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FLUID MECHANICS

FUNDAMENTALS AND APPLICATIONS

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FLUID MECHANICS

FUNDAMENTALS AND APPLICATIONS

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Dedication

To all students—In hopes of enhancing your desire and enthusiasm to explore the inner workings of our marvelous universe, of which fluid mechanics is a small but fascinating part; our hope is that this book enhances your love of learning, not only about fluid mechanics, but about life.

ABOUT THE AUTHORS

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Dr. Çengel is the coauthor of the widely adopted textbook *Thermodynamics: An Engineering Approach,* 4th edition (2002), published by McGraw-Hill. He is also the author of the textbook *Heat Transfer: A Practical Approach,* 2nd edition (2003), and the coauthor of the textbook *Fundamentals of Thermal-Fluid Sciences,* 2nd edition (2005), both published by McGraw-Hill. Some of his textbooks have been translated to Chinese, Japanese, Korean, Spanish, Turkish, Italian, and Greek.

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Professor Cimbala is the recipient of several outstanding teaching awards and views his book writing as an extension of his love of teaching. He is a member of the American Institute of Aeronautics and Astronautics (AIAA), the American Society of Mechanical Engineers (ASME), the American Society for Engineering Education (ASEE), and the American Physical Society (APS).

BRIEF CONTENTS

CONTENTS

CHAPTER THIRTEEN
OPEN-CHANNEL FLOW 679

CHAPTER FOURTEEN
TURBOMACHINERY 735

CHAPTER FIFTEEN
INTRODUCTION TO COMPUTATIONAL FLUID DYNAMICS 817

APPENDIX 1

PROPERTY TABLES AND CHARTS (SI UNITS) 885

APPENDIX 2

PROPERTY TABLES AND CHARTS (ENGLISH UNITS) 903

PREFACE

BACKGROUND

Fluid mechanics is an exciting and fascinating subject with unlimited practical applications ranging from microscopic biological systems to automobiles, airplanes, and spacecraft propulsion. Yet fluid mechanics has historically been one of the most challenging subjects for undergraduate students. Unlike earlier freshman- and sophomore-level subjects such as physics, chemistry, and engineering mechanics, where students often learn equations and then "plug and chug" on their calculators, proper analysis of a problem in fluid mechanics requires much more. Oftentimes, students must first assess the problem, make and justify assumptions and/or approximations, apply the relevant physical laws in their proper forms, and solve the resulting equations before ever plugging any numbers into their calculators. Many problems in fluid mechanics require more than just knowledge of the subject, but also physical intuition and experience. Our hope is that this book, through its careful explanations of concepts and its use of numerous practical examples, sketches, figures, and photographs, bridges the gap between knowledge and proper application of that knowledge.

Fluid mechanics is a mature subject; the basic equations and approximations are well established and can be found in numerous introductory fluid mechanics books. The books are distinguished from one another in the way the material is presented. An accessible fluid mechanics book should present the material in a *progressive order* from simple to more difficult, building each chapter upon foundations laid down in previous chapters. In this way, even the traditionally challenging aspects of fluid mechanics can be learned effectively. Fluid mechanics is by its very nature a highly visual subject, and students learn more readily by visual stimulation. It is therefore imperative that a good fluid mechanics book also provide quality figures, photographs, and visual aids that help to explain the significance and meaning of the mathematical expressions.

OBJECTIVES

This book is intended for use as a textbook in the first fluid mechanics course for undergraduate engineering students in their junior or senior year. Students are assumed to have an adequate background in calculus, physics, engineering mechanics, and thermodynamics. The objectives of this text are

- To cover the *basic principles and equations* of fluid mechanics
- To present numerous and diverse real-world *engineering examples* to give students a feel for how fluid mechanics is applied in engineering practice
- To develop an *intuitive understanding* of fluid mechanics by emphasizing the physics, and by supplying attractive figures and visual aids to reinforce the physics

The text contains sufficient material to give instructors flexibility as to which topics to emphasize. For example, aeronautics and aerospace engineering instructors may emphasize potential flow, drag and lift, compressible flow, turbomachinery, and CFD, while mechanical and civil engineering instructors may choose to emphasize pipe flows and open-channel flows, respectively. The book has been written with enough breadth of coverage that it can be used for a two-course sequence in fluid mechanics if desired.

