through real fluids. This discrepancy between theory and experiment, called the d'Alembert paradox, has since been resolved. Yet it demonstrated clearly the limitations of the theory of that day in solving fluid problems. Because of the conflict between theory and experiment, two schools of thought arose in the treatment of fluid mechanics, one dealing with the theoretical and the other with the practical aspects of fluid flow. In a sense, these two schools of thought have persisted to the present day, resulting in the mathematical field of *hydrodynamics* and the practical science of *hydraulics*.

Near the middle of the last century, Navier and Stokes succeeded in modifying the general equations for ideal fluid motion to fit those of a viscous fluid and in so doing showed the possibilities of explaining the differences between hydraulics and hydrodynamics. About the same time, theoretical and experimental work on vortex motion and separated flow by Helmholtz and Kirchhoff was aiding in explaining many of the divergent results of theory and experiment.

Meanwhile, hydraulic research went on apace, and large quantities of excellent data were collected. Unfortunately, this research led frequently to empirical formulas obtained by fitting curves to experimental data or by merely presenting the results in tabular form, and in many instances the relationship between physical facts and the resulting formula was not apparent.

Toward the end of the last century, new industries arose that demanded data on the flow of fluids other than water; this fact and many significant advances in our knowledge tended to arrest the empiricism of much hydraulic research. These advances were: (1) the theoretical and experimental work of Reynolds; (2) the development of dimensional analysis by Rayleigh; (3) the use of models by Froude, Reynolds, Vernon-Harcourt, Fargue, and Engels in the solution of fluid problems; and (4) the rapid progress of theoretical and experimental aeronautics in the work of Lanchester, Lilienthal, Kutta, Joukowsky, Betz, and Prandtl. These advances supplied new tools for the solution of fluid problems and gave birth to modern fluid mechanics. The single most important contribution was made by Prandtl in 1904 when he introduced the concept of the boundary layer. In his short, descriptive paper Prandtl, at a stroke, provided an essential link between ideal and real fluid motion for fluids with a small viscosity (e.g., water and air) and provided the basis for much of modern fluid mechanics.

In the twentieth century, fluid problems have been solved by constantly improving rational methods; these methods have produced many fruitful results and have aided in increasing knowledge of the details of fluid phenomena. The trend is certain to continue in large part because of the ever increasing power of the digital computer.

Another continuing trend is that toward greater complexity and challenge in fluid problems. The problems of water supply, irrigation, navigation and water power remain, but on a scale never imagined by the citizens of pre-Christian Rome. The range of new problems added in modern times is virtually infinite, including the sonic boom of the supersonic airplane; dispersion of man's wastes in lakes, rivers, and oceans; blood flow in veins, arteries, kidneys, hearts, and artificial heart and kidney machines; fuel pumping and exhaust flow in moon rockets; the design of 1 millon-ton super oil tankers for speed, cargo-pumping efficiency, and safety; and analysis and simulation of the world's weather and ocean currents. Thus, today fluid mechanics has become an essential part of such diverse fields as medicine, meteorology, astronautics, and oceanography, as well as of the traditional engineering disciplines.

1.2 Physical Characteristics of the Fluid State

Matter exists in two states—the solid and the fluid, the fluid state being commonly divided into the liquid and gaseous states.[1] Solids differ from liquids and liquids from

[1] Many would say that matter exists in four states—solid, liquid, gaseous, and plasma, the latter three being classified as fluids. The plasma state is the state of over 99% of the matter of the universe and is distinguished from the others because a significant number of its molecules are ionized. Hence, the plasma contains electrically charged particles and is susceptible to electromagnetic forces. Unfortunately, the intriguing subject of plasma dynamics is beyond the scope of this work.

gases in the spacing and latitude of motion of their molecules, these variables being large in a gas, smaller in a liquid, and extremely small in a solid. Thus it follows that intermolecular cohesive forces are large in a solid, smaller in a liquid, and extremely small in a gas. These fundamental facts account for the familiar compactness and rigidity of form possessed by solids, the ability of liquid molecules to move freely within a liquid mass, and the capacity of gases to fill completely the containers in which they are placed, while a liquid has a definite volume and a well-defined surface. In spite of the mobility and spacing of its molecules, a fluid is considered (for mechanical analysis) to be a *continuum* in which there are no voids or holes; this assumption proves entirely satisfactory for most engineering problems.[2]

A more rigorous mechanical definition of the solid and fluid states can be based on their actions under various types of stress. Application of tension, compression, or shear stresses to a solid results first in elastic deformation and later, if these stresses exceed the elastic limits, in permanent distortion of the material. Fluids possess elastic properties only under direct compression or tension. Application of infinitesimal shear stress to a fluid results in continual and permanent distortion. The inability of fluids to resist shearing stress gives them their characteristic ability to change their shape or to *flow*; their inability to support tension stress is an engineering assumption, but it is a well-justified assumption because such stresses, which depend on intermolecular cohesion, are usually extremely small.[3]

Because fluids cannot *support* shearing stresses, it does not follow that such stresses are nonexistent in fluids. During the flow of real fluids, the shearing stresses assume an important role, and their prediction is a vital part of engineering work. Without flow, however, shearing stresses cannot exist, and compression stress or *pressure* is the only stress to be considered.

