Swirling Base Injection for Supersonic Combustion Ramjets

Louis A. Povinelli* and Robert C. Ehlers†
NASA Lewis Research Center, Cleveland, Ohio

Introduction

SWITHENBANK and Chigier[1] have proposed that swirling base injection may be useful in supersonic combustion ramjets, i.e., scramjets. Substantial increases in mixing rates between the injected fuel and the airstream are postulated to occur due to the creation of radial and axial pressure gradients in the swirling flow. The existence of these pressure gradients as well as a region of reverse flow is analogous to the behavior of an axisymmetric jet issuing into a quiescent atmosphere. It was further proposed that injectors with variable swirl could be fitted into scramjet combustion chambers.[1] The rate of mixing, angle of jet expansion, and the size of the internal reverse flow region could be controlled by a variation in the amount of swirl. To date, no experimental data have been published which tests the concept of accelerated mixing due to swirl in supersonic streams. This study was performed to evaluate that concept.

Experimental Configurations

The two slender cone injectors tested in this study are shown in Fig. 1. The swirling flow model was identical to the nonswirler with one exception. That exception was the manner in which the gaseous injectant entered the model. Figure 1b shows the tangential entry configuration of the swirler while Fig. 1c shows the conventional passage for the nonswirling injector. A majority of the tests were conducted using helium as the injectant. The injection pressures were 25, 65, and 155 psia (1.7, 4.5, 10.7 × 10^5 N/m^2, respectively). All pressures were measured in the plenum upstream of the nozzle throat. Radial concentration surveys for helium were made at a position of 20 orifice radii downstream ($X/r_0 = 20$). The sampling technique is described in Ref. 2.

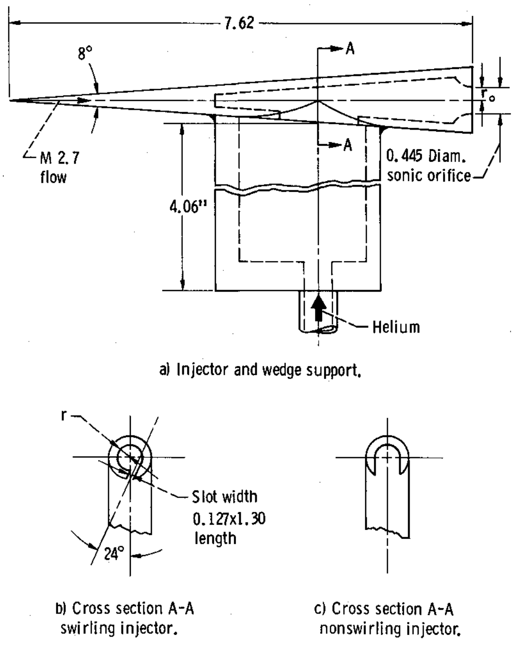

Fig. 1 Slender cone injectors with base injection. Dimensions in centimeters.

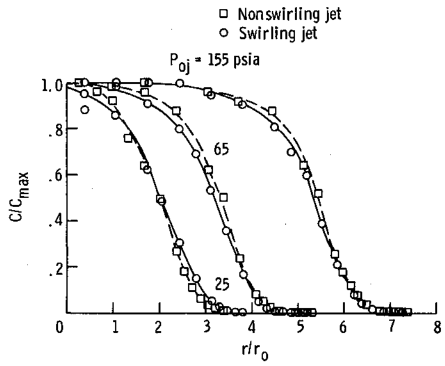

Fig. 2 Radial helium concentration profiles. $P_{0_\infty} = 25$ psia, $x/r_0 = 20$.

Cold nitrogen (275°K) was also used as an injectant. The injection pressure was 120 psia (8.3 × 10^5 N/m^2). The jet boundary locations were determined from radial temperature surveys. These surveys were made at $X/r_0 = 11$.

