Gas Turbines

This long-awaited, physics-first, design-oriented text describes and explains the underlying flow and heat transfer theory of secondary air systems. An applications-oriented focus throughout the book provides the reader with robust solution techniques, state-of-the-art three-dimensional computational fluid dynamics (CFD) methodologies, and examples of compressible flow network modeling. It clearly explains elusive concepts of windage, nonisentropic generalized vortex, Ekman boundary layer, rotor disk pumping, and centrifugally driven buoyant convection associated with gas turbine secondary flow systems featuring rotation. The book employs physics-based, design-oriented methodology to compute windage and swirl distributions in a complex rotor cavity formed by surfaces with arbitrary rotation, counterrotation, and no rotation. This text will be a valuable tool for aircraft engine and industrial gas turbine design engineers as well as graduate students enrolled in advanced special topics courses.

Bijay K. Sultanian is founder and managing member of Takaniki Communications, LLC, a provider of web-based and live technical training programs for corporate engineering teams, and an adjunct professor at the University of Central Florida, where he has taught graduate-level courses in turbomachinery and fluid mechanics since 2006. Prior to founding his own company, he worked in and led technical teams at a number of organizations, including Rolls-Royce, GE Aviation, and Siemens Power and Gas. He is the author of *Fluid Mechanics: An Intermediate Approach* (2015) and is a Life Fellow of the American Society of Mechanical Engineers.

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Gas Turbines

Internal Flow Systems Modeling

BIJAY K. SULTANIAN

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To my dearest friend Kailash Tibrewal, whose mantra of "joy in giving" continues to inspire me; my wife, Bimla Sultanian; our daughter, Rachna Sultanian, MD; our son-in-law, Shahin Gharib, MD; our son, Dheeraj (Raj) Sultanian, JD, MBA; our daughter-in-law, Heather Benzmiller Sultanian, JD; and our grandchildren, Aarti Sultanian, Soraya Zara Gharib, and Shayan Ali Gharib, for the privilege of their unconditional love and support!

Contents

Preface

Albert Einstein famously said, "Education is not the learning of facts, but the training of the mind to think." I have concluded over a 30-plus-year career spent bridging the gap between academic research and practical gas turbine design that current and future gas turbine, heat transfer, and secondary air systems (SAS) or internal air systems (IAS) design engineers (both academic and practitioners) must not only learn how and what to do but, more importantly, question why things are done the way they are so that we can find ways to do them better.

I have found the best approach to training the mind is summarized by another famous Einstein quote, "Everything should be made as simple as possible, but not simpler." The beauty of simplicity is that it makes learning contagious. For a topic as complex as fluid dynamics, a traditional, mathematics-first approach has failed many, as it tends to make the study of engineering far more complex, and less intuitive, than the physics-first approach that I use here. It is a technique that I have developed over a career spent learning from giants, practicing with the best and brightest, and teaching the future leaders of our industry.

Few people may know that I spent the first ten years of my professional career without ever solving for a rotating flow. It wasn't until 1981, when I began my PhD at Arizona State University, that I first became fascinated with a new and emerging technology: computational fluid dynamics, or CFD. Although CFD has since become a ubiquitous tool used by hundreds of industries, back then, in order to incorporate CFD into my research, I had to pick an obscure topic that I had to teach myself: the numerical prediction of swirling flow in an abrupt pipe expansion.

In the fall of 1985, I started my first postdoc job at Allison Gas Turbines (now Rolls-Royce). At Allison, I continued to develop prediction methods for turbulent swirling flows in gas turbine combustors using advanced turbulence models. For example, we successfully developed a low Reynolds number turbulence model to predict heat transfer across a mixed axial-radial flow in a rotor cavity. Even more exciting, we were able to predict nonentraining Ekman boundary layers on the rotor disks between the inner source region and the outer sink region. These were my first practical applications of the CFD-based modeling in gas turbine secondary air systems I first researched during my PhD.

Three years later, when I joined the heat transfer and secondary flow group at GE Aircraft Engines (GEAE), now called GE Aviation, I came across a new operational term – windage. Windage was a significant factor in calculating the thermal boundary conditions for gas turbine parts in contact with secondary air flows. Even though we had design tools to compute windage temperature rise (it always increased coolant air temperatures used in convective boundary conditions), there was no precise definition of what "windage" actually was.

