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Fluid Mechanics

(Fifth Edition)

流体力学

（第5版）

Frank M. White

清华大学出版社

内容简介

本书旨在传授流体力学的基本概念、基本理论和实际应用，为学生进入与流动相关的专业学习、科学研究或是工程设计打下基础。

本书共分十一章，包括：绪论、流体压力分布、控制体的积分关系、流体运动的微分关系、量纲分析与相似原理、管道中的粘流、物体绕流、势流与计算流体力学、可压缩流动、明渠流动、叶轮机械。前五章为流体力学的基础部分，后六章则与实际流动问题密切相关。本书很好地把握了流体力学中积分、微分、实验三种分析方法的平衡，十分注重现代流体力学知识的传播，例如，对湍流边界层理论作了较为深入的介绍，对计算流体力学也作了简要描述，便于学生毕业后学以致用。

本书内容丰富，观点新颖，图文并茂，语言流畅，所配的流动照片颇具启发性，很能激发学生对流体力学问题的兴趣与关注，是一本享有盛誉的流体力学基础教材。

本书特色

- 为学生提供了开放式、设计相关的习题作业，有益于学生活学活用。
- 随书提供EES软件帮助学生有效地使用计算机来模拟、求解和改进流体力学问题，部分习题可由EES求解。
- 习题中包括美国工程基础试题，通过书中光盘可进行交互式学习，学生可直接了解美国流体力学教学要求。
- 为学生和教师提供的“书网”，包括电子版的学生学习指南、流体力学专业网站、书中图片的幻灯片、以及EES网址，帮助学生更好地理解流体的主要概念。

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Fluid Mechanics (Fifth Edition)

Frank M. White

影 印 版 序

流体力学教科书种类繁多，读者对象、侧重点各有不同，有的是传统水力学的延续，有的则类似应用数学教材，就机械工程类的流体力学而言，F. M. White 教授所著的《流体力学》教材堪称精品之作。该书首版于 1979 年，正值作者开始担任美国机械工程学会（ASME）《流体工程学报》主编之时（1979—1990），之后，于 1986、1994、1999、2003 年分别作了 4 次修订，在国外尤其是美国，在机械工程系、宇航工程系的流体力学课中广泛采用，不少使用该书的教师对书的修订提出过建议，作者在书中还为此专门致谢。作者后来虽还担任 ASME 主编会和出版委员会主席（1991—1997）等学术要职，但却以流体力学教育家为学界所知，多次获得教学成果奖。

该书旨在教授流体力学的基本概念、基本理论和实际应用，为学生进入与流动相关的专业学习、科学研究或是工程设计打下基础。该书内容涵盖流体力学的关键概念、基本原理及其在实际工程中的广泛应用，内容均衡，通俗易懂，著述准确。作者通过其渊博的流体力学知识，旁征博引，涉猎古今，通过配备大量的流体力学问题照片，如：墨西哥湾的飓风、亚利桑那著名的罗斯福大坝、风洞中的风车实验、地热电厂里的蒸汽管桥、空中飞行的 NASA 太阳能飞机、穿越音障的 F-18 黄蜂号战机、风能发电农场等，将流体力学生动活泼地展示给了读者，内容、观点新颖。

该书共分十一章，包括：绪论、流体压力分布、控制体的积分关系、流体运动的微分关系、量纲分析与相似原理、管道中的粘流、物体绕流、势流与计算流体力学、可压缩流动、明渠流动、叶轮机械。前五章为流体力学的基础部分，后六章则与实际流动问题密切相关。该书很好地把握了流体力学中积分、微分、实验三种分析方法的平衡，十分注重现代流体力学知识的传播，例如，对湍流边界层理论作了较为深入的介绍，对计算流体力学也作了简要描述，便于学生毕业后学以致用。

