JOURNAL OF PROPULSION AND POWER
Vol. 17, No. 6, November–December 2001

Effects of Swirl and Skew Upon Supersonic Wall Jet in Crossflow

A. D. Cutler* and S. E. Doerner†
George Washington University, Joint Institute for Advancement of Flight Sciences, Hampton, Virginia 23681-2199

The results of an experimental investigation of the effects of swirl and skew on the mixing of a supersonic light gas jet injected from a flat wall into a supersonic airstream are presented. Tests were at nominally equal injectant mass flow rate, total pressure, and injector nozzle exit static pressure. Data include surveys of cross-sectional planes of the flow for several different cases of swirl and skew using cone static pressure, pitot, stagnation temperature, and gas sampling probes (with gas analysis system). The results are analyzed to determine mixing efficiency and lateral motions of the center of the injectant plume. The effect of combined swirl and skew on injectant mixing is to slightly increase mixing in the near field of injection, but there is little effect of either swirl or skew on mixing far downstream. Both swirl and skew slightly reduce penetration.

Nomenclature

d	=	injector exit diameter
h	=	duct height (38.6 mm)
M	=	Mach number
$\dot{m}$	=	mass flow rate
p	=	pressure
T	=	temperature
u_j	=	axial component velocity at injector nozzle exit
u	=	x component velocity
v_j	=	tangential component velocity at injector nozzle exit
x, y, z	=	coordinates
α	=	mass fraction injectant
β	=	skew angle
η	=	mixing efficiency
θ	=	pitch angle to wall
ρ	=	density
χ	=	mole fraction injectant

Subscripts

cm	=	mass flux weighted center
j	=	quantity at injectant nozzle exit
pit	=	pitot
t	=	total
∞	=	quantity at main nozzle exit

Introduction

THE size, weight, and specific thrust of supersonic combustion ramjet (scramjet) engines are determined, in part, by the distance that is required to mix and burn injected fuel in the combustor. Excessive mixing lengths lead to long combustors and to high wall heat transfer and friction. Practical injection schemes in a combustor often involve either injection of jets from a flat wall, either normal to the wall or inclined downstream[1–4] or injection from the base of ramps.[5] Ramp injectors can be designed to produce more rapid mixing than wall injectors by adding large-scale longitudinal vortex pairs, but they produce drag and can be susceptible to thermal damage. Methods for increasing the rate of mixing produced by wall injectors are therefore sought. Previous studies have shown that the effect of adding swirl to supersonic jets into a stagnant atmosphere (exit pressure and jet axial velocity maintained constant) is to increase jet spreading rate.[6] This effect was attributed to destabilization of the turbulent jet-air mixing layer by mean streamline curvature. It was further shown in these studies that if the jet is operated overexpanded (i.e., jet exit pressure below atmospheric) the inward propagating conical shock which emanates from the nozzle exit causes vortex breakdown within the jet. Breakdown leads to turbulence generation and more rapid mixing. Similar results have been observed with supersonic swirling jets injected into a parallel supersonic air flow.[7,8]

The effect of adding swirl to a jet of helium injected from a flat wall, pitched downstream at angle to the wall $\theta = 30$ deg, into a Mach 2 ducted airflow was investigated to determine whether the mixing rate in this more practical scramjet-like configuration could be increased.[9] Swirl was varied while maintaining constant injector nozzle internal geometry and axial velocity and pressure at the nozzle exit. However, for this set of conditions injectant mass flow rate decreased with swirl and stagnation pressure increased. After correcting for the differences in mass flow rates, it was concluded that mixing rate was substantially increased by swirl. However, the effects of the wall opposite the injector might have been significant, and the correction to equal mass flow rates in effect corrected to unequal opposite wall position. In addition, comparisons made on the basis of unequal injectant stagnation pressure are unsatisfactory because it is likely that the performance of any given class of injectors can be improved simply by injection at higher stagnation pressure. Also, the cost (and weight) of the engine fuel system is likely to increase as the fuel pressure increases.

Another observation of Ref. 9 was that the injectant-air plume that formed downstream of injection was displaced laterally when the jet was swirled, consistent with interaction of a streamwise vortex within the plume with its image in the injection wall. It was speculated that the flow around the pitched swirling jet was similar to the flow around a spinning cylinder in a crossflow, which rotates as a result of asymmetrical separation at the rear of the cylinder, generating lift on the cylinder (the Magnus effect).[10] However, the analogy of the swirling jet with a spinning cylinder is inadequate. A spinning cylinder mounted on the wall of the duct exerts a lateral force on the flow in reaction to the lift force it experiences, whereas a swirling jet introduces no lateral momentum unless injection is skewed. Several studies have indicated that skewed injection (without swirl) is effective in generating a streamwise vortex in low-speed flows.[11,12] On the basis of these arguments, it is speculated that the plume net circulation and/or penetration and/or degree of mixing with swirl are sensitive to the skew angle.

