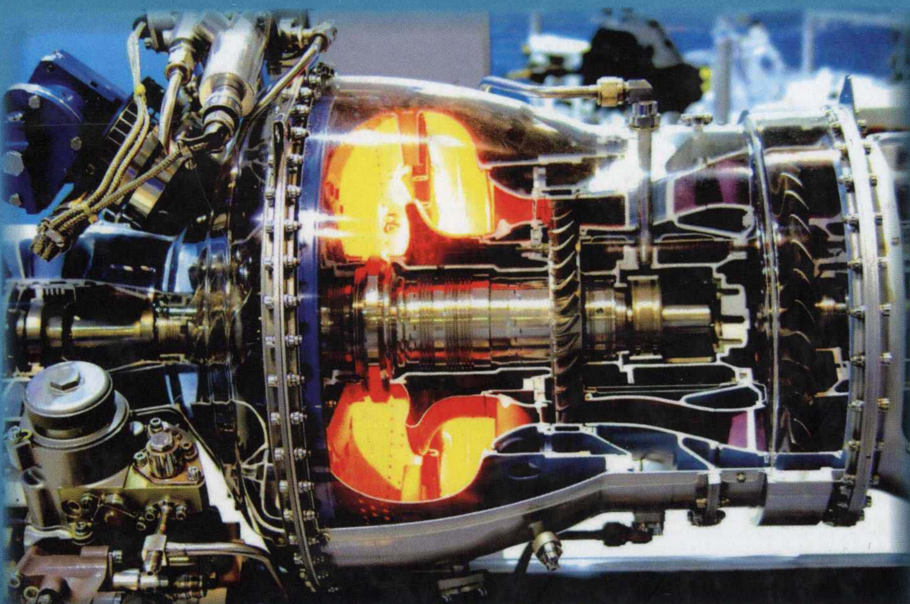
SECOND EDITION

Gas Turbine Heat Transfer and Cooling Technology



Je-Chin Han ▪ Sandip Dutta ▪ Srinath Ekkad

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Preface to the Second Edition

This book, *Gas Turbine Heat Transfer and Cooling Technology*, was first published in 2000. There have been many new technical papers available in the open literature over the last 10 years. These new published data provide gas turbine researchers, designers, and engineers with advanced heat transfer analysis and cooling technology development references. There is a need to revise the first edition by including the latest information in order to keep this book relevant for users. The second edition provides information on state-of-the-art cooling technologies such as advanced turbine blade film cooling and internal cooling schemes. It updates modern experimental methods for gas turbine heat-transfer and cooling research as well as advanced computational models for gas turbine heat-transfer and cooling performance predictions.

ASME Turbo Expo (IGTI International Gas Turbine Institute) has made conference CDs available to every year's attendees since 2000 (GT2000–GT2010). These conference CDs contain all gas turbine heat-transfer papers presented in each year's IGTI conference. The number of heat transfer–related conference papers has increased from about 100 in the year 2000 to about 200 in the year 2010. These reviewed technical papers are widely used in gas turbine heat transfer and added new knowledge to this field after the publication of our first edition.

This text is a revision of the first edition, not a new book. The major contents and framework have been based on the first edition. To keep the same book format, the revised second edition adds new information at the end of each chapter, mainly based on selected papers from the open literature published in 2000–2010. The open literature has many excellent articles available on this subject; however, we cannot use all of them in this book. To reduce the book size, we have mainly used our own published results in the second edition. We hope this book will be useful for the gas turbine community. We would be happy to receive constructive comments and suggestions on the material in the book.

Je-Chin Han
Sandip Dutta
Srinath Ekkad

Preface to the First Edition

Gas turbines are used for aircraft propulsion and in land-based power generation or industrial applications. Modern development in turbine-cooling technology plays a critical role in increasing the thermal efficiency and power output of advanced gas turbines. Research activities in turbine heat transfer and cooling began in the early 1970s; since then, many research papers, state-of-the-art review articles, and book chapters have been published. However, there is no book focusing entirely on the range of gas turbine heat-transfer issues and the associated cooling technologies.

This book is intended as a reference book for researchers and engineers interested in working with gas turbine heat-transfer and cooling technology. Specifically, it is for researchers and engineers who are new to the field of turbine heat-transfer analysis and cooling design; it can also be used as a textbook or reference book for graduate-level heat-transfer and turbomachinery classes.