Some of my colleagues thought of it as viscous dissipation, whereas others saw it resulting from friction on both stator and rotor surfaces. Just as I had done during my PhD, I went back to first principles (angular momentum and steady flow energy equations) to define windage in as simple terms as I could (not simpler). Not only did the simplicity of my definition of windage made it incredibly contagious among my colleagues at GEAE, but by using this new framework for windage, I was also able to develop one of my most successful design tools – BJCAVT. BJCAVT was the first program that could automatically compute windage and swirl distributions in a complex rotor cavity formed by surfaces under three conditions: arbitrary rotation, counterrotation, and no rotation. This program was extensively validated by numerous engine measurements; and in addition to being very user-friendly, it was solution-robust, always unconditionally converging in a few iterations with no user intervention. BJCAVT became widely popular and an integral part of GEAE design practice, initially at GEAE for all aero engines and later at GE Power Systems for all power generation gas turbines. Four years later, as a result of BJCAVT and other unique developments at GEAE, I was given my most prestigious managerial award in 1992 with the following citation:

> 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 few years later, Professor Tom Shih, a world authority on gas turbine internal cooling and CFD, invited me to coauthor a book chapter on Computations of Internal and Film Cooling. It is important to note that internal cooling design of high-temperature turbine airfoils derive its inlet boundary conditions from a SAS model of the gas turbine engine. These cooled airfoils are also simulated in the SAS model as resistive elements through pressure ratio versus effective area curves. In terms of the flow and heat transfer physics, a lot is common between airfoil internal cooling and SAS modeling; both are simulated in design through complex, locally one-dimensional flow networks. Internal cooling, however, entails one simplification. When the coolant air enters the rotating serpentine passages of a blade, it always assumes the state of solid-body rotation with the blade. In a rotor-rotor or rotor-stator cavity, however, the coolant air rotation in the bulk may in general be different from those of the rotor surfaces forming the cavity.

The interaction of windage and vortex temperature change in a rotor cavity is found to be a significant source of confusion in gas turbine design. Since most design codes have a built-in calculation of temperature change in an isentropic forced vortex, this change is inadvertently added to the windage temperature rise in the cavity. In 2004, to unravel the mystery of these and other related concepts, I was invited to Siemens Energy, Orlando, to give a lecture to a team of heat transfer and SAS engineers.

In 2006, I joined Siemens Energy full time to develop advanced tools for internal cooling design of turbine airfoils. At that time, the University of Central Florida (UCF) invited me to join the faculty as an adjunct professor for teaching a graduate course, "EML5402 – Turbomachinery," in the fall semester. I merrily accepted the invitation. This opportunity allowed me to bring my years of industry experience into the classroom to train the next generation of engineers to handle the challenges of designing future gas turbines. The following year, UCF asked me to teach the core graduate course, "EML5713 – Intermediate Fluid Mechanics," in the spring semester. To my surprise, I found that many students pursuing their graduate studies in the thermofluids stream didn't have a grasp on the first-principal fundamentals of fluid mechanics, particularly in the control volume analysis of various conservation laws and one-dimensional compressible flow in a duct featuring arbitrary area change, friction, heat transfer, and rotation. Hardly anyone in the class could physically explain (without using the Mach number equations of Fanno flows) why the Mach number of a subsonic compressible flow in a constant-area duct increases downstream due to wall friction, which is known to slow things down! Similarly, in this duct, if one eliminates friction (a practically difficult task!) and heats the flow, why does the total pressure decrease and the Mach number increase in the flow direction? Unlike incompressible flows, which are formally taught in most courses on fluid mechanics, compressible flows feature other nonintuitive behavior like choking when the flow velocity equals the speed of sound and the formation of a normal shock in the supersonic regime. All bets are off when such flows also involve duct rotation.

During the course of my teaching graduate courses at UCF, I realized that many students needed help in understanding the key foundational concepts of fluid mechanics. At the same time, the course on turbomachinery dealing with the design and analysis of primary flowpath aerothermodynamics inspired in me to develop a follow-up course dealing with secondary air systems modeling, which is the subject of this book. Since fluid mechanics is a prerequisite core course for advanced courses in the thermofluids stream, I decided to write my first textbook using a physics-first approach. That 600-page book, *Fluid Mechanics: An Intermediate Approach*, was published in July 2015 by Taylor & Francis.

While at Siemens Energy, I also realized that the engineers working on SAS modeling and internal cooling design needed some help on understanding the flow and heat transfer physics of various components of their models and not just follow their operational design practices. In 2007, I began a twenty-hour lecture series within Siemens titled "Physics-Based Secondary Air Systems Modeling." The response to this series was overwhelming, as more than 60 engineers globally joined these online lectures. Encouraged by this experience at Siemens, I taught a two-day preconference workshop on "Physics-Based Internal Air Systems Modeling" in conjunction with the ASME Turbo Expo 2009 in Orlando. I later taught this workshop in an eight-hour format at ASME Turbo Expo 2016 in Seoul, South Korea, and ASME Turbo Expo 2018 in Oslo, Norway. Teaching these workshops and publishing a graduate-level textbook on fluid mechanics gave me the confidence needed to finally write this textbook.

