

SEVENTH EDITION

FLUID MECHANICS



FRANK M. WHITE

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Fluid Mechanics

Seventh Edition

Frank M. White
University of Rhode Island





FLUID MECHANICS, Seventh EDITION

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

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General Approach

The seventh edition of *Fluid Mechanics* sees some additions and deletions but no philosophical change. The basic outline of eleven chapters, plus appendices, remains the same. The triad of integral, differential, and experimental approaches is retained. Many problem exercises, and some fully worked examples, have been changed. The informal, student-oriented style is retained. A number of new 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, to 1675 in this seventh edition. There are approximately 20 new problems added to each chapter. Most of these are basic end-of-chapter problems, classified according to topic. There are also Word Problems, multiple-choice Fundamentals of Engineering Problems, Comprehensive Problems, and Design Projects. The appendix lists approximately 700 Answers to Selected Problems.

The example problems are structured in the text to follow the sequence of recommended steps outlined in [Sect. 1.3](#), Problem-Solving Techniques.

The Engineering Equation Solver (EES) is available with the text and continues its role as an attractive tool for fluid mechanics and, indeed, other engineering problems. Not only is it an excellent solver, but it also contains thermophysical properties, publication-quality plotting, units checking, and many mathematical functions, including numerical integration. The author is indebted to Sanford Klein and William Beckman, of the University of Wisconsin, for invaluable and continuous help in preparing and updating EES for use in this text. For newcomers to EES, a brief guide to its use is 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 the development of Computational Fluid Dynamics. A very brief introduction to the acceleration field has been added. Boundary conditions for slip flow have been added. There is more discussion of the speed 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 submersible vehicle, ALVIN. The density distribution in the troposphere is now given explicitly. There are brief remarks on the great Greek mathematician, Archimedes.

[Chapter 3](#) has been substantially revised. Reviewers wanted Bernoulli's equation moved ahead of angular velocity and energy, to follow linear momentum. I did this and followed their specific improvements, but truly extensive renumbering and rearranging was necessary. Pressure and velocity conditions at a tank surface have an improved discussion. A brief history of the control volume has

been added. There is a better treatment of the relation between Bernoulli's equation and the energy equation. There is a new discussion of stagnation, static and dynamic pressures, and boundary conditions at a jet exit.

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

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

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

[Chapter 7](#) has an improved description of turbulent flow past a flat plate, plus recent reviews of progress in turbulence modeling with CFD. Two new aerodynamic advances are reported: the Finais Witherspoon redesign of the Kline-Fogelman airfoil and the increase in stall angle achieved by tubercles modeled after a humpback whale. The new Transition[®] flying car, which had a successful maiden flight in 2009, leads to a number of good problem assignments. Two other photos, Rocket Man 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 software. The Transition[®] autocar, featured in [Chapter 7](#), is attacked here by aerodynamic theory, including induced drag.

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

[Chapter 10](#) is basically the same, except for new photos of both plane and circular hydraulic 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 turbofan aircraft engines. The section on wind turbines has been updated, with new data and photos. A wind turbine-driven vehicle, which can easily move directly into the wind, has inspired new problem assignments.

[Appendix A](#) has new data on the bulk modulus of various liquids. [Appendix B](#), Compressible Flow Tables, has been shortened by using coarser increments (0.1) in Mach number. Tables with much smaller increments are now on the bookwebsite. Appendix E, Introduction to EES, has been deleted 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 website www.mhhe.com/white7e. Students have access to a Student Study Guide developed by Jerry Dunn at Texas A&M University. They are also able to utilize Engineering Equation Solver (EES), fluid

mechanics videos developed by Gary Settles of Pennsylvania State University, and CFD images and 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 Manual in PDF format. The Solutions Manual provides complete and detailed solutions, including problem statements and artwork, to the end-of-chapter problems. It may be photocopied for posting or preparing transparencies for the classroom. Instructors can also obtain access to C.O.S.M.O.S. for the seventh edition. C.O.S.M.O.S. is a Complete Online Solutions Manual Organization System that instructors can use to create exams and assignments, create custom content, and edit supplied problems and solutions.

