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Numerical exploration of dissimilar supersonic coaxial jets mixing

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ABSTRACT

Mixing of two coaxial supersonic dissimilar gases in free jet environment is numerically explored. Three dimensional RANS equations with a k–ε turbulence model are solved using commercial CFD software. Two important experimental cases (RELIEF experiments) representing compressible mixing flow phenomenon under scramjet operating conditions for which detail profiles of thermochemical variables are available are taken as validation cases. Two different convective Mach numbers 0.16 and 0.70 are considered for simulations. The computed growth rate, pitot pressure and mass fraction profiles for both these cases match extremely well with experimental values and results of other high fidelity numerical results both in far field and near field regions. For higher convective Mach number predicted growth rate matches nicely with empirical Dimotakis curve; whereas for lower convective Mach number, predicted growth rate is higher. It is shown that well resolved RANS calculation can capture the mixing of two supersonic dissimilar gases better than high fidelity LES calculations.

1. Introduction

The supersonic combustion ramjet (scramjet) offers potentially cheaper alternative for high Mach number flight to space as well as for military applications and is the preferred choice for air-breathing engine in hypersonic flight. Establishing an efficient supersonic combustion process over a wide range of flight Mach numbers still remains a challenging process. The fuel injection system and combustor geometry must simultaneously provide sufficient fuel–air mixing and minimal losses. Computational fluid dynamics (CFD) codes based on the Reynolds averaged Navier–Stokes (RANS) equations are extensively used in the development of high speed air breathing engines. The maturation of multipurpose CFD codes coupled with advancements in computer architectures has substantially reduced the turnaround time required to perform steady-state Reynolds-averaged simulations. Turbulence models employed in these codes employ many adhoc assumptions and empirically determined coefficients. So to make CFD methods a reliable tool and to apply with confidence in the design exercise, it needs to be validated against reliable experimental results that are representative of compressible mixing flow phenomenon encountered in scramjet combustors.

In the past, experimental studies of high speed mixing flows mostly focused on two stream planar mixing layers mainly to gain understanding on the effect of compressibility on mixing. For high speed flows, it is seen that slight variations in the mixing rate predictions resulting in large discrepancies in combustor performance. Dimotakis [1] reviews much of these literatures present in two stream planar mixing layers. However, the two stream planar mixing layers contain relatively small regions of high speed propulsion flows; while the mixing between partially mixed fuel–air plumes and fresh air ingested by engine intake occurs in the greater part of a high speed air breathing engine.

Gutmark et al. [2] considered the effects of convective Mach number on the mixing of circular, rectangular, and elliptical supersonic jets of various gases in a supersonic coflow of air. Rossman et al. [3] were consistent with findings on the effects of compressibility on mixing-layer growth rate such

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as the equation of Dimotakis [1]. He also found the ratio of compressible mixing-layer growth to incompressible mixing-layer growth rate as a function of convective Mach number (M_c), for the He–O_2 and the measured Argon growth rate with experiment. Carty [4] developed and validated a supersonic Helium–Air coannular jet facility. However, sufficient details could not be found for this experiment for code-validation purposes. Experimental studies of mixing of two coaxial supersonic streams (outer jet of air and an inner jet of either a Helium–oxygen mixture or pure Argon) in free jet environment carried out by Cutler et al. [5–7] generated important profiles for different flow parameters which are very useful for CFD validation studies. The streamwise development of the flow in the experimental condition is dominated by turbulent stresses instead of pressure forces, and calculations are sensitive to proper turbulence modeling. The two stream mixing layer which is formed between the center jet and the coflow near the nozzle exit depends on the injectants for shear and the compressibility of the mixing layer. The Helium condition is pressure matched at the nozzle exit resulting in a high convective Mach number of 0.7 representing the flow in scramjet combustor. The Argon condition, on the other hand, was both pressure and velocity matched which produced a mixing layer with a convective Mach number of 0.16. Free jet features of the flows provide easy access for both optical instrumentation and probes for detailed flow investigations. Being axisymmetric, a minimum number of experimental measurements are required to fully characterize the flow. The experiment contains comprehensive set of measurements including pitot pressure, mean and rms velocities, and gas sampling. The model geometry, flow conditions, and measurement uncertainties were all well documented, resulting in a package that was well suited for model validation efforts. Because of these attractive features of this experiment, it was adopted by a working group of the NATO Research and Technology Organization as a test case for their CFD development and validation activity.