If the plume of a swirling jet does contain net circulation, then favorable interactions with vortices created by other injectors, or

Received 7 July 2000; revision received 8 November 2000; accepted for publication 13 July 2001.

*Associate Professor, 227 Hunting Avenue, Building 647. Senior Member AIAA.

†Graduate Research Scholar Assistant; currently Senior Engineer, Raytheon Missile Systems Company, Tucson, AZ 85706. Member AIAA.

created in the airstream by other means, might be found that enhance mixing and/or penetration of injectant. For example, compare a laterally separated pair of counter-rotating swirling jets with a single nonswirling jet of the same total mass flow rate. The counter-rotating jet pair might be expected to achieve more rapid mixing than a single nonswirling jet (at least prior to the merging of the jet plumes) because the plume-air interfacial area is greater. Mutual interaction between the pair of streamwise vortices, induced by the swirling jets, would act to move the injectant away from wall, thus ensuring penetration.

Jacobsen et al.[13] have investigated the effects of swirl in the outer ports of a three-hole injector array of sonic injectors into a Mach 3 stream. The holes were circular and flush to the injection wall; the central injector axis was inclined 30 deg downstream, whereas the outer ones were normal to the wall. The central injector imparted no swirl, whereas the outer injectors could impart either no swirl or counter-rotating swirl in either of two possible directions, i.e., such that the swirl would in one case be expected to promote penetration and in the other inhibit it. Small increases in mixing were reported with either direction of swirl, but, surprisingly, there appeared to be little effect on penetration (the distance of the edge of the mixing region from the wall).

The objectives of the present work are to further investigate the effects of adding swirl to a jet of helium injected from a flat wall, inclined downstream at $\theta = 25$ deg, into a Mach 2 ducted airflow. More specifically, the objectives are to determine whether 1) swirl increases the streamwise rate at which mixing occurs when jet mass flow, stagnation pressure, and exit static pressure are held constant; 2) swirl produces a plume with net circulation, and, if so, to demonstrate beneficial vortex interactions; and 3) skew enhances any positive effects of swirl. Additional details on this work can be found in Doerner.[14]

Experiment

Facility

The experiment was conducted at the Transverse Jet Facility, located at the NASA Langley Research Center. This facility consists of a plenum, supplied with high-pressure air from a central compressor station, and containing an acoustic damper and flow conditioning screens. Mounted upon the plenum is a rectangular nominal Mach 2 convergent–divergent nozzle, with exit cross section 87.88 mm by 38.61 mm, and downstream of this is a matching constant-area duct. The length of the duct is adjustable from 123.8 to 327.0 mm in increments of 50.8 mm. A section view of the nozzle and duct, which includes the pressure taps and the injector assembly, is shown in Fig. 1a. The exit of the duct is open to the laboratory (the flow is nominally at atmospheric pressure), and air is discharged into an exhaust duct. The boundary-layer edge (99.5%) thickness in the duct (without injection) is approximately 1.69 mm + 0.0075 × (distance from nozzle exit, in mm). Although initial boundary-layer thickness can be an important parameter, it was not the subject of this investigation, and so was not varied. It is unlikely that the trends between no-swirl and swirl would be affected by boundary-layer thickness.

The injectant in this study is a mixture of 95.0% He and 5.0% O_2 supplied premixed from a trailer. A light gas was desired for this study to (qualitatively) simulate the injection of hydrogen in a scramjet; oxygen was present because the injectant was shared with another experiment, which required it.

The injector assembly is shown in Fig. 1b. A coordinate system is established in this figure, with the origin taken at the intersection of the injector nozzle axis and the duct wall: x is measured in the downstream direction, y normal to the surface, and z normal to these according to the right-hand rule. The injectant enters the injector plenum through the plenum cap, passed through the "top hat" insert where it acquires swirl (in the swirling cases), and then passes through an axisymmetric convergent–divergent nozzle where it is accelerated to supersonic speed. Two interchangeable top-hat inserts, identical to those used in Ref. 9 ("straight" and "low swirl" cases), are used in the experiment. In the first, which provides no swirl, the flow passes through radially drilled holes; in the second, which provides counterclockwise (looking downstream) swirl, the flow passes through tangentially drilled holes. The convergent–divergent nozzle is formed by one of two interchangeable nozzle inserts. The first, designed to be used with the swirl top hat insert, has an exit-to-throat area ratio of 2.0 and an exit diameter of 6.35 mm (identical to that in Ref. 9). The second, designed to be used with the no swirl insert, has an exit-to-throat area ratio of 2.3 and an exit diameter of 4.93 mm. The injector nozzle is contained within the nozzle block, which is mounted in the wall plate in such a way that it can rotate about the axis normal to the surface along the line $(x, z) = (0, 0)$. The skew angle β is the angle of rotation measured with respect to the symmetrical (in the x-y plane) position and is such that positive β produces positive z component of injection velocity. Skew angles of up to ± 25 deg are possible ($\beta = 0$ in Fig. 1).

