FLUID MECHANICS

RAYMOND C. BINDER

4TH EDITION

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PREFACE

Fluid mechanics is that study of fluid motion involving a rational method of approach based on general physical laws and consistent with the results of modern experimental study. The word *fluid* implies a treatment of both liquids and gases. Fluid mechanics uses the same principles employed in the mechanics of solids. The modern trend is to avoid a collection of specialized empirical data of limited applicability; the trend is to develop general relations, and to organize experimental observations in a form suitable for use over a wide range of conditions.

There is real economy and value in studying at one time the same principles underlying the flow of different fluids. Such a study tends to develop a sound background and to make one versatile in approaching problems new to him. Studying fluid mechanics is analogous to studying applied mechanics and thermodynamics as a broad, unified preparation for subsequent specialized courses.

The aim of this book is to present an introduction to the fundamentals of fluid mechanics. The wisdom of concentrating on all the minute details of all existing applications is open to some question, in view of the time usually available in a course and the possible development of new and unexpected applications.

A serious attempt has been made to provide a balanced treatment in a logical fashion, and to keep physical concepts and basic quantitative relations in the foreground. Physical concepts are stressed with the hope that once the student has a good physical picture he can proceed of his own accord, with interest, in understanding and analyzing flow phenomena.

Experience has shown that problem work on the part of the student is very helpful, if not necessary, to give him a working knowledge of the subject. Problem work offers the student a definite test and challenge to supplement his reading.

This book is divided into three parts:

Part I—*Basic Relations*
Part II—*Selected Topics in Fluid Mechanics*
Part III—*Further Analytical Study of Fluid Motion*

Part I presents an introduction to various fundamental physical relations and also provides tools which can be used to answer directly many practical problems. Part II gives information about different cases of flow and shows how the various basic relations can be applied. With Part I as a background, each chapter in Part II is essentially self-contained. This arrangement provides flexibility in arranging a course. Various chapters in Part II can be taken in a different sequence with difficulty.

Part III presents a more general, more analytical approach than that of Part I. Part III can be studied directly after Part I without first going over Part II.

It is not possible to give adequate, explicit credit to all those individuals and organizations who have directly and indirectly given aid in the preparation of this book. The writer, however, is deeply grateful to all of them for help, and wishes to acknowledge it as best he can. Many fellow workers, in industrial and research work, have made suggestions particularly as to material content. Various instructors and students in different schools have offered suggestions as to method of presentation. Dr. Theodore von Kármán and Dean Andrey A. Potter, each in his own particular way, has provided wise counsel and an outstanding stimulus. Dr. Warren E. Wilson and Dr. George V. Chillingar have made specific suggestions as to subject matter and arrangement of topics.

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Part I—Basic Relations

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PART I

BASIC RELATIONS

In approaching a problem we must establish what factors are known or given, and what factor we wish to determine. Then there is this question: What fundamental relations, equations, or tools are available for use in solving our problem?

There are certain relations which must hold in any case of flow. For example, we should be able to account for all material, all energy, and work. In any flow case there is a definite relation between force, mass, and acceleration.

This book is divided into three parts. Part I discusses the tools or basic relations. Chapter One defines some terms. Chapter Two covers fluids at rest. Chapter Three deals with the geometry of motion and material accounting. Chapter Four presents the relation between force, mass, and acceleration, whereas Chapter Five treats an energy accounting. Chapter Six discusses viscosity. Chapter Seven outlines techniques for organizing experimental data.

Part II, starting with Chapter Eight, serves several purposes. It gives information about different cases of flow. It also shows how basic relations are applied.

Part III presents a more general, more analytical approach than that of Part I.

CHAPTER ONE

INTRODUCTION SOME FLUID PROPERTIES

It may be permitted to doubt whether the public at large has any adequately realizing sense of the part which fluid mechanics plays, not only in our daily lives, but throughout the entire domain of Nature. Matter as we know it is either solid or fluid. . . .

