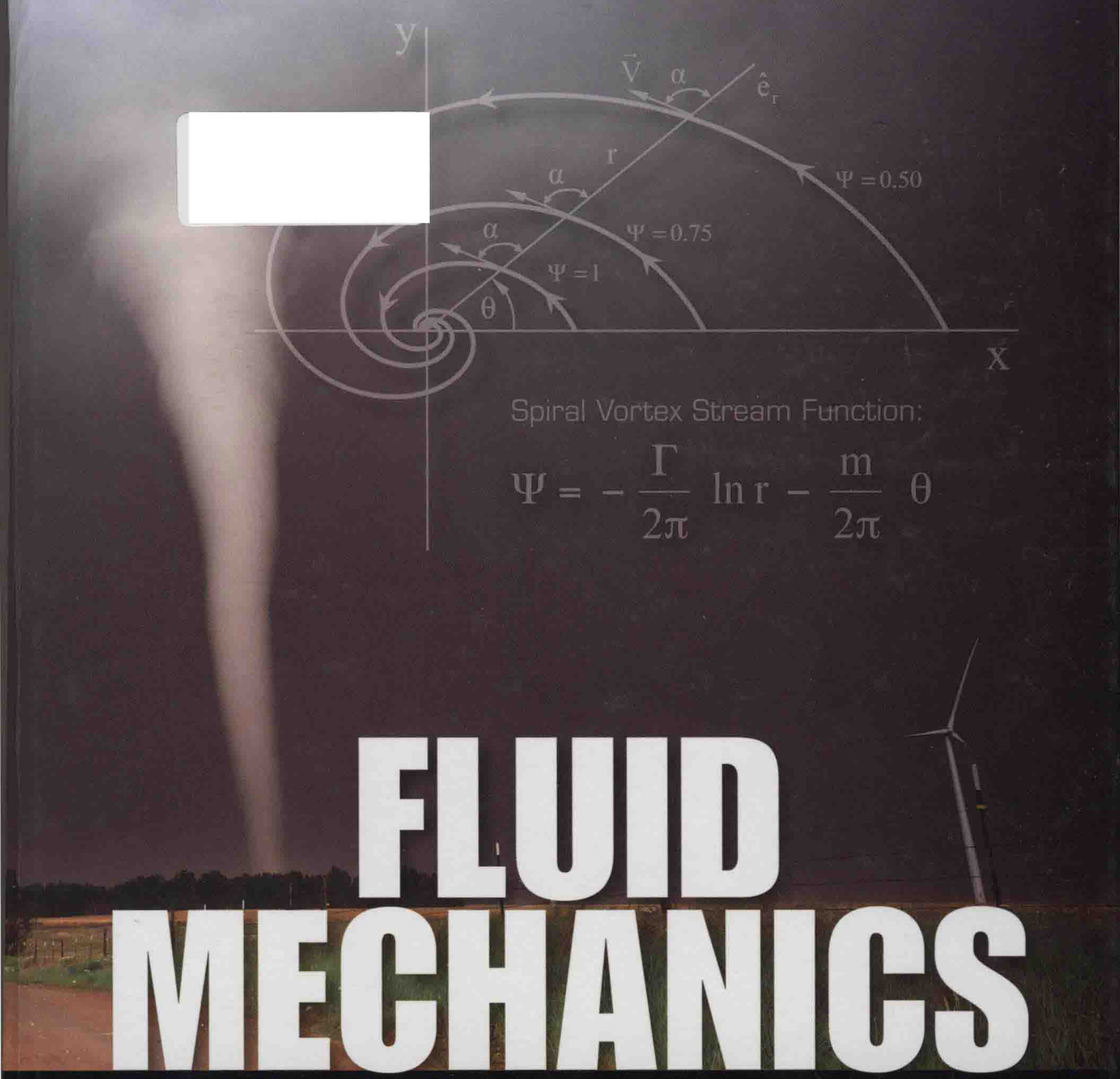

FLUID MECHANICS

An Intermediate Approach

Bijay K. Sultanian

CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20150420

International Standard Book Number-13: 978-1-4665-9898-0 (Hardback)

Library of Congress Cataloging-in-Publication Data

Sultanian, Bijay.
Fluid mechanics : an intermediate approach / Bijay Sultanian.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4665-9898-0 (hardcover : alk. paper) 1. Fluid mechanics. I. Title.