The book is the culmination of three decades of continuous learning in gas turbine industry and a decade of teaching graduate-level courses in turbomachinery and fluid mechanics at UCF. It has taken this long for me to study the fascinating, and sometimes counter-intuitive, world of gas turbine secondary flow systems to the point that I can present the most complex topics in a simplified way that will make learning these topics contagious.

I suggest the following syllabus for a three-credit graduate course (Turbomachinery II) in a sixteen-week semester:

Week 1: Chapter 1 (Overview of Gas Turbines for Propulsion and Power Generation)
Weeks 2–5: Chapter 2 (Review of Thermodynamics, Fluid Mechanics, and Heat Transfer)
Weeks 6–8: Chapter 3 (1-D Flow and Network Modeling)
Weeks 9–11: Chapter 4 (Internal Flow around Rotors and Stators)
Week 12: Chapter 5 (Labyrinth Seals)
Weeks 13–16: Chapter 6 (Whole Engine Modeling)

However, the course instructors are free to fine-tune this syllabus and reinforce it with their notes and/or additional reference material to meet their specific instructional needs. The book features a number of worked-out examples, chapter-end problems, and projects, which may be assigned as a team-project for students to work on during the entire semester.

Acknowledgments

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

My dream to study such a book originated during my twelve-year career at GE where I was so fortunate to have participated in the design and development of world's two largest and most efficient gas turbines: GE 90 to propel planes and steam-cooled 9H/7H to generate electricity. 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 (deceased) who introduced me to the concept of "physics-based" design predictions. Because it has become an integral part of my conviction, I have used the term "physics-based" very often in this book. I cannot wait to send Mr. Walker and Mr. Elovic each a printed copy of this book with my best compliments and highest regards!

A gift of knowledge is the greatest gift one can give and receive. Mr. Alan Walker gave me such a gift by sponsoring me to complete the two-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 involvements in the redesign of gas turbine enclosure ventilation system for the first full-speed no-load (FSNL) testing of the 9H machine, 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 development of other innovative methods and tools for concurrent design engineering of steam-cooled gas turbines.

I wish to thank Professor Ranganathan Kumar who invited me to teach graduate courses at UCF in 2006 as an adjunct faculty. Without this teaching opportunity my dream books would not have become textbooks. I continue to cherish a highly referenced book-chapter on Computations of Internal and Film Cooling that Professor Tom Shih and I coauthored at the turn of the twenty-first century.

I owe many thanks to my longtime friends Dr. Ray Chupp and Dr. John Blanton for reviewing Chapter 5 and Dr. Kok-Mun Tham and Dr. Larry Wagner for reviewing Chapter 6 and suggesting several improvements in these chapters.

I offer my sincere gratitude to Steve Elliot, my editor at Cambridge University Press, who believed in my book proposal and, more important, in my passion to complete this book. I thoroughly enjoy all my interactions with him. I wish to thank my content manager Mark Fox and all the staff at the Press for their exemplary support and professional communications during the entire book production process.

Last but not least, I will remain eternally grateful to all the readers, and more so to those who will be inspired to write someday a better textbook on this topic, making this one obsolete.

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About the Author

Dr. Bijay (BJ) K. Sultanian, PhD, PE, MBA, ASME Life Fellow is a recognized international authority in gas turbine heat transfer, secondary air systems, and Computational Fluid Dynamics (CFD). Dr. Sultanian is the 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 been teaching graduate-level courses in turbomachinery and fluid mechanics since 2006. As an active member of IGTI's Heat Transfer Committee since 1994, he has instructed a number of workshops at ASME Turbo Expos. His graduate-level textbook, *Fluid Mechanics: An Intermediate Approach*, was published in July 2015.

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), GE Aircraft Engines (now GE Aviation), GE Power Generation (now GE Water & Power), 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 ten-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 Life Fellow of the American Society of Mechanical Engineers (1986), a registered Professional Engineer (PE) in the State of Ohio (1995), a GE-certified Six Sigma Green Belt (1998), and an emeritus member of Sigma Xi, The Scientific Research Society (1984).

Dr. Sultanian received his BTech and MS in Mechanical Engineering from the Indian Institute of Technology, Kanpur (1971) and the Indian Institute of Technology, Madras (1978), respectively. He received his PhD in Mechanical Engineering from Arizona State University (1984) and his MBA from the Lally School of Management and Technology at Rensselaer Polytechnic Institute (1999).