Transverse Fuel-Injection Model for a Scramjet Propulsion System

Thomas R. A. Bussing* and Gary L. Lidstone†
Boeing Advanced Systems, Seattle, Washington

Contents

THE purpose of this article is to describe a model for transverse fuel injection. The model was incorporated into a package of computer programs designed to compute the flowfield about and through scramjet-powered hypersonic vehicles that are summarized in Refs. 1 and 2. The package consists of a series of two-dimensional/axisymmetric parabolized Navier-Stokes codes used to compute the flowfield about and through a desired hypersonic vehicle. The nose region is computed with the VSL code,[3] the forebody and external cowl region with the SCRAMP code, and the inlet region with the SCRINT code. The combustor and nozzle flowfields are computed with the SCORCH and SCHNOZ codes, respectively. Only parallel and slot fuel injection can be modeled with the package described in Refs. 1 and 2.

The fuel-injection region presents unique modeling problems due to the highly three-dimensional flowfield created by the injection process. Most fuel-injection methods of interest involve injecting fuel through discrete holes. Obstruction of the airflow caused by fuel injection creates a bow shock and subsequent separated regions (Fig. 1). Proper modeling of this region requires a solution method capable of solving the three-dimensional fully turbulent Navier-Stokes equations with finite-rate chemistry. Because of the current unavailability of an accurate and computationally efficient code, it was decided to use an integral model to approximate the three-dimensional fuel-injection region. The major contribution of this article is in the development of a fuel-injection model, which can simulate three-dimensional hydrogen (H_2) fuel injection and, therefore, better represent real scramjet propulsion systems.

Fuel-Injection Model

Cohen et al.[4] have proposed a methodology for predicting the fuel distribution downstream of a single row, multihole wall fuel injector. The method uses experimental correlations to characterize the injector flowfield in terms of initial fuel and airflow physical properties, and injector geometry. Figure 1 is a schematic representation of the fuel-injector flowfield. Injected fuel rapidly mixes with the inlet airflow, producing a two-dimensional region where the fuel-concentration profiles can be represented by skewed Gaussian distributions. Use of the fuel-injector correlations to produce the two-dimensional flow profile downstream of the injector location requires a specific methodology. The profile upstream of the fuel injectors is obtained from the two-dimensional inlet analysis. Given the specific injector geometry and flow conditions, the downstream fuel-concentration profiles are calculated based on the correlations. The correlations were determined experimentally for 60–120 deg H_2 injection.

Given the fuel-concentration profiles and the inlet air mass-flux distribution, the fuel mass-flux distribution can be determined. The various downstream flow profiles are calculated using the relations for conservation of mass, momentum, and energy. The new profiles are input into the combustor code where the mixture is allowed to mix further and react. Combustor performance and nozzle inflow profiles can be generated for various injector geometries and flow conditions. It is assumed that the flow in the three-dimensional injection zone is nonreacting, and that the region is thin compared to the length of the combustor.

A computer program has been written that uses this methodology to calculate flow conditions downstream of the fuel injector. The program uses the inlet exit profile from the SCRINT code, imposes the fuel distribution on the profile, and generates a new input profile for the SCORCH combustor code. The injection model is general and can be incorporated into other flow codes.

Results

Two example calculations are discussed in this article. The first is intended to show the effects of fuel injection on a uniform inlet profile. The second calculation considers the effects of fuel injection within a representative nose-to-tail scramjet powered hypersonic vehicle calculation.

Uniform Inlet Profile

An example case using a uniform combustor inlet profile has been formulated to illustrate the effects the injected fuel has on the incoming flow conditions. Flow conditions at the inlet-exit were determined from a one-dimensional scramjet code[5] using representative inlet losses for an inlet contraction ratio of 50 at a freestream Mach number of 20. Fuel-injector flow conditions were also determined using the scramjet code assuming a fuel total pressure of 1500 psi and total temperature of 2000 °R. Note that fuel is injected from both walls.

