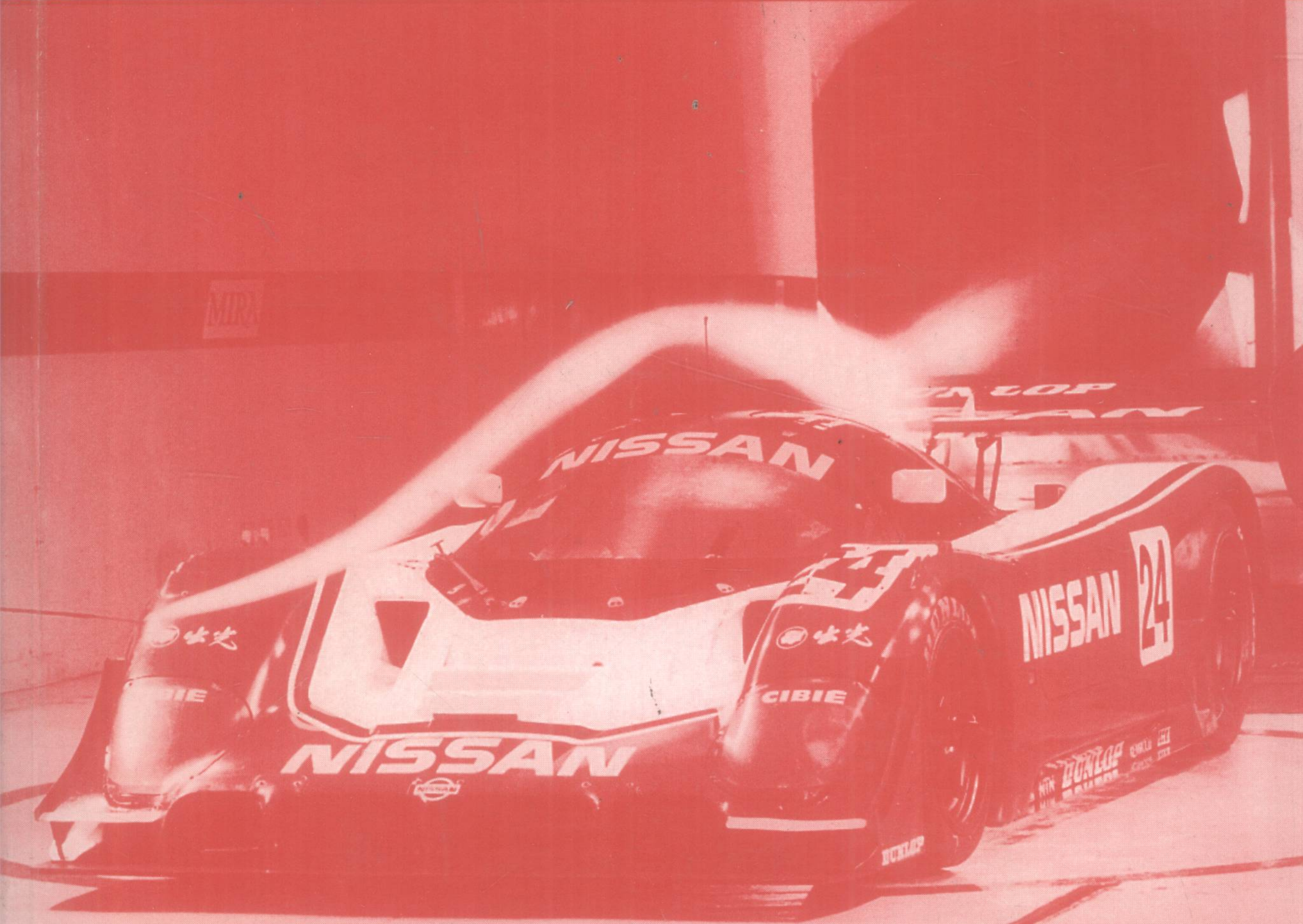
FIFTH EDITION

Introduction to Fluid Mechanics



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INTRODUCTION TO FLUID MECHANICS

FIFTH EDITION

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INTRODUCTION TO FLUID MECHANICS

PREFACE

This text was written for an introductory course in fluid mechanics. Our approach to the subject emphasizes the physical concepts of fluid mechanics and methods of analysis that begin from basic principles. The primary objective of this book is to help students develop an orderly approach to problem solving. Thus we always start from basic equations, state assumptions clearly, and try to relate results to expected physical behavior.

This approach is illustrated by the 109 example problems in the text. Solutions to these example problems demonstrate good solution techniques and explain troublesome points of theory. The format of the example problems sets them apart from the text, so they are easy to identify and follow.