Thus the flow of rivers and streams in their boundaries, . . . the circulation of the blood in our arteries and veins . . . the flight of the insect, the bird and the airplane; the movement of a ship in the water or of a fish in the depths, . . . these are all, in major degree, varied expressions of the laws of fluid mechanics . . . everywhere we find fluids and solids in reactive contact, usually in relative motion, and everywhere in this domain, the laws of fluid mechanics must control.—W. F. DURAND[1]

This chapter defines some terms and discusses units; these terms and units will be used in subsequent parts of the book.

Mechanics is a science concerned with the motion of bodies and the conditions governing such motion. The subject of mechanics is frequently divided into two general sections, one *kinematics* and the other *dynamics.* Kinematics deals with the geometry of motion without consideration of the forces causing that motion; kinematics is concerned with a description of *how* bodies move. Dynamics, on the other hand, is concerned with the action of forces on bodies.

1-1. Fluids

The term "fluid" can be characterized in different ways, as by molecular spacing and activity. In a fluid the spacing between molecules is greater than that in a solid. In a fluid the range of motion of the molecules is greater than that in a solid. For example, if a solid such as iron is heated sufficiently, the molecules become more violently agitated and less closely bound together, and the molten or fluid state finally results.

A more precise and useful definition of the word "fluid" can be formed on the basis of action under stress. A *fluid* is a substance which when in static equilibrium cannot sustain tangential or shear forces. A fluid yields continuously to tangential forces, no matter how small they are. This property of action under stress distinguishes between the two states of

[1] "The Outlook in Fluid Mechanics," *Journal of the Franklin Institute,* vol. 228, No. 2, August, 1939, page 183.

matter, the solid and the fluid. Imagine two plates of metal joined by a solid rivet, as shown in Fig. 1-1. The two parallel pulls tend to slide one plate with respect to the other; a shearing tendency is developed. For small pulls, the solid rivet sustains shear forces in static equilibrium. If a fluid, such as oil, water, or air, were subjected to a shear action, there would be continuous relative motion, even for small forces.

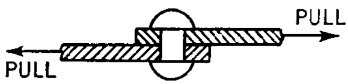

Fig. 1-1. Plates joined by a rivet.

Fluids are commonly divided into two subclasses: liquids and gases. A liquid occupies a definite volume, independent of the dimensions of the vessel in which it is contained. A liquid can have a free surface, like the surface of a lake. A gas, on the other hand, tends to expand to fill any container in which it is placed. In a gas the spacing between molecules is greater than that in a liquid. Sometimes a distinction is drawn between gases and vapors. A vapor, such as steam or ammonia, differs from a gas by being readily condensable to a liquid.

Gases are frequently regarded as compressible, liquids as incompressible. Strictly speaking, all fluids are compressible to some extent. Although air is usually treated as a compressible fluid, there are some cases of flow in which the pressure and density changes are so small that the air may be assumed to be incompressible. Illustrations are the flow of air in ventilating systems and the flow of air around aircraft and other craft at low speeds. Liquids, like oil and water, may be considered as incompressible in many cases; in other cases, the compressibility of such liquids is important. For instance, common experience shows that sound or pressure waves travel through water and other liquids; such pressure waves depend upon the compressibility or elasticity of the liquid.

Fluids will be discussed as continuous media. Actually, liquids and gases consist of molecules and atoms; fluid properties and phenomena are intimately related to molecular behavior. In many engineering problems, however, the mean free path of the molecule is small in comparison with the distances involved, and the flow phenomena can be studied by reference to bulk properties, without a detailed consideration of the behavior of the molecules.

1-2. Pressure

Shear force, tensile force, and compressive force are the three kinds of force which may act on any body. Fluids move continuously under the action of shear or tangential forces. It is well established that fluids are capable of withstanding a compressive stress, which is usually called pressure.

The term "pressure" will be used to denote a *force per unit area*. Probably a more descriptive label would be "pressure-intensity," but the briefer term "pressure" will be employed. Sometimes the term "pressure" is used in the sense of a total force, but this practice in fluid mechanics is apt to be confusing, and will not be followed in this book.

