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Computational Fluid Dynamics
The Basics with Applications

计算流体力学入门

John D. Anderson, JR.

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[1] IE=International Edition

Computational Fluid Dynamics The Basics with Applications

影印版序

计算流体力学自20世纪60年代以来有了迅猛的发展，今天已成为研究流体力学的理论、实验和计算三大支柱领域之一。计算流体力学在发展的同时，也广泛地应用于航空航天、动力工程、力学、物理和化学、建筑、水利、海洋、大气、环境、灾害等科学和工程的各个领域。也正因为如此，越来越多各个领域的科研、工程技术人员对计算流体力学开始产生兴趣，不少从来没有接触过或者接触很少的人渴望能了解和掌握计算流体力学，并将其应用到自己所从事的工作中去。然而，打开当今国内外各种各样的计算流体力学教科书、文献，甚至短期培训讲义，人们发现计算流体力学的知识面广，专业知识深、数学要求高，因而常常对它望而生畏，由此放弃进一步的学习念头。

由J.D.Anderson所写的《计算流体力学入门》一书正是针对这一现况，并根据他多年在各国讲授计算流体力学课程和各种短期培训的经验，为那些从来没有接触过计算流体力学，或从来没有在计算流体力学领域中工作过的各个领域的科研、工程技术人员和各类学生所编写的计算流体力学的入门书。当读者在读其他计算流体力学教科书和文献之前，当读者准备从事计算流体力学工作之前，这本《计算流体力学入门》是读者应该读的第一本书。

本书内容十分广泛，几乎涉及到计算流体力学的所有方面。全书共分4部分（12章），第1部分是基本原理和方程，第2部分是数值分析基础，第3部分是应用实例，第4部分是现代计算流体力学概述。读者可以从本书中了解到计算流体力学的基本术语和基本概述，掌握计算流体力学的基本原理和主要方法，系统地学习计算流体力学各个方面的基本知识，为今后进一步阅读和学习高深的计算流体力学方面的教科书和文献打下良好的基础。

本书有其独特的风格，作者尽最大努力用最通俗易懂的语言、生动形象的图表、循循善诱的教学方式引导读者从基本术语和概念出发、一步一步地进入计算流体力学整个领域，逐步了解掌握计算流体力学的基本原理、主要方法和应用技巧。计算流体力学是一门应用性很强的学科，

实践在应用中起着不可忽视的作用。作者特别强调在工程中的应用和实践，鼓励读者在学习过程中自己动手做作业，编程序和绘图。通过这些实践，读者能真正知道什么是计算流体力学，真正体会到什么是计算流体力学的实质和精髓。计算流体力学涉及面很广，读者企图通过读一本书或者学一门课就完全掌握计算流体力学的知识，特别是掌握计算流体力学在各个领域的应用是不切实际的，因此作者在写书时紧紧抓住计算流体力学核心内容（最基本的术语、概念和原理）进行讲解。读者在掌握这些基本知识后，就能为进入计算流体力学领域，掌握计算流体力学在各个领域的应用打下良好基础。

计算流体力学发展十分迅猛，任何一本书都不能全面讲述当代计算流体力学的全部知识，《计算流体力学入门》作为一本入门书籍，它只能对计算流体力学作一些基础知识的介绍。如果读者想在计算流体力学方面进一步提高和发展，必须在本书的基础之上，去学习计算流体力学更高深的研究生课程和参考有关文献。

综上所述，本书是一本有特色、有风格的入门教材，对于那些过去对计算流体力学从来没有接触过或者接触很少，但又渴望了解和学习，并期望短期内能掌握和应用计算流体力学的读者来说，它是一本很好的入门书；对于力学专业的大学生和非力学专业的研究生以及有关领域的科研、工程技术人员来说，它是一本学习计算流体力学的很好的教学参考书。