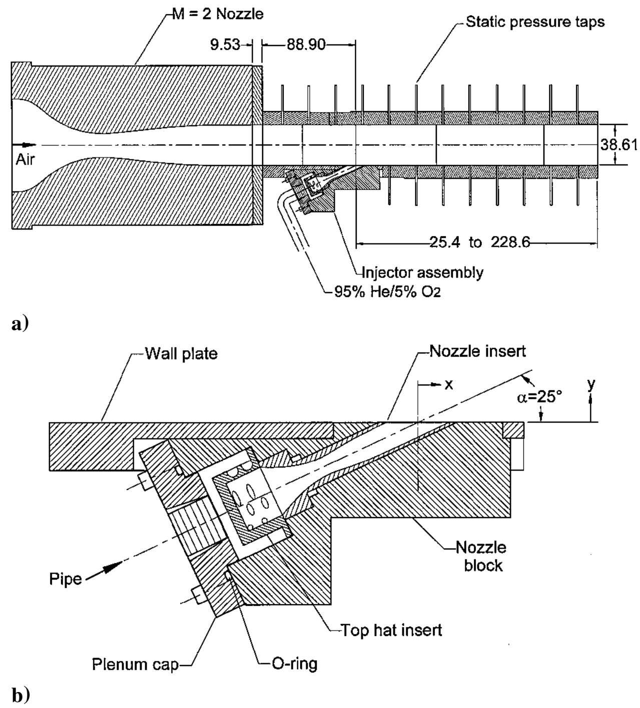

Fig. 1 Test model: a) nozzle, duct, and injector assembly and b) detail of injector assembly.

The injector nozzle inserts, with their associated top hat inserts, were sized to produce equal mass flow rate and exit pressure for equal supply (plenum) pressure. Injectant total pressure $p_{t,j}$ was chosen to provide nominally exit pressure matched conditions using the criterion of Mays et al.[2] Total pressure losses attendant to injection are believed to be small because flow through the holes in the top hat inserts is at low speed ($M \approx 0.2$) and the nozzles themselves are smoothly contoured. Thus, nozzle calculations were based on specified flow areas and assumed steady, isentropic, quasi-one-dimensional flow of the He-O_2 mixture (assumed a calorically perfect gas). In cases with swirl, the method of Ref. 15 was used, which additionally assumes a line vortex on the nozzle axis. Discrepancies between measured circulation and calculations by this method were observed to be in the range ±10–15%. (Ref. 15). With swirl the calculated resultant Mach number and flow angle to the axis at the edge of the jet ($\arctan(v_j/u_j)$) were 2.6 and 15 deg, respectively (Mach number and flow angle increase radially towards the axis of the nozzle). Without swirl the calculated Mach number was also 2.6. The ratios of axial velocity to airstream velocity u_j/u_∞ with and without swirl were calculated to be 2.4 and 2.5, respectively. The circulation of the jet divided by $u_\infty d$ for the swirl case was thus 2.1. Mass flow rates through the injector nozzles were measured as a function of plenum pressure using a calibrated orifice plate. Measured injector mass flow rates and various pressures and temperatures are given with uncertainties (which include instrument effects and the effects of run-to-run variations in flow conditions)

Table 1 Experimentally measured flow conditions

Variable	Mean	Uncertainty
$p_{t,\infty}$, kPa	794	± 5
p_{∞}, kPa	105.4	± 1.7
$T_{t,\infty}$, K	299	± 6
$p_{t,j}/p_{t,\infty}$	5.40	± 0.05
$T_{t,j}/T_{t,\infty}$	1.03	± 0.02
$\dot{m}_j$ swirl, kg/s	0.0333	± 0.0014
$\dot{m}_j$ no swirl, kg/s	0.0355	± 0.0015

in Table 1. All uncertainties are quoted for 95% probability limits (20:1 odds). The calculated mass flow rate at the $p_{t,j}$ and $T_{t,j}$ of Table 1 was 0.037 kg/s in both cases. The differences between calculated and measured injectant mass flow rates are caused by the effects of boundary layers and, with swirl, viscous effects in the vortex cores. The main nozzle exit Mach number was determined (by probe survey) to be 1.98 ± 0.01.

