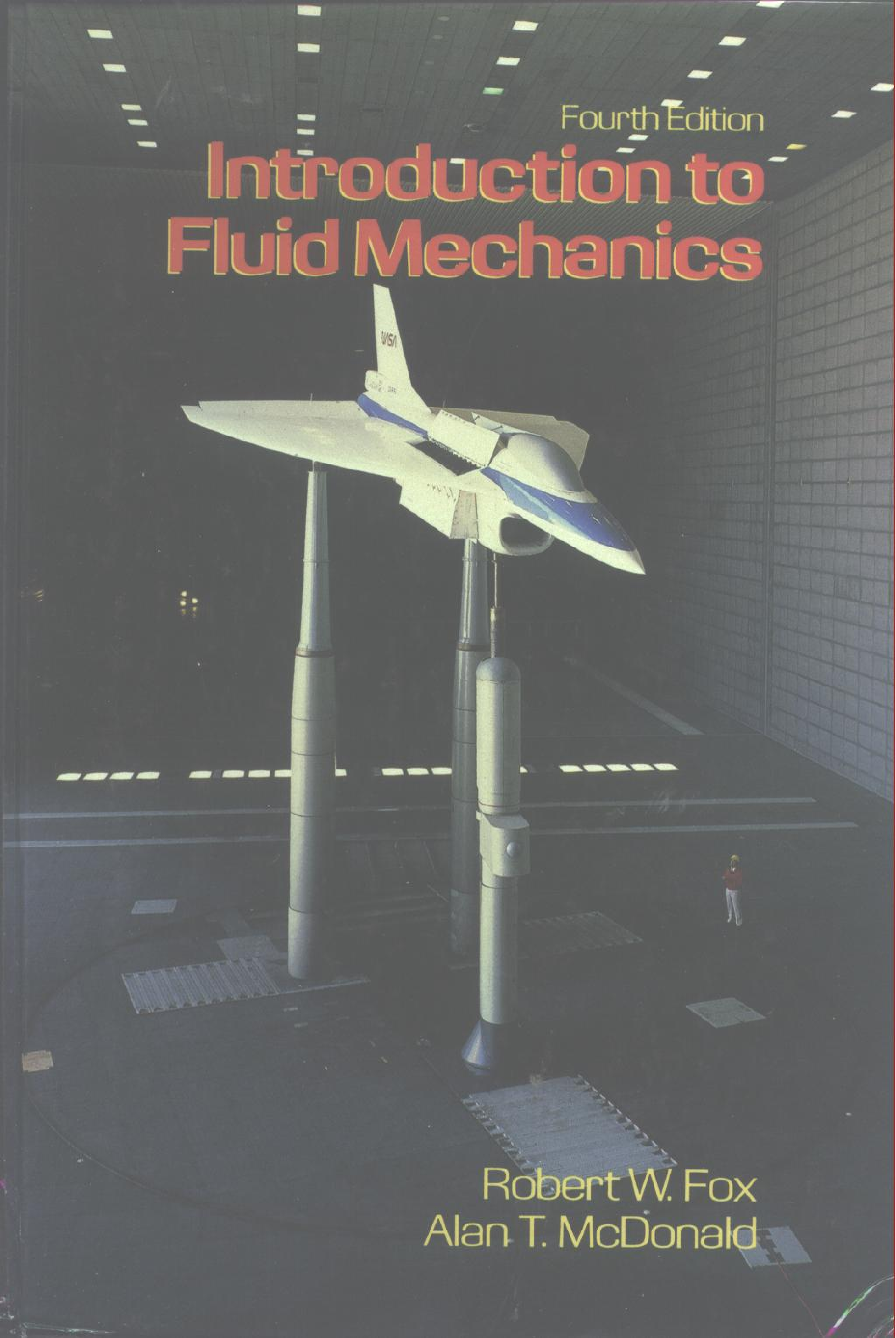
Fourth Edition

Introduction to Fluid Mechanics



Robert W. Fox
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INTRODUCTION TO FLUID MECHANICS

Fourth Edition

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On the Cover: *A Large Wind Tunnel and Model*

The cover photo shows a full-size "model" of a short takeoff, vertical landing, supersonic aircraft. The model is mounted 40 ft above the floor of the world's largest wind tunnel—the new 80 × 120 ft test section—at NASA Ames Research Center. (The man on the tunnel floor shows the scale.)