Atmospheric pressure is the force exerted on a unit area due to the weight of the atmosphere. Many pressure-measuring instruments indicate relative or *gage* pressure. Gage pressure is the difference between the pressure of the fluid measured and atmospheric pressure. *Absolute* pressure is the sum of gage pressure plus atmospheric pressure. The word "vacuum" is frequently used in referring to pressures below atmospheric.

Example. Assume that the atmospheric pressure is 14.7 pounds per square inch. A pressure of 5 pounds per square inch gage would mean an absolute pressure of $14.7 + 5$ or 19.7 pounds per square inch. A vacuum of 4 pounds per square inch would mean an absolute pressure of $14.7 - 4$ or 10.7 pounds per square inch.

Note in the foregoing example that the *pound* is used as a unit of force. When using the American system, the *pound* will be taken *only* as a unit of *force*.

1-3. Force and mass

A quantity which has both magnitude and direction is called a *vector* quantity. A quantity which has magnitude only is called a *scalar* quantity. The linear *displacement* of a moving point, or a very small particle, is its change of position. Displacement is a directed distance or a vector quantity; displacement has both magnitude and direction. The linear *velocity* of a moving particle is defined as the time rate at which the particle is changing position, or the rate of displacement with respect to time. Velocity is a vector quantity with both magnitude and direction; the magnitude of velocity is frequently called *speed.* Linear *acceleration* is defined as the rate of change of linear velocity with respect to time; acceleration also is a vector quantity.

If the linear velocity of a moving particle changes, some force is causing that change. For example, imagine a particle or body moving in a certain direction along a straight line. If the magnitude of the velocity is increasing in the direction of motion, the body is accelerating, and a force is acting in the direction of acceleration to cause the velocity change. A particle may be moving in a curved path, with constant speed or constant magnitude of velocity. There is an acceleration, however, because the velocity direction is changing, and a force must be acting on the particle to change the velocity direction. A basic relation in both solid-body and fluid mechanics is the dynamic equation

Force equals mass times acceleration

Note that mass is a scalar quantity; it has magnitude only. The foregoing is a vector equation, with the vector force in the same direction as the vector acceleration.

A consistent set of units, following modern practice, will be employed in order to avoid confusion. When using the American system, the *pound* will be taken as a unit of force and the *slug* as a unit of mass. As an example, one pound is the force acting on a mass of one slug which will accelerate the body by one foot per second each second. Inertia or sluggishness is a mass tendency to resist any force causing acceleration. The word "slug" was probably prompted by the word "sluggishness."

In the CGS (centimeter-gram-second) system the dyne is a force acting on a mass of one gram which will accelerate it one centimeter per second per second. In the MKS (meter-kilogram-second) system the force of one newton acting on a mass of one kilogram accelerates it one meter per second per second.

1-4. Density and specific weight

Each body in the universe exerts a force of gravitational attraction on every other body. The earth attracts a body on its surface, the earth attracts the moon, and the sun attracts the earth and other planets of the solar system. The force of gravitational attraction which the earth exerts on a body is called the *weight* of the body. Weight is *not* the same as mass. A body of mass m is attracted by the earth with a force of magnitude mg, where g is the gravitational acceleration. The weight of a given mass changes as the gravitational acceleration changes.

Density ρ (Greek letter rho) is defined as *mass* per unit volume. For example, water, at a certain temperature and pressure, has a density ρ of 1.94 slugs per cubic foot. For standard sea-level air, at 59 degrees Fahrenheit and 14.7 pounds per square inch absolute, the density ρ is 0.002378 slug per cubic foot.

Specific weight γ (Greek letter gamma) is defined as weight per unit volume. Specific volume v is defined as volume per unit weight and is the reciprocal of specific weight. Since force equals mass times acceleration,

$$\gamma = \rho g \qquad \rho = \frac{\gamma}{g} \tag{1-1}$$

For example, if g at a particular locality is 32.174 feet per second^2, the water with a density of 1.94 slugs per cubic foot would have a specific weight of (32.174)(1.94) or about 62.42 pounds per cubic foot. Unless otherwise specified, the subsequent discussions and problem work in this text will take g as 32.2 feet per second^2 (about 980 centimeters per second^2) and the specific weight of fresh water at the earth's surface as 62.4 pounds per cubic foot. Standard sea-level air has a specific weight of 0.0765 pound per cubic foot.