PHILOSOPHY AND GOAL

We have adopted the same philosophy as that of the texts *Thermodynamics: An Engineering Approach* by Y. A. Çengel and M. A. Boles, *Heat Transfer: A Practical Approach* by Y. A. Çengel, and *Fundamentals of Thermal-Fluid Sciences* by Y. A. Çengel and R. H. Turner, all published by McGraw-Hill. Namely, our goal is to offer an engineering textbook that

- Communicates directly to the minds of tomorrow's engineers in a *simple yet precise* manner
- Leads students toward a clear understanding and firm grasp of the *basic principles* of fluid mechanics
- Encourages *creative thinking* and development of a *deeper understanding* and *intuitive feel* for fluid mechanics
- Is *read* by students with *interest* and *enthusiasm* rather than merely as an aid to solve problems

It is our philosophy that the best way to learn is by practice. Therefore, special effort is made throughout the book to reinforce material that was presented earlier (both earlier in the chapter and in previous chapters). For example, many of the illustrated example problems and end-of-chapter problems are *comprehensive,* forcing the student to review concepts learned in previous chapters.

Throughout the book, we show examples generated by *computational fluid dynamics* (CFD), and we provide an introductory chapter on CFD. Our goal is not to teach details about numerical algorithms associated with CFD—this is more properly presented in a separate course, typically at the graduate level. Rather, it is our intent to introduce undergraduate students to the capabilities and limitations of CFD as an *engineering tool.* We use CFD solutions in much the same way as we use experimental results from a wind tunnel test, i.e., to reinforce understanding of the physics of fluid flows and to provide quality flow visualizations that help to explain fluid behavior.

CONTENT AND ORGANIZATION

This book is organized into 15 chapters beginning with fundamental concepts of fluids and fluid flows and ending with an introduction to computational fluid dynamics, the application of which is rapidly becoming more commonplace, even at the undergraduate level.

- Chapter 1 provides a basic introduction to fluids, classifications of fluid flow, control volume versus system formulations, dimensions, units, significant digits, and problem-solving techniques.

- Chapter 2 is devoted to fluid properties such as density, vapor pressure, specific heats, viscosity, and surface tension.
- Chapter 3 deals with fluid statics and pressure, including manometers and barometers, hydrostatic forces on submerged surfaces, buoyancy and stability, and fluids in rigid-body motion.
- Chapter 4 covers topics related to fluid kinematics, such as the differences between Lagrangian and Eulerian descriptions of fluid flows, flow patterns, flow visualization, vorticity and rotationality, and the Reynolds transport theorem.
- Chapter 5 introduces the fundamental conservation laws of mass, momentum, and energy, with emphasis on the proper use of the mass, Bernoulli, and energy equations and the engineering applications of these equations.
- Chapter 6 applies the Reynolds transport theorem to linear momentum and angular momentum and emphasizes practical engineering applications of the finite control volume momentum analysis.
- Chapter 7 reinforces the concept of dimensional homogeneity and introduces the Buckingham Pi theorem of dimensional analysis, dynamic similarity, and the method of repeating variables—material that is useful throughout the rest of the book and in many disciplines in science and engineering.
- Chapter 8 is devoted to flow in pipes and ducts. We discuss the differences between laminar and turbulent flow, friction losses in pipes and ducts, and minor losses in piping networks. We also explain how to properly select a pump or fan to match a piping network. Finally, we discuss various experimental devices that are used to measure flow rate and velocity.
- Chapter 9 deals with differential analysis of fluid flow and includes derivation and application of the continuity equation, the Cauchy equation, and the Navier–Stokes equation. We also introduce the stream function and describe its usefulness in analysis of fluid flows.
- Chapter 10 discusses several *approximations* of the Navier–Stokes equations and provides example solutions for each approximation, including creeping flow, inviscid flow, irrotational (potential) flow, and boundary layers.
- Chapter 11 covers forces on bodies (drag and lift), explaining the distinction between friction and pressure drag, and providing drag coefficients for many common geometries. This chapter emphasizes the practical application of wind tunnel measurements coupled with dynamic similarity and dimensional analysis concepts introduced earlier in Chapter 7.
- Chapter 12 extends fluid flow analysis to compressible flow, where the behavior of gases is greatly affected by the Mach number, and the concepts of expansion waves, normal and oblique shock waves, and choked flow are introduced.
- Chapter 13 deals with open-channel flow and some of the unique features associated with the flow of liquids with a free surface, such as surface waves and hydraulic jumps.

- Chapter 14 examines turbomachinery in more detail, including pumps, fans, and turbines. An emphasis is placed on how pumps and turbines work, rather than on their detailed design. We also discuss overall pump and turbine design, based on dynamic similarity laws and simplified velocity vector analyses.
- Chapter 15 describes the fundamental concepts of computational fluid dynamics (CFD) and shows students how to use commercial CFD codes as a tool to solve complex fluid mechanics problems. We emphasize the *application* of CFD rather than the algorithms used in CFD codes.

