Chapter Two: Injection and Mixing in Supersonic Flow

Review

Much work has been done toward developing effective injector concepts for mixing of supersonic flows. Basic research began decades ago and has continued with mixed results until the present day. Because no one injector concept has completely satisfied all design requirements for multiple applications, a great number of injector concepts have been developed and tested. Some of the major categories are flush-mounted transverse injectors, tangential slot injectors, shaped injectors, and "structural interference injectors", which will be defined and discussed shortly. A thorough review of work through 1991 can be found in Reference 8.

Flush-mounted injectors are among the simplest available, both conceptually and physically. In its simplest form a flush-mounted injector is no more than a circular tube connecting a chamber of pressurized injectant fluid to the lower-pressure primary flow with which it is to mix, as shown in Figure 2.1. This simplicity has undoubtedly added to the popularity of flush-mounted injectors, but they are desirable for other reasons as well. Another primary advantage of flush-mounted injectors is that they do not introduce structural obstacles into the flowfield. Structural objects placed in supersonic flows increase drag and the "wetted area" on which the skin friction acts, and they often generate shocks which introduce pressure losses. Furthermore, the supersonic flowfield environment is a harsh one due to extreme temperatures and pressures, and survivability of structures becomes an issue. For all these reasons, flush-mounted injectors have been studied at least since the mid-nineteen sixties. (See References 9 through 12 and their references.) Schetz and Billig *et. al.*[9, 10] concentrated on the nearfield structure of normal injection into supersonic flow, developing rather useful semi-empirical techniques for analysis and prediction of injectant penetration into and interaction with the primary flow. Rogers[11, 12] investigated the effects of dynamic pressure ratios and injector spacing on the mixing characteristics of normal jets of sonic hydrogen, and McClinton[13] complemented the work with similar studies of injection with downstream angles between thirty and ninety degrees. More recently, Mays *et al.*[14] extended the database to downstream angles as low as fifteen degrees for sonic helium at two pressure ratios and discovered that low-angled injectors have downstream mixing rates as high as those for normal injection, though the initial mixing is lower and the associated shocks are weaker oblique shocks (implying lower total pressure losses). Davis *et al.*[15] conducted similar studies at ten degrees with supersonic air mixed with a tracer. Next Fuller *et al.*[16-17] studied the effects of injector yaw on low downstream-angled injectors, proving that yaw increases the overall mixing area but does somewhat inhibit core mixing. Finally, Riggins and McClinton[18] compared a single transverse injector angled downstream at thirty degrees with two leading "structural interference" designs in a numerical study of flow losses and thrust potential. The flush-mounted injector was found to compare favorably with the others in the study.

Tangential slot injectors have been considered more a cooling mechanism than a mixing mechanism, and mixing data involving slot injectors is rare. Schetz *et al.*[8] provide an interesting survey and analysis of data published through 1991 and draw the conclusion that in the downstream (i.e. farfield) mixing region slot injectors perform comparably with other types of injectors, though in the injection region mixing is quite poor. King *et. al.*[19] attempted to improve the initial mixing of tangential slot injectors by combining them with normal injectors downstream of the slots, and found that the combination did have faster mixing rates than the tangential slots alone.