SI units are used in approximately 70 percent of example and end-of-chapter problems. English Engineering units are retained in some problems to provide experience with this traditional system and to highlight conversions among unit systems that may be derived from fundamentals.

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

The material has been selected carefully, and a broad range of topics suitable for a one- or two-semester course in fluid mechanics at the junior or senior level is included. We assume a background in rigid-body dynamics and mathematics through differential equations. A background in thermodynamics is desirable for the study of one-dimensional compressible flow.

The presentation has been 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 internal viscous incompressible flows (Chapter 8).
- Applications for external viscous incompressible flows (Chapter 9).
- Analysis of fluid machinery and system applications (Chapter 10).
- Analysis and applications of one-dimensional compressible flow (Chapters 11 and 12).

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The Summary Objectives list at the end of each chapter indicates terminology and concepts that should be understood and tasks that one should be able to complete after studying the chapter.

Chapter 4 deals with analysis using both finite and differential control volumes. The Bernoulli equation is derived (in optional Section 4-4.1) as an example of the application of basic equations to a differential control volume. Having the Bernoulli equation available for use in Chapter 4 affords the opportunity to include more challenging problems dealing with the momentum equation for finite control volumes.

Another derivation of the Bernoulli equation is presented in Chapter 6, where it is obtained by integrating the Euler equations along a streamline. If an instructor prefers to delay introducing the Bernoulli equation, then the challenging problems from Chapter 4 may be assigned during study of Chapter 6.

We have made a major effort to improve clarity of writing in this fifth edition. We were aided by a most thorough and detailed review prepared by Dr. Albert L. Hale, formerly of Bell Laboratories, and we are grateful for his significant contribution. Subtle changes and improvcments throughout the text facilitate teaching of the material and emphasize its practical applications.

End-of-chapter problems in the fifth edition have been reduced in number to about 1250. However, many problems have been combined and contain multiple parts. Most of these have been structured so that all parts need not be assigned at once, and many subparts have been designed to explore "What if?" questions.

Approximately 350 problems are new or modified, and many of them include a component best suited for analysis using a spreadsheet or computer program. These problems are identified by a computer icon in the margin. Many of these "computer" problems have been designed so the computer component provides a parametric investigation of a single-point solution. Where appropriate, these are keyed to the *FM Software Supplement* that may be downloaded from the John Wiley & Sons, Inc. website (www.wiley.com/college/fox). Again, subparts of the problems may be assigned as stand-alone problems.

We have included almost 100 new open-ended problems. These may be thought-provoking questions intended to test understanding of fundamental concepts, or they may require creative thought, synthesis, and/or narrative discussion.

The *Solutions Manual* for the fifth edition continues a tradition established by Fox and McDonald: It contains a complete, detailed solution for each of the 1250 homework problems. Prepared in the same way as the example problems, each solution begins from basic equations, clearly states assumptions, reduces basic equations to computing equations, obtains an algebraic result, and finally substitutes numerical values to calculate the answer. Solutions may be reproduced for classroom or library use, eliminating the labor of problem solving for the instructor who adopts the text.

Each problem in the *Solutions Manual* is rated for difficulty level and keyed to the relevant section of the text. This makes it easy for the instructor to assign homework problems at the appropriate difficulty level for each section of the book. The *Solutions Manual,* in paperback book or CD-ROM form, is available from the publisher when the text is adopted.

Where appropriate, we have begun using open-ended *design problems* in place of traditional laboratory experiments. Design problems encourage students to spend more time exploring applications of fluid mechanics principles to the design of devices and systems. In the fifth edition, design problems are included with the end-of-chapter problems.

The presentation of fluid property data in Appendix A has been expanded to include detailed tables of properties for air and water at various temperatures. Viscosity data for water and air at various temperatures may be read accurately from new Tables A.7 through A.10, rather than estimated from the plots of Figs A.2 and A.3. However, the plots are retained to show the trends of temperature dependence for liquids and gases, the approximate viscosities of less common fluids, and the relative magnitudes of liquid and gas viscosities. Computing equations are included for the computer models of air and water property values.

Many worthwhile videos are available to clarify and demonstrate basic principles of fluid mechanics. These are referenced in the text where their use would be appropriate and are also identified by supplier in Appendix C.

The *Software Supplement* is designed to allow students to vary the parameters of a problem solution in order to explore the behavior of the solution. This supplement includes fluid property and standard atmosphere data and has modules to analyze accelerating control volumes, pipe flow head loss, and one-dimensional compressible flow. (The program also displays the Ts diagram for each compressible flow problem.) Because computing software is readily available, the tables for computation of compressible flow (Appendix E) have been condensed. In their place we encourage students to program the computing equations as functions of Mach number on a spreadsheet or calculator for use in solving problems. Plots have been added to show trends in property ratios as functions of Mach number.