该书的重要特色是贯彻以学生为本的思想，课文的讲解配以充足的例题，每一章节最后都给出该章节概要，习题则分为三类：传统习题、综合习题、设计习题，习题与章节内容的关系也予以列表给出，十分利于学生自习。该书充分利用现代教学技术为学生学习服务，提供一张光盘，其中包括一套颇有特色的软件工具——工程方程求解器（Engineering Equation Solver，EES），含有流体的热力学性质、数学函数等，学生可有效地使用计算机来模拟、求解和改进流体力学问题。该软件的使用在书的附录 E 中专门介绍。光盘还为学生和教师提供了一“书网”，包括电子版的学生学习指南、交互式美国工程基础试题、流体力学专业网站、书中图片的幻灯片以及 EES 网址等。另外，与该书配套出版的还有教师用的习题答案。

2003 年，当我们下决心在清华大学工程力学系的流体力学课中采用英文原版教材时，对国外的相关教材做了一些调研，认为该书内容丰富、观点新颖，图文并茂，所配的流动问题照片颇具启发性，很能激发学生对流体力学问题的兴趣与关注。习题数量共有 1650 题之多，教师的选择余地大，半数习

题给出答案，便于学生自修自习。教学实践表明，该书深受同学欢迎，为教学的成功提供了良好的基础，确实是一本享有盛誉的流体力学基础教材。

随着我国高校教学平台的建立与拓宽，以及根据国外机械类学科设置和课程设计的经验，流体力学早已不再局限于力学专业。该书的适用范围因而包括力学、机械工程（含热能、汽车、精密仪器等）、航空航天等领域的本科学生，对于应用数学、石油化工等领域的学生也是一本理想的参考书。

清华大学工程力学系 流体力学研究所 所长
教育部长江学者奖励计划特聘教授
符 松

Preface

General Approach

The fifth edition of *Fluid Mechanics* includes a number of additions and deletions, but no change in the philosophy of the book. The basic outline of 11 chapters, plus appendices, remains the same. The triad of integral, differential, and experimental approaches is retained. New problem exercises have been added, and many problems and worked examples have been changed. The informal, student-oriented style is retained. A number of new photographs and figures have been added.

Learning Tools

The total number of problem exercises continues to increase, from 1089 in the first edition to 1169 in the second, 1392 in the third, 1500 in the fourth, and now 1650 in this fifth edition. Most of these are basic end-of-chapter problems, classified according to topic. There are also word problems, multiple-choice Fundamentals of Engineering Exam problems, comprehensive problems, and design projects. The appendix lists answers to selected problems.

The example problems have been newly restructured throughout the text, following the sequence of steps outlined in Sec. 1.13 in order to provide a uniform problem-solving approach for students.

The Engineering Equation Solver (EES), described in Appendix E, is bound in with the text and continues its role as an attractive software tool for modeling and solving fluid mechanics and, indeed, other engineering problems. Not only is EES an excellent solver; it also contains thermophysical properties, publication-quality plotting, units checking, and many mathematical functions. The author is indebted to Sanford Klein and William Beckman, of the University of Wisconsin and F-Chart Inc., for invaluable and continuous help in preparing and updating EES for use in this text.

Content Changes

There are some revisions in each chapter. Chapter 1 has been toned down considerably, with heavier topics moved to later chapters. New discussion and figures have been added on the important topic of flow visualization.

Chapter 2 has added new material on pressure transducers.

Chapter 3 introduces a list of specific suggestions on handling the difficult linear momentum equation. Bernoulli's equation still comes last and is not broken out into a new chapter. I try to stress that the Bernoulli relation is dangerously restricted and is often misused by both students and graduate engineers.

Chapter 4 now includes the derivation of laminar Poiseuille pipe flow, as an example of an exact solution to the Navier-Stokes equation. The topic is revisited briefly in Chapter 6. If you disagree with this sequence, just hold back and treat Sections 4.10 and 4.11 later in your course.

Chapter 5 now has a complete section on the selection of scaling variables for a dimensional analysis. By deciding in advance how to scale and present the data, ambiguity is reduced or eliminated.

Chapter 6 has added a new section on head loss and friction factor. Laminar and turbulent pipe flow have been separated for greater clarity. Turbulence modeling has been broken out as a separate section. New data have been added on minor losses, and new flow meters have been discussed. Orifice and nozzle meters now include the compressible flow correction factor.