The motivation for studies of shaped injectors with nozzles is the belief that the key to successful mixing lies not in large-scale manipulations of the primary flow or injectant stream after injection but in relatively small-scale details of the injector itself, which are believed to create and set in motion important structures of various scales (both large and small) within the injectant plume. Thus, shaped nozzle injectors are not exactly a separate category but more of a special subset within most every category of injectors. Gutmark *et al.*[20] conducted mixing and combustion tests of several shaped injectors, including conventional circles and ellipses but also less conventional squares and other polygons. Their research revealed that the shape of the injector plays a definite role in mixing of the injectant with the primary flow, at least in the injector region. Of particular note is the importance of the angles and the alignment of vertices to vortical strength and shock formation. Similar findings resulted from an independent study by Kopchenov and Lomkov[21]. Samimy *et al.*[22] investigated the use of small tabs to disturb the flow at the exit of a circular injector nozzle and found a significant increase in entrainment of primary flow when either two or four tabs were used. Kraus and Cutler[23] studied the effects of swirling the injectant inside the injector nozzle and found that swirl does improve mixing, albeit not without cost (additional complexity and higher total pressure losses). In another investigation of the importance of nozzle details, King *et al.*[24] discovered that roughness elements as small as ten percent of the thickness of the injectant boundary layer inside the injector can greatly affect the development of streamwise structures that influence mixing. Finally, Haimovitch *et al.*[25] implemented a number of shaped nozzle injectors, including circular injectors with and without tabs, an elliptical injector, a tapered slot injector, and others, in a complicated wall injector of the "structural interference" type. Although the nearfield effects due to some of the noncircular nozzles were dramatic, flow visualization in the farfield revealed few but distinct differences in mixing, suggesting that the common wall injector structure and its associated flow characteristics may mask some of the differences observed by other researchers.

"Structural interference injectors" can be defined as injectors that deliberately disturb the mainstream flowfield by placing into it some mechanical (though usually static) element. The role of the mechanical element may be to produce shocks, to provide a recirculation region to stabilize a flame, or simply to raise the injector itself out of the boundary layer. Designers of structural interference injectors accept the losses inherent to mechanically disturbed supersonic flowfields in exchange for the superior mixing characteristics such injectors are believed to possess. Examples of structural interference injectors include wall-mounted wedges for shock-enhanced combustion[26] and (at least loosely fitting into this category) backward-facing steps with injection at the base[27].

One of the more popular injector concepts in recent years is a structural interference injector that can be thought of as a three-dimensional variation of a backward-facing step. While backward-facing steps have been investigated for supersonic mixing, Drummond *et al.*[27] suggest that ordinary backward-facing steps trap the injectant in corners and do not allow sufficient penetration of the mixture into the primary flow. The three-dimensional variation of the design breaks the backward-facing step into a number of discrete segments across the flowfield and separates them by smooth channels designed to draw the energetic primary flow into the mixing region. The backward-facing step then becomes a wall-mounted wedge or ramp with the injector or injectors set into the face of the step.

A number of variations of this ramp injector concept have been investigated, including the so-called swept ramps, unswept ramps, compression ramps and expansion ramps. Some typical designs are shown in Figure 2.1. One extensive, mostly experimental research program has been conducted by Northam *et al.*[25, 28-32] at NASA Langley Research Center. An equally extensive, mostly computational study of similar injectors has been made at the same location by Riggins, McClinton, and their associates[1, 27, 33]. Work has also been done at the University of Virginia[34] and at NASA Lewis Research Center[35].