Tests with both injectors were performed in an $M2.7$ airstream having a total pressure of 25 psia (1.7 × 10^5 N/m^2). Both injectors were aligned with the flow (zero degree angle of attack).

Previous work in the literature has established that jet penetration correlates with pressure ratio (injection-to-freestream). Therefore, in the present study, the behavior of the two injectors was compared on the basis of equal injection pressure.

Results

The radial concentration surveys for helium are shown in Fig. 2. The six profiles result from using three injection pressures with both the swirling and nonswirling injectors. As seen in the figure there is only a slight difference in the helium distribution due to swirl. The maximum difference between the swirling and nonswirling results amounts to $\frac{1}{4}$ of an orifice radius ($r/r_0 = 0.25$) and is equivalent to the inside diameter of the sampling probe. On the basis of this test it appears that the postulation regarding accelerated mixing due to swirl is not correct.

Since the dynamic pressure ratio with helium injection was relatively low it was decided to use nitrogen injection. Radial nitrogen temperature surveys are shown in Fig. 3. The jet boundary was assumed to be located at the point of zero temperature difference between the local total temperature (T_0) and freestream total temperature (T_{0_∞}). It is seen in Fig. 3 that both the swirling and nonswirling jet boundaries are identical, i.e.,

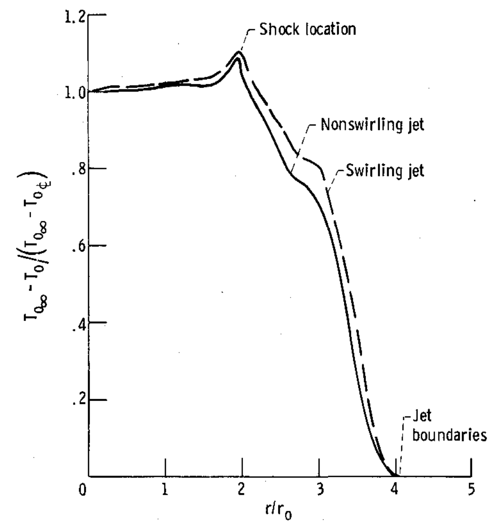

Fig. 3 Radial nitrogen temperature profiles. $P_{0_\infty} = 25$ psia, $x/r_0 = 11$, $P_{0j} = 120$ psia, $T_{0_\infty} = 340$°K, $T_{0j} = 275$°K.

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* Aerospace Research Scientist—Airbreathing Engines Division. Associate Fellow AIAA.
† Research Operations Engineer—Airbreathing Engines Division.

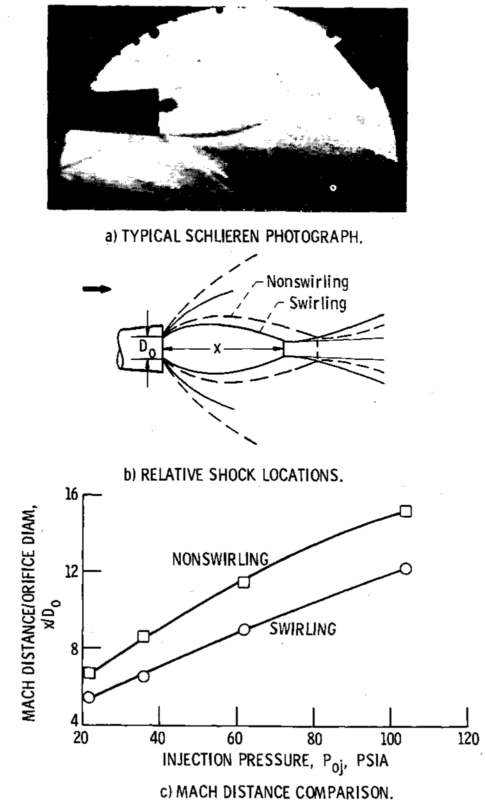

Fig. 4 Shock structure comparison.

$r/r_0 = 4$. This result indicates that the effect of swirl on the jet boundary position in supersonic flow is negligible.

