SEVENTH EDITION

FLUID MECHANICS

FRANK M. WHITE

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Viscous Fluid Flow

Fluid Mechanics

Seventh Edition

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About the Author

Frank M. White is Professor Emeritus of Mechanical and Ocean Engineering at the University Rhode Island. He studied at Georgia Tech and M.I.T. In 1966 he helped found, at URI, the fir department of ocean engineering in the country. Known primarily as a teacher and writer, he ha received eight teaching awards and has written four textbooks on fluid mechanics and heat transfer.

From 1979 to 1990 he was editor-in-chief of the *ASME Journal of Fluids Engineering* and th served from 1991 to 1997 as chairman of the ASME Board of Editors and of the Publicatio Committee. He is a Fellow of ASME and in 1991 received the ASME Fluids Engineering Award. H lives with his wife, Jeanne, in Narragansett, Rhode Island.

To Jeanne

Contents

Preface

General Approach

The seventh edition of *Fluid Mechanics* sees some additions and deletions but no philosophic change. The basic outline of eleven chapters, plus appendices, remains the same. The triad of integra differential, and experimental approaches is retained. Many problem exercises, and some fully worke examples, have been changed. The informal, student-oriented style is retained. A number of ne photographs and figures have been added. Many new references have been added, for a total of 43 The writer is a firm believer in "further reading," especially in the postgraduate years.

Learning Tools

The total number of problem exercises continues to increase, from 1089 in the first edition, 1675 in this seventh edition. There are approximately 20 new problems added to each chapter. Most these are basic end-of-chapter problems, classified according to topic. There are also Word Problem multiple-choice Fundamentals of Engineering Problems, Comprehensive Problems, and Desi Projects. The appendix lists approximately 700 Answers to Selected Problems.

The example problems are structured in the text to follow the sequence of recommended ste outlined in Sect. 1.3, Problem-Solving Techniques.

The Engineering Equation Solver (EES) is available with the text and continues its role as attractive tool for fluid mechanics and, indeed, other engineering problems. Not only is it an excelle solver, but it also contains thermophysical properties, publication-quality plotting, units checking, an many mathematical functions, including numerical integration. The author is indebted to Sanfo Klein and William Beckman, of the University of Wisconsin, for invaluable and continuous help preparing and updating EES for use in this text. For newcomers to EES, a brief guide to its use found on this book's website.

Content Changes

There are some revisions in each chapter.

Chapter 1 has added material on the history of late 20th century fluid mechanics, notably t development of Computational Fluid Dynamics. A very brief introduction to the acceleration field ha been added. Boundary conditions for slip flow have been added. There is more discussion of the spee of sound in liquids. The treatment of thermal conductivity has been moved to Chapter 4.

Chapter 2 introduces a photo, discussion, and new problems for the deep ocean submersib vehicle, ALVIN. The density distribution in the troposphere is now given explicitly. There are brie remarks on the great Greek mathematician, Archimedes.

Chapter 3 has been substantially revised. Reviewers wanted Bernoulli's equation moved ahead angular velocity and energy, to follow linear momentum. I did this and followed their speci improvements, but truly extensive renumbering and rearranging was necessary. Pressure and veloci conditions at a tank surface have an improved discussion. A brief history of the control volume ha been added. There is a better treatment of the relation between Bernoulli's equation and the energ equation. ~~There is a new discussion of stagnation, static and dynamic pressures, and bounda~~ conditions at a jet exit.

Chapter 4 has a great new opener: CFD for flow past a spinning soccer ball. The total tin derivative of velocity is now written out in full. Fourier's Law, and its application to the differenti energy equation, have been moved here from Chapter 1. There are 21 new problems, including sever slip-flow analyses.

The Chapter 5 introduction expands on the effects of Mach number and Froude number, instea of concentrating only on the Reynolds number. Ipsen's method, which the writer admires, is retaine as an alternative to the pi theorem. The new opener, a giant disk-band-gap parachute, allows fo several new dimensional analysis problems.