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In preparation, the writer got stuck on [Chapter 3](#) but was rescued by the following reviewers: Serhiy Yarusevych of the University of Waterloo; H. Pirouz Kavehpour and Jeff Eldredge of the University of California, Los Angeles; Rayhaneh Akhavan of the University of Michigan; Soyoun Lee and Steve Cha of the University of Illinois, Chicago; Georgia Richardson of the University of Alabama; 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 Island. The writer continues to be indebted to many others who have reviewed this book over the various years and editions.

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

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Fluid Mechanics



Hurricane Rita in the Gulf of Mexico, Sept. 22, 2005. Rita made landfall at the Texas-Louisiana border and caused billions of dollars in wind and flooding damage. Though more dramatic than typical applications in this text, Rita is a true fluid flow, strongly influenced by 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 is enormous: breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmills, pipes, missiles, icebergs, engines, filters, jets, and sprinklers, to name a few. When you think about it, 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 and experiment. Since fluid flow is a branch of mechanics, it satisfies a set of well-documented basic laws, and thus a great deal of theoretical treatment is available. However, the theory is often

frustrating because it applies mainly to idealized situations, which may be invalid in practical problems. The two chief obstacles to a workable theory are geometry and viscosity. The basic equations of fluid motion ([Chap. 4](#)) are too difficult to enable the analyst to attack arbitrary geometrical configurations. Thus most textbooks concentrate on flat plates, circular pipes, and other easy geometries. It is possible to apply numerical computer techniques to complex geometries, and specialized textbooks are now available to explain the new *computational fluid dynamics* (CFD) approximations and methods [1–4].¹ This book will present many theoretical results while keeping their limitations in mind.

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

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

1.2 History and Scope of Fluid Mechanics

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

From the birth of Christ to the Renaissance there was a steady improvement in the design of such flow systems as ships and canals and water conduits but no recorded evidence of fundamental improvements in flow analysis. Then Leonardo da Vinci (1452–1519) stated the equation of conservation of mass in one-dimensional steady flow. Leonardo was an excellent experimentalist, and his notes contain accurate descriptions of waves, jets, hydraulic jumps, eddy formation, and both low-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 (1643–1727) postulated his laws of motion and the law of viscosity of the linear fluids now called newtonian. The theory first yielded to the assumption of a “perfect” or frictionless fluid, and eighteenth-century mathematicians (Daniel Bernoulli, Leonhard Euler, Jean d’Alembert, Joseph-Louis Lagrange, and Pierre-Simon Laplace) produced many beautiful solutions of frictionless-flow problems. Euler, [Fig. 1.1](#), developed both the differential equations of motion and their integrated form, now called the Bernoulli equation. D’Alembert used them to show his famous paradox: that a body immersed in a frictionless fluid has zero drag. These beautiful results amounted to overkill, since perfect-fluid assumptions have very limited application in practice and most engineering flows are dominated by the effects of viscosity. Engineers began to reject what they regarded as a totally unrealistic theory and developed the science of *hydraulics*, relying almost entirely on experiment. Such experimentalists as Chézy, Pitot, Borda, Weber, Francis, Hagen, Poiseuille, Darcy, Manning, Bazin, and Weisbach produced data on a variety of flows such as open channels, ship resistance, pipe flows, waves, and turbines. All too often the data were used in raw form without regard to the fundamental physics of flow.



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

At the end of the nineteenth century, unification between experimental *hydraulics* and theoretical *hydrodynamics* finally began. William Froude (1810–1879) and his son Robert (1846–1920) developed laws of model testing; Lord Rayleigh (1842–1919) proposed the technique of dimensional analysis; and Osborne Reynolds (1842–1912) published the classic pipe experiment in 1883, which showed the importance of the dimensionless Reynolds number named after him. Meanwhile, viscous flow theory was available but unexploited, since Navier (1785–1836) and Stokes (1819–1903) had successfully added newtonian viscous terms to the equations of motion. The resulting Navier-Stokes equations were too difficult to analyze for arbitrary flows. Then, in 1904, a German engineer, Ludwig Prandtl (1875–1953), [Fig. 1.2](#), published perhaps the most important paper ever written on fluid 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, patched onto a nearly inviscid outer layer, where the Euler and Bernoulli equations apply. Boundary-layer theory has proved to be a very important tool in modern flow analysis. The twentieth-century foundations for the present state of the art in fluid mechanics were laid in a series of broad-based experiments and theories by Prandtl and his two chief friendly competitors, Theodore von Kármán (1881–1963) and Sir Geoffrey I. Taylor (1886–1975). Many of the results sketched here from a historical point of view will, of course, be discussed in this textbook. More historical details can be found in Refs. 12 to 14.