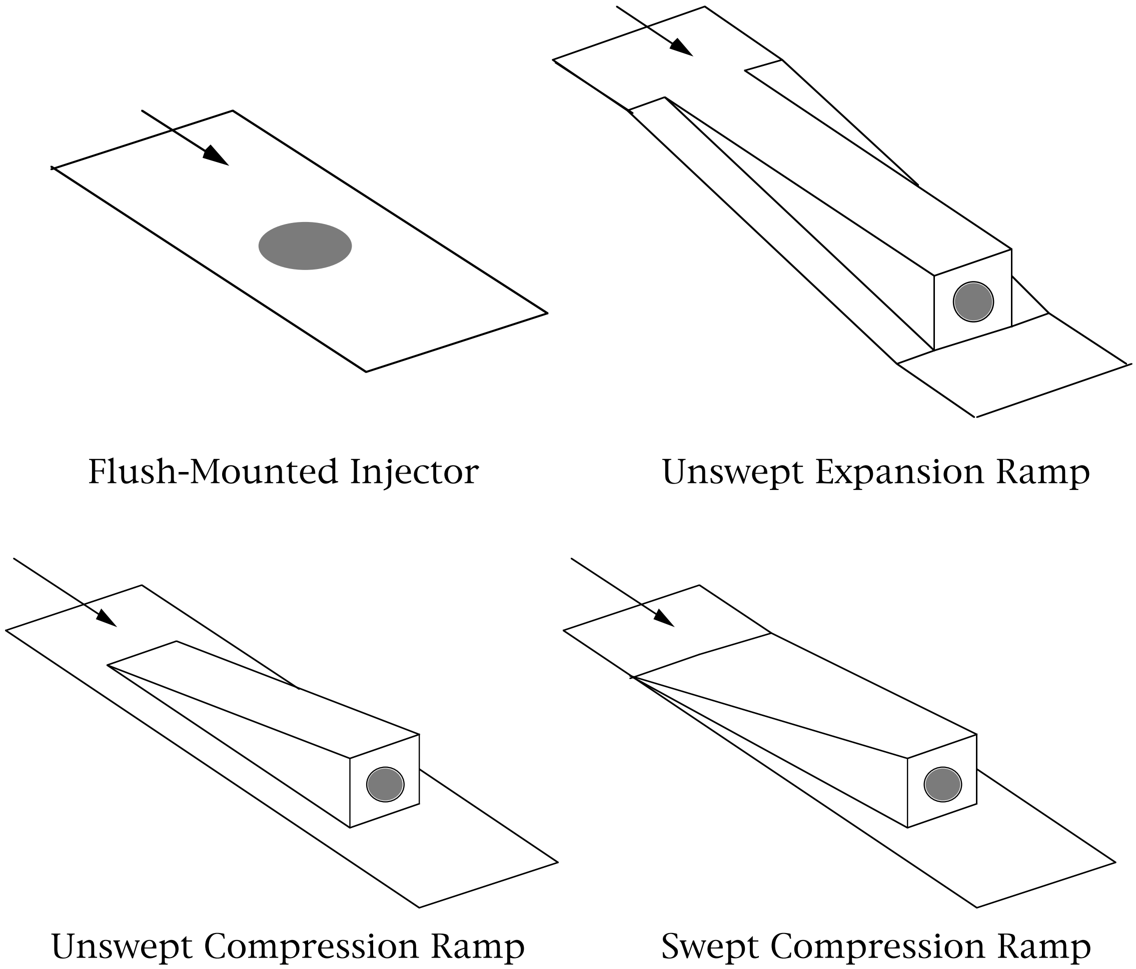

Figure 2.1. Typical Flush and Structural-Interference Injector Configurations. Arrows Denote Direction of Freestream Flow.

A certain amount of useful information can be gained from a brief review of the Northam research program. In 1989 Northam *et. al.* introduced a swept compression ramp of the style shown in Figure 2.1, with the idea that reducing the width of the ramp downstream should force an increase in spillage of primary flow off the sides of the ramp, and therefore an increase in the strength of the resulting vortical structures. Experimental tests demonstrated that combustor performance of this injector scheme was comparable to that reported using normal injectors. This unusually rapid near-parallel jet mixing was due to the longitudinal vorticity generated by the injector ramps[36]. The experiments and calculations showed that the injectors were effective in promoting the lateral spreading of the fuel jets. The Northam ramp is not without flaws, however. Studies of such ramps have shown that injectant penetration is a major limitation to mixing[32], suggesting a need to improve penetration. Furthermore, the design retains one of the major drawbacks of all structural interference injectors, in that it places large structures into the primary flowfield itself, causing significant shocks, increased drag (by blocking a sizable portion of the flowfield with an immobile, solid structure instead of only a moving injectant plume, and elevated skin friction. Additionally, the performance of all ramps is closely connected to the details of their geometry, requiring careful control of thermal degradation (i.e. cooling) at flight conditions.

Present Injectors

Two injector concepts were chosen for inclusion in this study. The first is a complex flush-mounted injector array composed of nine closely-spaced transverse elliptical nozzles. The second is a generic version of the common ramp injector. Careful explanation of each will be given below.