Chapter 6 has a new formula for entrance length in turbulent duct flow, sent to me by tw different researchers. There is a new problem describing the flow in a fuel cell. The new opener, th Trans-Alaska Pipeline, allows for several innovative problems, including a related one on th proposed Alaska-Canada natural gas pipeline.

Chapter 7 has an improved description of turbulent flow past a flat plate, plus recent reviews progress in turbulence modeling with CFD. Two new aerodynamic advances are reported: the Finaisl Witherspoon redesign of the Kline-Fogelman airfoil and the increase in stall angle achieved b tubercles modeled after a humpback whale. The new Transition® flying car, which had a successf maiden flight in 2009, leads to a number of good problem assignments. Two other photos, Rocket Ma over the Alps, and a cargo ship propelled by a kite, also lead to interesting new problems.

Chapter 8 is essentially unchanged, except for a bit more discussion of modern CFD softwar The Transition® autocar, featured in Chapter 7, is attacked here by aerodynamic theory, includin induced drag.

Chapter 9 benefited from reviewer improvement. Figure 9.7, with its 30-year-old curve-fits f the area ratio, has been replaced with fine-gridded curves for the area-change properties. The curv fits are gone, and Mach numbers follow nicely from Fig. 9.7 and either Excel or EES. New Trends Aeronautics presents the X-43 Scramjet airplane, which generates several new problem assignment Data for the proposed Alaska-to-Canada natural gas pipeline provides a different look at friction choking.

Chapter 10 is basically the same, except for new photos of both plane and circular hydraul jumps, plus a tidal bore, with their associated problem assignments.

Chapter 11 has added a section on the performance of gas turbines, with application to turbofa aircraft engines. The section on wind turbines has been updated, with new data and photos. A win turbine-driven vehicle, which can easily move directly into the wind, has inspired new proble assignments.

Appendix A has new data on the bulk modulus of various liquids. Appendix B, Compressib Flow Tables, has been shortened by using coarser increments (0.1) in Mach number. Tables with muc smaller increments are now on the bookswebsite. Appendix E, Introduction to EES, has been delete and moved to the website, on the theory that most students are now quite familiar with EES.

Online Supplements

A number of supplements are available to students and/or instructors at the text websi www.mhhe.com/white7e. Students have access to a Student Study Guide developed by Jerry Dunn Texas A&M University. They are also able to utilize Engineering Equation Solver (EES), flui mechanics videos developed by Gary Settles of Pennsylvania State University, and CFD images an animations prepared by Fluent Inc. Also available to students are Fundamentals of Engineering (FE Exam quizzes, prepared by Edward Anderson of Texas Tech University.

Instructors may obtain a series of PowerPoint slides and images, plus the full Solutions Manua in PDF format. The Solutions Manual provides complete and detailed solutions, including proble statements and artwork, to the end-of-chapter problems. It may be photocopied for posting preparing transparencies for the classroom. Instructors can also obtain access to C.O.S.M.O.S. for th seventh edition. C.O.S.M.O.S. is a Complete Online Solutions Manual Organization Syste instructors can use to create exams and assignments, create custom content, and edit supplie problems and solutions.

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The following prereviewers gave many excellent suggestions for improving the manuscrip Rolando Bravo of Southern Illinois University; Joshua B. Kollat of Penn State University; Dani Maynes of Brigham Young University; Joseph Schaefer of Iowa State University; and Xiangchu Xuan of Clemson University.

In preparation, the writer got stuck on Chapter 3 but was rescued by the following reviewer Serhiy Yarusevych of the University of Waterloo; H. Pirouz Kavehpour and Jeff Eldredge of th University of California, Los Angeles; Rayhaneh Akhavan of the University of Michigan; Soyour Steve Cha of the University of Illinois, Chicago; Georgia Richardson of the University of Alabam Krishan Bhatia of Rowan University; Hugh Coleman of the University of Alabama-Huntsville; D.V Ostendorf of the University of Massachusetts; and Donna Meyer of the University of Rhode Islan The writer continues to be indebted to many others who have reviewed this book over the vario years and editions.