Profiles calculated by the correlations downstream of the injection process are plotted in Figs. 2 and 3 for injector angles 10 to 90 deg. Note that the Cohen et al.[4] correlations were extrapolated for injection angles below 60 deg. Fuel-concentration levels are shown in Fig. 2 in terms of hydrogen mass fraction. For this exercise, the same amount of fuel was assumed to enter the duct from the top and bottom walls. Concentration-level peaks are the highest for the lower injection angles due to a lower level of penetration. These concentration profiles are imposed on the duct airflow while maintaining conservation of mass, momentum, and energy.

The highest reduction in axial velocity occurs for the 90-deg injection angle. However, the highest vertical velocity did not

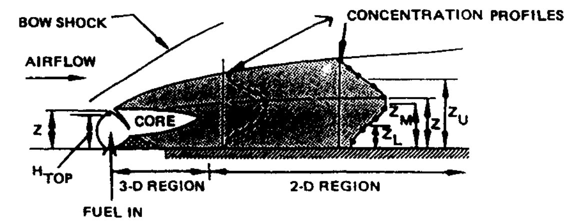

Fig. 1 Schematic representation of a fuel-injector flowfield.

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*Principal Engineer. Member AIAA.

†Specialist Engineer.

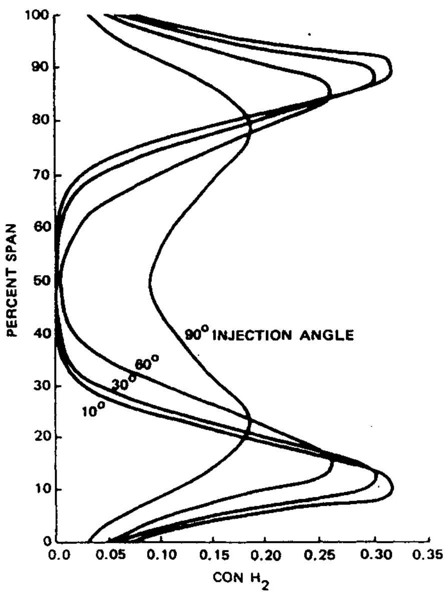

Fig. 2 Combustor inlet hydrogen mass-fraction profiles downstream of fuel injection (M = 20, phi = 5, and inlet contraction ratio = 50; uniform profile).

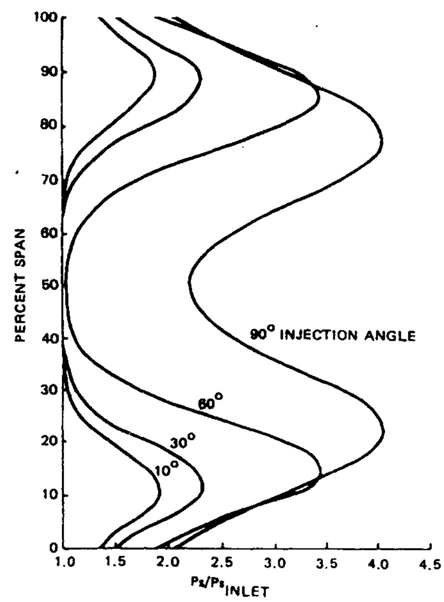

Fig. 3 Combustor inlet pressure profiles downstream of fuel injection (M = 20, phi = 2, and inlet contraction ratio = 50; uniform profile).

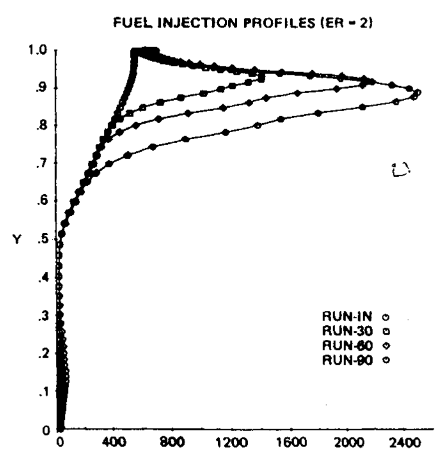

Fig. 4 Combustor inlet pressure profiles downstream of fuel injection (M = 16, phi = 2, nose-to-tail profile).

occur with 90-deg injection but with 60-deg injection, due to the combined effect of the hydrogen concentration level and injection flow angle.