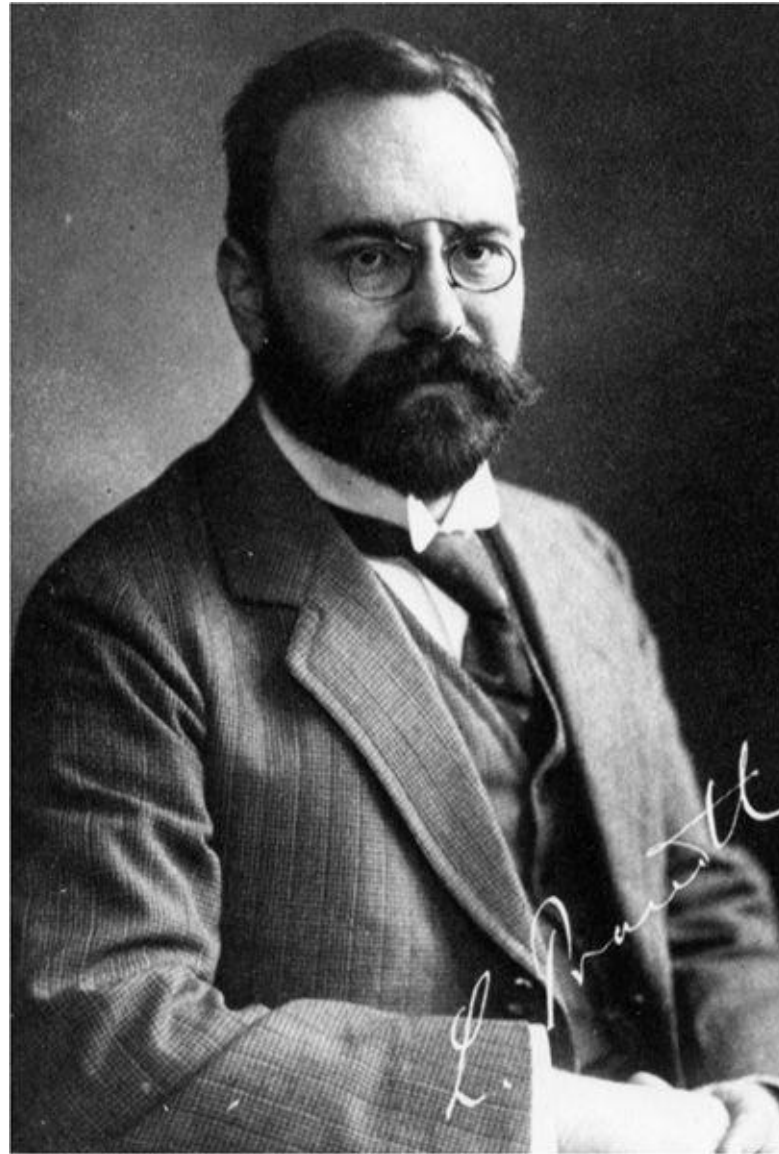


Fig. 1.2 Ludwig Prandtl (1875–1953), often called the “father of modern fluid mechanics” [15], developed boundary layer theory and many other innovative analyses. He and his students were pioneers in flow visualization techniques. [Aufnahme von Fr. Struckmeyer, Gottingen, courtesy AIP Emilio Segre Visual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

The second half of the twentieth century introduced a new tool: Computational Fluid Dynamics (CFD). The earliest paper on the subject known to this writer was by A. Thom in 1933 [47], a laborious, but accurate, hand calculation of flow past a cylinder at low Reynolds number. Commercial digital computers became available in the 1950s, and personal computers in the 1970s, bringing CFD into adulthood. A legendary first textbook was by Patankar [3]. Presently, with increases in computer speed and memory, almost any laminar flow can be modeled accurately.

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