普通高等院校航空航天双语教学用书

MODERN COMPRESSIBLE FLOW: WITH HISTORICAL PERSPECTIVE (THIRD EDITION)

现代可压缩流：以历史的视角（第3版）

（双语教学译注版）

[美]小约翰·D. 安德森(John D. Anderson, Jr.) 著

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内容提要

本书共分为三个部分，涵盖了经典可压缩流理论、经典可压缩流中的复杂问题和现代可压缩流的相关内容。第一部分（第1～第5章）介绍了经典可压缩流理论，包括无黏可压缩流积分形式控制方程、激波和膨胀波、喷管流等；第二部分（第6～第10章）介绍了无黏可压缩流微分形式控制方程、非定常波运动、速度势方程和线化流动，以及锥形流等；第三部分（第11～第17章）介绍了超声速流动数值求解技术、时间推进技术、典型的三维超声速流、跨声速和高超声速流，以及高温气体特性和基本示例等。

本书可以作为航空航天工程、机械工程和工程力学专业的高年级本科生和第一年研究生教材，也适于相关专业人员参考使用。

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出版说明

适合教学和专业发展的双语教材的编写、引进和出版，是我国高等院校双语教学示范课程建设的重要内容之一。针对目前我国高等院校推广的双语教学课程建设项目，中航出版传媒有限责任公司（航空工业出版社）作为国内航空航天领域领先的专业出版机构，与国内各航空航天院校积极探索，根据各院校的实际教学需求，对国外成熟的、优秀的航空航天教材进行了甄选，形成了独具特色的航空航天类双语版专业教材。部分优选出的权威的、经典的教材已经在国内部分院校的教学实践中进行了使用，不仅获得了教师和学生的肯定，而且取得了业内专家和学者的一致认同。

本套丛书所包含的双语教材均是由从事相关专业教学工作多年的一线教师根据教学实践内容编写、翻译或译注而成的。其出版形式，既有中英文对照版，又有译注版。在中英文对照版中，教材编写者根据不同的教学安排对原版教材进行了取舍，集中精选了适合教学计划的内容编撰成双语教学精选版。译注版对原版教材中的要点进行了注释，这样可以使学生在学习过程中更容易厘清知识脉络，抓住重点，增加了注释的双语版教材基本保持了英文原版教材的结构和篇幅，不同的是，每章前面都增加了一部分提炼出来的知识要点。本套丛书所引进的原版教材，多是国外专业教材中的经典作品，被国外多所院校广泛采用，并经多次再版修订。此外，本套丛书基本保留了原版书的量和单位符号，公式中的矢量和标量等也大多沿用了原书的符号系统。

本套丛书的出版是我国航空航天专业教材出版领域的创新之举，得到了国内各航空航天相关院校的大力支持，由既熟悉原版教材，又具备丰富的双语教学经验和系统专业知识的任课教师担任丛书的编写者，他们在繁重的教学工作之余完成了各自书稿的编写和翻译工作，在此对他们的辛勤付出表示感谢!

由于出版工作繁杂，本套丛书难免会有疏漏、差错及不妥之处，敬请读者指正。

ABOUT THE AUTHOR
作者介绍

小约翰·D. 安德森，1937 年 10 月 1 日出生于宾夕法尼亚州的兰卡斯特市。1959 年以优异的成绩毕业于佛罗里达大学，获得航空工程学士学位。1959—1962 年，他作为随军任务科学家在莱特·帕特森空军基地航空航天实验室工作。1962—1966 年，他进入俄亥俄州立大学学习，并在美国国家自然科学基金会和 NASA 奖学金的资助下，攻读航空航天工程学博士学位。1966 年，他加入美国海军军械实验室，任高超声速研究组的首席科学家。1973 年他成为马里兰大学航空航天工程系系主任，并自 1980 年起在那里任教授，1982 年获得该校“杰出学者 / 教师”称号。1986—1987 年大学假期期间，安德森博士担任史密斯学会美国国家航空航天博物馆查尔斯·林德伯格（又译林白，Lindbergh，C.，1902—1974）馆的馆长。他作为该馆的空气动力学专业特别顾问，一直坚持每周去该馆一天，研究和撰写空气动力学史。在马里兰大学，他除了担任航空航天工程学教授外，还于 1993 年被聘为自然科学哲学和科学委员会全职教员，并在 1996 年被聘为历史系教员。1996 年，他被授予“格伦·L. 马丁航空航天工程教育杰出教授”称号。1999 年，他从马里兰大学退休，并获“荣誉退休教授”称号。他目前是史密斯学会美国国家航空航天博物馆空气动力学馆的馆长。