In light of the promise shown by wall-mounted ramp injectors in mixing and combustion tests such as the Northam series mentioned above, and recognizing the inherent disadvantages of any structural interference injector, a natural question arises: Is it possible to design an injector that possesses the same positive qualities as a wall-mounted ramp injector without actually introducing physical structure into the flowfield? Such a design would benefit greatly from reduced skin friction and drag, and might show substantially improved pressure recovery characteristics. The most important feature of such an injector would be its ability to produce the strong, streamwise vortices for which wall-mounted ramps are known. Creation of such longitudinal vortices has long been identified as an important technique for mixing augmentation[37]. Another important feature of the ramp injectors is the low angle made by both the injectant fluid and the ramp structure with respect to the freestream. The low angle of the injectant fluid ensures that most of its momentum is added to the thrust of the vehicle, and the low angle of the structure causes the formation of oblique shocks, rather than stronger normal shocks.

The flush-mounted injector array studied in this investigation was designed for exactly that purpose: to create streamwise vortices for mixing augmentation in much the same way that ramp injectors do, but with only low-angled, flush-mounted injectors. It was conceived by Dr. J.A. Schetz of VPI&SU and first described in Reference 38. The basic principle of its operation is to form from the injectant fluid a well-formed and carefully designed obstacle, in order to create and sustain significant streamwise vortices, which aid in the mixing of the injectant with the primary fluid. To this end the injector array enhances and augments the weak pair of counterrotating vortices that form at the sides of an isolated underexpanded injectant plume , which are otherwise too poorly formed to serve a meaningful role in mixing. It is further hoped that this arrangement of low-angled injectors will at the same time improve penetration over that of isolated low-angle injectors and possibly over that of wall-mounted ramps.

A diagram of the injector array layout is shown in Figures 2.2 and 2.3. All nozzles have the same diameter, d = 0.0625 inches (1.59 mm). As shown in the figure, the row of nozzles furthest upstream have no yaw and are spaced so that their centers are 3d apart. The transverse angle of these first nozzles is fifteen degrees. The second row of nozzles is centered 7d downstream from the center of the first and has a transverse injection angle of thirty degrees. This second row is spaced so that their centers are only 2.5d apart, and the outer injectors are yawed inward by fifteen degrees. The third row is centered 7d downstream from the center of the second row and has a transverse injection angle of forty-five degrees. The centers of the nozzles in this last row are only 2d apart horizontally, and the outer injectors are yawed inward by thirty degrees. The length of each nozzle is determined by the equation

$$length = d/\sin(\alpha) \tag{2.1}$$

where α is the transverse injection angle.

The intended behavior of the injector can be described as follows: As shown in the figure, the primary airstream flows left to right. The first row of nozzles have a transverse injection angle of only fifteen degrees, so the shock structure associated with the injectant plume will be oblique and weak, minimizing the total pressure losses to the primary flow that passes through the shock structure. Part of the primary airstream flows around the injectant plume, but the rest is displaced upward and flows above the plume as though traveling along a ramp. The second row of nozzles produces another weak shock, reinforces the plume, and forces it higher, but since the nozzles of the second row are more closely spaced the flow at the outermost edges (both primary airflow and injectant from the first row of nozzles) is not supported and is free to flow downward and outward from the plume. The third row drives the injectant plume even higher but once again does not support the outer edges, allowing even more "spillage" of injectant and primary air. The intended behavior of the injector array is that the spillage of air and injectant at the edges of the plume will create skew-induced streamwise vortices much like those of the ramp injector. In fact, this design has been called an "aerodynamic ramp."

An experimental investigation of the behavior of this injector array was conducted by R.P. Fuller in Virginia Tech's 9 x 9 inch (23 x 23 cm) blowdown supersonic wind tunnel. Sonic helium was injected into air with a freestream Mach number of 3, a total pressure of 6.5 atm, and a total temperature of approximately 528 R (293 K). These conditions yielded a freestream Reynolds number of 2.5×10^7 per foot (8.3×10^7 per meter). The test section was 4.5 inches (11 cm) high, 9.0 inches (23 cm) wide, and approximately 12 inches (30 cm) long. The total pressure of the injected helium was 7.0 atm, which