This aircraft uses the ejector concept, in which relatively cool fan air is directed to the ejector system—the inlet louvers visible along the aircraft fuselage—to produce lift. This creates a relatively cool flow field on the ground beneath the vehicle. The remaining air is exhausted out the rear nozzle to provide thrust for forward flight.

A key test objective was to measure the thrust augmentation of the ejector system. Full-scale testing allows duplication of flight Reynolds number, which is important in the transition from hover to wing-borne flight following vertical takeoff. Large-scale testing also provides more reliable powerplant and ejector performance data than small-scale tests. The very large test section minimizes extraneous effects on vertical force data.

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PREFACE

This text was written for an introductory course in fluid mechanics. Our approach to the subject in the Fourth Edition is unchanged. The physical concepts of fluid mechanics and analysis methods, beginning from basic principles, are emphasized throughout. The primary objective of this book is to help students develop an orderly approach to problem solving. Thus we start from basic equations, state assumptions clearly, and relate results to expected physical behavior. The approach is illustrated by the 125 example problems in the text. Solutions to these examples have been prepared to demonstrate good solution techniques and to explain troublesome points of theory. The example problems are set apart from the text in format, so they are particularly easy to follow.

In the Fourth Edition, the international system of units (SI) again is used in approximately 70 percent of the example problems and end-of-chapter problems. English engineering units are retained in the remaining problems to provide experience with this traditional system and to highlight methods of conversion among unit systems.

Complete explanations in the text, together with numerous detailed examples, make this book understandable for students. This allows the instructor freedom to depart from conventional lecture teaching methods. Classroom time can be used to bring in outside material, expand on special topic areas (such as non-Newtonian flow, boundary-layer flow, lift and drag, or measurement methods), solve example problems, or explain any difficult points of the assigned homework. Thus each class period can be used most appropriately to satisfy student needs.

The material in this book has been selected carefully. There is a detailed presentation of a broad range of topics suitable for a one- or two-semester course in fluid mechanics at the junior or senior level. Introductory courses in rigid-body dynamics and mathematics through integral calculus are necessary prerequisites. Some background in thermodynamics is desirable for the study of one-dimensional compressible flow.

The presentation is organized into broad topic areas:

- Introductory concepts, scope of fluid mechanics, and fluid statics (Chapters 1, 2, and 3).
- Development and application of control volume forms of basic equations (Chapter 4).
- Development and application of differential forms of basic equations (Chapters 5 and 6).
- Dimensional analysis and correlation of experimental data (Chapter 7).
- Applications for incompressible flow (internal flows in Chapter 8 and external flows in Chapter 9).
- Analysis and applications of flow in open channels (Chapter 10).

- Analysis and applications of fluid machinery (Chapter 11).
- Analysis and applications of one-dimensional compressible flow (Chapters 12 and 13).

Summary Objectives listed at the end of each chapter indicate specific concepts that should be understood and tasks students should be able to do after they have studied the material.

Major additions in the Fourth edition include a new chapter (Chapter 11) on fluid machinery, a new section on supersonic channel flow, and a large number of new homework problems. A *Software Supplement* is being developed independently for use with the text.

The new chapter on fluid machinery emphasizes actual machinery and applications. Pump curves are included in a separate appendix to allow treatment of a variety of realistic fluid system applications. The new section on supersonic channel flow with shocks permits a meaningful discussion of supersonic wind tunnel flows. With the addition of 440 new end of chapter problems, the Fourth Edition now contains 1500 problems for homework assignment and student exercises so that as many as eight semesters may be covered without repeating problem assignments. Some end of chapter problems are best solved by writing simple calculator or computer programs (these are identified by the double dagger symbol). Selected computer programs are contained in the *Software Supplement*.

