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Book Reviews

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Gas Turbine Emissions

T. C. Lieuwen and V. Yang, Cambridge University Press, Cambridge, England, U.K., 2013, 368 pp., $125

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For over 25 years working on combustion and emissions from engines as well as teaching them, I have used a number of books with a variety of scopes, styles, and organizations. In recent decades, however, due to importance of adverse environmental impacts of fossil-fuel combustion and simultaneous fuel-economy enhancement, whether pressed by market dynamics, regulations, policy, or human health concerns, I was yearning for a book that presents a 360 deg coverage of emissions from engines, specifically gas turbine ones. *Gas Turbine Emissions* by Lieuwen and Yang comes as close as one can get to what I was looking, for the following reasons.

The book design and coverage strives to implement a systems-engineering approach in its broadest sense and brings in one place the knowledge and experiences gained by some of the best experts on the subject matter. First, it has a balanced coverage of both aircraft and ground-based gas turbine engines in separate and logically ordered chapters in which commonalities and differences between the two cases are described and presented effectively. Second, the book anatomy is prudently divided into three parts. In the first part, the authors carefully describe the requirements imposed on low-emission combustor designs in terms of metrics, constraints, and system interactions for both engine application types and then engage in overviews of worldwide regulatory issues. This part of the book authoritatively and skillfully sets the stage and creates an irresistible urge on the part of the reader to finish the rest. This is of especial importance to those who are new in the field, desire to fill knowledge gap with recently-developed understandings, or wish to migrate/expand from other engines, such as reciprocating internal-combustion engines, into gas turbine emissions.

With the availability of large-scale computers capable of high-speed calculations, simulation of key and relevant processes contributing to emission of pollutants and then sewing them together into a coherent package has created a powerful tool in the hands of the combustor designers to minimize the use of the costly Edisonian approach and provided a more intelligent and economically efficient design methodology. For this, however, reliable models are required. This important topic is covered in the second part of the book in a concise, well organized, coherent, and easy-to-read style. Carbonaceous particulate matter formation, gaseous aerosol precursors (i.e., volatile particulates), and NO_x and CO formation control are three major chapters in this part of the book. After brief discussions of current and future regulation methods, soot-mass/smoke-number correlations, and gas/particulate sampling issues, the chapter delves into a thorough and systematic discussion of formation/oxidation fundamental mechanisms. One of the unique features of this book is the coverage of solid carbonaceous particulate emission and gaseous aerosol formations in two separate chapters. The primary processes of interest in the latter subject involve low-vapor pressure species forming new particles and/or condensing in the atmosphere outside the engine. Hence, the chapter on aerosol focuses on various species that can be considered gaseous aerosol precursors, such as components of the families of SO_x and organic species (fuel HC and its fragments, partially-oxidized HC, PAH formed during combustion, and lubricant oil).

The chapter on gaseous emissions in part two first builds the necessary background on low- and high-temperature hydrocarbon oxidation mechanisms in a concise and targeted manner to offer readers a fundamental understanding of the CO emissions and then addresses some of the most important issues on CO level prediction in practical systems, such as degree of mixedness and turbulence/chemistry coupling. I found the NO_x coverage to be one of the most efficient, concise, and informative presentations seen in the literature. Different NO formation mechanisms, such as thermal, prompt, fuel-bound, NNH route and N_2O kinetic pathway are described in a very lucid manner. The NO_x reduction strategies naturally came next. Here, thermal de-NO_x and reburning are introduced. The impact of pressure on both CO and different formations mechanisms of NO_x are shown to be of noticeable importance. NO_2 formation brings this chapter to its conclusion.

The remaining chapter in the second part of the book is on a very interesting emerging area in gas turbine emissions where extensive levels of exhaust gas recirculation (EGR) or use of oxygen instead of air (called oxyfuel) are employed as reactants. One application of such systems is in the area of carbon capture and storage. Use of EGR is promoted in fuel flexibility, high-hydrogen-content fuels, and static/dynamic stability in lean-

premixed combustors. After discussing emission requirements for the EGR and oxyfuel combustions, the authors probe into details of combustor considerations and emission trends and chemical kinetic aspects for both applications. Interestingly, the authors demonstrate that the positive influence of the EGR on NO_x emissions stems from lowered O_2 levels in reactants, kinetic effects of CO_2 and H_2O on radical pool, and the mixedness level needed to achieve low NO_x values.

By this time, I felt that any reader would be well equipped to move into the fascinating and highly informative third part of this book. Here, the reader is taken into a journey in which two important technology applications are discussed. It is in this part of the book that a reader will experience the interplay between fundamental understanding of combustion and emission of pollutants, which was thoroughly covered earlier, and its transformation into the design of the current and future combustors in the context of aircraft and ground-based gas turbine engines.

After describing differences between aircraft engines and current premixed industrial gas turbines (i.e., liquid versus gaseous fuels and a broader aircraft operating profile), the first case study focuses on premixed or partially premixed combustors. Here, attention is on implementation of the concept of staging in lean-premixed prevaporized (LPP) mixture and its consequences on the design of the combustor components. In this case, some key research results on fully premixed combustion are presented to indicate difficulties and therefore justify pursuing a more pragmatic approach, that is, partially premixed combustor design strategy. Topics such as prevaporization, degrees of homogeneity, combustion efficiency, lean stability, autoignition, and flashback are all presented in a coherent and clear style. The authors here convincingly explain and justify the rationale for transition into partially premixed combustors and lean premixing (using lean direct injectors). Dependence of the degree of premixing on the operating condition was rightfully cited as the main issue with all partially premixing lean burners, for which the LDI approach was covered to show its potential in reducing this problem. Then, they discuss lifted flames as a means of controlling the degree of partial premixing with operating condition, which demands piloting for stability. The coverage so far builds a good foundation for discussion of the partially premixing with internal pilots as practiced in some cited engines. One also finds coverage of a select sample of fuel nozzles specific for this strategy. Lastly, operability issues (part-load emissions, stability and lean blowout, ignition, thermal managements, pattern factor, combustor pressure losses, combustion oscillations, and alternative fuels) are presented to portray a well rounded picture of the main topic of this chapter.

The last chapter is about industrial gas turbines presenting a comprehensive work on treatment of conventional, nonpremixed, and dry low-NO_x (DLN) emissions. The book in this chapter first presents a very thorough summary of the fundamental processes common in such engines to build a foundation for a better understanding of the rest, where several specific design solutions are described and elaborated. Topics such as fuel types, flame characteristics, flame stabilization, heat release and burnout, NO formation in premixed and nonpremixed flames, impact of mixing quality on NO formation, and last, the staging at part and idle operation are all described meticulously and methodically.

When I read the last page, I was highly energized and motivated to wish that there were even more chapters to read, given the presentation style and the format used. For example, noise emission, although not a chemical emission, would have been a good addition to the set, considering its growing importance. Also, a dedicated chapter on liquid atomization and fuel nozzles would be a valuable addition to the book. Last, use of color images should further facilitate information transfer and discussions in part three of this unique book.

In summary, *Gas Turbine Emissions* is comprehensive and presents a well rounded and valuable coverage of relevant/important factors that impact emissions of regulated pollutants at the fundamental level. Armed with this solid background, it describes design strategies researched and implemented in production engines in a systematic manner. The book is of tremendous value to upper undergraduate and graduate students, scientists and research engineers, those who would like to enter the field, application engineers, and new product designers, and it will remain a very rich reference book for years to come. Essentially, one can begin a highly informative journey on gas turbine emissions with this book and, for more details, resort to a wealth of carefully selected citations listed at the end of each chapter.

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