The injector exit diameter in this experiment is not small in relation to the distance between the injection wall and the wall opposite. The effect of the opposite wall is to reflect the bow shock back onto the fuel plume, reducing penetration in comparison to injection into an infinite stream by turning the flow back towards the injection surface. However, the present distance is representative of a practical implementation in a hydrogen-fueled scramjet engine. The equivalence ratio, that is to say the ratio of injectant mass flow rate to airflow in the duct, is about 0.3 of the ratio for stoichiometric combustion of hydrogen in air (0.0292). Thus, a practical application might utilize three such injectors across the width of the duct (not unreasonable given its aspect ratio), giving an overall equivalence ratio of about 0.9, nearly stoichiometric.

Instrumentation

Pressure measurements were acquired using strain-gauge-type transducers, with duct wall measurements performed with an electronic pressure-scanning system. Temperatures were measured using type T thermocouples. All data acquisition was with a PC-based system.

Flowfield surveys were conducted using a cone static pressure, a pitot, a stagnation temperature, and a gas sampling probe simultaneously mounted in a streamlined rake, which was swept in the y and z directions under computer control. The cone static pressure probe consisted of a 10-deg semivertex angle cone, with four equispaced 0.25-mm-diam sensor holes drilled normal to the surface, 4.06 mm from the tip, and connected internally. The pitot (pressure) probe was square cut at its tip, with i.d. of 0.36 mm and o.d. of 0.64 mm. The stagnation temperature probe consisted of a miniature thermocouple probe, 0.20 mm in diameter, with a cylindrical shroud 0.76 mm i.d. and 1.27 mm o.d., open at the upstream end and vented downstream. The gas sampling probe was 0.76 mm i.d. and 1.27 mm o.d. at the tip and diverged conically both internally and externally, with final i.d. of 2.29 mm. This design ensured that the flow entering the probe was supersonic, the sampled flow being shocked subsonic within the internal diverging passage.

Sampled gas was preconditioned by bringing it to 0°C and ambient pressure by passing it through coils in an ice bath, and then venting to atmosphere. Upstream of the vent, a small fraction of the sampled gas (which varied, but was typically 10–15%) was drawn off and passed through a length of straight tube over the sensor tip of a hot-film anemometer and through a choked orifice into a vacuum pump. Under these conditions the sensor was sensitive only to gas composition. The device was regularly calibrated for mole fraction injectant by forming known mixtures of injectant and air using flow controllers, passing these known mixtures of injectant and air though it, and curve fitting the response. Uncertainties in flow rate indicated by the flow controllers was $\pm 1\%$. Random error in the mole fraction measurement was very small, although the device did experience some drift in calibration. When this drift exceeded ± 0.005 in mole fraction, it was recalibrated. The resultant uncertainty in mole fraction from all sources is ± 0.01.

Table 2 Test cases

Case	Swirl	β, deg	Splitter
N0	——	0	——
N25	——	25	——
S0	X	0	——
S25	X	25	——
S-25	X	−25	——
S25X	X	25	X

Probes were spaced equally 6.35 mm (in z) apart on the rake. Data were acquired simultaneously with all probes with surveys at increments in z of 6.35 mm or 3.175 mm and at the same y locations. This allowed data taken at multiple rake locations to be organized to give data from the different probes at the same y, z locations. After the rake moved to a given sample location, there was a pause of 0.3 s prior to data acquisition. This time was determined in separate experiments to be sufficient to allow the pitot probe and gas sampling probe/gas analysis system responses to stabilize. Data were acquired at the exit of the duct, with surveys at different x achieved by simply building the duct to different heights. Comparison of wall-pressure data for various duct heights (with and without the presence of the rake) established that the different heights produced consistent data.

The gas analysis system was calibrated in terms of mole fraction injectant χ. These data were converted to mass fraction injectant α. The pitot and cone static probe data taken together with χ were reduced to obtain p and M using the Rayleigh pitot formula and numerical solutions for conical flow over the cone static probe obtained by the Taylor–MacColl method. T, ρ, and u could then be obtained from these results together with the thermocouple probe measurements. All calculations assumed steady flow of calorically perfect gases. Further details of the experimental techniques, and associated uncertainties, can be found in Refs. 14 and 16.