Chapter 7 has new discussion of computational fluid dynamics (CFD) and more detail on the boundary layer approximations. A new section has been added on creeping flow.

Chapter 8, except for new problems and references, is much the same. I suspect that this is the most extensive treatment of potential flow in an undergraduate text.

Chapter 9 has more discussion of Fanno and Rayleigh flow and presents some of the new trends in aeronautics, both subsonic and supersonic.

Chapter 10 has more discussion of Froude numbers and has improved the treatment of gradually varied flow transitions, thanks to Professor Bruce E. LaRock of the University of California, Davis. A simple finite-difference varied flow scheme has been added that is useful when field measurements are sparse. The concept of a compound weir has been introduced.

Chapter 11 is much the same, except for improvements and corrections suggested by Professor Gordon Holloway of the University of New Brunswick.

Supplements

The Student Resources CD-ROM contains the Limited Academic Version of the EES program; information on use of the software; and scripted EES problems from the textbook. The Limited Academic Version is a scaled-down version of EES that does not expire; the full Academic Version of EES, which needs to be renewed annually through use of a new password, is also available to adopters of *Fluid Mechanics*, by downloading from the EES website as before.

The Book Website contains a Student Study Guide, prepared by Professor Jerry Dunn of Texas Tech University, that provides a concise review of all major topics covered in a first course; interactive versions of the FE Exam questions found in the text, prepared by Professor Edward Anderson of Texas Tech University, that are suitable for exam preparation or for self-testing; a link to the EES website; and PowerPoint versions of all text figures.

The Solutions Manual provides complete and detailed solutions, including problem statements and artwork, to all the end-of-chapter problems.

Acknowledgments

As usual, so many people have helped me that I cannot remember or list them all. Throughout the writing, many much-appreciated suggestions and improvements were given by Gordon Holloway of the University of New Brunswick. All of the revisions and additions, including the Solutions Manual, were read and perfected by my colleague Elizabeth J. Kenyon. Many other reviewers and correspondents gave helpful suggestions, encouragement, corrections, and materials: Alex Smits, Princeton University; Ray Taghavi, University of Kansas; Ganesh Raman, Illinois Institute of Technology; Phil Combs, B. D. Fuller, and Wayne Stroupe, U.S. Army Waterways Experiment Station; John Cimbala, Pennsylvania State University; Sheldon Green, University of British Columbia; Nikos J. Mourtos, San Jose State University; Jacques Lewalle, Syracuse University; Richard McCuen, University of Maryland; Andris Skattebo, Scandpower A/S; Bruce E. Larock, University of California, Davis; Sandra Barrette and Joan Zimmer, Badger Meter, Inc.; Dean Mohan, PCB Piezotronics; Andrei Smirnov and Ismail Celik, West Virginia University; Fernando Tavares de Pinho of CEFT–Transport Phenomena Research Centre, Portugal; S. Y. Son, Ken Kihm, and J. C. Han, Texas A&M University; Ethan Lipman, University of California, Davis; Deborah Pence, Oregon State University; Debendra K. Das, University of Alaska, Fairbanks; John Gay and Nick Galante, U.S. Navy; Dimitre Karamanev, the University of Western Ontario; Jay M. Khodadadi, Auburn University; John Foss, Michigan State University; William Palm and Raymond Wright, University of Rhode Island; Haecheon Choi, Seoul National University, Korea; Lee Jay Fingersh, National Renewable Energy Laboratory; John Sheridan, Monash University; Jason Reese, University of London; Samuel S. Sih, Walla Walla College; Chihyung Wen, Da-Yeh University, Taiwan; Tim Gourlay, Australian Maritime College; Azer Yalin, Colorado State University; Donald E. Richards, Rose-Hulman Institute; Bob Oakberg, Montana State University; Brian James Savilonis, Worcester Polytechnic Institute; Ryoichi S. Amano, Ph.D., University of Wisconsin–Milwaukee; James D. McBrayer, P.E., D.Sc., University of Central Florida; Don L. Boyer, Arizona State University; Savas Yavuzkurt, Pennsylvania State University; Abdul I. Barakat, University of California, Davis; James A. Liburdy, Oregon State University; Clement Kleinstreuer, North Carolina State University, Raleigh; Robert G. Oakberg, Montana State University. On the spot reviews, Dr. John W. Nicklow, P.E., P.H., Southern Illinois University Carbondale; Gary Tatterson, North Carolina A&T State University; Anthony J. McHugh, University of Illinois; Soyoung Cha, University of Illinois–Chicago; Donald Carlucci, Stevens Institute of Technology; Darrell W. Pepper, Ph.D., University of Nevada–Las Vegas; and Farhan H. Chowdhury, Bangladesh University of Engineering and Technology.