Many other reviewers and correspondents gave good suggestions, encouragement, correction and materials: Elizabeth J. Kenyon of MathWorks; Juan R. Cruz of NASA Langley Research Cente LiKai Li of University of Science and Technology of China; Tom Robbins of National Instrument Tapan K. Sengupta of the Indian Institute of Technology at Kanpur; Paulo Vatavuk of Unicam University; Andris Skattebo of Scand-power A/S; Jeffrey S. Allen of Michigan Technologic University; Peter R. Spedding of Queen’s University, Belfast, Northern Ireland; Iskender Sahin Western Michigan University; Michael K. Dailey of General Motors; Cristina L. Archer of Stanfo University; Paul F. Jacobs of Technology Development Associates; Rebecca Cullion-Webb of th University of Colorado at Colorado Springs; Debendra K. Das of the University of Alaska Fairbank Kevin O’Sullivan and Matthew Lutts of the Associated Press; Lennart Lüttig and Nina Koliha REpower Systems AG, Hamburg, Germany; Chi-Yang Cheng of ANSYS Inc.; Debabrata Dasgupta The Indian Institute of Technology at Kharagpur; Fabian Anselmet of the Institut de Recherche sur l Phenomenes Hors Equilibre, Marseilles; David Chelidze, Richard Lessmann, Donna Meyer, Aru Shukla, Peter Larsen, and Malcolm Spaulding of the University of Rhode Island; Craig Swanson Applied Science Associates, Inc.; Jim Smay of Oklahoma State University; Deborah Pence of Orego State University; Eric Braschoss of Philadelphia, PA.; and Dale Hart of Louisiana Tech University.

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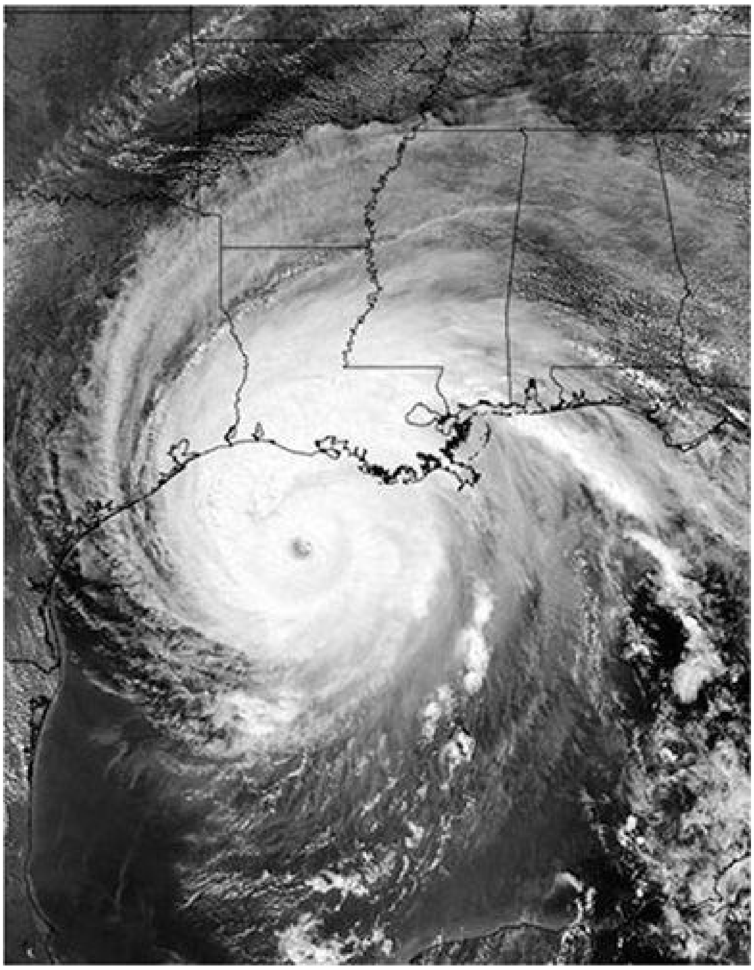
Finally, the continuing support and encouragement of my wife and family are, as always, muc appreciated. Special thanks are due to our dog, Sadie, and our cats, Cole and Kerry.