安德森博士出版了 8 本专著：美国学术出版社出版的《气体动力学激光器：导论》（1976 年）；麦格劳 – 希尔（McGraw–Hill）公司出版的《飞行导论：工程和历史》（1978，1984，1989，2000，2005，2008），《现代可压缩流：以历史的视角》（1982，1990，2003），《空气动力学基础》（1984，1991，2001，2007），《高超声速和高温气体动力学》（1989），《计算流体力学：基础与应用》（1995），《飞行器性能与设计》（1999）；剑桥大学出版社出版的《空气动力学历史及其对飞行器的影响》（1997，1998）。他发表了涉及辐射空气动力学、再入气动热力学、气动化学激光、计算流体力学、应用空气动力学、高超声速流和航空史等相关的论文 120 多篇。安德森博士被收入《美国名人录》。他是 AIAA 荣誉会员、伦敦英国

皇家航空学会会员。他还是 Tau Beta Pi 荣誉学会、Sigma Tau 荣誉学会、Phi Kappa Phi 荣誉学会、Phi Eta Sigma 荣誉学会，以及美国工程教育学会、科学史学会和技术史学会会员。1988 年，他被选为 AIAA 教育委员会副主席。1989 年，他获得美国工程教育学会和 AIAA 联合颁发的 John Leland Atwood 奖，以表彰他“对航空航天工程教育的贡献所产生的永久性的影响”。1995 年，他被授予 AIAA 航空航天文献奖，以表彰其“在航空航天工程领域编写了因易读、表述清晰且包括历史内容而在世界范围内引起广泛赞誉的本科生和研究生教材”。1996 年，他被选为 AIAA 出版委员会副主席。最近（2000 年），他被 AIAA 授予航天学“冯·卡门讲师”荣誉称号。

从 1987 年到现在，安德森博士一直是 McGraw–Hill 公司航空航天工程系列丛书的资深顾问编辑。

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 Hypersonics 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 the University of 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 continued with the Air and Space Museum one day each week as their Special Assistant for Aerodynamics, doing research and writing on the history of aerodynamics. In addition to his position as professor of aerospace engineering, in 1993, he was made a full faculty member of the Committee for the History and Philosophy of Science and in 1996 an affiliate member of the History Department at the University of Maryland. In 1996, he became the Glenn L. Martin Distinguished Professor for Education in Aerospace Engineering. In 1999, he retired from the University of Maryland and was appointed Professor Emeritus. He is currently the Curator for Aerodynamics at the National Air and Space Museum, Smithsonian Institution.

Dr. Anderson has published eight books: *Gasdynamic Lasers: An Introduction,* Academic Press (1976), and under McGraw-Hill, *Introduction to Flight* (1978, 1984, 1989, 2000), *Modern Compressible Flow* (1982, 1990), *Fundamentals of Aerodynamics* (1984, 1991), *Hypersonic and High Temperature Gas Dynamics* (1989), *Computational Fluid Dynamics: The Basics with Applications* (1995), *Aircraft Performance and Design* (1999), and *A History of Aerodynamics and Its Impact on Flying Machines,* Cambridge University Press (1997 hardback, 1998 paperback). He is the author of over 120 papers on radiative gasdynamics, reentry aerothermodynamics, gasdynamic and chemical lasers, computational fluid dynamics, applied aerodynamics, hypersonic flow, and the history of aeronautics. Dr. Anderson is in *Who's Who in America.* He is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is also a fellow of the Royal Aeronautical Society, London. He is a member of Tau Beta Pi, Sigma Tau, Phi Kappa Phi, Phi Eta Sigma, The American Society for Engineering Education, the History of Science Society, and the Society for the History of Technology. In 1988, he was elected as Vice President of the AIAA for Education. In 1989, he was awarded the John Leland Atwood Award jointly by the American Society for Engineering Education and the American Institute of Aeronautics and Astronautics "for the lasting influence of his recent contributions to aerospace engineering education." In 1995, he was awarded the AIAA Pendray Aerospace Literature Award "for writing undergraduate and graduate textbooks in aerospace engineering which have received worldwide acclaim for their readability and clarity of presentation, including historical content." In 1996, he was elected Vice President of the AIAA for Publications. He has recently been honored by the AIAA with its 2000 von Karman Lectureship in Astronautics.