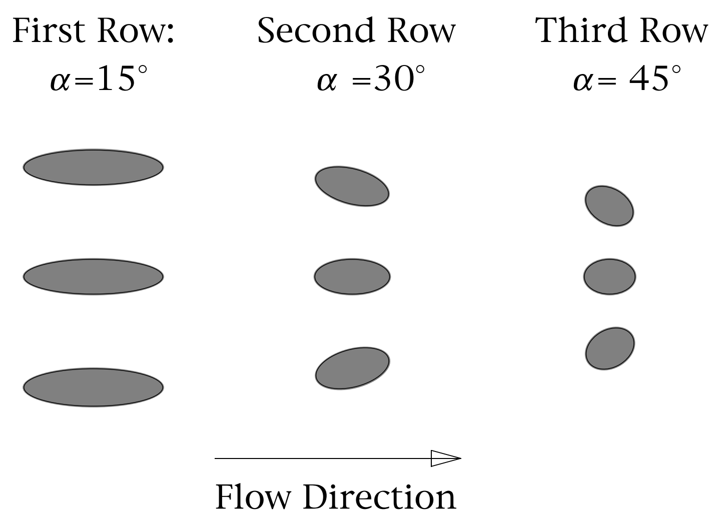

Figure 2.2 Injector Array Layout.

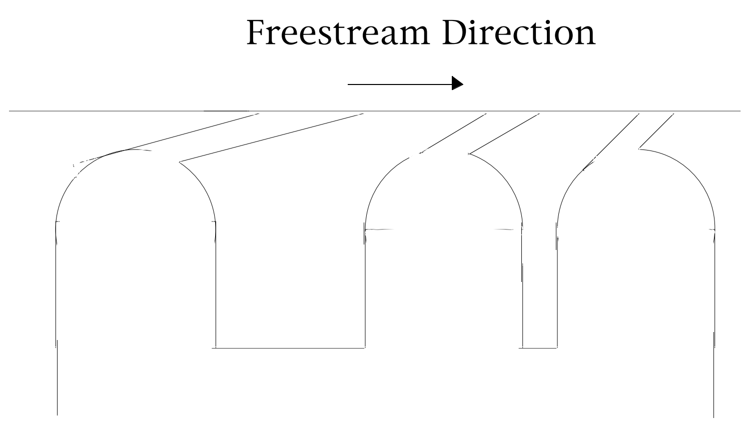

Figure 2.3 Injector Array Configuration.

corresponds to 5X underexpansion by the calculation method of Schetz and Billig[9] and following the recommendations of Mays *et al.*[14] for helium injection into a Mach 3 freestream. The total temperature of the injectant was approximately 293 K. Data from this series of experiments includes crossflow nanoshadowgraphs, surface flow visualization, and concentration measurements. Concentration measurements were taken via probe sampling at one axial station located 43 effective diameters downstream of the center of the first injector, where the effective diameter d_{eff} is taken to be 3d or 0.188 inches (4.76 mm). Data from these experiments have been previously reported in Reference 38.

The second injector tested in this investigation is a generic variation of the common ramp design. Despite the successes of the Northam ramp the present design differs in a few significant ways. It is unswept, in an attempt to reduce flow blockage and drag. It is neither a pure compression ramp nor a pure expansion ramp but has characteristics of both. It has four injector ports set into the face of each ramp instead of one. And it is taller and narrower than the Northam ramps, in an attempt to increase penetration. A schematic of a single injector of the type used in this investigation is shown in Figure 2.4.

The ramp injector is expected to function in the following manner. In the figure, the primary flow travels from left to right. As the primary flow encounters the beginning of the ramp an oblique shock wave is generated, which is expected to reflect and strike the mixing region downstream, thereby aiding mixing though the baroclinic mechanism. A portion of the primary flow passes through the oblique shock and makes its way up the ramp, and the rest flows down the expansion ducts beside the ramp. Because the primary flow is supersonic, the expanding flow accelerates and pressure decreases. The pressure gradient between the flow above the ramp and that beside it causes spillage of the flow above the ramp into the expansion ducts. The spilling flow is expected to "roll up" into skew-induced, streamwise vortices in the corners of the expansion ducts, and these vortices are further expected to entrain injectant and to carry it away from the wall for mixing with the primary flow. The injectant itself comes from four low-angled, supersonic, elliptical nozzles, one roughly in each corner of the ramp face. Downstream of the ramp face is a recirculation region, which is considered advantageous for flame stability in combustion applications.