The static temperature showed the highest temperature reduction for the 10-deg injection case. Temperature reduction can have a serious effect on the combustor process. Chemical reaction times will be increased substantially if temperatures fall below 1800 °R (see Ref. 6). Figure 3 shows the static-pressure profiles after the injection process. The plot shows that large increases in static pressure are possible with fuel injection. The duct-flow pressure was found to increase up to four times the inflow pressure level for the 90-deg injection case. The pressure rose primarily due to the blockage created by the injected hydrogen. Pressure increases in the combustor flowfield can reduce reaction times and increase combustion efficiency. The injection pressure rise could also be used to tailor the flow conditions within the scramjets, so that they could operate over a wide range of flight conditions. A description of the effect of pressure, temperature, and fuel equivalence ratio on H_2-air reaction times is given in Ref. 6.

Changes in the scramjet duct-flow properties, due to the injection process, can create vastly different combustor and nozzle performance. Variations in injector geometry and flow conditions can provide an endless number of trade study possibilities.

Representative Nose-to-Tail Calculation

The nose-to-tail method described, including transverse fuel injection, was applied to a generic scramjet-powered hypersonic vehicle geometry. The calculation was run at a Mach number of 16 and a fuel equivalence ratio of 2. Hydrogen was injected from both the upper and lower walls.

Figure 4 illustrates the inlet duct-flow pressure profiles before and after the injection process for injection angles of 30, 60, and 90 deg. In this case, averaged duct-flow conditions were used in the correlations to calculate the fuel-concentration profiles. The inflow pressure profile shows the boundary-layer generated on the vehicle forebody (lower half of the duct) and the pressure increases caused by fuel injection. Increases in pressure are of the same magnitude in the upper and lower half of the duct. However, the absolute level of pressure increase in the lower half of the duct is small due to the lower inflow pressure. Further details on the method and the test cases described can be found in Ref. 7.

Acknowledgment

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References

[1]Krawczyk, W. J., Sinha, R. N., Harris, T. B., York, B. J., and Dash, S. M., "Computational Models for the Analysis/Design of Hypersonic Scramjet Components – Part 2: Inlet and Ramp/Forebody Models," AIAA Paper 6-1596, June 1986.

[2]Dash, S. M., Sinha, N., Wolf, D. E., and York, B. J., "Computational Models for the Analysis/Design of Hypersonic Scramjet Components – Part 1: Combustor and Nozzle Models," AIAA Paper 86-1595, June 1986.

[3]Holcomb, J. E., Curtis, J. T., and Shope, F. L., "A New Version of the CVEQ Hemisphere Viscous Shock-Layer Program for Equilibrium Air," Arnold Engineering Development Center, TN, AEDC-TMR-85-V7, Feb. 1985.

[4]Cohen, L. S., Coulter, L. J., and Egan, W. J., "Measurements of the Penetration and Mixing of Gases Injected Into Subsonic and Supersonic Airstreams," AIAA Paper 70-714, June 1970.

[5]Anderson, A. G., "SCRAM – A Program to Compute Supersonic Ramjet Performance," NASA Langley Research Center, Hypersonic Propulsion Branch, April 1968.

[6]Bussing, T. R. A. and Eberhardt, S., "Chemistry Associated with Hypersonic Vehicles," AIAA Paper 87-1292, June 1987.

[7]Bussing, T. R. A. and Lidstone, L. L., "An Improved Computational Model for a Scramjet Propulsion System," AIAA Paper 87-2078, June-July 1987.