From 1987 to the present, Dr. Anderson has been the senior consulting editor on the McGraw-Hill Series in Aeronautical and Astronautical Engineering.

PREFACE TO THE THIRD EDITION
第3版序言

如同前两版一样，第3版的目的是：为读者提供一个课堂学习或者自学可压缩流的易懂且有趣的学习工具。像在第1版中提到的一样，本书编写过程中，故意使用了一些口语化的表述，目的是为了能够和读者交谈，并获得其注意力，使其注意力自始至终在教材中。前两版的编写思想，如以历史的视角，同样延续到第3版。

学生、教师和实践专业人员对前两版表现出极大的赞同。因此，第3版整体上包含了第2版的所有内容，仅更新了少数内容。第3版相较于第2版，更新的内容如下：

1. 在每章的开头增加了预览框，可使读者对本章即将学习内容的性质和重要性有个宏观的认识。设计预览框是为了提高读者对于本章内容的兴趣。同时提供的本章路线图可以帮助读者以更大的视角来看本章内容，从而在琐碎的数学推导和物理细节中发现本章的思路。

2. 更多重点放在可压缩流的物理机理上，以增强内容的基础性。

3. 为加快对可压缩流物理的理解，增加了相当数量的物理机理的说明性例子。

4. 鉴于计算流体力学（CFD）持续在可压缩流研究的各个方面承担重要的角色，第3版加强了CFD的内容。本书不是一本关于CFD的教材，但是为了加强对可压缩流基础的理解，本书在必要的程度上单独讨论了CFD内容。

5. 在原有课后练习的基础上，增加了新的习题。McGraw-Hill提供了一个关于课后习题的答案手册。

6. 与新加入的内容一起，增加了一些新的插图和照片。

本书可作为高年级本科生和第一年研究生的可压缩流学习教材。所有章节大体上可以分为三部分，指导教师可以根据需要组成一个课程：

1. 第1～第5章组成了经典可压缩流的核心，包含有激波、膨胀波和喷管流等。这些章节的推导主要是代数形式的。

2. 第6～第10章针对经典可压缩流中稍微复杂的问题，数学推导主

要是偏微分方程。

3．第 11～第 17 章涉及可压缩流中更现代的内容，比如，使用计算流体力学方法学习可压缩流更复杂的现象，以及高温气体的一般特征。

总的来说，本书为 21 世纪的学生提供一本平衡了经典和现代可压缩流知识的教材。

特别感谢为第 3 版的出版付出辛苦努力的人们：

1．我的学生，以及世界各地的学生和读者，对前两版教材提供了热情的反馈，为我带来作为一个工程教育工作者的终极乐趣。

2．我的家庭，为提供了作为丈夫、父亲和祖父的终极乐趣。

3．我在马里兰大学、国家航空航天博物馆、世界各地的其他学术和研究机构，以及工业部门的同事，帮助拓展了我的视野。

4．Susan Cunningham，作为我的打字员，在补充手稿准备方面做了卓越的工作。

最后，可压缩流是个令人兴奋的学科——令人兴奋地学习，令人兴奋地教学，令人兴奋地著述。本书的目的也是为了使读者感到兴奋，并使可压缩流的学习是一种享受。因此，本书的作者如此说：读下去，并乐在其中吧！

PREFACE TO THE THIRD EDITION

The purpose of the third edition is the same as that of the earlier editions: to provide a teaching instrument, in the classroom or independently, for the study of compressible fluid flow, and at the same time to make this instrument *understandable* and *enjoyable* for the reader. As mentioned in the Preface to the First Edition, this book is intentionally written in a rather informal style in order to *talk* to the reader, to gain his or her interest, and to keep the reader absorbed from cover to cover. Indeed, all of the philosophical aspects of the first two editions, including the inclusion of a historical perspective, are carried over to the third edition.