Experimental Cases

Six experimental cases are reported, as summarized in Table 2. These include cases with swirling (S) and nonswirling (N) jets with skew angles of −25, 0, and 25 deg injected from a flat wall. The last case S25X was conceived to test for the possibility of producing favorable vortex interactions. The idea was that if the injectant plume had net circulation interaction with a "mirror image" plume would result in improved penetration, i.e., the upflow induced by one vortex would cause the other to move away from the wall and vice versa. Rather than construct a second injector, a splitter plate was mounted in the duct, which produced an artificial plane of symmetry. This plate spanned the duct at $z = 20.3$ mm (parallel to the end walls which are at $z = \pm 87.9$ mm), and extended from $x = 0$ to the downstream end. The leading edge was sharp so that flow ahead of it was not influenced by its presence, and flow in the portion of the duct between 20.3 mm $< z <$ 87.9 mm was discharged at supersonic speed to the atmosphere.

Results

Mole Fraction Injectant

Figures 2–4 shows surveys of χ at, respectively, $x/h = 0.67, 3.31$, and 5.93, looking downstream. Positive z (and also skew) is to the right, injection is from the bottom, and swirl is counterclockwise. The box outlining each contour plot coincides with the duct wall. Only the N0 case and the S25 case were obtained at $x/h = 0.67$. In the N0 case the injectant plume is horseshoe shaped, whereas in the S25 case the plume is elongated, leaning toward the right. In both cases the plume tends to circularize, increase in diameter, and rise away from the surface moving downstream. All of the cases at $x/h = 3.31$ are shown in Fig. 3. By comparing cases N0 and N25 and also cases S-25, S0, and S25, it can be seen that the effect of skew is to move the plume slightly in the direction of skew, the more so nearer the injection wall. By comparing the S cases to the N cases, it can be seen that swirl slightly reduces penetration and shears the plume, with injectant near the surface being displaced to the left in relation to injectant farther from the surface. However, neither swirl

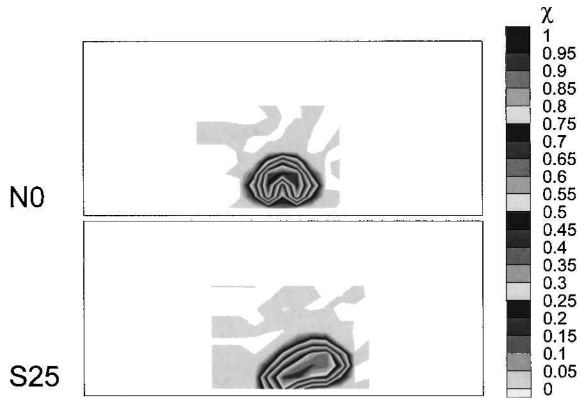

Fig. 2 Contours of χ and outline of duct walls for various cases at $x/h = 0.67$.

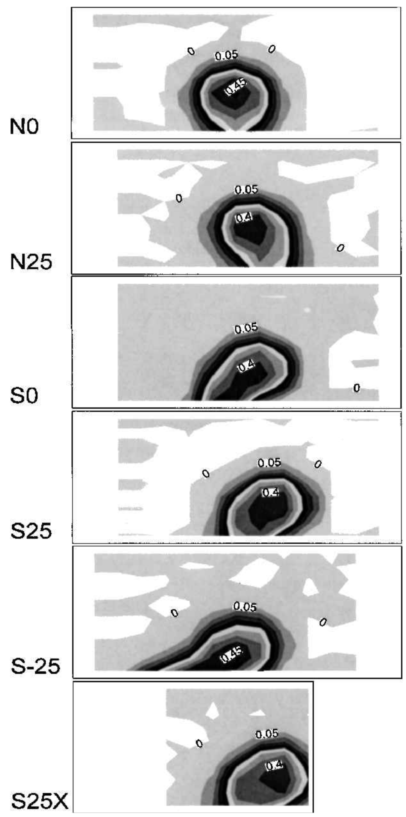

Fig. 3 Contours of χ at $x/h = 3.31$. Contours levels as in Fig. 2.

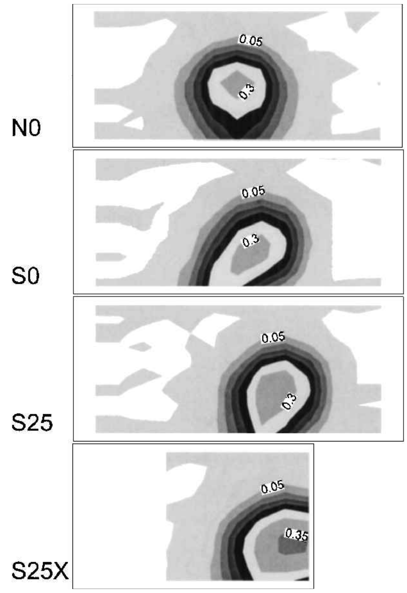

Fig. 4 Contours of χ at $x/h = 5.93$.