1-5. Density of liquids

In many flow problems it is necessary to know the density of a fluid. The density can be calculated if the specific gravity is known. The specific gravity of a substance is defined as the ratio of its density (or specific weight) to the density (or specific weight) of some standard substance. For liquids the standard usually employed is either water at 4 degrees centigrade (39.2 degrees Fahrenheit), or water at 60 degrees Fahrenheit. The specific gravities of some liquids at atmospheric pressure are listed in Table 1-1. The physical properties of some common lubricants are included in Chapter Eighteen, Lubrication.

Example. If the specific gravity of a certain oil is 0.80, then the specific weight of this oil is 0.80(62.4) or 49.92 pounds per cubic foot.

TABLE 1-1
SPECIFIC GRAVITIES OF SOME COMMON LIQUIDS
(Referred to water at 39.2 degrees Fahrenheit)

	Specific gravity	Temperature, degrees Fahrenheit
Alcohol, ethyl	0.807	32
Benzene	0.899	32
Gasoline	0.66–0.69	
Glycerine	1.260	32
Mercury	13.546	68
Oil, castor	0.969	59
Oil, linseed (boiled)	0.942	59
Turpentine	0.873	60.8

[2] *Smithsonian Physical Tables*, 9th rev. ed., vol. 120, Smithsonian Institution, Washington, 1954.

1-6. Equation of state for gases

The density of a gas can be calculated from the equation of state, or pressure-volume-temperature relation. The "ideal" or "perfect" gas law is commonly employed.[3] This simple equation of state is

$$p\,(\text{volume}) = KT \tag{1-2}$$

where p is the absolute pressure, T is absolute temperature of any definite

[3] In thermodynamics the term "ideal" or "perfect" gas is sometimes defined as one that obeys the relation $pv = R_0T$. In hydrodynamics an "ideal" or "perfect" fluid is sometimes defined as one which is frictionless. Although this book will avoid this double use, the distinction should be noted in reading current literature.

quantity of gas, and K is a gas constant which depends on the quantity of gas considered and the units in which the pressure, temperature, and volume are expressed.

If t is the thermometer reading on the Fahrenheit scale, the absolute temperature $T = t + 459.3 = t + 460$ (approximately). The absolute temperature using the Fahrenheit scale is often expressed in degrees Rankine. For example, a temperature reading of 70 degrees Fahrenheit would correspond to an absolute temperature of $460 + 70 = 530$ degrees Rankine.

If p is expressed in pounds per square foot, v in cubic feet per pound, and T in degrees Rankine, the equation of state can be written

$$pv = R_0 T \tag{1-3}$$

where R_0 is a particular gas constant; some average values of R_0 for this particular set of units are listed in Table 1-2.

In various cases it is convenient to deal with density directly and express the equation of state in the form

$$p = \rho R T \tag{1-4}$$

Some average values of R are given in Table 1-2 for the case in which p is expressed in pounds per square foot, T in degrees Rankine, and ρ in slugs per cubic foot. For example, for air at 59 degrees Fahrenheit and 14.7 pounds per square inch absolute, R is 1716 and the density is 0.002378 slug per cubic foot. Since $v = 1/\rho g$, a comparison of the two foregoing equations shows that $R = gR_0$.

TABLE 1-2

SOME AVERAGE FACTORS FOR GASES

	R_0	R
Air	53.3	1,716
Carbon dioxide	34.9	1,124
Carbon monoxide	55.1	1,774
Helium	386	12,430
Hydrogen	767	24,700
Methane	96.2	3,098
Oxygen	48.25	1,554

Application of Avogadro's principle, that "all gases at the same pressures and temperatures have the same number of molecules per unit volume," indicates that the product of molecular weight M and the gas constant R_0 is the same for all gases. The product MR_0 is sometimes called a "universal gas constant"; a convenient approximate value is 1546. For practical purposes (not requiring a high degree of precision) R_0 can be taken as 1546 divided by the molecular weight of the gas.

For real gases, Equation (1-2) is accurate at ordinary temperatures