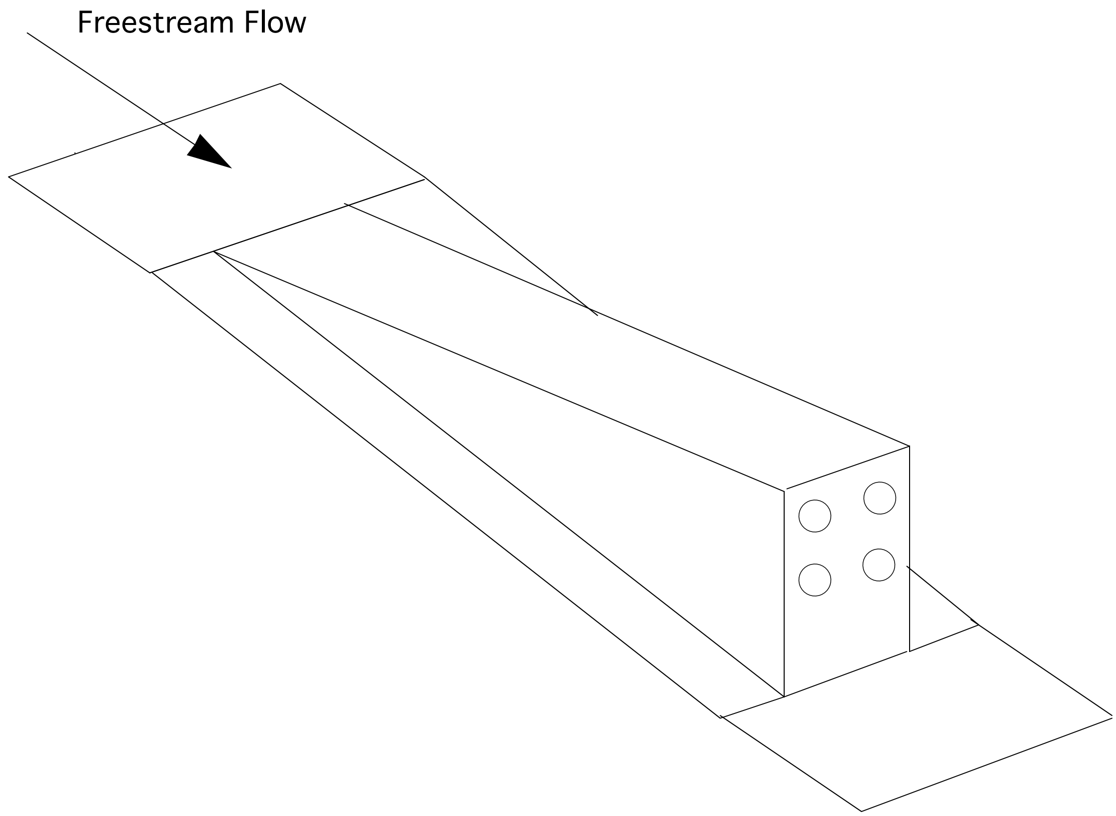

Figure 2.4. Schematic of the Investigated Ramp Injector.

As part of a larger experimental and computational study conducted at Wright-Patterson Air Force Base[39], injectant concentration, stagnation pressure, and stagnation temperature data from an experiment involving a number of these injectors was made available for comparison purposes. All injector nozzles have injection angles of 11.77 degrees. The bottom nozzles have no yaw, but the top nozzles are yawed outward at ten degrees. In the wind-tunnel tests the freestream Mach number was 4.5, the total pressure was 21.0 atm, the total temperature was 1080 R (600 K), and the freestream fluid was air. The injectant was a mixture of helium and air (helium mole fraction .396) at Mach 2.669. The total pressure was 6.16 atm and the total temperature was 560 R (311 K). Data was collected at two axial stations, 10.0 and 20.0 ramp-heights downstream of the injector faces.