AIAA JOURNAL
Vol. 44, No. 3, March 2006

Introduction: Combustion Modeling and Large Eddy Simulation: Development and Validation Needs for Gas Turbines

THIS issue of the *AIAA Journal* provides the first of two special sections that focus on recent advances in the area of combustion modeling and large eddy simulation (LES) for gas turbine combustors. Emphasis has been placed on validation requirements and future development and research needs to advance the fidelity and predictive accuracy of LES at device-relevant conditions. This project follows up on well-attended invited sessions addressing these crucial and timely issues at the 42nd AIAA Aerospace Sciences Meeting (ASM) at Reno, Nevada, on 10–11 January 2004. The sessions were organized by the AIAA Terrestrial Energy Systems Technical Committee (TC) and by the AIAA Fluid Dynamics TC Working Group on LES. Eight papers selected from the invited sessions and two other separately invited papers were assembled to provide a state-of-the-art perspective from both the fundamental and applied viewpoints. The four papers presented in this issue are foundational and introduce the contemporary issues related to modeling and validation. The remaining six papers, which will be published in the next *AIAA Journal* issue, are by design more practical and provide a hierarchy of case studies aimed at the progressive prediction of key phenomena observed in actual devices.

Invited papers presented by Mongia[1] (General Electric Aircraft Engines) and by Kim and Syed[2] (Pratt and Whitney) at the 42nd AIAA ASM have provided one of the most recent perspectives from industry aimed at advancing the state of the art in LES for gas turbine combustor design and analysis. It is clear that designers must now be more innovative than ever before and extend system designs beyond the envelope of "trial-and-error" experience to meet product demands for better performance and durability. Development of next-generation systems requires optimal flow-path integration and thermal management. Flow processes are inherently turbulent, and enhanced performance and operability between the turbomachinery and combustor are imperative for improved control of combustion over a wide range of operating conditions.

It is generally agreed that LES now provides a means to study coupled combustion, transport, and multiphase processes in parameter spaces that are unattainable using the direct numerical simulation (DNS) technique, with a degree of fidelity that is far more accurate than conventional computational fluid dynamics methods based on the Reynolds-averaged Navier–Stokes (RANS) approximation. Significant model development and validation is required, however, to achieve acceptable levels of confidence in the accuracy of predictions from various models, and it is well recognized that validation requirements for LES are far more stringent than for other methods. Compared to other methods, the application of LES comes with an extremely strict set of algorithmic requirements that must be rigorously enforced. Care must be taken to ensure that conservation properties are enforced and that dissipation, dispersion, and operator splitting techniques do not introduce numerical errors that compete with the subgrid-scale (SGS) models. Moreover, although SGS issues for LES have motivated intense research in the past 30 years, less attention has been devoted to the equally relevant boundary condition (BC) modeling aspects, which are often overlooked. Because actual BC choices select flow solutions, emulating particularly desired flow realizations demands precise characterization of their initial (e.g., inflow) and other relevant conditions (e.g., of asymptotic-flow or at solid and facility boundaries). This flow characterization issue is a very challenging one when laboratory realizations are involved, because their reported information is typically insufficient to fully characterize the flow conditions.

Unlike the RANS approach, which solves equations averaged over time, over spatially homogeneous directions, or across an ensemble of equivalent flows, LES maintains both the temporal and spatial characteristics of the turbulence. The assumption that LES accurately captures these dynamical processes must be validated for a hierarchy of cases to quantify the accuracy with which a given model can represent the actual physical phenomena of interest. Given these requirements, the content of these special sections has been divided into two distinct areas. Papers in this issue by Oefelein et al., Sidwell et al., Li and Gutmark, and Gutmark et al. focus on the foundational issues related to systematic model validation, with emphasis placed on algorithmic requirements, validation requirements, and accurate BC implementation. A representative series of "building block" simulations and experiments are described that emulate specific phenomena observed in gas turbine combustors. Oefelein et al., for example, present a systematic progression of studies with emphasis placed on the development and implementation of well-defined BCs and tight coupling with key target experiments that make use of advanced laser-diagnostics to generate validation data.

The primary objective of the four invited studies presented in the current issue is to provide a systematic analysis of the current state of the art and assist in the development of technical performance metrics for model validation. From this perspective, Sidwell et al. present a set of insights similar to that of Oefelein et al., but with emphasis placed on the "SimVal" combustor, which has been designed to focus on lean-premixed combustion processes at elevated chamber pressures. This research provides validation data for enclosed swirling flames at typical turbine operating conditions in a geometry that has well-characterized acoustic, thermal, and flow BCs. It also provides a platform to investigate the effects of multiple-fuel-injector configurations and fuel variability issues.

The papers by Li and Gutmark and by Gutmark et al. are complementary to the first two papers and present research focused on incorporating actual aeroderivative swirl-cup injectors into experimental configurations in a manner that facilitates the application of advanced diagnostics. A major focus of these two papers is sensitivity of the flow and combustion dynamics to BC specifics at open (inlet/outlet) boundaries, supplementing the discussion of BC characterization issues at combustor walls in the paper by Sidwell et al. Identifying appropriate space/time data acquisition and suitable postprocessing to achieve closure of the overall BC modeling for LES based on laboratory data are addressed in this context. This research provides a mechanism to test advanced combustion models by providing detailed data sets that characterize the flow from actual production-level injectors.

Collectively, these papers provide a synopsis of the phenomenological requirements for further model development and needs related to the detailed analyses of the space–time characteristics of small-scale turbulence-chemistry interactions. With the foundational aspects of the problem in place, papers presented in the next issue of the *AIAA Journal* will focus on the practical issues related to flow complexity and the progressive prediction of key phenomena observed in actual devices.

We would like to express our sincere gratitude to the many authors and participants of this project for providing this broad perspective, and to the *AIAA Journal* Chief Editor, Dr. Elaine Oran, for recognizing the timeliness and importance of this subject.

References

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