In addition to the major changes, subtile changes and improvements have been made throughout the text. These have emphasized: improved pedagogy, more current data for real situations, more applications, design problems, and computer applications.

The *Solutions Manual* for the Fourth Edition continues the tradition established for this text. The *Solutions Manual*—available from the publisher when the text is adopted—contains a complete, detailed, full-size solution for each of the 1500 homework problems. Each solution has been prepared using the format of the example problems. Solutions may be photocopied for classroom or library use, eliminating the labor of problem solving for the instructor using the text.

The new *Instructor's Guide* in the *Solutions Manual* gives a difficulty rating for each problem and keys each problem to the relevant text section. This makes it simple to assign homework at the desired difficulty range for each section of the book.

We have been using open-ended *design problems* several times each semester in place of traditional laboratory experiments. These problems give students more time to explore the application of fluid mechanics principles to the design of devices and systems. Selected design problems have been placed in the *Instructor's Guide*, along with suggestions for their use.

The *Software Supplement* is designed to allow students to play the *What if?* game. Parameters are easy to vary so their effects on system behavior can be identified readily. The *Supplement* includes software for analysis of fluid properties, standard atmosphere, accelerating control volumes, pipe flow head loss, surface depth in open-channel flow, and one-dimensional compressible flow. For each compressible flow case, the temperature-entropy diagram may be plotted if desired. Hints for using the software also are presented in the *Instructor's Guide*.

Many fine instructional videos and films are available to further clarify and demonstrate basic principles in fluid mechanics. We refer to them in the text where their use is appropriate; a complete list of suppliers and titles is included in Appendix C.

When our students have finished this course, we expect them to be able to apply the basic equations to a variety of problems, including new problems that they have not encountered previously We emphasize physical understanding throughout to make students aware of the variety of phenomena that occur in real fluid flow situations. By minimizing the number of "magic formulas" and emphasizing the fundamental approach, we believe students will develop confidence in their ability to apply the material and will be able to reason out solutions to challenging problems.

The book also is well suited for independent study by students or practicing engineers. Its readability and clear examples help to build student confidence. The summary objectives at the end of each chapter may be used for review or to assess the achievement of educational goals.

We recognize that no single approach can satisfy all needs. We are grateful to the many students and faculty whose comments have helped us improve the Fourth Edition. We especially thank the reviewers for the Fourth Edition, who were: Seppo Korpela of The Ohio State University, Darryl Alofs of University of Missouri—Rolla, Jim Liburdy of Clemson University, Stanley Berger of University of California—Berkeley, Willem Brutsaert of University of Maine, Charles Merkle of The Pennsylvania State University, Frank Champagne of University of Arizona, Chris Rogers of Tufts University, Eugene Kordyban of University of Detroit, Ed Shaughnessy of Duke University, and Edgar O'Rear of University of Oklahoma. Professors Merkle and O'Rear provided particularly detailed and insightful reviews.

Thanks also are due to our wives, Beryl and Tania, who from behind the scenes supported the long hours of preparation that went into this effort. As always, we welcome criticisms and suggestions from interested readers or users of this book.

Robert W. Fox
Alan T. McDonald

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Chapter 1

INTRODUCTION

The goal of this texbook is to provide a clear, concise introduction to the subject of fluid mechanics. In beginning the study of any subject, a number of questions may come to mind. Students in the first course in fluid mechanics might ask:

What is fluid mechanics all about?
Why do I have to study it?
Why should I want to study it?
How does it relate to subject areas with which I am already familiar?

In this chapter we shall try to present at least qualitative answers to these and similar questions. This should serve to establish a base and a perspective for our study of fluid mechanics. Before proceeding with the definition of a fluid, we digress for a moment with a few pointed comments to students.