TA357.S8626 2016
532--dc23 2015014594

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

FLUID MECHANICS
An Intermediate Approach

To my parents, teachers, and friends; wife, Bimla;

daughter, Rachna; son, Dheeraj (Raj); son-in-law, Shahin; and grandchildren,

Aarti, Soraya, and Shayan, who have immensely enriched my life.

Preface

This book is a unique blend of my passion in fluid mechanics, 40+ years of industry experience, and nearly a decade of teaching graduate-level courses in turbomachinery and fluid mechanics at the University of Central Florida (UCF). Fluid mechanics can be the most beautiful and most enjoyable area of engineering. Its true beauty lies not in its mathematical descriptions but in the understanding of its underlying physics—the deeper you go, the more beautiful it feels. This is one subject that is vividly displayed in all aspects of nature—a rich source of complex flow visualization. In this book, as a refreshing change, the mathematics follows the flow physics, not the other way around.

After over 35 years of industry experience in rocket propulsion, thermal and fluid flow modeling of processes in steel plant engineering, development of physics-based methods and tools for the design of some of the most advanced gas turbines for aircraft propulsion and power generation, and extensive application of three-dimensional (3D) computational fluid dynamics (CFD) technology to the solutions of many design problems, I moved to Orlando, Florida, in 2006 to work for Siemens Energy. UCF invited me that year to join the faculty as an adjunct professor and teach the graduate course "EML5402—Turbomachinery" in the fall semester. I immediately accepted the assignment. It allowed me to bring my industry experience into the classroom to train a new generation of talent for the practical, rather than the theoretical, problems facing today's engineers. The following year, UCF invited me to teach another graduate course, "EML5713—Intermediate Fluid Mechanics," in the spring semester. The class size grew each year, from around 15 in 2007 to around 40 by the fall of 2013. In teaching the second course, I struggled to find an adequate textbook that stressed the fundamental physical harmony of fluid flows as a prerequisite to formulas and problem solving. Faced with this challenge, I did what any great engineer would do: I designed one that did.

Most undergraduate engineering programs include only a couple of courses on fluid mechanics. The students taking these courses are generally exposed to the concepts of statics and dynamics from prior courses on solid mechanics. As a result, many tend to find the new concepts of fluid mechanics overwhelming and nonintuitive. Due to a continued emphasis on mathematical treatment, rather than the physical introduction to the subject, many students lose sight of the beauty and simplicity of fluid mechanics in favor of simply committing to memory its mathematical equations, including the difficult Navier–Stokes equations (which are nonlinear partial differential equations in three coordinate directions). They soon start treating these undergraduate fluids courses as just another course in advanced mathematics, developing little understanding of the underlying physical concepts. The pressure of examinations and grades in these courses only reinforces this treatment.

As a prerequisite to many advanced graduate courses in the thermofluids stream, many students are required to take some form of graduate-level intermediate fluid mechanics as one of their core courses. Students, weary of their undergraduate experiences, are often immediately frustrated by the prospect of dealing with even more complex mathematics, at times in tensor notation! Although many can recite complex formulas, when asked to articulate the difference between the static pressure and total pressure in plain English, and how to compute the latter in incompressible and compressible flows, they cannot. The difference between static temperature and total temperature or the concept of adiabatic wall temperature is surprisingly hard to articulate in plain English without a fundamental physical understanding. Adding stationary (inertial) and rotating reference frames only amplifies these hidden issues. Overreliance on the Bernoulli equation is a classic demonstration of where a mathematics-first approach fails many engineering students. The concept of choking in one-dimensional compressible flows, for example, can be exceedingly complicated using a mathematics-first approach, but asking students to take a step back to first visualize the phenomenon in nature and understand the physical concept of Mach number can lead to a world of difference. Although many students may be conversant with the equations of Fanno and Rayleigh flows, they find it hard to explain in layman's terms how wall friction accelerates a subsonic airflow in a constant-area duct with or without heating.