Each chapter contains a large number of end-of-chapter homework problems suitable for use by instructors. Most of the problems that involve calculations are in SI units, but approximately 20 percent are written in English units. Finally, a comprehensive set of appendices is provided, giving the thermodynamic and fluid properties of several materials, not just air and water as in most introductory fluids texts. Many of the end-of-chapter problems require use of the properties found in these appendices.

LEARNING TOOLS

EMPHASIS ON PHYSICS

A distinctive feature of this book is its emphasis on the physical aspects of the subject matter in addition to mathematical representations and manipulations. The authors believe that the emphasis in undergraduate education should remain on *developing a sense of underlying physical mechanisms* and a *mastery of solving practical problems* that an engineer is likely to face in the real world. Developing an intuitive understanding should also make the course a more motivating and worthwhile experience for the students.

EFFECTIVE USE OF ASSOCIATION

An observant mind should have no difficulty understanding engineering sciences. After all, the principles of engineering sciences are based on our *everyday experiences* and *experimental observations.* Therefore, a physical, intuitive approach is used throughout this text. Frequently, *parallels are drawn* between the subject matter and students' everyday experiences so that they can relate the subject matter to what they already know.

SELF-INSTRUCTING

The material in the text is introduced at a level that an average student can follow comfortably. It speaks *to* students, not *over* students. In fact, it is *self-instructive.* Noting that the principles of science are based on experimental observations, most of the derivations in this text are largely based on physical arguments, and thus they are easy to follow and understand.

EXTENSIVE USE OF ARTWORK

Figures are important learning tools that help the students "get the picture," and the text makes effective use of graphics. It contains more figures and illustrations than any other book in this category. Figures attract attention and stimulate curiosity and interest. Most of the figures in this text are intended to serve as a means of emphasizing some key concepts that would otherwise go unnoticed; some serve as page summaries.

CHAPTER OPENERS AND SUMMARIES

Each chapter begins with an overview of the material to be covered. A *summary* is included at the end of each chapter, providing a quick review of basic concepts and important relations, and pointing out the relevance of the material.

NUMEROUS WORKED-OUT EXAMPLES WITH A SYSTEMATIC SOLUTIONS PROCEDURE

Each chapter contains several worked-out *examples* that clarify the material and illustrate the use of the basic principles. An *intuitive* and *systematic* approach is used in the solution of the example problems, while maintaining an informal conversational style. The problem is first stated, and the objectives are identified. The assumptions are then stated, together with their justifications. The properties needed to solve the problem are listed separately. Numerical values are used together with their units to emphasize that numbers without units are meaningless, and unit manipulations are as important as manipulating the numerical values with a calculator. The significance of the findings is discussed following the solutions. This approach is also used consistently in the solutions presented in the instructor's solutions manual.

A WEALTH OF REALISTIC END-OF-CHAPTER PROBLEMS

The end-of-chapter problems are grouped under specific topics to make problem selection easier for both instructors and students. Within each group of problems are *Concept Questions,* indicated by "C," to check the students' level of understanding of basic concepts. The problems under *Review Problems* are more comprehensive in nature and are not directly tied to any specific section of a chapter – in some cases they require review of material learned in previous chapters. Problems designated as *Design and Essay* are intended to encourage students to make engineering judgments, to conduct independent exploration of topics of interest, and to communicate their findings in a professional manner. Problems designated by an "E" are in English units, and SI users can ignore them. Problems with the are solved using EES, and complete solutions together with parametric studies are included on the enclosed DVD. Problems with the are comprehensive in nature and are intended to be solved with a computer, preferably using the EES software that accompanies this text. Several economics- and safety-related problems are incorporated throughout to enhance cost and safety awareness among engineering students. Answers to selected problems are listed immediately following the problem for convenience to students.

USE OF COMMON NOTATION

The use of different notation for the same quantities in different engineering courses has long been a source of discontent and confusion. A student taking both fluid mechanics and heat transfer, for example, has to use the notation Q for volume flow rate in one course, and for heat transfer in the other. The need to unify notation in engineering education has often been raised, even in some reports of conferences sponsored by the National Science Foundation through Foundation Coalitions, but little effort has been made to date in this regard. For example, refer to the final report of the "Mini-Conference on Energy Stem Innovations, May 28 and 29, 2003, University of Wisconsin." In this text we made a conscious effort to minimize this conflict by adopting the familiar thermodynamic notation $\dot{V}$ for volume flow rate, thus reserving the notation Q for heat transfer. Also, we consistently use an overdot to denote time rate. We think that both students and instructors will appreciate this effort to promote a common notation.