Fluid Mechanics



Hurricane Rita in the Gulf of Mexico, Sept. 22, 2005. Rita made landfall at the Texa Louisiana border and caused billions of dollars in wind and flooding damage. Though mo dramatic than typical applications in this text, Rita is a true fluid flow, strongly influenced b the earth's rotation and the ocean temperature. (*Photo courtesy of NASA*.)

1.1 Preliminary Remarks

Fluid mechanics is the study of fluids either in motion (fluid *dynamics*) or at rest (fluid *statics* Both gases and liquids are classified as fluids, and the number of fluid engineering applications enormous: breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmill pipes, missiles, icebergs, engines, filters, jets, and sprinklers, to name a few. When you think about i almost everything on this planet either is a fluid or moves within or near a fluid.

The essence of the subject of fluid flow is a judicious compromise between theory ar experiment. Since fluid flow is a branch of mechanics, it satisfies a set of well-documented bas laws, and thus a great deal of theoretical treatment is available. However, the theory is ofte frustrating because it applies mainly to idealized situations, which may be invalid in practic ~~problems. The two chief obstacles to a workable theory are geometry and viscosity. The~~ bas equations of fluid motion (Chap. 4) are too difficult to enable the analyst to attack arbitrary geometr configurations. Thus most textbooks concentrate on flat plates, circular pipes, and other ea geometries. It is possible to apply numerical computer techniques to complex geometries, ar specialized textbooks are now available to explain the new *computational fluid dynamics* (CFI approximations and methods [1–4].[1] This book will present many theoretical results while keepi their limitations in mind.

The second obstacle to a workable theory is the action of viscosity, which can be neglected on in certain idealized flows (Chap. 8). First, viscosity increases the difficulty of the basic equatior although the boundary-layer approximation found by Ludwig Prandtl in 1904 (Chap. 7) has great simplified viscous-flow analyses. Second, viscosity has a destabilizing effect on all fluids, giving ris at frustratingly small velocities, to a disorderly, random phenomenon called *turbulence*. The theory turbulent flow is crude and heavily backed up by experiment (Chap. 6), yet it can be quite serviceab as an engineering estimate. This textbook only introduces the standard experimental correlations f turbulent time-mean flow. Meanwhile, there are advanced texts on both time-mean *turbulence ar turbulence modeling* [5, 6] and on the newer, computer-intensive *direct numerical simulation* (DN of fluctuating turbulence [7, 8].

Thus there is theory available for fluid flow problems, but in all cases it should be backed up b experiment. Often the experimental data provide the main source of information about specific flow such as the drag and lift of immersed bodies (Chap. 7). Fortunately, fluid mechanics is a highly visu subject, with good instrumentation [9–11], and the use of dimensional analysis and modeling concep (Chap. 5) is widespread. Thus experimentation provides a natural and easy complement to the theor You should keep in mind that theory and experiment should go hand in hand in all studies of flu mechanics.

1.2 History and Scope of Fluid Mechanics

Like most scientific disciplines, fluid mechanics has a history of erratically occurring ear achievements, then an intermediate era of steady fundamental discoveries in the eighteenth ar nineteenth centuries, leading to the twenty-first-century era of “modern practice,” as we sel centeredly term our limited but up-to-date knowledge. Ancient civilizations had enough knowledge solve certain flow problems. Sailing ships with oars and irrigation systems were both known prehistoric times. The Greeks produced quantitative information. Archimedes and Hero of Alexandr both postulated the parallelogram law for addition of vectors in the third century B.C. Archimed (285–212 B.C.) formulated the laws of buoyancy and applied them to floating and submerged bodie actually deriving a form of the differential calculus as part of the analysis. The Romans bu extensive aqueduct systems in the fourth century B.C. but left no records showing any quantitati knowledge of design principles.

From the birth of Christ to the Renaissance there was a steady improvement in the design of su flow systems as ships and canals and water conduits but no recorded evidence of fundament improvements in flow analysis. Then Leonardo da Vinci (1452–1519) stated the equation conservation of mass in one-dimensional steady flow. Leonardo was an excellent experimentalist, ar his notes contain accurate descriptions of waves, jets, hydraulic jumps, eddy formation, and both lov drag (streamlined) and high-drag (parachute) designs. A Frenchman, Edme Mariotte (1620–1684 built the first wind tunnel and tested models in it.

