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Technical Notes

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Impact of Axial Vortices on Mixing at a High Convective Mach Number

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Introduction

IN recent years the ramp injector as first suggested by Waitz et al.[1] has become one of the preferred strategies to deliver fuel in scramjet combustors. While maintaining a beneficial low injection angle, which ensures that most of the fuel momentum is recovered in the thrust balance, ramp injectors increase the mixing performance by creating axial vortices, which increase the fuel penetration and the fuel/air contact surface. Axial vortices of similar strength are also created by the cantilevered ramp injector,[2,3] a variant of the ramp injector specifically designed for fuel injection in shcramjet[4] inlets.

The increase in mixing associated with axial vortices has been assessed through experimental work by Naughton et al.,[5] where the addition of swirl to a turbulent freejet at a freestream Mach number of 3.5 is found to increase the mixing efficiency by as much as 34%. Similarly, the effect of the axial vortices on the mixing performance is assessed numerically by Riggins and Vitt[6] for a ramp injector flowfield by removing artificially the cross-stream velocities at the point of injection. This is found not to affect the mixing efficiency in the near field, but to decrease the mixing efficiency by more than 20% in the far field. The investigations by Naughton et al.[5] and Riggins and Vitt[6] are performed at a low convective Mach number[7] not exceeding 0.3.

The effect of axial vortices has not yet been quantified at a high convective Mach number. The use of a high convective Mach number is particularly important as it increases the mixing efficiency[3] and the fuel exit momentum significantly. The primary objective of this Note is hence to assess the increase in mixing induced by the axial vortices of the cantilevered ramp injector at a high convective Mach number of 1.5. The problems investigated herein are representative of inert mixing occurring in a shcramjet inlet. The results are obtained with the WARP (Window Allocatable Resolver for Propulsion) code outlined in Refs. 3 and 8.

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Problem Setup

The effect of the ramp-generated axial vortices on the mixing efficiency is assessed by comparing the mixing obtained by a freejet (shown in Fig. 1) to the one obtained by a cantilevered ramp injector (as illustrated in Fig. 2), which assumes an infinite array of injectors along the z coordinate. To isolate the effect of the axial vortices, both configurations share the same fuel/air contact surface at the point of injection and the same fuel and air inflow conditions. A third, planar configuration is considered, consisting of fuel injected from a backward-facing step (as schematized in Fig. 3). A comparison between the mixing obtained by the planar configuration to the one obtained by the freejet configuration is performed to assess the effect of a change in fuel/air interface length. For all cases the cross-sectional area of the fuel per unit depth (along the z coordinate) is not altered.

Inflow Properties

The inflow conditions for the fuel and air are as shown in Table 1. Fuel injection is assumed to take place after the first shock in the inlet of an external compression shcramjet at a flight Mach number of 11, which is designed assuming a flight dynamic pressure of 67 kPa, two equal strength inlet shocks, and a 900 K temperature prior to the detonation wave. The fuel is injected at a global equivalence ratio of 1, at a convective Mach number of 1.5, and at matched pressure with the air. The corresponding velocity difference between the hydrogen jet and the freestream is of 2960 m/s for all cases. The hydrogen stagnation temperature is of 1780 K, which is a desirable high value as the fuel is expected to cool the exposed surfaces of the engine and of the injector.

Mixing Efficiency

The air-based mixing efficiency is defined as the ratio between the reacting mass flux of oxygen and the predicted mass flow rate

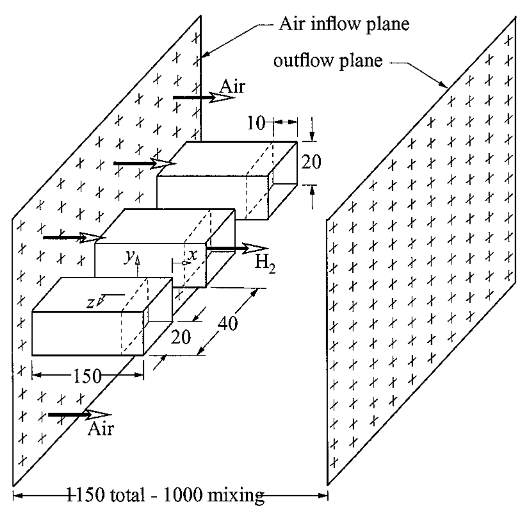

Fig. 1 Design of the freejet injector; all dimensions are in millimeters.

