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Extended abstract

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LARGE-EDDY SIMULATION OF UNDEREXPANDED NATURAL GAS JETS

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Abstract Large-Eddy Simulations (LES) based on scale-selective implicit filtering are carried out in order to study the effect of nozzle pressure ratios on the characteristics of highly underexpanded jets. Pressure ratios ranging from 3 to 9 with Reynolds numbers of the order 70000 to 150000 are considered. The studied configuration agrees well with the classical picture of the structure of highly underexpanded jets. The coherent structures of the jet are investigated using Proper Orthogonal Decomposition (POD). The statistics of scalar dissipation rate are investigated in detail. Using the first POD modes, we reconstruct the scalar fields and provide the link between the dominant modes and the dissipative structures.

INTRODUCTION

Compressible jets are encountered in a vast number of applications of which perhaps the best known lie within aerospace and aeronautics fields involving propulsion and aircraft design [1, 2]. Jets are present also in Direct Injection (DI) Natural Gas (NG) powered internal combustion engines where compressed natural gas is injected into the cylinder [4].
Large-Eddy Simulation of supersonic jets is a relatively new topic [2, 3] in comparison to LES of subsonic jets [5]. The challenges in LES of supersonic flows concern the simultaneous treatment of shocks and turbulence. One aims at capturing the discontinuity with simultaneously using accurate, centered schemes for the turbulent flow. In the present study we augment the viscous stress tensor $\sigma_{ij} = \mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) + (\mu_b - \frac{2}{3}\mu)\frac{\partial u_i}{\partial x_j}\delta_{ij}$, with a modeled bulk viscosity μ_b which is the approach by Cook and Cabot [7]. This shock capturing approach is applied in a density based fourth order Runge-Kutta code written using the OpenFOAM code. We have used this approach previously in studies of highly underexpanded jets [8]. The objectives of the paper are to enrich the previous picture on nitrogen jets by investigating the following aspects: 1) we aim to investigate natural gas jets in moderately and highly underexpanded flow conditions using LES, and 2) we aim to show the link between the dominant POD-modes to the jet mixing, in particular dissipative flow structures will be statistically analyzed and also analyzed in terms of POD reconstruction.

RESULTS

The present simulation setup is depicted in Fig. 1. The present LES reproduces the characteristic aspects of supersonic jets including 1) the Mach disk, 2) slip lines, 3) intense turbulence, and 4) sound field. In Fig. 2 we demonstrate the helical nature of the first POD modes for various pressure ratios. In the previous study [8] we showed that the dominant flow structures of highly underexpanded jets are helical in character. Furthermore, we showed that the POD time coefficients explain the transient characteristics of the jets including one-to-one match between the dominant pressure frequencies.

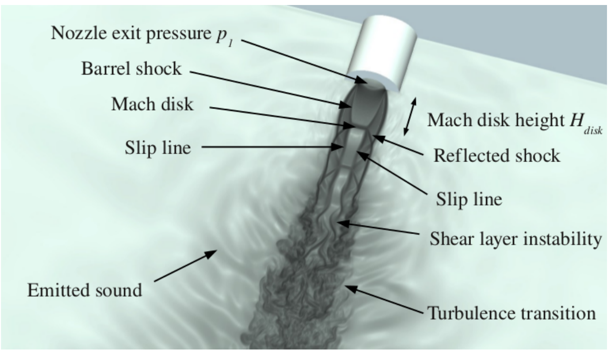

Figure 1. Visualization of the flow configuration.

In the present paper we enrich the previous picture in underexpanded jets by analyzing natural gas injection instead of nitrogen. The results give significant insight to fuel injection process in NG-engines. We shall investigate in detail the mixture formation process and show how the resolved scalar dissipation rate $\chi_{res} = -\rho|\nabla c|^2$, as shown in Fig. 3, behaves as a function of NPR. As seen in Fig. 3, it is noted that the dissipative structures appear as an elongated fibers which are

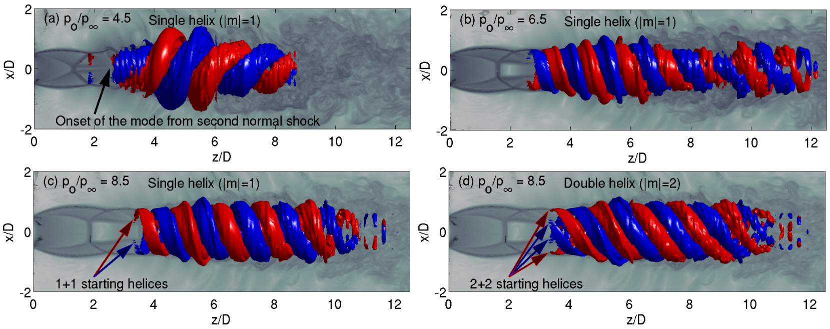

Figure 2. The helical density modes in 3d constructed from the 2d mode pair (1,2) using the phase function. (a) $p_o/p_\infty = 4.5$, $|m| = 1$, (b) $p_o/p_\infty = 6.5$, $|m| = 1$, (c) $p_o/p_\infty = 8.5$, $|m| = 1$, (d) $p_o/p_\infty = 8.5$, $|m| = 2$.

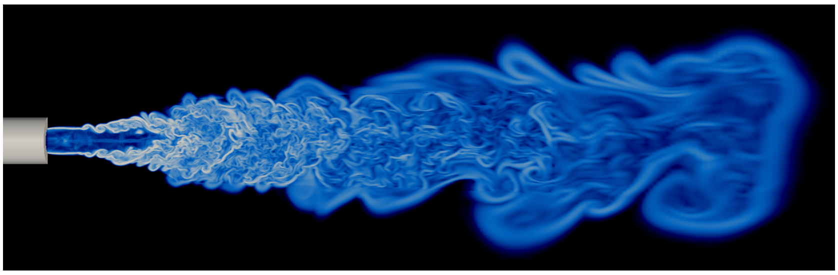

Figure 3. Visualization of scalar dissipation in a moderately underexpanded jet at nozzle pressure ratio 3.

highly entangled. A full assessment of the statistical characteristics of these structures will be provided in the final paper. Furthermore, we use POD to show the role of coherent structures in the dissipation peaks. The study paves the way for future investigation of supersonic combustion using LES and Flamelet Generated Manifolds (FGM).

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