Because fluids at rest cannot contain shearing stresses, no component of stress can exist in a static fluid tangent to a solid boundary or tangent to an arbitrary section passed through the fluid. This means that pressures must be transmitted to solid boundaries or across arbitrary sections *normal* to these boundaries or sections at every point. Furthermore, if a *free body* of fluid is isolated as in Fig. 1.1, pressure must be shown as acting *inward* (p_1) and on the free body (according to the usual conventions of mechanics for compression stress). Pressures exerted by the fluid on the container (p_2) will of course act *outward*, but their reactions (p_3) will act inward on the fluid as before. Another property of fluid pressure is that, at a point in a fluid at rest, it has the same magnitude in all directions; this may be proved by considering a convenient two-dimensional[4] free body of fluid (Fig. 1.2) having unit width normal to the plane of the paper. Taking p_1,

[2] An important exception is a gas at very low pressure (rarefied gas), where intermolecular spacing is very large and the "fluid" must be treated as an aggregation of widely separated particles. It follows that the continuum assumption is valid only when the smallest physical length scale in a flow is much larger than the average spacing between or than the mean free path of (about 1 μm or $10^{-4} - 10^{-5}$ in.) molecules composing the fluid.

[3] Tests on some very pure liquids have shown them to be capable of supporting tension stresses up to a few thousands of pounds per square inch, but such liquids are seldom encountered in engineering practice.

[4] A more general proof using a three-dimensional element yields the same result.

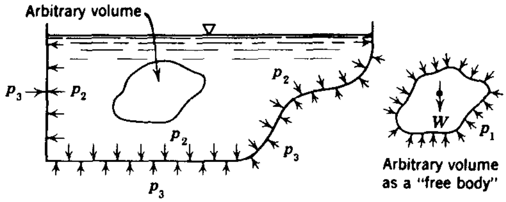

Fig. 1.1

p_2, and p_3 to be the mean pressures on the respective surfaces of the element, ρ the density[5] of the fluid, g_n the acceleration due to gravity and writing the equations of static equilibrium:

$$\sum F_x = p_1\,dz - p_3 ds \sin\theta = 0$$

$$\sum F_z = p_2\,dx - \rho g_n\,dx\,dz/2 - p_3\,ds\cos\theta = 0$$

From geometry, $dz = ds \sin\theta$ and $dx = ds \cos\theta$. Substituting the first of these relations into the first equation above gives $p_1 = p_3$, whatever the size of dz; substituting the second relation into the second equation yields $p_2 = p_3 + \rho g_n dz/2$, whatever the size of dx. From these equations it is seen that p_1 and p_3 approach p_2 as dz approaches zero. Accordingly it may be concluded that at a point ($dx = dz = 0$) in a static[6] fluid $p_1 = p_2 = p_3$, and the pressure there is the same in all directions.

With the pressure at a point the same in all directions, it follows that the pressure has no vector sense and hence is a *scalar* quantity; however, the differential forces produced by the action of pressures on differential areas are vectors because they have

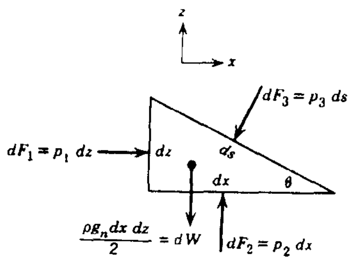

Fig. 1.2

[5] A summary of symbols and their dimensions is given in Appendix 1.

[6] For the flow of an ideal (inviscid) fluid the same result may be proved, but for viscous fluid motion the presure at a point is generally not the same in all directions owing to the action of shearing stress; however, this is of small consequence in most engineering problems, where shear stress is usually small compared to pressure (or normal stress).

directions normal to the areas. The resultant forces obtained by the integration of the differential forces also are vector quantities.

Another well-known aspect of fluid pressure (which needs no formal proof) is that pressures imposed on a fluid at rest are transmitted undiminished to all other points in the fluid; this follows directly from the static equilibrium of adjacent elements and the fact that the fluid mass is a continuum. This aspect finds practical expression in the hydraulic lift used in automobile service stations.

The reader may be uneasy concerning the treatment of liquids and gases by the same principles in view of their obvious differences of compressibility. In problems where compressibility is of small importance (and there are many of these in engineering), liquids and gases may be treated similarly, but where the effects of compressibility are predominant (as in high speed gas flow) the behavior of liquids and gases is quite dissimilar and is governed by very different physical laws. Usually, when compressibility is unimportant, fluid problems may be solved successfully with the principles of mechanics; when compressibility predominates, thermodynamics and heat transfer concepts must be used as well.

1.3 Units, Density, Specific Weight, Specific Volume, Specific Gravity

The world is presently changing to the use of a single international language of units. The adopted system is the metric *Système International d'Unités* (SI). Many countries have already changed to SI units and the United States is moving toward use of the metric system in lieu of the currently used English (or U.S. customary) system. Unfortunately, both types of units will be used for many years. Accordingly, in this edition of this book, both the metric (SI) system and the English FSS (foot-slug-second) system of units are used. However, usually in illustrative examples and problems only one set of units is used within each example or problem.

For the SI and FSS unit systems, there are four basic dimensions through which fluid properties are expressed. These base dimensions and their associated units (and symbols) are:

Dimension	SI Unit	English FSS Unit
Length (L)	metre (m)	foot (ft)
Mass (M)	kilogram(kg)	slug (−)
Time (t)	second (s)	second (s)
Thermodynamic temperature (T)[7]	kelvin (K)	degree Rankine (°R)

In the SI and FSS systems, the above units are known as base units. There are also a number of other units that are derivable from base units and that have special names, for example,

[7] Here T°C = T K − 273.15 while T°F = T°R − 459.6. The normal freezing and boiling points of water are (0°C, 32°F) and (100°C, 212°F), respectively.