Table 1 Test cases

			Air inflow			Hydrogen inflow		
Case	Configuration	Turbulent?	Pressure, Pa	Temperature, K	Mach number	Pressure, Pa	Temperature, K	Mach number
C5	Cantilevered	Yes	4,758	462	7.73	4,758	410	4.1
J5	Freejet	Yes	4,758	462	7.73	4,758	410	4.1
J5P	Freejet	Yes	14,274	462	7.73	4,758	410	4.1
J5T	Freejet	Yes	14,274	1,386	7.73	4,758	410	4.1
P5	Planar	Yes	4,758	462	7.73	4,758	410	4.1
P51	Planar	No	4,758	462	7.73	4,758	410	4.1

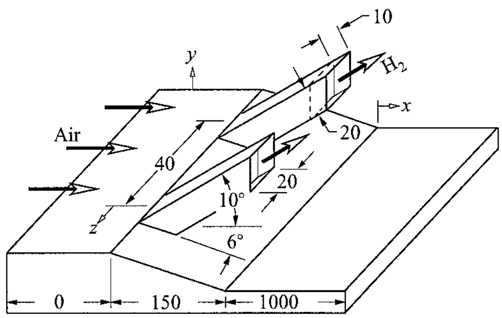

Fig. 2 Design of the cantilevered ramp injector; all dimensions are in millimeters unless otherwise noted.

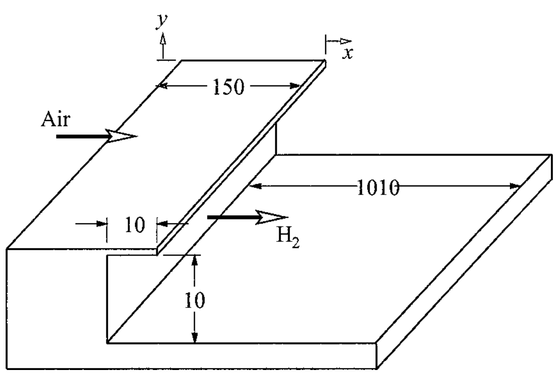

Fig. 3 Design of the planar injector; all dimensions are in millimeters.

of oxygen through the shcramjet inlet, that is,

$$\eta_m \equiv \int_b c^R_{O_2}\,\mathrm{d}\dot{m} \bigg/ \dot{m}_{O_2,\ \mathrm{engine}} \qquad (1)$$

where the mass flow rate of air per unit depth entering a 0.7-m inlet corresponds to $\dot{m}_{O_2,\ \mathrm{engine}} = 1.363$ kg/ms and where the reacting mass fraction of oxygen $c^R_{O_2}$ corresponds to

$$c^R_{O_2} = \min\left(c_{O_2}, c^S_{O_2} c_{H_2} \big/ c^S_{H_2}\right) \qquad (2)$$

with the stoichiometric mass fraction of hydrogen $c^S_{H_2}$ equal to 0.02876 and the stoichiometric mass fraction of oxygen $c^S_{O_2}$ equal to 0.22824. More details about this definition of the mixing efficiency can be found in Section 5.2 of Ref. 9.

Boundary Conditions

For each configuration inflow and outflow boundary conditions are specified at the entrance and exit planes, respectively. For the freejet and cantilevered ramp injector configurations symmetry planes are located at $z = 20$ mm and 0. The top boundary (along the y coordinate) for the freejet and the planar configurations is set to outflow. For the freejet configuration a symmetrical boundary condition is specified at the bottom of the domain, going through the center plane of the injectors to minimize the number of nodes used. For the cantilevered ramp injector and the planar configurations the bottom boundary is a wall at a fixed temperature. More details about the boundary conditions for the cantilevered ramp injector configuration can be found in Ref. 3. In all cases the wall temperature is fixed to the air freestream temperature.

Numerical Considerations

The governing equations solved are the nonreacting Favre-averaged Navier–Stokes equations closed by the Wilcox $k\omega$ turbulence model[10] and the Wilcox dilatational dissipation term.[11] These have been validated[3,9] vs the experimental data of ramp injectors[1,12] with overall good agreement observed. The marching window acceleration technique[8] is used and is observed to result in a 10–20 times decrease in computing time with convergence to steady state reached in typically less than 250 effective iterations. The same convergence criterion, turbulent Prandtl number, and turbulent Schmidt number are used as in Ref. 3, and no entropy correction term is used along with the Yee–Roe scheme as it is found to be overly diffusive and unnecessary for this mixing flowfield.[3] The mesh is constructed such that the mesh density is similar for the three configurations. More specifically, the mesh dimensions correspond to $319 \times 187 \times 42$, $350 \times 45 \times 44$, and 269×187 for the cantilevered ramp injector, freejet, and planar mixing configurations, respectively. Separate grid-convergence studies indicate a relative error on the mixing efficiency varying between 3–5% for the laminar planar mixing case and 7–22% for both the freejet and the cantilevered ramp injector cases. The node spacing at all surfaces is set to 30 μ, which translates into a value for y^+ ranging between 2 and 3 in the mixing region. This has been observed[3] to be sufficiently small for an accurate representation of the wall shear stress and boundary-layer profiles in the injector domain. For all three configurations a 1-cm-long fuel runway zone is specified inside the injector to avoid a singularity in the turbulence and flow properties at the point of injection. This alleviates the sensitivity of the $k\omega$ model to the freestream value of ω, which is fixed to 10 times the flow speed.[13]