1-1 NOTE TO STUDENTS

In writing this book we have kept you, the student, uppermost in our minds; the book is written for you. It is our strong feeling that classroom time should not be devoted to a regurgitation of textbook material by the instructor. Instead, the time should be used to amplify the textbook material by discussing related material and applying basic principles to the solution of problems. The necessary conditions for accomplishing this goal are: (1) a clear, concise presentation of the fundamentals that you, the student, can read and understand, and (2) your willingness to read the text material before going to class. We have assumed responsibility for meeting the first condition. You must assume responsibility for satisfying the second condition. There probably will be times when we fall short of satisfying these objectives. If so, we would appreciate hearing of these shortcomings either directly or through your instructor.

It goes without saying that an introductory text is not all-inclusive. Your instructor undoubtedly will expand on the material presented, suggest alternative approaches to topics, and introduce additional new material. We encourage you to refer to the many other fluid mechanics textbooks and references available in the library; where another text presents a particularly good discussion of a given topic, we shall refer to it directly. We also encourage you to learn from your fellow students and from the graduate assistant(s) assigned to the course as well as from your instructor.We assume that you have had an introduction to thermodynamics (either in a basic physics course or an introductory course in thermodynamics) and prior courses in statics, dynamics, and differential and integral calculus. No attempt will be made to restate this subject material; however, the pertinent aspects of this previous study will be reviewed briefly when appropriate.

It is our strong belief that one learns best by *doing*. This is true whether the subject under study is fluid mechanics, thermodynamics, or golf. The fundamentals in any of these cases are few, and mastery of them comes through practice. *Thus it is extremely important, in fact essential, that you solve problems.* The numerous problems included at the end of each chapter provide the opportunity to gain facility in applying fundamentals to the solution of problems. You should avoid the temptation to adopt a "plug and chug" approach to solving problems. Most of the problems are such that this approach simply will not work. In solving problems we strongly recommend that you proceed using the following logical steps:

1. State briefly and concisely (in your own words) the information given.
2. State the information to be found.
3. Draw a schematic of the system or control volume to be used in the analysis. Be sure to label the boundaries of the system or control volume and label appropriate coordinate directions.
4. Give the appropriate mathematical formulation of the *basic* laws that you consider necessary to solve the problem.
5. List the simplifying assumptions that you feel are appropriate in the problem.
6. Complete the analysis algebraically before substituting numerical values.
7. Substitute numerical values (using a consistent set of units) to obtain a numerical answer.
    a. Reference the source of values for any physical properties.
    b. Be sure the significant figures in the answer are consistent with the given data.
8. Check the answer and review the assumptions made in the solution to make sure they are reasonable.
9. Label the answer.

In your initial work this problem format may seen unnecessary. However, such an orderly approach to the solution of problems will reduce errors, save time, and permit a clearer understanding of the limitations of a particular solution. This approach also prepares you for communicating your solution method and results to others, as will often be necessary in your career. This format is used in all example problems presented in this text; answers to example problems are given to three significant figures.

Most engineering calculations involve measured values or physical property data. Every measured value has associated with it an experimental uncertainty. The uncertainty in a measurement can be reduced with care and by applying more precise measurement techniques, but cost and time needed to obtain data rise sharply as measurement precision is increased. Consequently, few engineering data are sufficiently precise to justify the use of more than three significant figures.

The principles of specifying the experimental uncertainty of a measurement and of estimating the uncertainty of a calculated result are reviewed in Appendix F. These should be understood thoroughly by anyone who performs laboratory work. We suggest you take time to review Appendix F before performing laboratory work or solving the homework problems at the end of this chapter.

1-2 DEFINITION OF A FLUID

Fluid mechanics deals with the behavior of fluids at rest and in motion. It is logical to begin with a definition of a *fluid*: a fluid is a substance that deforms continuously under the application of a shear (tangential) stress no matter how small the shear stress may be.

