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Simulation of Supersonic Combustion in Three-Dimensional Configurations

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A turbulence model that calculates the turbulent Prandtl and Schmidt numbers as part of the solution, addresses turbulence/chemistry interactions, and accounts for compressibility effects is used to simulate supersonic combustion in two three-dimensional experiments: the SCHOLAR experiment, which employs vitiated air and hydrogen fuel, and the HyShot experiment, which employs air and hydrogen fuel. Two chemical kinetic models are employed: one employs reaction rates that are functions of temperature, whereas the other employs rates that are both functions of pressure and temperature. In general, fair to good agreement is indicated with available measurements.

I. Introduction

SIMULATION of turbulent combustion in scramjet engines requires highly sophisticated models to address the complex flow physics involved. Earlier work [1] using turbulence models that only consider velocity fluctuations, such as k-ε or k-ω models, demonstrated the profound influence of the turbulent Prandtl number Pr_t, and turbulent Schmidt number Sc_t, on the simulation. Thus, low values of Sc_t can enhance mass transfer and subsequent heat release to such an extent that they may result in unstarts. On the other hand, high values of Sc_t will result in the reduction of turbulent mass transfer to levels that could not sustain combustion. Similarly, reduced values of Pr_t result in increased thermal diffusion away from the flame holding, with the result that flame blowout may occur.

When dealing with reacting high-speed flows, concentrations and temperature fluctuations are as important as velocity fluctuations. Thus, to asses the role of such fluctuations on supersonic combustion, equations for the variance and dissipation rate of enthalpy and concentrations are required. Rather than rely on equations suited for low-speed flow or empirical formulations, required equations were derived from the exact compressible Navier–Stokes equations and were modeled term by term. The approach employed followed procedures established in the k-ζ turbulence closure model [2]. Thus, the complete set consists of six equations: turbulence kinetic energy or variance of velocity k, variance of vorticity or enstrophy ζ, variance of enthalpy $\tilde{h}''^2$, and its dissipation rate ε_h, variance of concentrations σ, and its dissipation rate ε_Y. The resulting set of equations is tensorially consistent, Galilean invariant, coordinate-system independent, and is free of wall or damping functions.

Compressibility at high Mach numbers limits the spreading rate of injected fuel and has a significant influence on mixing of fuel and oxidizer. The model of [3] was used. This model was validated by three sets of supersonic mixing experiments [4–6], in which detailed measurements of velocity profiles, turbulent kinetic energy, and turbulent stresses were presented.

Turbulence/Chemistry interaction plays a major role in supersonic combustion. The traditional manner in which such interactions are addressed is through the use of assumed and/or evolution probability density functions (PDFs). Calculations employing both approaches were compared in [7] for supersonic combustion of parallel streams. It was shown there that both formulations yield comparable mean flow. However, assumed PDFs were unable to predict higher order correlations, such as those involving chemical source terms, with any reasonable accuracy. Computations employing evolution PDFs are time consuming and require excessive storage because the solution is carried out using a Monte Carlo method. Because of this, all higher order correlations involving chemical production terms were modeled in [8].

The present work employs the model of [8], which presents the detailed set of model equations and validations using 2-D/axisymmetric experiments involving mixing and combustion. The next step of the validations process is to apply the model of [8] to 3-D supersonic combustion experiments that exhibit some of the geometric complexities of proposed scramjet designs. One such experiment is referred to as the SCHOLAR experiment [9,10]. This experiment, which was conducted at the NASA Langley Research Center Direct-Connect Supersonic Combustion test facility, is one of the experiments adopted by a working group of the NATO Research and Technology Organization as a test case for CFD development and validation activity.

The model design of the experiment was based on a simulation using the viscous upwind algorithm for complex flow analysis (VULCAN) code [11] with emphasis on avoiding large regions of subsonic recirculating flows. It became evident later that the design resulted in a situation in which chemical reactions greatly lagged mixing with the result that combustion took place downstream of the hydrogen injector.

A CFD simulation of the SCHOLAR experiment was carried out by a number of authors [12,13] using the VULCAN code. This code has no provisions for calculating the turbulent Schmidt and Prandtl numbers as part of the solution but has limited capability in addressing chemistry/turbulent interactions using assumed PDFs. A rather detailed sensitivity study of the various parameters that could conceivably affect the flow in the combustor was undertaken. It was concluded that the solution was greatly effected by the selection of the turbulent Prandtl and Schmidt numbers and the turbulence and chemical kinetic models. In spite of this exhaustive study none of the parameters considered resulted in the prediction of the correct ignition location.

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