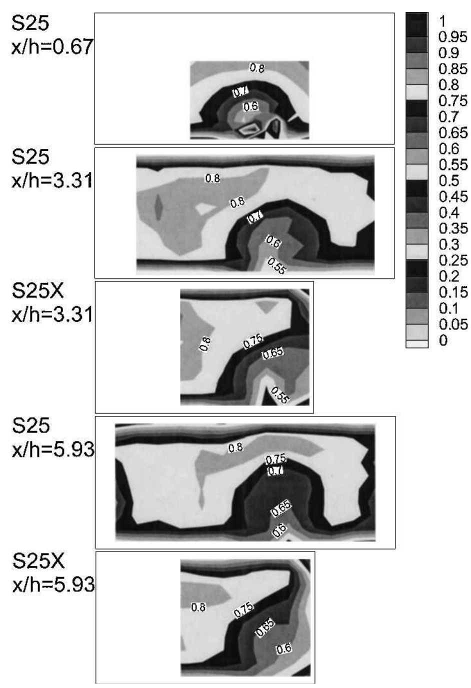

Fig. 5 Contours of $p_{\mathrm{pit}}/p_{t,\infty}$ and outline of duct walls for the S25 and S25X cases.

nor skew appear to have much effect on mixing. By comparing S25 and S25X, it can be seen that inserting the splitter plate to form a plane of symmetry has little effect on the mixing at this location. At $x/h = 5.93$, shown in Fig. 4, the plumes in the N0, S0, and S25 cases are more like each other in shape and size than at $x/h = 3.31$. The general trend is that the effects of the swirl and skew become less important moving downstream. The plumes diameters are several times the boundary-layer thickness at this point and nearly detached from the wall, so that the boundary layers probably do not control the plume development. The effect of the splitter plate (S25X) at this downstream location appears to be to raise injectant mole fraction near the bottom right corner, i.e., to slightly reduce mixing in the vicinity of the splitter, as might be expected.

Figure 5 shows contours of pitot pressure referenced to the airstream inlet total pressure for the S25 and S25X cases (identical except without and with splitter). The injectant plume and boundary layers are visible in these plots as regions of pitot pressure deficit. Surveys with the splitter plate were not conducted at $x/h = 0.67$, but comparisons at $x/h = 3.31$ and 5.93 indicate that the effect of the splitter was primarily confined to within 7.5 mm of the splitter surface. For these latter planes the surveys were at 6.35 mm spacing in z and do not adequately resolve the end-wall boundary layers. It may be concluded that the effect of the splitter outside this relatively thin boundary layer is minimal. Thus, because the splitter acts like a symmetry plane outside the boundary layer the plume has relatively little circulation (if it did, the plume would rise through interaction with the image in this plane).

Parameters

Figure 6 shows the peak mass fraction injectant $\alpha_{\max}$ plotted as a function of streamwise position for each case. Lower $\alpha_{\max}$ indicates better mixing. For hydrogen-air combustion the stoichiometric value of α is 0.0284 so that $\alpha_{\max}$ less than this implies complete mixing. At $x/h = 0.67$ the mixing is slightly greater for the S25 case than

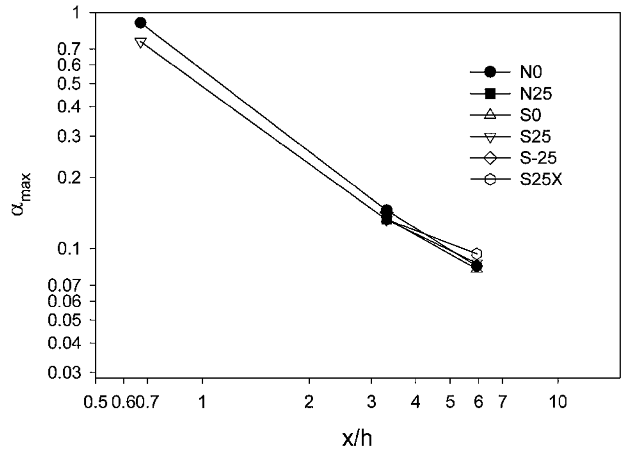

Fig. 6 Streamwise development of peak mass fraction injectant.