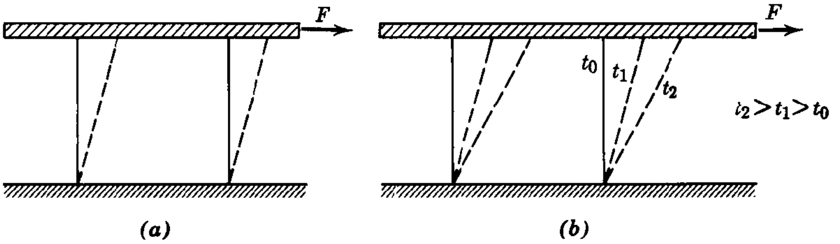

Fig. 1.1 Behavior of (a) solid and (b) fluid, under the action of a constant shear force.

Thus fluids comprise the liquid and gas (or vapor) phases of the physical forms in which matter exists. The distinction between a fluid and the solid state of matter is clear if you compare fluid and solid behavior. A solid deforms when a shear stress is applied, but it does not deform continuously.

In Fig. 1.1 the behavior of a solid (Fig. 1.1*a*) and a fluid (Fig. 1.1*b*) under the action of a constant shear force are contrasted. In Fig. 1.1*a* the shear force is applied to the solid through the upper of two plates to which the solid has been bonded. When the shear force is applied to the plate, the block is deformed as shown. From our previous work in mechanics, we know that, provided the elastic limit of the solid material is not exceeded, the deformation is proportional to the applied shear stress, $\tau = F/A$, where A is the area of the surface in contact with the plate.

To repeat the experiment with a fluid between the plates, use a dye marker to outline a fluid element as shown by the solid lines (Fig. 1.1*b*). When the force, F, is applied to the upper plate, the fluid element continues to deform as long as the force is applied. The fluid in direct contact with the solid boundary has the same velocity as the boundary itself; there is no slip at the boundary. This is an experimental fact based on numerous observations of fluid behavior.[1] The shape of the fluid element, at successive instants of time $t_2 > t_1 > t_0$, is shown (Fig. 1.1*b*) by the dashed lines, which represent the positions of the dye markers at successive times. Because the fluid motion continues under the application of a shear stress, we may alternatively define a fluid as a substance that cannot sustain a shear stress when at rest.

1-3 SCOPE OF FLUID MECHANICS

Having defined a fluid and noted the characteristics that distinguish it from a solid, we might ask the question: "Why study fluid mechanics?"

Knowledge and understanding of the basic principles and concepts of fluid mechanics are essential to analyze any system in which a fluid is the working medium. The design of virtually all means of transportation requires application of the principles of fluid mechanics. Included are aircraft for both subsonic and supersonic flight, ground effect machines, hovercraft, vertical takeoff and landing aircraft requiring minimum runway length, surface ships, submarines, and automobiles. In recent years automobile manufacturers have given more consideration to aerodynamic design. This has been true for some time for the designers of both racing cars and boats. The design of propulsion systems for space flight as well as for toy rockets is based on

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[1] The no-slip condition is demonstrated in the NCFMF film, *Fundamentals of Boundary Layers*, F. H. Abernathy, principal. A complete list of fluid mechanics film titles and sources is given in Appendix C.

the principles of fluid mechanics. The collapse of the Tacoma Narrows Bridge in 1940 is evidence of the possible consequences of neglecting the basic principles of fluid mechanics.[2] It is commonplace today to perform model studies to determine the aerodynamic forces on, and flow fields around, buildings and structures. These include studies of skyscrapers, baseball stadiums, smokestacks, and shopping plazas.

The design of all types of fluid machinery including pumps, fans, blowers, compressors, and turbines clearly requires knowledge of the basic principles of fluid mechanics. Lubrication is an application of considerable importance in fluid mechanics. Heating and ventilating systems for private homes, large office buildings, and underground tunnels, and the design of pipeline systems are further examples of technical problem areas requiring knowledge of fluid mechanics. The circulatory system of the body is essentially a fluid system. It is not surprising that the design of blood substitutes, artificial hearts, heart-lung machines, breathing aids, and other such devices must rely on the basic principles of fluid mechanics.

Even some of our recreational endeavors are directly related to fluid mechanics. The slicing and hooking of golf balls can be explained by the principles of fluid mechanics (although they can be corrected only by a golf pro!).