The response to the first two editions from students, faculty, and practicing professionals has been overwhelmingly favorable. Therefore, for the third edition, all of the content of the second edition has been carried over virtually intact, with only minor changes made here and there for updating. The principal difference between the third and second editions is the addition of much *new* material, as follows:

1. Each chapter starts with a Preview Box, an educational tool that gives the reader an overall perspective of the nature and importance of the material to be discussed in that chapter. The Preview Boxes are designed to heighten the reader's interest in the chapter. Also, chapter roadmaps are provided to help the reader see the bigger picture, and to navigate through the mathematical and physical details buried in the chapter.
2. Increased emphasis has been placed on the physics associated with compressible flow, in order to enhance the fundamental nature of the material.
3. To expedite this physical understanding, a number of new illustrative worked examples have been added that explore the physics of compressible flow.
4. Because computational fluid dynamics (CFD) continues to take on a stronger role in various aspects of compressible flow, the flavor of CFD in the third edition has been strengthened. This is not a book on CFD, but CFD is discussed in a self-contained fashion to the extent necessary to enhance the fundamentals of compressible flow.
5. New homework problems have been added to the existing ones. There is a solutions manual for the problems available from McGraw-Hill for the use of the classroom instructor.
6. Consistent with all the new material, a number of new illustrations and photographs have been added.

This book is designed to be used in advanced undergraduate and first-year graduate courses in compressible flow. The chapters divide into three general categories, which the instructor can use to mold a course suitable to his or her needs:

1. Chapters 1–5 make up the core of a basic introduction to classical compressible flow, with the treatment of shock waves, expansion waves, and nozzle flows. The mathematics in these chapters is mainly algebra.
2. Chapters 6–10 deal with slightly more advanced aspects of classical compressible flow, with mathematics at the level of partial differential equations.
3. Chapters 11–17 cover more modern aspects of compressible flow, dealing with such features as the use of computational fluid dynamics to study more complex phenomena, and the general nature of high-temperature flows.

Taken in total, the book provides the twenty-first-century student with a balanced treatment of both the classical and modern aspects of compressible flow.

Special thanks are given to various people who have been responsible for the materialization of this third edition:

1. My students, as well as students and readers from all over the world, who have responded so enthusiastically to the first two editions, and who have provided the ultimate joy to the author of being an engineering educator.
2. My family, who provide the other ultimate joy of being a husband, father, and grandfather.
3. My colleagues at the University of Maryland, the National Air and Space Museum, and at many other academic and research institutions, as well as industry, around the world, who have helped to expand my horizons.
4. Susan Cunningham, who, as my scientific typist, has done an excellent job of preparing the additional manuscript.

Finally, compressible flow is an exciting subject—exciting to learn, exciting to teach, and exciting to write about. The purpose of this book is to excite the reader, and to make the study of compressible flow an enjoyable experience. So this author says—read on and *enjoy*.

John D. Anderson, Jr.

PREFACE TO THE FIRST EDITION
第1版序言

本书旨在为读者提供一个课堂学习或者自学可压缩流的工具。在编写过程中，作者故意使用了一些口语化的表述，目的是为了能够和读者交谈，并获得其注意力，使其注意力自始至终在教材中。本书可以作为航空航天工程、机械工程和工程力学专业的高年级本科生及第一年研究生的教材，也可以为希望从现代的视角获得可压缩流全貌的实践工程师提供参考。另外，由于可压缩流的基本原理和结果实际上需要涉及所有的物理科学，本书对所有的工程师都有所帮助，包括物理学家和化学家。

这是一本关于现代可压缩流的书。关于“现代”这个词的广泛的定义，在1.6节给出。大体上说，本书包含了在过去的两个世纪内发展的经典可压缩流的基础知识，同时还有在过去的几十年里发展的两个重要的新方向，即：