张德良

于北京

ABOUT THE AUTHOR

John D. Anderson, Jr., was born in Lancaster, Pennsylvania, on October 1, 1937. He attended the University of Florida, graduating in 1959 with high honors and a Bachelor of Aeronautical Engineering Degree. From 1959 to 1962, he was a lieutenant and task scientist at the Aerospace Research Laboratory at Wright-Patterson Air Force Base. From 1962 to 1966, he attended the Ohio State University under the National Science Foundation and NASA Fellowships, graduating with a Ph.D. in aeronautical and astronautical engineering. In 1966 he joined the U.S. Naval Ordnance Laboratory as Chief of the Hypersonic Group. In 1973, he became Chairman of the Department of Aerospace Engineering at the University of Maryland, and since 1980 has been professor of Aerospace Engineering at Maryland. In 1982, he was designated a Distinguished Scholar/Teacher by the University. During 1986–1987, while on sabbatical from the university, Dr. Anderson occupied the Charles Lindbergh chair at the National Air and Space Museum of the Smithsonian Institution. He continues with the Museum in a part-time appointment as special assistant for aerodynamics. In addition to his appointment in aerospace engineering, in 1993 he was elected to the faculty of the Committee on the History and Philosophy of Science at Maryland.

Dr. Anderson has published five books: *Gasdynamic Lasers: An Introduction*, Academic Press (1976), and with McGraw-Hill, *Introduction to Flight*, 3d edition (1989), *Modern Compressible Flow*, 2d Edition (1990), *Fundamentals of Aerodynamics*, 2d edition (1991), and *Hypersonic and High Temperature Gas Dynamics* (1989). He is the author of over 100 papers on radiative gasdynamics, re-entry aerothermodynamics, gas dynamic and chemical lasers, computational fluid dynamics, applied aerodynamics, hypersonic flow, and the history of aerodynamics. Dr. Anderson is in *Who's Who in America*, and is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is also a Fellow of the Washington Academy of Sciences, and a member of Tau Beta Pi, Sigma Tau, Phi Kappa Phi, Phi Eta Sigma, The American Society for Engineering Education (ASEE), The Society for the History of Technology, and the History of Science Society. He has received the Lee Atwood Award for excellence in Aerospace Engineering Education from the AIAA and the ASEE.

To Sarah-Allen, Katherine, and Elizabeth
for all their love and understanding

PREFACE

This computational fluid dynamics (CFD) book is *truly for beginners*. If you have never studied CFD before, if you have never worked in the area, and if you have no real idea as to what the discipline is all about, then this book is for you. Absolutely no prior knowledge of CFD is assumed on your part—only your desire to learn something about the subject is taken for granted.

The author's single-minded purpose in writing this book is to provide a simple, satisfying, and motivational approach toward presenting the subject to the reader who is learning about CFD for the first time. In the workplace, CFD is today a mathematically sophisticated discipline. In turn, in the universities it is generally considered to be a graduate-level subject; the existing textbooks and most of the professional development short courses are pitched at the graduate level. The present book is a *precursor* to these activities. It is intended to "break the ice" for the reader. This book is *unique* in that it is intended to be read and mastered *before* you go on to any of the other existing textbooks in the field, *before* you take any regular short courses in the discipline, and *before* you endeavor to read the existing literature. The hallmarks of the present book are *simplicity* and *motivation*. It is intended to prepare you for the more sophisticated presentations elsewhere—to give you an overall appreciation for the basic philosophy and ideas which will then make the more sophisticated presentations more meaningful to you later on. The mathematical level and the prior background in fluid dynamics assumed in this book are equivalent to those of a college senior in engineering or physical science. Indeed, this book is targeted primarily for use as a one-semester, senior-level course in CFD; it may also be useful in a preliminary, first-level graduate course.

There are no role models for a book on CFD at the undergraduate level; when you ask ten different people about what form such a book should take, you get ten different answers. This book is the author's answer, as imperfect as it may be, formulated after many years of thought and teaching experience. Of course, to achieve the goals stated above, the author has made some hard choices in picking and arranging the material in this book. It is *not* a state-of-the-art treatment of the modern, sophisticated CFD of today. Such a treatment would blow the uninitiated reader completely out of the water. This author knows; he has seen it happen over and over again, where a student who wants to learn about CFD is totally turned off by the advanced treatments and becomes unmotivated toward continuing further. Indeed, the purpose of this book is to prepare the reader to benefit from such advanced treatments *at a later date*. The present book provides a general perspective on CFD; its purpose is to turn you, the reader, on to the subject, not to intimidate you. Therefore, the material in this book is predominately an intuitive, physically oriented approach to CFD. A CFD expert, when examining this book, may at first think that some of it is "old-fashioned," because some of the material covered here was the state of the art in 1980. But this is the point: the older, tried-and-proven ideas form a wonderfully intuitive and meaningful learning experience for the uninitiated reader. With the background provided by this book, the reader can then progress to the more sophisticated aspects of CFD in graduate school and in the workplace. However, to increase the slope of the reader's learning curve, state-of-the-art CFD techniques *are* discussed in Chap. 11, and some very recent and powerful examples of CFD calculations are reviewed in Chap. 12. In this fashion, when you finish the last page of this book, you are already well on your way to the next level of sophistication in the discipline.