Many practicing engineers dealing with fluid flows in various industries are, as a result of the classic academic approach (coupled with dependence on one or more in-house or commercial codes to perform design calculations), surprisingly weak in their intuitive understanding of the physics of these flows. When questioned about the accuracy of their calculations, often an unshaken faith in design tools and their predictions is the answer. For many in the industry, if they, and their competition, have been doing it in a particular way for so many years, it must be right!

With the availability of so many user-friendly commercial 3D CFD codes, today's challenge in the application of 3D CFD technology to design lies not in high-quality and high-fidelity grid generation or in obtaining a fully converged solution with the state-of-the-art numerical schemes and turbulence models but in properly interpreting their computed 3D CFD results for intended design applications. Only a strong foundation in fluid mechanics will help the CFD lovers to make good sense of their 3D CFD results.

I strongly believe that this book will benefit not only the graduate and senior undergraduate students of fluid mechanics pursuing their degree programs in the thermofluids stream but also many practicing engineers dealing with thermofluids in the design of commercial and military planes; submarines and cruise ships; automobiles; jet and rocket propulsion; oil and gas pipelines; gas turbines, steam turbines, and generators; pumps and compressors; air-conditioning and refrigeration units; heat exchangers; artificial hearts and valves; dams and irrigation systems; and many other areas of thermofluids engineering.

This book will come to many senior undergraduate and graduate-level students, and practicing engineers, as a breath of fresh air. Empowered by the knowledge gained from this book, these students and engineers will develop a unique insight into various fluid flow phenomena and will fall in love with the subject like never before. With focus on a clear understanding of the key fundamental concepts (which are amply illustrated by a number of worked-out real-world examples), this book will help readers develop a variety of problem-solving skills to handle practical fluids engineering problems. For example, they will master the techniques of control volume analysis of mass, linear momentum, angular momentum, and energy in both inertial and non-inertial reference frames. They will also develop an unprecedented intuitive understanding of one-dimensional compressible flows, including Fanno flows, Rayleigh flows, isothermal flows, normal shocks, oblique shocks, and isentropic Prandtl–Meyer expansion flows. By eliminating most of the key conceptual gaps for senior undergraduate and graduate-level students, the book will help them transition to learning new topics in advanced graduate courses in thermofluids.

The book also includes two value-added chapters on special topics that reflect the state-of-the-art in design applications of fluid mechanics. Chapter 9 deals with the key details of physics-based modeling of both incompressible and compressible flow networks. These details, notwithstanding the current reality that a number of commercial flow network codes are used in many industries, are not found in any leading contemporary book on fluid mechanics. Chapter 10 focuses on the applications of CFD technology to practical industrial design problems, often in concert with related flow network solutions, rather than presenting the mathematical details of CFD numerical formulations and solution methods. Additionally, this chapter includes a physics-based methodology to post-process 3D CFD results to generate section-averaged values for their useful interpretations and design applications.

The book is deemed to be an indispensable companion to all students and practicing engineers engaged in various designs, both new and upgrades, involving fluid flow and heat transfer. Chapters 1 through 4 form the core course in fluid mechanics. To develop a solid foundation in this subject, all engineers dealing with thermofluids, both in industries and in universities, must master the material presented in the first four chapters.

At universities around the world, at least three distinct graduate or senior undergraduate courses in fluid mechanics can be taught using this textbook. The following syllabi are suggested for these courses; instructors, however, are free to fine-tune these syllabi and reinforce them with their notes and/or additional reference material to meet their specific instructional needs:

1. Intermediate fluid mechanics—a graduate-level core course in fluid mechanics for senior undergraduate and graduate students pursuing MS and PhD programs in the thermofluids stream (fluid mechanics, heat transfer, propulsion, turbomachinery aerodynamics, combustion, etc.): fluids core course (Chapters 1 through 4) and selected topics from Chapters 5 through 8.
2. Compressible flows or gas dynamics—a senior-level undergraduate course on compressible flows or gas dynamics: selected topics from fluids core course (Chapters 1 through 4) and Chapter 5.
3. Industrial fluid mechanics—an elective graduate-level course primarily targeted at practicing engineers in various industries dealing with fluids engineering: fluids core course (Chapters 1 through 4) and selected topics from Chapters 5, 9, and 10 and Appendix G.