A CHOICE OF SI ALONE OR SI/ENGLISH UNITS

In recognition of the fact that English units are still widely used in some industries, both SI and English units are used in this text, with an emphasis on SI. The material in this text can be covered using combined SI/English units or SI units alone, depending on the preference of the instructor. The property tables and charts in the appendices are presented in both units, except the ones that involve dimensionless quantities. Problems, tables, and charts in English units are designated by "E" after the number for easy recognition, and they can be ignored easily by the SI users.

COMBINED COVERAGE OF BERNOULLI AND ENERGY EQUATIONS

The Bernoulli equation is one of the most frequently used equations in fluid mechanics, but it is also one of the most misused. Therefore, it is important to emphasize the limitations on the use of this idealized equation and to show how to properly account for imperfections and irreversible losses. In Chapter 5, we do this by introducing the energy equation right after the Bernoulli equation and demonstrating how the solutions of many practical engineering problems differ from those obtained using the Bernoulli equation. This helps students develop a realistic view of the Bernoulli equation.

A SEPARATE CHAPTER ON CFD

Commercial *Computational Fluid Dynamics* (CFD) codes are widely used in engineering practice in the design and analysis of flow systems, and it has become exceedingly important for engineers to have a solid understanding of the fundamental aspects, capabilities, and limitations of CFD. Recognizing that most undergraduate engineering curriculums do not have room for a full course on CFD, a separate chapter is included here to make up for this deficiency and to equip students with an adequate background on the strengths and weaknesses of CFD.

APPLICATION SPOTLIGHTS

Throughout the book are highlighted examples called *Application Spotlights* where a real-world application of fluid mechanics is shown. A unique feature of these special examples is that they are written by *guest authors*. The Application Spotlights are designed to show students how fluid mechanics has diverse applications in a wide variety of fields. They also include eye-catching photographs from the guest authors' research.

GLOSSARY OF FLUID MECHANICS TERMS

Throughout the chapters, when an important key term or concept is introduced and defined, it appears in **black** boldface type. Fundamental fluid mechanics terms and concepts appear in **blue** boldface type, and these fundamental terms also appear in a comprehensive end-of-book glossary developed by Professor James Brasseur of The Pennsylvania State University. This unique glossary is an excellent learning and review tool for students as they move forward in their study of fluid mechanics. In addition, students can test their knowledge of these fundamental terms by using the interactive flash cards and other resources located on our accompanying website (www.mhhe.com/cengel).

CONVERSION FACTORS

Frequently used conversion factors, physical constants, and frequently used properties of air and water at 20°C and atmospheric pressure are listed on the front inner cover pages of the text for easy reference.

NOMENCLATURE

A list of the major symbols, subscripts, and superscripts used in the text are listed on the inside back cover pages of the text for easy reference.

SUPPLEMENTS

These supplements are available to adopters of the book:

STUDENT RESOURCES DVD

Packaged free with every new copy of the text, this DVD provides a wealth of resources for students including Fluid Mechanics Videos, a CFD Animations Library, and EES Software.

ONLINE LEARNING CENTER

Web support is provided for the book on our Online Learning Center at www.mhhe.com/cengel. Visit this robust site for book and supplement information, errata, author information, and further resources for instructors and students.

ENGINEERING EQUATION SOLVER (EES)

Developed by Sanford Klein and William Beckman from the University of Wisconsin–Madison, this software combines equation-solving capability and engineering property data. EES can do optimization, parametric analysis, and linear and nonlinear regression, and provides publication-quality plotting capabilities. Thermodynamics and transport properties for air, water, and many other fluids are built-in and EES allows the user to enter property data or functional relationships.

FLUENT FLOWLAB® SOFTWARE AND TEMPLATES

As an integral part of Chapter 15, "Introduction to Computational Fluid Dynamics," we provide access to a student-friendly CFD software package developed by Fluent Inc. In addition, we provide over 40 FLUENT FLOWLAB templates to complement the end-of-chapter problems in Chapter 15. These problems and templates are unique in that they are designed with both a *fluid mechanics learning objective* and a *CFD learning objective* in mind.

INSTRUCTOR'S RESOURCE CD-ROM (AVAILABLE TO INSTRUCTORS ONLY)

This CD, available to instructors only, offers a wide range of classroom preparation and presentation resources including an electronic solutions manual with PDF files by chapter, all text chapters and appendices as downloadable PDF files, and all text figures in JPEG format.

COSMOS CD-ROM (AVAILABLE TO INSTRUCTORS ONLY)

This CD, available to instructors only, provides electronic solutions delivered via our database management tool. McGraw-Hill's COSMOS allows instructors to streamline the creation of assignments, quizzes, and tests by using problems and solutions from the textbook—as well as their own custom material.

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