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Large Eddy Simulation of Swirling Particle-Laden Flow in a Model Axisymmetric Combustor

Joseph C. Oefelein, Vaidyanathan Sankaran and Tomasz G. Drozda
Combustion Research Facility, MS 9051
E-mail: oefelei@sandia.gov

Application of the Large Eddy Simulation (LES) technique provides the formal ability to treat the wide range of multidimensional time and length scales that exist in turbulent reacting flows in a computationally feasible manner. The large energetic-scales are resolved directly. The small "subgrid-scales" are modeled. This allows simulation of the complex multiple-time multiple-length scale coupling between processes in a time-accurate manner.

The combination of LES, high-performance massively-parallel computing and advanced experimental capabilities in combustion science offer unprecedented opportunities for synergistic high-fidelity investigations. Complementary information extracted from state-of-the-art experiments and detailed simulations that identically match the experimental geometry and operating conditions present new opportunities to understand the central physics of turbulence-chemistry interactions. Understanding these fundamental processes is crucial for the design and development of next generation combustion systems.

As part of an effort to systematically develop LES for both science and engineering, Joe Oefelein, Vaidya Sankaran and Tom Drozda have been performing a series of benchmark simulations aimed at assessing the predictive capabilities of LES for a variety of conditions. As one example, they have recently performed calculations that focus on the ability of LES to predict dilute spray dynamics in a model coaxial combustion chamber. The approach in all cases is to identify target experiments that isolate key phenomenological processes of importance. Here, calculations have been performed and compared to the experimental data acquired by Sommerfeld et al. (Int. J. Heat & Fluid Flow 12(1), 20, 1991; J. Fluids Eng. 114, 648, 1992; Int. J. Multiphase Flow 19(6), 1093, 1993). The primary objective was to gain a clearer understanding regarding the predictive nature of the calculations.

Sommerfeld et al. provides detailed measurements of swirling particle-laden flow in a model combustion chamber that consists of a sudden pipe expansion with a centered (primary) and annular (secondary) jet discharging into a cylindrical test section. A schematic of the experimental apparatus and matching computational domain is shown in Figure 1. The experimental measurements were acquired using a one-component phase-Doppler-anemometer (PDA) to obtain mean and rms gas-phase and particle-phase statistics of velocity and particle size.

A representative LES solution is given in Figure 2, which shows the instantaneous particle distribution in the region of interest superimposed on the corresponding turbulent velocity field. Radial slices at axial locations of 0.78, 1.6, 2.7 and 3.5 are also shown. The four radial cross-sections correspond to the axial stations where PDA measurements were made. Representative comparisons between measured and modeled results are given in Figure 3, which shows the mean and rms values of velocity. Symbols represent measured data and lines represent time-averaged LES results. These comparisons represent a small subset of the available results and provide a reasonable representation of the level of accuracy achieved in the simulations.

In all cases, the agreement between the measured and modeled results is excellent. We achieve the best agreement on the gas-phase mean values, which clearly falls within the experimental error bounds. Similar agreement is achieved with respect to the gas-phase rms values, with only slight degradation. Comparisons between the particle phase quantities are not quite as good, but exhibit similar trends and are still well within the experimental uncertainties. These results are particularly significant because there are no tuned constants used in any of the models. The only controlling parameters are the grid spacing and implementation of boundary conditions.

The agreement with the experimental results highlights the predictive capabilities of LES when implemented with the appropriate numerics, grid resolution and boundary conditions. Case studies such as this provide a clearer understanding of the effectiveness and feasibility of current state-of-the-art models and a quantitative understanding of relevant modeling issues by analyzing the characteristic parameters and scales of importance. The novel feature of the results presented is that they establish a baseline level of confidence in our ability to simulate complex flows at conditions representative of those typically observed in gas-turbine (and similar) combustors.