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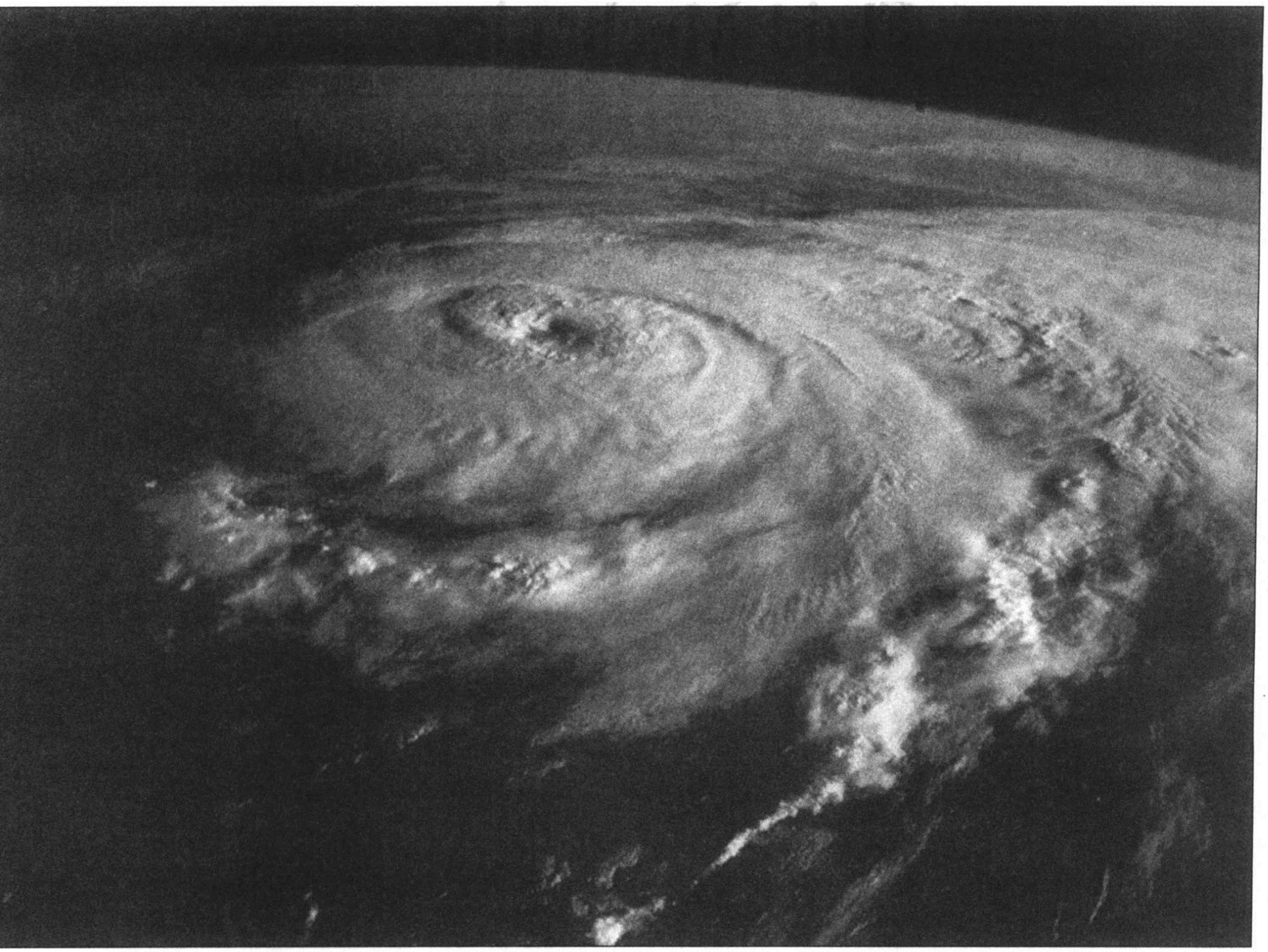
Fluid Mechanics