Discussion

Figure 4 shows a hierarchy in mixing efficiencies equal, at the domain exit, to 3, 10, 24, and 40% for the planar laminar, planar turbulent, three-dimensional, freejet and cantilevered injector cases, respectively. There is a ratio of 2.4 between the mixing efficiencies of the freejet and the two-dimensional planar case, whereas a smaller ratio of 1.7 is present between the cantilevered injector and the freejet. Although significant, the influence of the axial vortices on the mixing is here found to be of lesser importance than the transition from a two-dimensional planar to a three-dimensional freejet. This increase in mixing is attributed to the augmentation in contact surface area for the freejet, which, at the point of injection, exhibits twice the surface area of the planar case. The freejet exhibits a mixing efficiency growth 2.4 times the one of the planar case even though the contact surface area is only twice larger. This could be caused by a numerical error related to the grid, or it could also be caused by the effective contact surface increasing slightly along the streamwise coordinate for the freejet, as a result of the spreading of the mixing layer.

The increase in mixing efficiency observed for case C5, compared to case J5, is caused partly by the stretch of the fuel/air contact surface through the axial vortices and partly by the high pressure and temperature of the incoming air at the point of injection. The high

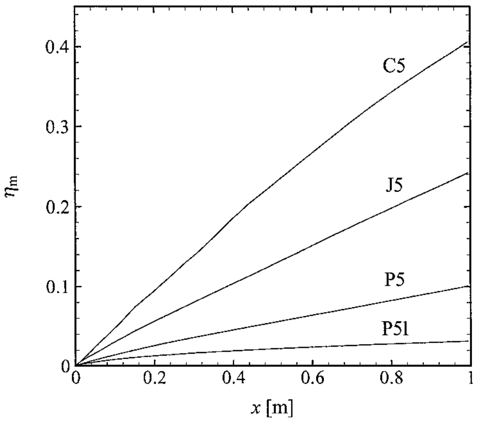

Fig. 4 Comparison of the mixing efficiency of a planar laminar case (P5l), a planar turbulent case (P5), a freejet (J5), and a cantilevered ramp injector (C5).

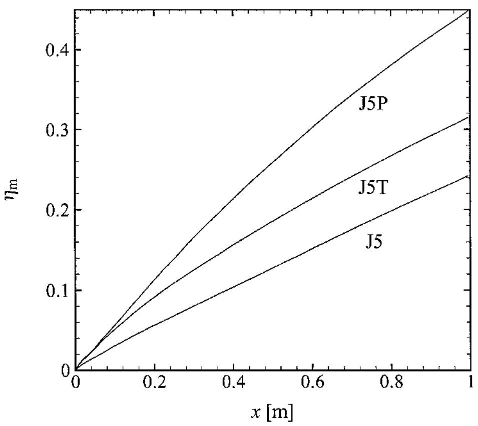

Fig. 5 Mixing efficiency of a freejet (case J5), a freejet with a threefold increase in the incoming air pressure (case J5P), and a freejet with the incoming air pressure and temperature multiplied by 3 (case J5T).

pressure originates from the flow compression around and above the cantilevered injector, whereas the high temperature is created by both flow compression and boundary-layer heating. A high pressure of the incoming air is beneficial to the mixing efficiency because the growth rate of the turbulent mixing layer is independent of the pressure. A high pressure generally induces a higher density of the flow, which increases the amount of oxygen present in the turbulent mixing layer, consequently increasing the mass flow rate of $c^R_{O_2}$, resulting in higher mixing efficiency. Figure 5 shows a comparison between the freejet case J5 and two additional cases: J5P and J5T. A threefold increase of the air density (case J5P) results in a mixing efficiency increase close to two times the one of case J5, despite the reduction in contact surface caused by the higher air pressure compressing the fuel jet. Case J5T keeps the air density the same by increasing both the air temperature and pressure by a factor of three. Interestingly, this also results in an appreciable rise in the mixing efficiency. This is caused by an increase in the speed of sound of the incoming air, which effectively lowers the turbulent Mach number, decreases the importance of the dilatational dissipation term, and consequently increases the spreading rate of the mixing layer.