Problems involving the momentum of fluids could finally be analyzed after Isaac Newton (164
1727) ~~postulated his laws of motion and the law of viscosity of the linear fluids now called newtonia~~
The theory first yielded to the assumption of a “perfect” or frictionless fluid, and eighteenth-centu mathematicians (Daniel Bernoulli, Leonhard Euler, Jean d’Alembert, Joseph-Louis Lagrange, an Pierre-Simon Laplace) produced many beautiful solutions of frictionless-flow problems. Euler, Fi 1.1, developed both the differential equations of motion and their integrated form, now called th Bernoulli equation. D’Alembert used them to show his famous paradox: that a body immersed in frictionless fluid has zero drag. These beautiful results amounted to overkill, since perfect-flu assumptions have very limited application in practice and most engineering flows are dominated b the effects of viscosity. Engineers began to reject what they regarded as a totally unrealistic theo and developed the science of *hydraulics*, relying almost entirely on experiment. Such experimentalis as Chézy, Pitot, Borda, Weber, Francis, Hagen, Poiseuille, Darcy, Manning, Bazin, and Weisbac produced data on a variety of flows such as open channels, ship resistance, pipe flows, waves, an turbines. All too often the data were used in raw form without regard to the fundamental physics flow.

Fig. 1.1 Leonhard Euler (1707–1783) was the greatest mathematician of the eighteen century and used Newton’s calculus to develop and solve the equations of motion of inviscid flo He published over 800 books and papers. [*Courtesy of the School of Mathematics and Statisti University of St Andrew, Scotland.*]

At the end of the nineteenth century, unification between experimental *hydraulics* and theoreti *hydrodynamics* finally began. William Froude (1810–1879) and his son Robert (1846–192 developed laws of model testing; Lord Rayleigh (1842–1919) proposed the technique of dimension analysis; and Osborne Reynolds (1842–1912) published the classic pipe experiment in 1883, whi showed the importance of the dimensionless Reynolds number named after him. Meanwhile, viscou flow theory was available but unexploited, since Navier (1785–1836) and Stokes (1819–1903) ha successfully added newtonian viscous terms to the equations of motion. The resulting Navier-Stok equations were too difficult to analyze for arbitrary flows. Then, in 1904, a German engineer, Ludw Prandtl (1875–1953), Fig. 1.2, published perhaps the most important paper ever written on flu mechanics. Prandtl pointed out that fluid flows with small viscosity, such as water flows and airflow can be divided into a thin viscous layer, or *boundary layer*, near solid surfaces and interfaces, patch onto a nearly inviscid outer layer, where the Euler and Bernoulli equations apply. Boundary-lay theory has proved to be a very important tool in modern flow analysis. The twentieth-centu foundations for the present state of the art in fluid mechanics were laid in a series of broad-bas experiments and theories by Prandtl and his two chief friendly competitors, Theodore von Kárm (1881–1963) and Sir Geoffrey I. Taylor (1886–1975). Many of the results sketched here from historical point of view will, of course, be discussed in this textbook. More historical details can found in Refs. 12 to 14.

Fig. 1.2 Ludwig Prandtl (1875–1953), often called the "father of modern fluid mechanic [15], developed boundary layer theory and many other innovative analyses. He and his studen were pioneers in flow visualization techniques. [*Aufnahme von Fr. Struckmeyer, Gotting courtesy AIP Emilio Segre Visual Archives, Lande Collection.*]

The second half of the twentieth century introduced a new tool: Computational Fluid Dynami (CFD). The earliest paper on the subject known to this writer was by A. Thom in 1933 [47], laborious, but accurate, hand calculation of flow past a cylinder at low Reynolds numbe Commercial digital computers became available in the 1950s, and personal computers in the 197 bringing CFD into adulthood. A legendary first textbook was by Patankar [3]. Presently, wi increases in computer speed and memory, almost any laminar flow can be modeled accuratel