This book is in part the product of the author's experience in teaching a one-week short course titled "Introduction to Computational Fluid Dynamics," for the past ten years at the von Karman Institute for Fluid Dynamics (VKI) in Belgium, and in recent years also for Rolls-Royce in England. With this experience, this author has discovered much of what it takes to present the elementary concepts of CFD in a manner which is acceptable, productive, and motivational to the first-time student. The present book directly reflects the author's experience in this regard. The author gives special thanks to Dr. John Wendt, Director of the VKI, who first realized the need for such an introductory treatment of CFD, and who a decade ago galvanized the present author into preparing such a course at VKI. Over the ensuing years, the demand for this "Introduction to Computational Fluid Dynamics" course has been way beyond our wildest dreams. Recently, a book containing the VKI course notes has been published; it is *Computational Fluid Dynamics: An Introduction*, edited by John F. Wendt, Springer-Verlag, 1992. The present book is a greatly expanded sequel to this VKI book, aimed at a much more extensive presentation of CFD pertinent to a one-semester classroom course, but keeping within the basic spirit of simplicity and motivation.

This book is organized into four major parts. Part I introduces the basic thoughts and philosophy associated with CFD, along with an extensive discussion of the governing equations of fluid dynamics. It is vitally important for a student of CFD to fully understand, and feel comfortable with, the basic physical equations; they are the lifeblood of CFD. The author feels so strongly about this need to fully understand and appreciate the governing equations that every effort has been made to thoroughly derive and discuss these equations in Chap. 2. In a sense, Chap. 2 stands independently as a "mini course" in the governing equations. Experience has shown that students of CFD come from quite varied backgrounds; in turn, their understanding of the governing equations of fluid dynamics ranges across the spectrum from virtually none to adequate. Students from the whole range of this spectrum have continually thanked the author for presenting the material in Chap. 2; those from the "virtually none" extreme are very appreciative of the opportunity to become comfortable with these equations, and those from the "adequate" extreme are very happy to have an integrated presentation and comprehensive review that strips away any mystery about the myriad of different forms of the governing equations. Chapter 2 emphasizes the philosophy that, to be a good computational fluid dynamicist, you must first be a good fluid dynamicist.

In Part II, the fundamental aspects of numerical discretization of the governing equations are developed; the discretization of the partial differential equations (finite-difference approach) is covered in detail. Here is where the basic numerics are introduced and where several popular numerical techniques for solving flow problems are presented. The finite-volume discretization of the integral form of the equations is covered via several homework problems.

Part III contains applications of CFD to four classic fluid dynamic problems with well-known, exact analytical solutions, which are used as a basis for comparison with the numerical CFD results. Clearly, the *real-world applications of CFD* are to problems that do *not* have known analytical solutions; indeed, CFD is our mechanism for solving flow problems that cannot be solved in any other way. However, in the present book, which is intended to introduce the reader to the *basic aspects* of CFD, nothing is gained by choosing applications where it is difficult to check the validity of the results; rather everything is gained by choosing simple flows with analytical solutions so that the reader can fundamentally see the strengths and weaknesses of a given computational technique against the background of a known, exact analytical solution. Each application is worked in great detail so that the reader can see the direct use of much of the CFD fundamentals which are presented in Parts I and II. The reader is also encouraged to write his or her own computer programs to solve these same problems, and to check the results given in Chaps. 7 to 10. In a real sense, although the subject of this book is *computational* fluid dynamics, it is also a vehicle for the reader to become more thoroughly acquainted with fluid dynamics per se. This author has intentionally emphasized the physical aspects of various flow problems in order to enhance the reader's overall understanding. In some respect, this is an example of the adage that a student really learns the material of course N when he or she takes course $N + 1$. In terms of some aspects of basic fluid dynamics, the present book represents course $N + 1$.