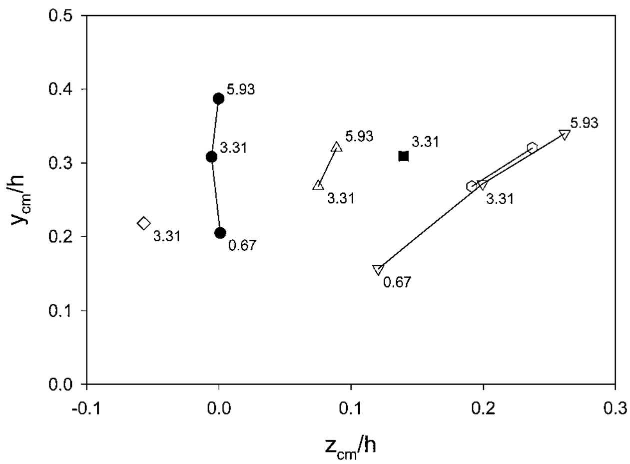

Fig. 7 Transverse motion of mass flux weighted plume center (labels are *x/h*). Symbols as in Fig. 6.

for the N0 case. This suggests that some of the mixing enhancement mechanisms proposed to be associated with swirl might indeed be effective in the near field. However, at $x/h = 3.31$ and 5.93 there are no significant differences among the cases, except that at $x/h = 5.93$ the mixing is slightly less for the S25X case than for the N0, S0, or S25 cases. It appears that, far downstream, the mixing is unaffected by skew or swirl, but is slightly reduced by the proximity of the splitter plate (symmetry plane). "Complete" mixing is projected to occur around $x/h = 15$.

Several quantities were obtained by integration of the data over the survey planes. The injectant mass flow rate was obtained from

$$\dot{m}_{j,\text{probe}} = \int \rho u \alpha \, \mathrm{d}A \tag{1}$$

Mass flow rates obtained in this way for the various cases and streamwise locations were randomly distributed within ±6% of the results obtained by direct calibration of the injector. Most of this scatter is believed to be caused by a sparse distribution of data within the planes and problems with interpolation between the wall and the data points nearest the wall. This result provides a check of the internal consistency of the data.

The injectant mass-flux-weighted location of the center of mass was obtained from

$$(y_{\text{cm}}, z_{\text{cm}}) = \frac{\int \rho u \alpha(y, z) \, \mathrm{d}A}{\dot{m}_{j,\text{probe}}} \tag{2}$$

The results are shown in Fig. 7. The penetration (distance y_{cm}) is greatest at all x locations for the nonswirling cases (N0 and N25), with skew having little effect. Swirl reduces penetration, particularly for the negatively skewed case (S-25). The change in penetration between $x/h = 0.67$ and 5.93 is nearly the same for the N0 and S25 cases, with the difference being in the near field, i.e., between $x/h = 0$ and 0.67. Positive lateral displacement (distance z_{cm}) is produced by swirl, and a larger amount is produced by positive skew. The effects of swirl and skew are roughly additive, with negative skew and positive swirl canceling to produce slightly negative lateral displacement. For those case where surveys were acquired at multiple x/h locations, the data seem to extrapolate linearly to z_{cm}, $y_{\text{cm}} = 0$, 0, i.e., $y_{\text{cm}} \propto z_{\text{cm}}$. Lateral movements of the plume in the swirl cases are much less than would be expected for a single isolated streamwise vortex with the same circulation as that contained in the jet at the injector nozzle exit. The lateral movement of such a vortex at a height y above the injection surface in a streamwise distance Δx as a result of the image of the vortex in the injection surface can be estimated from $\Delta z = \Delta x(v_j/u_\infty)(d/4y)$. Using the calculated values of v_j/u_j and u_j/u_∞ and the experimental y_{cm} (case S25), the equation gives $\Delta z_{\text{cm}}/h = 0.23$, 0.34, 0.23 in the ranges $x/h = 0$ to 0.67, 0.67 to 3.31, and 3.31 to 5.93, respectively. This compares to the experimental $\Delta z_{\text{cm}}/h = 0.12$, 0.079, 0.062. Thus, the circulation contained by the plume appears to be much less than that contained by the swirling jet at injection.