Overall, this textbook will serve as an effective prerequisite for advanced courses on turbulent shear flows, CFD, turbulence modeling, and so on. The major highlights of this textbook include the following:

- Mathematical treatment follows flow physics, not the other way around.
- Over 60 systematically worked-out real-world examples.
- Over 100 chapter-end problems for which the Solutions Manual is available to all instructors who adopt this textbook for teaching their university courses in fluid mechanics.
- Over 250 figures.
- Clearly explained key thermofluids concepts: rothalpy, stream thrust, impulse pressure, forced/free vortices, windage, vorticity, and circulation.
- Control volume analysis of linear momentum and angular momentum in both inertial and non-inertial reference frames.
- Enhanced intuitive understanding of internal compressible flows through the use of various flow functions: total- and static-pressure mass flow functions, total- and static-pressure impulse functions, and normal shock function.

- Physics-based modeling of compressible flow over all Mach numbers in a variable-area duct with friction, heat transfer, and rotation with internal choking and normal shock formation.
- Compressible and incompressible flow network modeling (Chapter 9).
- Strengths and weaknesses of state-of-the-art turbulent flow CFD predictions, including physics-based post-processing of 3D CFD results for design applications (Chapter 10).
- Compressible flow tables with equations used to generate the tabular values (Appendix A).
- Closed-form analytical solution of the coupled heat transfer and work transfer in a rotating duct flow (Appendix B).
- Systematically derived equations to compute pressure and temperature changes in isentropic free and forced vortices (Appendix C).
- Systematically derived equations to transfer stagnation (total) flow properties from a stationary reference frame to a rotating reference frame and vice versa (Appendix D).

Dr. Bijay (BJ) Sultanian
Founder & Managing Member, Takaniki Communications LLC
Adjunct Professor, The University of Central Florida

Acknowledgments

This is my dream book! A contribution of this magnitude would not have been possible without the perpetual love and support of my entire family, to whom I shall forever remain indebted.

The inspiration for this dream book originated during my 12-year career at General Electric (GE). I am very fortunate to have participated in the design and development of two of the world's largest and most efficient gas turbines: the GE 90 to propel planes and the steam-cooled 9H/7H to generate power. The challenges of heat transfer and cooling/sealing flow designs in these machines were beyond anything I had experienced before. Among all my distinguished colleagues at GE, three individuals stand out: Mr. Ernest Elovic and Mr. Larry Plemmons at GE Aircraft Engines (GEAE) and Mr. Alan Walker at GE Power Generation. They are my true professional heroes. I owe my most sincere gratitude to Mr. Elovic and Mr. Plemmons, who introduced me to the concept of physics-based design predictions. Since it has become an integral part of my conviction, I have used the term "physics based" very often in this book. For the Managerial Award I received at GEAE in 1992, every word in the following citation, crafted by Mr. Elovic, continues to inspire me to this day:

> On behalf of Advanced Engineering Technologies Department, it gives me great pleasure to present to you this Managerial Award in recognition of your significant contributions to the development of improved physics-based heat transfer and fluid systems analysis methodologies of rotating engine components. These contributions have resulted in more accurate temperature and pressure predictions of critical engine parts permitting more reliable designs with more predictable life characteristics.

A gift of knowledge is the greatest gift one can give and receive. Mr. Walker gave me such a gift by sponsoring me to complete the 2-year executive MBA program at the Lally School of Management and Technology. While I remain greatly indebted to Mr. Walker for this unprecedented recognition, I also thank him for keeping my technical skills vibrant through my direct involvement in the redesign of the gas turbine enclosure ventilation system for the first full-speed no-load testing of the 9H machine; the robust design of a high-pressure inlet bleed heat system; CFD-based high-performance exhaust diffuser designs in conjunction with a joint technology development program with Toshiba, Japan; and other challenging design activities, including the applications of 3D CFD technology.

