GAS TURBINE EMISSIONS

The development of clean, sustainable energy systems is one of the grand challenges of our time. Most projections indicate that combustion-based energy conversion systems will remain the predominant approach for the majority of our energy usage. Moreover, gas turbines will remain a very significant technology for many decades to come, whether for aircraft propulsion, power generation, or mechanical drive applications. This book compiles the key scientific and technological knowledge associated with gas turbine emissions into a single authoritative source. The book has three parts: the first part reviews major issues with gas turbine combustion, including design approaches and constraints, within the context of emissions. The second part addresses fundamental issues associated with pollutant formation, modeling, and prediction. The third part features case studies from manufacturers and technology developers, emphasizing the system-level and practical issues that must be addressed in developing different types of gas turbines that emit pollutants at acceptable levels.

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Gas Turbine Emissions

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Foreword

Alan H. Epstein

When I first became interested in jet engines, smoke trails from the then ultramodern Boeing 707s were an arresting feature of that modern world. Ten years later, smoke was regulated and the U.S. Federal Aviation Administration had canceled the Boeing 2707 supersonic airliner program in the midst of growing environmental concerns. Back in the early 1960s, ground-based gas turbines were a very small business and concern for the environment was only minor. Over the five decades since the 707, the role of gas turbines in our society has greatly expanded, and concern regarding their emissions has grown even faster. Now, the electric power generation gas turbine business has outgrown that of aircraft engines and emissions have become a market discriminator. Indeed, large fortunes have been won and lost on the basis of the emissions performance of land-based gas turbine engines. On the aero engine side, emissions performance is now featured in engine marketing campaigns.

Combustion emissions might be thought an arcane topic. It is certainly complex. It is also of great importance to our society given the dominance of gas turbines for aircraft propulsion and power generation. There are three, basically independent, complicated problems associated with gas turbine emissions – the design of low-emissions combustors, the prediction of the effects of emissions on human health and the global environment, and the formulation of balanced and effective policy and regulation. These challenges are important to three very different groups – technical folk, businesspeople, and policy makers and regulators. This book will be of interest to them all.

For the technical community, the science of how emissions are generated in a gas turbine combustor and their interactions with the atmosphere has always been a fascinating but challenging subject. The relatively recent concern for climate change has increased the complexity of the atmospheric science problem, especially for aircraft engines, from one mainly concerned with local air quality at low altitude to more complex interactions at the tropopause and in the stratosphere. During the last fifty years, design engineers have risen to the environmental challenge by realizing combustors with much lower emissions while at the same time significantly increasing reliability and life. One important aspect of combustor engineering, however, has

not changed over this time – we still do not have the technology needed to predict gas turbine emissions from first principles. The lack of first principles capabilities drives up product development costs and business risk.

Policy makers and regulators, who are not necessarily technical experts in the fields they regulate, face interesting challenges as well. These can be grouped into three general categories – technical, political, and diplomatic. Technical questions include, for example, consideration of currently unregulated emissions such as very small particulates and CO_2, as well as the role uncertainty plays in resolving conflicting requirements such as NO_x and CO_2. Political challenges abound and include issues such as how to best balance environmental protection with economic growth and how to balance local air quality with global climate change. Gas turbine emissions have also become a major diplomatic challenge. Aviation is the most international of endeavors, both in manufacture and operation. Most engines have parts and major subsections designed and manufactured in several countries. Aircraft take off and land in different countries thousands of times a day and so fall under the purview of more than one regulator. It is critical to the efficient operation of the world's air transportation system that regulations be harmonized across the globe. This is the job of the International Civil Aviation Organization (ICAO), a branch of the United Nations with 189 member states. Getting 189 countries to agree on anything has never been easily or quickly achieved. The rise of climate change as a major worldwide issue with its attendant political and economic implications has only increased the complications of international rule making.

From the point of view of technical and policy folks, gas turbine combustor emissions bring fascinating challenges. For the business community, the fascination turns to dread. Why the dichotomy? The confluence of regulation and technical challenge generates business uncertainty and risk, with financial penalties large enough to destroy a business. Manufacturers of ground-based engines are often contractually responsible for the price of the electric power not produced if an engine is deficient. An engine that does not meet local air quality standards cannot be operated, and may incur liabilities that dwarf the price of the engine. Manufacturers of aircraft engines face similar challenges; that is, until an engine meets emissions requirements, it will not be certified by regulatory authorities. Such engines cannot be legally shipped, and so the airplanes, which cost ten times more than the engine, cannot be delivered. Gas turbine development can cost up to two billion U.S. dollars, so long production runs are needed to amortize the cost. The business risk associated with emissions regulations is further amplified by the long-lived nature of the products. Engines typically have service lives of thirty years or more. Over this time span, emissions regulations usually change. Increased stringency can reduce the residual value of an engine, hinder sales, and even prohibit operation of engines in the field. Additional uncertainty is introduced by the degree to which regulations are not harmonized across political boundaries since niche markets cannot support high development costs. Thus, business planning for gas turbine emissions is a challenge – and a concern.