In the beginning, we thought of covering all aspects of gas turbine–related heat-transfer and cooling problems. After careful survey, however, we decided to focus on the heat-transfer and cooling issues related to turbine airfoils only, because a vast amount of information on this subject alone is available in the published literature. Assembling all the scattered information in a single compilation requires a great deal of effort. The book does not include combustor liner cooling and turbine disk-cooling problems although they are important to gas turbine hot gas path component designs. The book is divided into eight chapters:

Chapter 1 *Fundamentals*. Discusses the need for turbine cooling, gas turbine heat-transfer problems, and cooling methodology

Chapter 2 *Turbine Heat Transfer*. Discusses turbine rotor and stator heat-transfer issues, including endwall and blade tip region under engine conditions as well as under simulated engine conditions

Chapter 3 *Turbine Film Cooling*. Includes turbine rotor and stator blade film cooling and a discussion of the unsteady high free-stream turbulence effect on simulated cascade airfoils

Chapter 4 *Turbine Internal Cooling*. Includes impingement cooling, rib-turbulated cooling, pin-fin cooling, and compound and new cooling techniques

Chapter 5 *Turbine Internal Cooling with Rotation*. Discusses the effect of rotation on rotor coolant passage heat transfer

Chapter 6 *Experimental Methods*. Includes heat-transfer and mass-transfer techniques, liquid crystal thermography, optical techniques, flow and thermal field measurement techniques

Chapter 7 *Numerical Modeling.* Discusses governing equations and turbulence models and their applications for predicting turbine blade heat transfer and film cooling and turbine blade internal cooling

Chapter 8 *Final Remarks.* Provides suggestions for future research in this area

The open literature has many excellent articles available on this subject; however, we cannot use all of them in this book. We do not claim any new ideas in this book, but we do attempt to present the topic in a systematic and logical manner. We hope this book is a unique compilation and is useful for the gas turbine community. We would be happy to receive constructive comments and suggestions on the material in the book.

Je-Chin Han
Sandip Dutta
Srinath Ekkad

Authors

Je-Chin Han received his BS from National Taiwan University, MS from Lehigh University, and his ScD from MIT in 1976, all in mechanical engineering. He joined Texas A&M University in 1980 and has been doing research on gas turbine heat transfer and cooling technology for aircraft propulsion and in land-based power generation or industrial applications for more than 35 years. Currently he is a Texas A&M University Distinguished Professor and holder of the Marcus C. Easterling Endowed Chair.

Sandip Dutta received his BS from IIT, Kharagpur, MS from Louisiana State University, and PhD from Texas A&M University in 1995, all in mechanical engineering. He has worked in both academia and industry. Currently he is with General Electric in the power generation gas turbines division located in Greenville, South Carolina.

Srinath Ekkad received his BS from Jawaharlal Nehru Technological University, India, MS from Arizona State University, and PhD from Texas A&M University in 1995, all in mechanical engineering. Since then, he has worked at Rolls-Royce and Louisiana State University. He is currently a professor of mechanical engineering at Virginia Tech, leading gas turbine–related efforts as director of Commonwealth Center for Aerospace Propulsion Systems.

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Fundamentals

1.1 Need for Turbine Blade Cooling

1.1.1 Recent Development in Aircraft Engines

Gas turbines are used for aircraft propulsion and in land-based power generation or industrial applications. Thermal efficiency and power output of gas turbines increase with increasing turbine rotor inlet temperatures (RIT). This is dramatically illustrated in Figure 1.1, which plots specific core power production (which can be related to specific thrust) as a function of turbine RIT. The engines tend to track fairly close to the ideal performance line, which represents a cycle power output with 100% efficient turbines with no leakage or cooling flows. Clearly, increasing RIT is one of the key technologies in raising gas turbine engine performance. Figure 1.2 shows that the RIT in advanced gas turbines are far higher than the melting point of the blade material: therefore, turbine blades need to be cooled. To double the engine power in aircraft gas turbines, the RIT should increase from today's 2500°F to 3500°F using the same amount of cooling air (3%–5% of compressor bleed air). Meanwhile, the compressor pressure ratio should increase from today's 20 times the compression ratio to 40 times the compression ratio, or even higher, as shown in Figure 1.3. This means that future aircraft gas turbines would have a higher turbine inlet temperature with the same amount of hotter cooling air from high-pressure compressor bleed. Therefore, high-temperature material development such as thermal barrier coating (TBC) or highly sophisticated cooling schemes is an important issue that needs to be addressed to ensure high-performance, high-power gas turbines for the next century. To reach this goal, the U.S. Department of Defense (DOD), NASA, and U.S. aircraft gas turbine manufacturers established the long-range R&D program known as integrated high-performance turbine engine technology (IHPTET). Begun in 1993, it was targeted with doubling the engine power by the year 2003 (Daly, 1993). Research and Development funds are provided by the U.S. Air Force, Navy, Army, and NASA, and by the U.S. gas turbine manufacturers such as GE Aircraft Engines, Pratt & Whitney, Allison, and Allied Signal. Research is performed at U.S. government laboratories, industrial