Conclusions

The effects of swirl and skew on the mixing and penetration of a supersonic jet of light gas, injected from a flat wall, pitched at 25 deg to the wall into a Mach 2 ducted flow of air have been investigated. Experiments were conducted at nominally constant injectant mass flow rate, stagnation pressure, and nozzle exit static pressure. Cases had either no swirl or swirl combined with either 25, 0, or −25 deg of skew. It was proposed that swirl would increase injectant mixing. The effect of combined swirl and skew is to slightly increase mixing in the near field of injection; however, there is little effect of swirl and/or skew on mixing downstream. Both swirl and skew slightly reduce penetration. It was also proposed that the plume produced by swirling and/or skewed injection would have circulation and that this might be used to produce beneficial interactions between plumes. However, the circulation is small, much less than within the swirling jet at injection, and beneficial interactions could not be found.

Acknowledgments

The authors would like to acknowledge NASA Langley Research Center, which provided financial support and experimental facilities through Grants NCC-1-217 and NCC-1-370, technical monitor G. S. Diskin.

References

[1]McClinton, C. R., "The Effect of Injection Angle on the Interaction Between Sonic Secondary Jets and a Supersonic Free Stream," NASA TN D-6669, Feb. 1972.

[2]Mays, R. B., Thomas, R. H., and Schetz, J. A., "Low Angle Injection into a Supersonic Flow," AIAA Paper 89-2461, July 1989.

[3]Thomas, R. H., Schetz, J. A., and Billig, F. S., "Gaseous Injection in High Speed Flow," *Proceedings of the 9th International Symposium on Air Breathing Engines*, Greek General Secretariat for Research and Technology and National Technical Univ. of Athens, Sept. 1989.

[4]Fuller, E. J., Mays, R. B., Thomas, R. H., and Schetz, J. A., "Mixing Studies of Helium in Air at High Supersonic Speeds," *AIAA Journal*, Vol. 30, No. 9, 1992, pp. 2234–2243.

[5]Eklund, D. R., Stouffer, S. D., and Northam, G. B., "Study of a Supersonic Combustor Employing Swept Ramp Fuel Injectors," *Journal of Propulsion and Power*, Vol. 13, No. 6, 1997, pp. 697–704.

[6]Cutler, A. D., Levey, B. S., and Kraus, D. K., "Near Field Flow of Supersonic Swirling Jets," *AIAA Journal*, Vol. 33, No. 5, 1995, pp. 876–881.

[7]Naughton, J. W., Cataffesta, L. N., III, and Settles, G. S., "An Experimental Study of Compressible Turbulent Mixing Enhancement in Swirling Jets," *Journal of Fluid Mechanics*, Vol. 330, 1997, pp. 271–305.

[8]Cattafesta, L. N., III, and Settles, G. S., "Experiments on Shock/Vortex Interaction," AIAA Paper 92-0315, Jan. 1992.

[9]Kraus, D. K., and Cutler, A. D., "Mixing of Swirling Jets in a Supersonic Duct Flow," *Journal of Propulsion and Power*, Vol. 12, No. 1, 1995, pp. 170–177.

[10]Gilmore, C. P., "Spin Sail," *Popular Science*, Vol. 224, No. 1, 1984, pp. 70–73.

[11]Compton, D. A., and Johnston, J. P., "Streamwise Vortex Production by Pitched and Skewed Jets in a Turbulent Boundary Layer," *AIAA Journal*, Vol. 30, No. 3, 1992, pp. 640–647.

[12]Zhang, X., and Collins, M. W., "Flow and Heat Transfer in a Turbulent Boundary Layer Through Skewed and Pitched Jets," *AIAA Journal*, Vol. 31, No. 9, 1993, pp. 1590–1599.

[13]Jacobsen, L. S., Schetz, J. A., Gallimore, S. D., and O'Brien, W. F., "Mixing Enhancement by Jet Swirl in a Multiport Injector Array in Supersonic Flow," FEDSM99-7248, *Proceedings of the 3rd American Society of Mechanical Engineers/JSME Joint Fluids Engineering Conference*, Vol. 4, edited by P. A. Pfund, Y. Matsumoto, and H. Hayami, ASME, San Francisco, CA, July 1999, pp. 685–691.

[14]Doerner, S. E., "Effects of Jet Swirl on Mixing of a Light Gas Jet in a Supersonic Airstream," Master's Thesis, School of Engineering and Applied Science, George Washington Univ., Washington, DC, May 1999.

[15]Cutler, A. D., and Barnwell, R. W., "Vortex Flow in a Convergent-Divergent Nozzle," *AIAA Journal*, Vol. 37, No. 10, 1999, pp. 1329–1331.

[16]Cutler, A. D., and Johnson, C. H., "Analysis of Intermittency and Probe Data in a Supersonic Flow with Injection," *Experiments in Fluids*, Vol. 23, No. 1, 1997, pp. 38–47.