I thank Prof. Ranganathan Kumar, who invited me to teach graduate courses at the University of Central Florida (UCF) in 2006 as an adjunct faculty. Without this teaching opportunity, my dream book would not have become a textbook. I remain sincerely thankful to Prof. J-C Han and Prof. Tom Shih, who wholeheartedly supported my book proposal with their rave reviews. I will continue to cherish a highly referenced book chapter on computations of internal and film cooling that Dr. Shih and I coauthored at the turn of this century.

I owe many thanks to my friends Dr. Larry Wagner, who spent countless hours going through most of the chapters in this book and timely providing me with very helpful changes, and Dr. Kok-Mun Tham, who reviewed Chapter 10 and suggested several improvements.

During the course of teaching "EML5713—Intermediate Fluid Mechanics" at UCF, the first four chapters of this book were class-tested in the fall semester of 2013 and the first eight chapters, covering the entire course syllabus, in the fall semester of 2014. I extend my heartfelt thanks to all my students who provided me with valuable feedback that significantly improved the final manuscript of the book.

I offer my sincere gratitude to Mr. Jonathan Plant, acquiring executive editor at Taylor & Francis, who believed in my book proposal and, more importantly, believed in my passion to complete this book on time. I thoroughly enjoyed all my conversations with him. I thank Mrs. Laurie Oknowsky for her excellent initial project coordination, Mr. Ed Curtis and Ms Ramya Gangadharan for superbly managing the high-quality book editing and production process, and all the staff at Taylor & Francis for their exemplary support and professional communications.

Last but not least, I remain eternally grateful to all readers who will take the following advice to heart: if you want to learn fluid mechanics in all its simplicity, beauty, and practicality, study this book in depth. If you want to learn even more, teach this subject to others. If you want to learn even more than that, and thoroughly enjoy this subject, I hope you will one day write an even better book than this. After all, since all fluid flows are governed by only the four fundamental laws of conservation of mass, momentum, energy, and entropy, how difficult can this subject really be?

Author

Bijay Sultanian, PhD, PE, MBA, ASME Fellow, is a recognized international authority in gas turbine heat transfer, secondary air systems, and computational fluid dynamics (CFD). Dr. Sultanian is a founder and managing member of Takaniki Communications LLC (www.takaniki.com), a provider of high-impact, web-based, and live technical training programs for corporate engineering teams. Dr. Sultanian is also an adjunct professor at the University of Central Florida, where he has taught graduate-level courses in turbomachinery and fluid mechanics since 2006. As an active member of the IGTI's Heat Transfer Committee since 1994, he has instructed a number of workshops at ASME/IGTI Turbo Expos.

During his three decades in the gas turbine industry, Dr. Sultanian has worked in and led technical teams at a number of organizations, including Allison Gas Turbines (now Rolls-Royce), General Electric (GE) Aircraft Engines (now GE Aviation), GE Power Generation (now GE Power & Water), and Siemens Energy (now Siemens Power & Gas). He has developed several physics-based improvements to legacy heat transfer and fluid systems design methods, including new tools to analyze critical high-temperature gas turbine components with and without rotation. He particularly enjoys training large engineering teams at prominent firms around the globe on cutting-edge technical concepts and engineering and project management best practices.

During his initial 10-year professional career, Dr. Sultanian made several landmark contributions toward the design and development of India's first liquid rocket engine for a surface-to-air missile (Prithvi). He also developed the first numerical heat transfer model of steel ingots for optimal operations of soaking pits in India's steel plants.

Dr. Sultanian is a Fellow of the American Society of Mechanical Engineers (1986); a registered professional engineer in the State of Ohio (1995); International WHO'S WHO of Professionals (1999); a GE-certified Six Sigma Green Belt (1998); Member, GE Aircraft Engines, Engineering Design Board, Heat Transfer (1997–1999); and an emeritus member of Sigma Xi, the Scientific Research Society (1984).

Dr. Sultanian earned BS and MS degrees in mechanical engineering at the Indian Institute of Technology, Kanpur (1971), and the Indian Institute of Technology, Madras (1978), respectively. He earned a PhD in mechanical engineering at Arizona State University, Tempe (1984), and an MBA at the Lally School of Management and Technology at Rensselaer Polytechnic Institute (1999).

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