1．现代计算流体力学：高速计算机的发展为流体机理分析带来革命性变化，并使此前认为棘手的问题解决成为可能。今天可压缩流的学习必须将这些数值方法作为可压缩流不可或缺的部分；这也是本书的一个方面。例如，读者会发现关于有限差分技术的冗长的讨论，包括在一些重要应用中创造过奇迹的时间推进技术。

2．高温流。现代可压缩流经常包含高速空气动力学、燃烧和能量转换，所有这些在高温气体流动中占有支配性位置。因此，这些高温效应必须包含在可压缩流的基础学习中，这是本书的另一个方面。例如，读者会发现关于平衡和非平衡流的广泛介绍，以及在一些基本问题中的应用，如激波和喷管流。

简言之，今天的现代可压缩流是经典分析和计算技术、高温气体效应的混合体。本书的目的之一就是提供对于可压缩流的现代视角的理解，以将经典可压缩流中的重要内容和现代计算流体技术和高温气体动力学关联起来。从这个意义上讲，本书的处理有些特别：这代表将和经典可压缩流有实质性的偏离。但是同时，本书详细地讨论了可压缩流的经典基础及其重要的物理含义。实际上，只要你浏览一下本书的目录就会发现，

前半部分是非常经典的内容。从第 1 章至第 7 章，加上其他章节的部分内容，就可以组成一个高年级本科生一个学期的课程。本书的第二部分就有了“现代”特点。整本书组成完整的高年级本科生和第一年研究生一个学年的教学内容。

本书的另一个特色是其包含的可压缩流的历史视角。作者确信，对于现代技术相关的历史背景和传统的了解，是工程教育不可分割的一部分。绝大多数的工程专业人员和学生缺少这种历史的知识和了解，本书尝试添补这种空白。例如，本书阐述了超声速喷管是何人、在何种情形下发展的，可压缩流的现代方程在过去的几个世纪里如何发展的，伯努利、欧拉、亥姆霍兹、兰金、普朗特、布塞曼、葛劳渥等都是什么人，以及他们对可压缩流的现代科学做出了何种贡献？按照这个思路，本书延续了作者此前完成一本书的写作传统（《飞行导论：工程和历史》1978，McGraw–Hill 公司，纽约），即同时包含了历史摘记和工程内容。

每章的最后给出了课后习题。这些习题通常比较简单，主要是让学生对学习的内容有实际理解。

为了保持合理而可接受的篇幅，本书没有涉及跨声速和黏性流部分。但是最好在掌握了本书的基础内容后，学习一下上述内容。

本书是 1973 年开始在马里兰大学教授研究生一年级可压缩流课程的产物。这些年来，许多学生敦促作者将课堂笔记整理成书。本人无法无视这种鼓励，因此就产生了这本书。因此，本书某种程度上是献给我所有的学生的，由于他们，我获得了教学和工作的快乐。

本书也要献给我的妻子 Sarah–Allen，及我的两个女儿 Katherine 和 Elizabeth，因为我错过了大量的作为丈夫和父亲的时间。他们的理解非常重要，这里我要再次说感谢。另外，还有一直做幕后工作的 Edna Brothers 和 Sue Osborn，他们以极大的奉献精神输完手稿。还有，作者希望感谢史密斯国家航空航天博物馆馆长 Richard Hallion 博士，其有益的意见和持续开放的博物馆为我的历史研究提供了广泛的档案。

PREFACE TO THE FIRST EDITION

This book is designed to be a teaching instrument, in the classroom or independently, for the study of compressible fluid flow. It is intentionally written in a rather informal style in order to *talk* to the reader, to gain his or her interest, and to be absorbed from cover to cover. It is aimed primarily at senior undergraduate and first-year graduate students in aerospace engineering, mechanical engineering, and engineering mechanics; it has also been written for use by the practicing engineer who wants to obtain a cohesive picture of compressible flow from a modern perspective. In addition, because the principles and results of compressible flow permeate virtually all fields of physical science, this book should be useful to engineers in general, as well as to physicists and chemists.