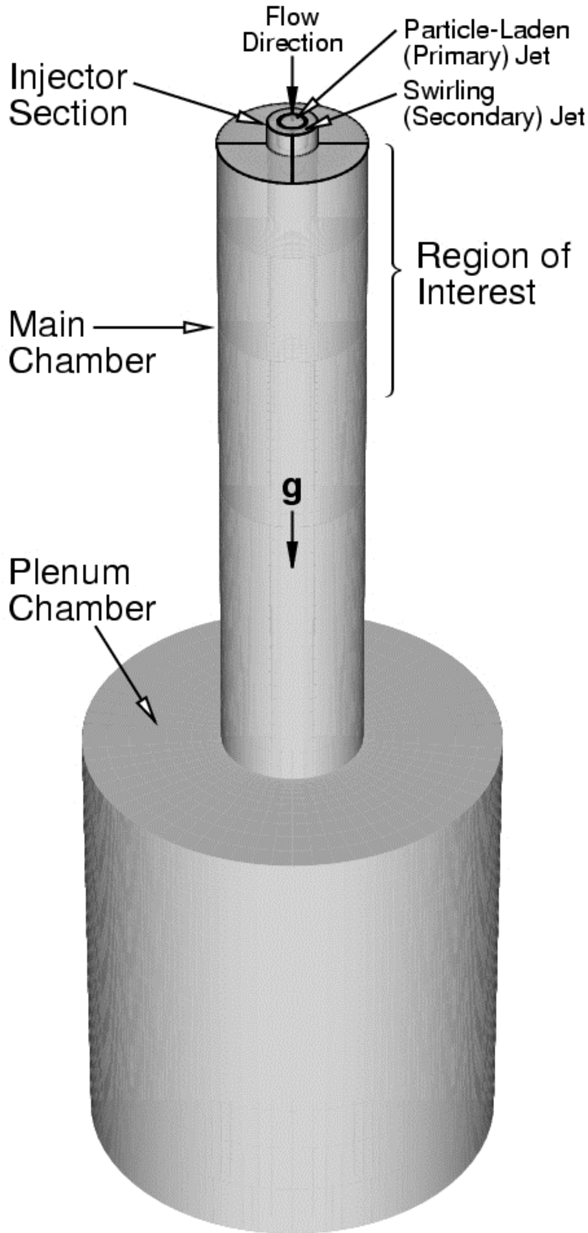
Figure Captions

Figure 1. Schematic of the experimental apparatus employed by Sommerfeld et al.

Figure 2. Representative LES results showing the instantaneous particle distribution superimposed on the corresponding turbulent velocity field.

Figure 3. Time-averaged mean and RMS profiles of the dimensionless gas-phase velocity field. Symbols represent measured data from Sommerfeld et al., lines represent LES results.

Figure 4. Joe Oefelein (PMTS), Vaidya Sankaran (PD) and Tom Drozda (PD) joined Sandia in 2000, 2006 and 2005, respectively, and are in the Reacting Flow Research Department. They received their Ph.D.'s from Penn State, Georgia Tech and Pitt and have extensive experience in the development and application of the large-eddy-simulation technique, large-scale scientific computing and parallel processing. (Photograph taken by Daniel Strong)



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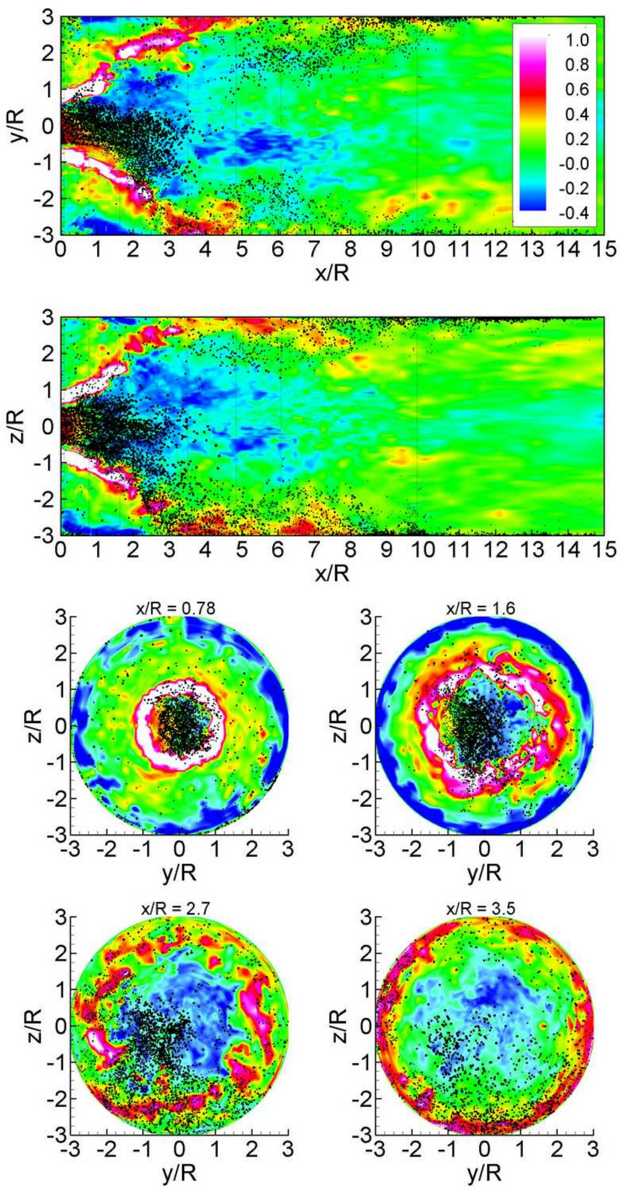

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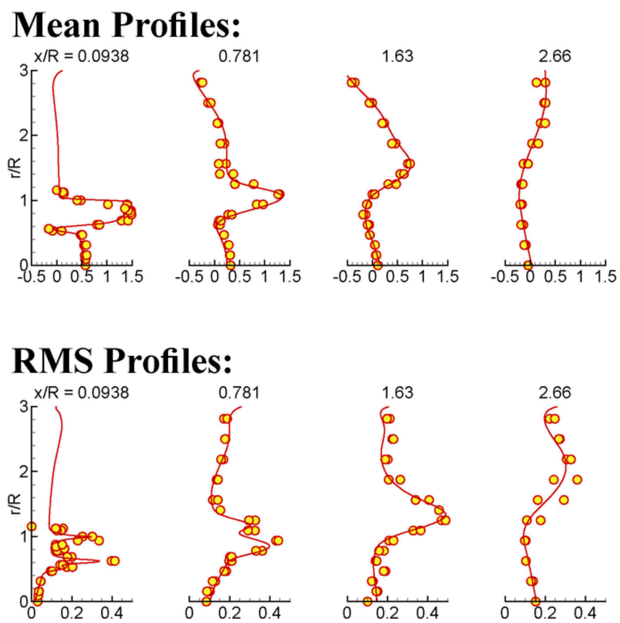

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