These are hard problems. These are interesting problems. These are important problems at the confluence of engineering, regulation, and business. This book is the first to cover both the technical and regulatory aspects of gas turbine emissions. With chapters authored by some of the world's experts in their respective fields, it has the breadth and depth to be of interest to all the stakeholders. It is valuable for experts in the field and informative for those just getting involved.

Preface

The development of clean, sustainable energy systems is one of the grand challenges of our time. Environmental and energy security concerns, coupled with growing energy demand, require us to increase, diversify, and optimize the use of energy sources while reducing the adverse environmental impacts of energy production, transmission, and use. In particular, we are confronted with four interacting issues: climate change, local air and water quality, energy supply, and energy security. Global warming has led to significant discussions about reductions of carbon dioxide emissions. Meanwhile, concerns about energy security and supplies for a growing utilization base are driving us to consider broader and more reliable energy resources. Finally, local air quality concerns are driving interest in other pollutants that lead to, for example, acid rain or photochemical smog, and that have additional implications for the management of power plant operations and emissions.

Gas turbines will continue to be an important combustion-based energy conversion device for many decades to come, for aircraft propulsion, ground-based power generation, and mechanical-drive applications. At present, gas turbines are a principal source of new power-generating capacity throughout the world, and the dominant source for air-breathing flight vehicles as well. Over the last decade, power generation from alternative sources, such as solar and wind, has significantly increased. Nevertheless, most projections indicate that the relative fraction of energy supplied by these sources will remain small, even several decades from now. These projections also indicate that gas-turbine-based combined cycle plants will continue to represent the majority of new power generation capacity. Moreover, as the supply of intermittent renewables grows, gas turbines will play an increasingly important role in stabilizing the electrical grid, where the supply and demand of electric power must match at every instant in time. The topic of gas turbine emissions, both traditional pollutants (NO_x, CO, UHC, particulates) and CO_2, is clearly of significant interest.

In the aviation sector, emissions regulations continue to tighten. Climate change may lead the worldwide community to begin taxing carbon emissions for aircraft, and cloud formation associated with water vapor emissions continues to be an area of research. Particulate and NO_x emissions can significantly influence local air quality

and can be controlled by appropriate combustor designs. Changes to engine cycles and pressure ratio to increase fuel efficiency, however, generally promote the production of emissions such as NO_x, and, thus, maintaining safe, reliable, low-emission aircraft engines is an increasingly important issue.

The present volume compiles the key scientific and technological knowledge associated with gas turbine emissions into a single authoritative source. The book consists of three parts. The first part provides an overview of major issues relating to gas turbine combustion, including design approaches and constraints, at both the component and system levels, within the context of emissions. It also addresses approaches to meeting regulatory requirements. Important considerations for design optimization are discussed across all metrics of significance for gas turbine operation, including cost, safety, and reliability. The second part addresses fundamental issues associated with pollutant formation, characterization, modeling, and prediction. This part treats aerosol soot precursors, soot, NO_x, and CO. In addition, it includes a chapter on emissions from gas turbines with significant levels of exhaust gas recirculation, or whose exhaust will be used for enhanced oil recovery or sequestered in geologic formations; in these cases, the emissions-related concerns are quite different. The third part of this book presents case studies from manufacturers and technology developers, emphasizing the system-level and practical issues that must be addressed in developing different types of gas turbines that emit pollutants at acceptable levels. It is our hope that this book will provide a valuable resource to workers in this field, as a foundation both for scientists researching various aspects of gas turbine emissions and for technology developers who translate this fundamental knowledge into products.

This book would not have been possible without assistance from many individuals. Peter Gordon encouraged this project and supported us throughout. Our assistant Glenda Duncan was a tremendous help … a great help in the numerous tasks associated with preparing the text. We owe a great debt of gratitude to Jong-Chan Kim for his enormous effort in editing figures and ensuring that the illustrations are of the highest quality. Dilip Sundaram deserves special appreciation for indexing the book.