This is a book on *modern* compressible flows. An extensive definition of the word "modern" in this context is given in Sec. 1.6. In essence, this book presents the fundamentals of classical compressible flow as they have evolved over the past two centuries, but with added emphasis on two new dimensions that have become so important over the past two decades, namely:

1. *Modern computational fluid dynamics*. The high-speed digital computer has revolutionized analytical fluid mechanics, and has made possible the solution of problems heretofore intractable. The teaching of compressible flow today must treat such numerical approaches as an integral part of the subject; this is one facet of the present book. For example, the reader will find lengthy discussions of finite-difference techniques, including the time-marching approach, which has worked miracles for some important applications.
2. *High-temperature flows*. Modern compressible flow problems frequently involve high-speed aerodynamics, combustion, and energy conversion, all of which can be dominated by the flow of high-temperature gases. Therefore, such high-temperature effects must be incorporated in any basic study of compressible flow; this is another facet of the present book. For example, the reader will find extensive presentations of both equilibrium and nonequilibrium flows, with application to some basic problems such as shock waves and nozzle flows.

In short, the modern compressible flow of today is a mutually supportive mixture of classical analysis along with computational techniques, with the treatment of high-temperature effects being almost routine. One purpose of this book is to provide an understanding of compressible flow from this modern point of view. Its intent is to interrelate the important aspects of classical compressible flow with the recent techniques of computational fluid dynamics and high-temperature gas dynamics. In this sense, the present treatment is somewhat unique; it represents a substantial departure from existing texts in classical compressible flow. However, at the same time, the classical fundamentals along with their important physical implications are discussed at length. Indeed, the first half of this book, as seen from a glance at the Table of Contents, is very classical in scope. Chapters 1 through 7, with selections from other chapters, constitute a solid, one-semester senior-level course. The second half of the book provides the "modern" color. The entire book constitutes a complete one-year course at the senior and first-year graduate levels.

Another unique aspect of this book is the inclusion of an historical perspective on compressible flow. It is the author's strong belief that an appreciation for the historical background and traditions associated with modern technology should be an integral part of engineering education. The vast majority of engineering professionals and students have little knowledge or appreciation of such history; the present book attempts to fill this vacuum. For example, such questions are addressed as who developed supersonic nozzles and under what circumstances, how did the modern equations of compressible fluid flow develop over the centuries, who were Bernoulli, Euler, Helmholtz, Rankine, Prandtl, Busemann, Glauert, etc., and what did they contribute to the modern science of compressible flow? In this vein, the present book continues the tradition established in one of the author's previous books (*Introduction to Flight: Its Engineering and History,* McGraw-Hill, New York, 1978) wherein historical notes are included with the technical material.

Homework problems are given at the end of most of the chapters. These problems are generally straightforward, and are designed to give the student a practical understanding of the material.

In order to keep the book to a reasonable and affordable length, the topics of transonic flow and viscous flow are not included. However, these are topics which are best studied after the fundamental material of this book is mastered.

This book is the product of teaching the first-year graduate course in compressible flow at the University of Maryland since 1973. Over the years, many students have urged the author to expand the class notes into a book. Such encouragement could not be ignored, and this book is the result. Therefore, it is dedicated in part to all my students, with whom it has been a joy to teach and work.

This book is also dedicated to my wife, Sarah-Allen, and my two daughters, Katherine and Elizabeth, who relinquished untold amounts of time with their husband and father. Their understanding is much appreciated, and to them I once again say hello. Also, hidden behind the scenes but ever so present are Edna Brothers and Sue Osborn, who typed the manuscript with such dedication. In addition, the author wishes to thank Dr. Richard Hallion, Curator of the National Air and Space Museum of the Smithsonian Institution, for his helpful comments and for continually opening the vast archives of the museum for the author's historical research. Finally, I wish to thank my many professional colleagues for stimulating discussions on compressible flow and what constitutes a modern approach to its teaching. Hopefully, this book is a reasonable answer.

John D. Anderson, Jr.

第 1 章知识要点

- 可压缩流发展的历史脉络和本书的主要内容
- 热力学复习，包括内能、焓、熵、压缩性等概念，热力学第一定律和第二定律等
- 物体上的气动力计算方法
- 了解现代可压缩流的内涵