Since the swirl was introduced 1 in. upstream of the jet exhaust some of the swirl may have decayed by the time the injectant reached the nozzle exhaust plane. Hence, an additional set of measurements was made using an insert located inside the injector, immediately upstream of the nozzle. This insert was a small plug having three spiral grooves on the periphery. These grooves made the injectant turn 135° over the length of the insert (0.64 cm). The measurements showed that the radial helium concentration profiles for the swirling injector with the insert were slightly lower ($\Delta r/r_0 = 0.25$) than the nonswirling injector profiles. Again this difference was equivalent to the inside diameter of the sampling probe. Hence, swirl does not give rise to accelerated mixing in supersonic flow.

In the course of this investigation, schlieren photographs were made of the base flow region of the injectors. A typical photo is shown in Fig. 4a. The highly underexpanded jet gives rise to the usual envelope (or barrel) structure which terminates in a Mach disc and two reflected waves. Slip lines can also be seen emanating from the reflection points. Figure 4b shows a comparison of the shock structure for both the swirling and nonswirling jets. It is noted that the distance to the Mach disk from the exit orifice is greater for the nonswirling jet. Figure 4c shows a comparison of this distance as a function of injection pressure. It has been shown that this distance is only a function of the static pressure ratio.[3] Hence, the curves shown in Fig. 4c indicate that the exit pressure of the swirling jet is less than that of the nonswirling jet. Since strong radial pressure and velocity gradients are an integral part of vortex flows it is conceivable that the jet exit pressure, integrated over the exit area, is less for the swirling jet than for the nonswirling one. The pressure decrease may be due to the increased viscous losses in the nozzle.

Since the jet boundary positions for both injectors were found to be identical, it must be concluded that the changes in shock structure are not indicative of a change in the 0% injectant boundary. It follows that the change in shock position indicates a change in the streamlines within the flow. The radial distribution of the injectant should therefore be different for the swirling and nonswirling cases. The experimental data, shown in Fig. 2, show that the radial distributions are, in fact, dissimilar.

The Mach disk position has an important implication as far as injection normal (rather than coaxial) to the stream is concerned. This is so because the distance from the injection orifice to the Mach disk position is proportional to the amount of jet penetration obtained in supersonic streams. Hence it appears that swirling jet flow would yield less penetration than nonswirling flow when injection normal to the freestream is employed.

In conclusion, the concept of accelerated mixing in supersonic streams due to swirl has been tested. The results indicate that swirl does not produce any enhancement of mixing.

Note Added in Proof

Since this Note was prepared for publication, a report[4] has been published dealing with the effect of swirl on co-axial jet mixing in a supersonic stream. From a comparison of nonswirl and swirl data, it was concluded in Ref. 4 that the swirl had no discernible effect on the mixing. That conclusion is in agreement with the results of this study.

References

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Best Finite Elements Distribution around a Singularity

Isaac Fried* and Shok Keng Yang†
Boston University, Boston Mass.

Introduction

As long as the solution, both in boundary value problems and eigenvalue problems, does not include singularities, increasing the degree of the interpolation functions inside the elements will always result in an increase in the rate of convergence of the finite element method. In fact,[1] if the interpolation (shape) functions inside the element include a complete set of polynomials of degree p then for problems of the $2m$th order ($m = 1$ in harmonic problems and $m = 2$ in biharmonic problems) the error in the energy in boundary value problems and the error in the eigenvalues in eigenvalue problems is $0[h^{2(p+1-m)}]$ where h is the diameter of the element. The reason for this is that any smooth function (without singularities) can be approximated as closely as desired by polynomials. If, however, the solution function includes a singularity then around the singular point the function itself or its derivatives up from a certain degree can no more be approximated by polynomials. Increasing the order of the interpolation functions inside the element will not result, with a given mesh, in

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* Assistant Professor, Department of Mathematics. Associate Member AIAA.
† Graduate Student, Department of Mathematics.