Part IV deals with some topics which are more advanced than those discussed earlier in the book but which constitute the essence of modern state-of-the-art algorithms and applications in CFD. It is well beyond the scope of this book to present the *details* of such advanced topics—they await your attention in your future studies. Instead, such aspects are simply *discussed* in Chap. 11 just to give you a preview of coming attractions in your future studies. The purpose of Chap. 11 is just to acquaint you with some of the ideas and vocabulary of the most modern CFD techniques being developed today. Also, Chap. 12 examines the future of

CFD, giving some very recent examples of pioneering applications; Chap. 12 somewhat closes the loop of this book by extending some of the motivational ideas first discussed in Chap. 1.

The matter of *computer programing per se* was another hard choice faced by the author. Should detailed computer listings be included in this book as an aid to the reader's computer programing and as a recognition of the importance of efficient and modular programing for CFD? The decision was *no*, with the exception of a computer listing for Thomas' algorithm contained in the solution for Couette flow and listed in App. A. There are good and bad programming techniques, and it behooves the reader to become familiar and adept with efficient programming. However, this is *not the role of the present book.* Rather, you are encouraged to tackle the applications in Part III by writing your own programs as you see fit, and not following any prescribed listing provided by the author. This is assumed to be part of your learning process. The author wants you to get your own hands "dirty" with CFD by writing your own programs; it is a vital part of the learning process at this stage of your CFD education. On the other hand, detailed computer listings for all the applications discussed in Part III *are listed in the Solutions Manual for this book.* This is done as a service to classroom instructors. In turn, the instructors are free to release to their students any or all of these listings as deemed appropriate.

Something needs to be said about *computer graphics*. It was suggested by one reviewer that some aspects of computer graphics be mentioned in the present book. It is a good suggestion. Therefore, in Chap. 6 an entire section is devoted to explaining and illustrating the different computer graphic techniques commonly used in CFD. Also, examples of results presented in standard computer graphic format are sprinkled throughout the book.

Something also needs to be said about the role of *homework problems* in an introductory, senior-level CFD course, and therefore about homework problems in the present book. This is a serious consideration, and one over which the author has mulled for a considerable time. The actual applications of CFD—even the simplest techniques as addressed in this book—require a substantial learning period before the reader can actually do a reasonable calculation. Therefore, in the early chapters of this book, there is not much opportunity for the reader to practice making calculations via homework exercises. This is a departure from the more typical undergraduate engineering course, where the student is usually immersed in the "learning by doing" process through the immediate assignment of homework problems. Insead, the reader of this book is immersed in first learning the basic vocabulary, philosophy, ideas, and concepts of CFD before he or she finally encounters applications—the subject of Part III. Indeed, in these applications the reader is finally encouraged to set up calculations and to get the experience of doing some CFD work himself or herself. Even here, these applications are more on the scale of small *computer projects* rather than homework problems per se. Even the reviewers of this book are divided as to whether or not homework problems should be included; exactly half the reviewers said yes, but the others implied that such problems are not necessary. This author has taken some middle ground. There are homework problems in this book, but not very many. They are included in several chapters to help the reader think about the details of some of the concepts being discussed in the text. Because there are no established role models for a book in CFD at the undergraduate level for which the present book is aimed, the author prefers to leave the generation of large numbers of appropriate homework problems to the ingenuity of the readers and instructors—you will want to exercise your own creativity in this regard.

This book is in keeping with the author's earlier books in that every effort has been made to discuss the material in an easy-to-understand writing style. This book will *talk to you* in a conversational style in order to expedite your understanding of material that sometimes is not all that easy to understand.