Conclusions

This study reveals that the fourfold increase in the air-based mixing efficiency between the cantilevered ramp injector and the planar configuration is observed to be caused by, in order of importance, 1) the increased fuel/air contact surface present in three dimensions, 2) the stretching of the fuel/air interface by the axial vortices, and 3) the higher pressure and temperature present at injection. However, this is expected to only occur at a high convective Mach number. At a low convective Mach number the axial vortices are expected to play a more significant role primarily because of the cross-stream shear that they induce being more important compared to the longitudinal shear induced by the convective Mach number.

For the freejet configuration it is observed that a threefold increase in the incoming air pressure while keeping the incoming air temperature constant results in a 80% increase in the mixing efficiency. This is postulated to be because of the mixing efficiency growth being a function of the density of the incoming air, which increases threefold in this case. On the other hand, a threefold increase in the incoming air temperature while keeping the incoming air density constant results in a 32% increase in the mixing efficiency. This is attributed to a reduction of the importance of compressibility effects as the flow temperature increases.

Finally, it is cautioned that the numerical results here obtained are dependent on the Wilcox $k\omega$ turbulence model including the Wilcox dilatational dissipation correction. One of the known deficiencies of the Wilcox $k\omega$ model is in not predicting accurately the growth of an axisymmetric mixing layer,[13] similar to the one present in the freejet case. Also, the dilatational dissipation correction has not been validated in the open literature for an axisymmetric mixing layer. Further, only one geometry and one set of fuel and air inflow conditions have been investigated herein. It is questionable whether the same trends would be observed with a different turbulence model, in experiments, for a different geometry, or for different fuel and air inflow conditions.

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References

[1]Waitz, I. A., Marble, F. E., and Zukoski, E. E., "Investigation of a Contoured Wall Injector for Hypervelocity Mixing Augmentation," *AIAA Journal*, Vol. 31, No. 6, 1993, pp. 1014–1021.

[2]Sislian, J. P., and Schumacher, J., "A Comparative Study of Hypersonic Fuel/Air Mixing Enhancement by Ramp and Cantilevered Ramp Injectors," AIAA Paper 99-4873, Nov. 1999.

[3]Parent, B., Sislian, J. P., and Schumacher, J., "Numerical Investigation of the Turbulent Mixing Performance of a Cantilevered Ramp Injector," *AIAA Journal*, Vol. 40, No. 8, 2002, pp. 1559–1566.

[4]Dudebout, R., Sislian, J. P., and Oppitz, R., "Numerical Simulation of Hypersonic Shock-Induced Combustion Ramjets," *Journal of Propulsion and Power*, Vol. 14, No. 6, 1998, pp. 869–879.

[5]Naughton, J. W., Cattafesta, L. N., and Settles, G. S., "An Experimental Study of the Effect of Streamwise Vorticity on Supersonic Mixing Enhancement," AIAA Paper 89-2456, July 1989.

[6]Riggins, D. W., and Vitt, P. H., "Vortex Generation and Mixing in Three-Dimensional Supersonic Combustors," *Journal of Propulsion and Power*, Vol. 11, No. 3, 1995, pp. 419–426.

[7]Papamoschou, D., and Roshko, A., "The Compressible Turbulent Shear Layer: an Experimental Study," *Journal of Fluid Mechanics*, Vol. 197, No. 1, 1988, pp. 453–477.

[8]Parent, B., and Sislian, J. P., "The Use of Domain Decomposition in Accelerating the Convergence of Quasihyperbolic Systems," *Journal of Computational Physics*, Vol. 179, No. 1, 2002, pp. 140–169.

[9]Parent, B., "Computational Study of Fuel Injection in a Shcramjet Inlet," Ph.D. Dissertation, Graduate Dept. of Aerospace Science and Engineering, Univ. of Toronto, Toronto, Aug. 2002.

[10]Wilcox, D. C., "Reassessment of the Scale Determining Equation for Advanced Turbulence Models," *AIAA Journal*, Vol. 26, No. 11, 1988, pp. 1299–1310.

[11]Wilcox, D. C., "Dilatation-Dissipation Corrections for Advanced Turbulence Models," *AIAA Journal*, Vol. 30, No. 11, 1992, pp. 2639–2646.

[12]Donohue, J. M., McDaniel, J. C., and Haj-Hariri, H., "Experimental and Numerical Study of Swept Ramp Injection into a Supersonic Flowfield," *AIAA Journal*, Vol. 32, No. 9, 1994, pp. 1860–1867.

[13]Wilcox, D. C., *Turbulence Modeling for CFD*, DCW Industries, 1994.

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