Hurricane Elena in the Gulf of Mexico. Unlike most small-scale fluids engineering applications, hurricanes are strongly affected by the Coriolis acceleration due to the rotation of the earth, which causes them to swirl counterclockwise in the Northern Hemisphere. The physical properties and boundary conditions which govern such flows are discussed in the present chapter. *(Courtesy of NASA/Color-Pic Inc–E.R. Degginger/Color-Pic Inc.)*

Chapter 1
Introduction

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 geometric 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, 2, 29].[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. Textbooks now present digital-computer techniques for turbulent flow analysis [32], but they are modeled, not exact, based on empirical assumptions regarding the time mean of the turbulent stress field.

[1]Numbered references appear at the end of each chapter.

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 flows, such as the drag and lift of immersed bodies (Chap. 7). Fortunately, fluid mechanics is a highly visual subject, with good instrumentation [4, 5, 35], 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 The Concept of a Fluid

From the point of view of fluid mechanics, all matter consists of only two states, fluid and solid. The difference between the two is perfectly obvious to the layperson, and it is an interesting exercise to ask a layperson to put this difference into words. The technical distinction lies with the reaction of the two to an applied shear or tangential stress. *A solid can resist a shear stress by a static deflection; a fluid cannot.* Any shear stress applied to a fluid, no matter how small, will result in motion of that fluid. The fluid moves and deforms continuously as long as the shear stress is applied. As a corollary, we can say that a fluid at rest must be in a state of zero shear stress, a state often called the hydrostatic stress condition in structural analysis. In this condition, Mohr's circle for stress reduces to a point, and there is no shear stress on any plane cut through the element under stress.

Given this definition of a fluid, every layperson also knows that there are two classes of fluids, *liquids* and *gases*. Again the distinction is a technical one concerning the effect of cohesive forces. A liquid, being composed of relatively close-packed molecules with strong cohesive forces, tends to retain its volume and will form a free surface in a gravitational field if unconfined from above. Free-surface flows are dominated by gravitational effects and are studied in Chaps. 5 and 10. Since gas molecules are widely spaced with negligible cohesive forces, a gas is free to expand until it encounters confining walls. A gas has no definite volume, and when left to itself without confinement, a gas forms an atmosphere that is essentially hydrostatic. The hydrostatic behavior of liquids and gases is taken up in Chap. 2. Gases cannot form a free surface, and thus gas flows are rarely concerned with gravitational effects other than buoyancy.

Figure 1.1 illustrates a solid block resting on a rigid plane and stressed by its own weight. The solid sags into a static deflection, shown as a highly exaggerated dashed line, resisting shear without flow. A free-body diagram of element A on the side of the block shows that there is shear in the block along a plane cut at an angle θ through A. Since the block sides are unsupported, element A has zero stress on the left and right sides and compression stress $\sigma = -p$ on the top and bottom. Mohr's circle does not reduce to a point, and there is nonzero shear stress in the block.

By contrast, the liquid and gas at rest in Fig. 1.1 require the supporting walls in order to eliminate shear stress. The walls exert a compression stress of $-p$ and reduce Mohr's circle to a point with zero shear everywhere—that is, the hydrostatic condition. The liquid retains its volume and forms a free surface in the container. If the walls are removed, shear develops in the liquid and a big splash results. If the container is tilted, shear again develops, waves form, and the free surface seeks a horizontal configuration, pouring out over the lip if necessary.