When students finish the fluid mechanics course, we expect them to be able to apply the basic equations to a variety of problems, including problems they have not encountered previously. We emphasize physical concepts throughout to help students model the variety of phenomena that occur in real fluid flow situations. We minimize the use of "magic formulas" and emphasize the systematic and fundamental approach to problem solving. By following this format, we believe students develop confidence in their ability to apply the material and find they can reason out solutions to rather challenging problems.

The book is well suited for independent study by students or practicing engineers. Its readability and clear examples help to build confidence. The Summary Objectives at the end of each chapter are useful for review or to assess achievement of educational goals.

We recognize that no single approach can satisfy all needs, and we are grateful to the many students and faculty whose comments have helped us improve upon the earlier editions of this book. We especially thank our reviewers for the fifth edition: Richard Gardner of Washington University (St. Louis), Craig Hoff of Lawrence Technological University, Deane Kihara of the University of Hawaii at Manoa, Cesar Mendoza-Cabrales of Columbia University, Charles Meneveau of Johns Hopkins University, and M. Erol Ulucakli of Lafayette College.

We appreciate the unstinting support of our wives, Beryl and Tania. They alone are aware of the number of hours that went into this effort!

Criticisms and suggestions from interested readers of this book are welcome.

Robert W. Fox
Alan T. McDonald
West Lafayette, Indiana
August 1998

Table G.1 SI Units and Prefixes[a]

SI Units	Quantity	Unit	SI Symbol	Formula
SI base units:	Length	meter	m	—
	Mass	kilogram	kg	—
	Time	second	s	—
	Temperature	kelvin	K	—
SI supplementary unit:	Plane angle	radian	rad	—
SI derived units:	Energy	joule	J	$N \cdot m$
	Force	newton	N	$kg \cdot m/s^2$
	Power	watt	W	J/s
	Pressure	pascal	Pa	N/m^2
	Work	joule	J	$N \cdot m$

SI prefixes	Multiplication Factor	Prefix	SI Symbol
	$1\,000\,000\,000\,000 = 10^{12}$	tera	T
	$1\,000\,000\,000 = 10^{9}$	giga	G
	$1\,000\,000 = 10^{6}$	mega	M
	$1\,000 = 10^{3}$	kilo	k
	$0.01 = 10^{-2}$	centi[b]	c
	$0.001 = 10^{-3}$	milli	m
	$0.000\,001 = 10^{-6}$	micro	μ
	$0.000\,000\,001 = 10^{-9}$	nano	n
	$0.000\,000\,000\,001 = 10^{-12}$	pico	p

[a] Source: ASTM Standard for Metric Practice E 380–97, 1997.

[b] To be avoided where possible.

Table G.2 Conversion Factors and Definitions

Fundamental Dimension	English Unit	Exact SI Value	Approximate SI Value
Length	1 in.	0.0254 m	—
Mass	1 lbm	0.453 592 37 kg	0.454 kg
Temperature	1°F	5/9 K	—

Definitions:

Acceleration of gravity:	$g = 9.8066$ m/s^2 (= 32.174 ft/s^2)
Energy:	Btu (British thermal unit) ≡ amount of energy required to raise the temperature of 1 lbm of water 1°F (1 Btu = 778.2 ft · lbf)
	kilocalorie ≡ amount of energy required to raise the temperature of 1 kg of water 1 K (1 kcal = 4187 J)
Length:	1 mile = 5280 ft; 1 nautical mile = 6076.1 ft = 1852 m (exact)
Power:	1 horsepower ≡ 550 ft · lbf/s
Pressure:	1 bar ≡ 10^5 Pa
Temperature:	degree Fahrenheit, $T_F = \frac{9}{5}T_C + 32$ (where T_C is degrees Celsius)
	degree Rankine, $T_R = T_F + 459.67$
	Kelvin, $T_K = T_C + 273.15$ (exact)
Viscosity:	1 Poise ≡ 0.1 kg/(m · s)
	1 Stoke ≡ 0.0001 m^2/s
Volume:	1 gal ≡ 231 in.^{3} (1 ft^3 = 7.48 gal)

Useful Conversion Factors:

1 lbf = 4.448 N
1 lbf/in.^{2} = 6895 Pa
1 Btu = 1055 J
1 hp = 746 W = 2545 Btu/hr
1 kW = 3413 Btu/hr
1 quart = 0.000946 m^3 = 0.946 liter
1 kcal = 3.968 Btu

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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 to accomplish 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 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 seem 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 rounded 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.

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