As stated earlier, a unique aspect of this book is its intended use in *undergraduate* programs in engineering and physical science. Since the seventeenth century, science and engineering have developed along two parallel tracks: one dealing with pure experiment and the other dealing with pure theory. Indeed, today's undergraduate engineering and science curricula reflect this tradition; they give the student a solid background in both experimental and theoretical techniques. However, in the technical world of today, computational mechanics has emerged as a new third approach, along with those of experiment and theory. Every graduate will in some form or another be touched by computational mechanics in the future. Therefore, in terms of fluid dynamics, it is *essential* that CFD be added to the curriculum at the *undergraduate* level in order to round out the three-approach world of today. This book is intended to expedite the teaching of CFD at the undergraduate level and, it is hoped, to make it as pleasant and painless as possible to both student and teacher.

A word about the *flavor* of this book. The author is an aerodynamicist, and there is some natural tendency to discuss aeronautically related problems. However, CFD is *interdisciplinary*, cutting across the fields of aerospace, mechanical, civil, chemical, and even electrical engineering, as well as physics and chemistry. While writing this book, the author had readers from all these areas in mind. Indeed, in the CFD short courses taught by this author, students from all the above disciplines have attended and enjoyed the experience. Therefore, this book contains material related to other disciplines well beyond that of aerospace engineering. In particular, mechanical and civil engineers will find numerous familiar applications discussed in Chap. 1 and will find the ADI and pressure correction techniques discussed in Chap. 6 to be of particular interest. Indeed, the application of the pressure correction technique for the solution of a viscous incompressible flow in Chap. 9 is aimed squarely at mechanical and civil engineers. However, no matter what the application may be, please keep in mind that the material in this book is *generic* and that readers from many fields are welcome.

What about the sequence of material presented in this book? Can the reader hop around and cut out some material he or she may not have time to cover, say in a given one-semester course? The answer is essentially yes. Although the author has composed this book such that consecutive reading of all the material in sequence will result in the broadest understanding of CFD at the introductory level, he recognizes that many times the reader and/or instructor does not have that luxury.

Therefore, at strategic locations throughout the book, specifically highlighted GUIDEPOSTS appear which instruct the reader where to go in the book and what to do in order to specifically tailor the material as he or she so desires. The location of these GUIDEPOSTS is also shown in the table of contents, for ready reference.

The author wishes to give special thanks to Col. Wayne Halgren, professor of aeronautics at the U.S. Air Force Academy. Colonel Halgren took the time to study the manuscript of this book, to organize it for a one-semester senior course at the Academy, and to field-test it in the classroom during the spring of 1993. Then he graciously donated his time to visit with the author at College Park in order to share his experiences during this field test. Such information coming from an independent source was invaluable, and a number of features contained in this book came out of this interaction. The fact that Wayne was one of this author's doctoral students several years ago served to strengthen this interaction. This author is proud to have been blessed with such quality students.

The author also wishes to thank all his colleagues in the CFD community for many invigorating discussions on what constitutes an elementary presentation of CFD, and especially the following reviewers of this manuscript: Ahmed Busnaina, Clarkson University; Chien-Pin Chen, University of Alabama–Huntsville; George S. Dulikravich, Pennsylania State University; Ira Jacobson, University of Virginia; Osama A. Kandil, Old Dominion University; James McDonough, University of Kentucky; Thomas J. Mueller, University of Notre Dame; Richard Pletcher, Iowa State University; Paavo Repri, Florida Institute of Technology; P. L. Roe, University of Michigan–Ann Arbor; Christopher Rutland, University of Wisconsin; Joe F. Thompson, Mississippi State University; and Susan Ying, Florida State University. This book is, in part, a product of those discussions. Also, special thanks go to Ms. Susan Cunningham, who was the author's personal word processor for the detailed preparation of this manuscript. Sue loves to type equations—she should have had a lot of fun with this book. Of course, special appreciation goes to two important institutions in the author's life—the University of Maryland for providing the necessary intellectual atmosphere for producing such a book, and my wife, Sarah-Allen, for providing the necessary atmosphere of understanding and support during the untold amount of hours at home required for writing this book. To all of you, I say a most heartfelt thank you.

So, let's get on with it! I wish you a productive trail of happy reading and happy computing. Have fun (and I really mean that).

John D. Anderson, Jr.

COMPUTATIONAL FLUID DYNAMICS
The Basics with Applications

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