The list of applications of the principles of fluid mechanics could be extended considerably. Our main point here is that fluid mechanics is not a subject studied for purely academic interest; rather, it is a subject with widespread importance both in our everyday experiences and in modern technology.

Clearly, we cannot hope to consider in detail even a small percentage of these and other specific problems of fluid mechanics. Instead, the purpose of this text is to present the basic laws and associated physical concepts that provide the basis or starting point in the analysis of any problem in fluid mechanics.

1-4 BASIC EQUATIONS

Analysis of any problem in fluid mechanics necessarily begins, either directly or indirectly, with statements of the basic laws governing the fluid motion. The basic laws, which are applicable to any fluid, are:

1. The conservation of mass.
2. Newton's second law of motion.
3. The principle of angular momentum.
4. The first law of thermodynamics.
5. The second law of thermodynamics.

Clearly, not all basic laws always are required to solve any one problem. On the other hand, in many problems it is necessary to bring into the analysis additional relations, in the form of equations of state or constitutive equations, that describe the behavior of physical properties of fluids under given conditions.

You probably recall studying properties of gases in basic physics or thermodynamics. The *ideal gas* equation of state

$$p = \rho RT \tag{1.1}$$

is a model that relates density to pressure and temperature for many gases for calculations of engineering accuracy under normal conditions. In Eq. 1.1, R is the gas

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[2] For dramatic evidence of aerodynamic forces in action, see the short film, *Collapse of the Tacoma Narrows Bridge* (see Appendix C).

constant. Values of R are given in Appendix A for several common gases; p and T in Eq. 1.1 are the absolute pressure and absolute temperature, respectively. Example Problem 1.1 illustrates use of the ideal gas equation of state.

It is obvious that the basic laws with which we shall deal are the same as those used in mechanics and thermodynamics. Our task will be to formulate these laws in suitable forms to solve fluid flow problems and to apply them to a wide variety of problems.

We must emphasize that there are, as we shall see, many apparently simple problems in fluid mechanics that cannot be solved analytically. In such cases we must resort to more complicated numerical solutions and/or results of experimental tests.

Not all measurements can be made to the same degree of accuracy and not all data are equally good; the validity of data should be documented before test results are used for design. A statement of the probable uncertainty of data is an important part of reporting experimental results completely and clearly. Analysis of uncertainty also is useful during experiment design. Careful study may indicate potential sources of unacceptable error and suggest improved measurement methods.

1-5 METHODS OF ANALYSIS

The first step in solving a problem is to define the system that you are attempting to analyze. In basic mechanics, extensive use was made of the free-body diagram. In thermodynamics closed or open systems were considered. In this text we use the terms *system* and *control volume*. The importance of defining the system or control volume before applying the basic equations in the analysis of a problem cannot be overemphasized. At this point we review the definitions of systems and control volumes.

1-5.1 System and Control Volume

A system is defined as a fixed, identifiable quantity of mass; the system boundaries separate the system from the surroundings. The boundaries of the system may be fixed or movable; however, there is no mass transfer across the system boundaries.

In the familiar piston-cylinder assembly from thermodynamics, Fig. 1.2, the gas in the cylinder is the system. If a high-temperature source is brought in contact with the left end of the cylinder, the piston will move to the right; the boundary of the system thus moves. Heat and work may cross the boundaries of the system, but the quantity of matter within the system boundaries remains fixed. There is no mass transfer across the system boundaries.

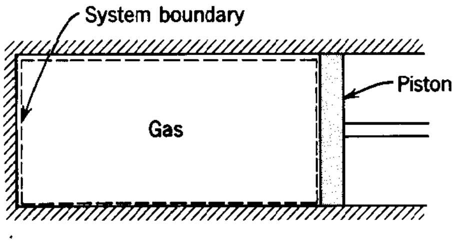

Fig. 1.2 Piston-cylinder assembly.

EXAMPLE 1.1—First Law Application to Closed System

A piston-cylinder device contains 0.95 kg of oxygen initially at a temperature of 27 C and a pressure of 150 kPa. Heat is added to the gas and it expands at constant