Number of CFD studies [5,7,8–11] with different level of turbulence modelings starting from two equation turbulence models [9,10] to more advanced LES model [11] were reported in the literature for this experimental condition in last few years. RANS calculations employing structured finite difference code VULCAN [12] along with the k–ω turbulence model [13] showed non-physical discontinuities in slope of mole fraction and pitot pressure which were attributed to inadequacies in the turbulence model. Baurle and Edwards [11] adopted hybrid RANS/LES approach over RANS calculation as the latter is shown to depend heavily on the modeled turbulent transport of heat and mass transfer. LES results of Baurle and Edwards [11] are shown to be no more predictive than the baseline Reynolds-averaged predictions. Moreover, LES approach for engineering applications is very costly in terms of computing resource. It is clear that supersonic mixing of coaxial nonreating jets requires further studies to have better predictive capabilities and the search for a reliable numerical tool for solving the engineering problems of high speed air breathing propulsion is still continuing. Supersonic mixing layer of two dissimilar gases, although geometrically simple, represents canonically the physical process of mixing under compressible condition similar to scramjet combustor. In this paper, experimental condition of nonreacting mixing of two coaxial supersonic streams is numerically explored by using a commercial CFD software [14] and results were

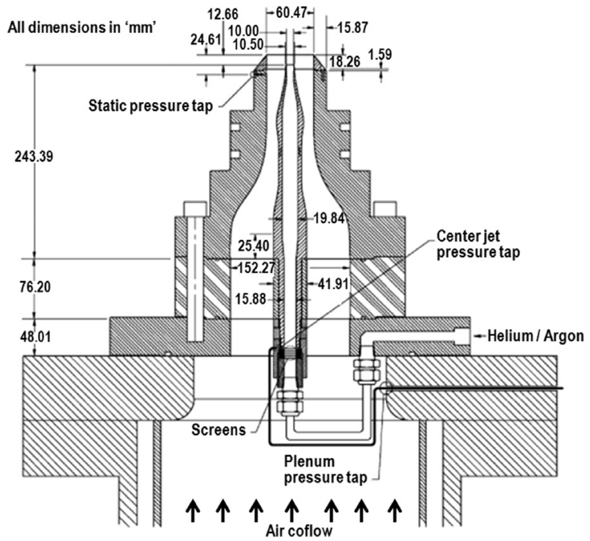

Fig. 1. Coaxial jet-nozzle assembly (reproduced from Ref. [9]).

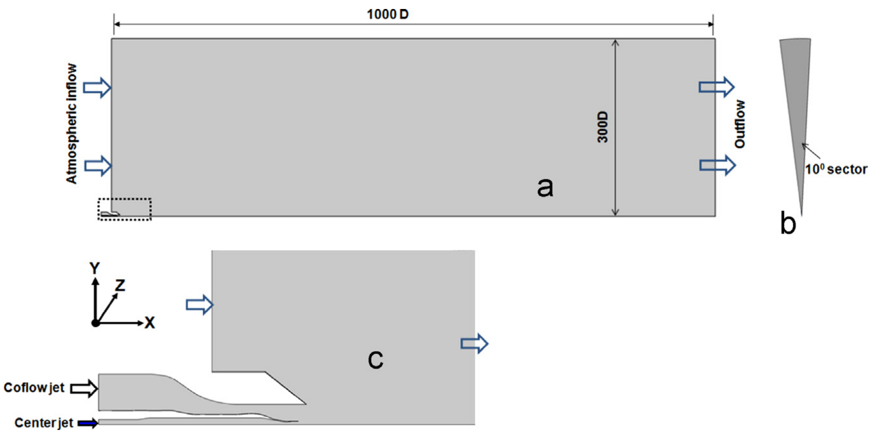

Fig. 2. Computational domain with boundary details, (a) front view, (b) side view and (c) blown up view near the nozzle.