NASA TECHNICAL NOTE

NASA TN D-5322

c.1 c.1

NASA TN D-5322

TECH LIBRARY KAFB, NM

0133223

LOAN COPY: RETURN TO
AFWL (WLIL-2)
KIRTLAND AFB, N MEX

A STUDY OF HELIUM PENETRATION AND SPREADING IN A MACH 2 AIRSTREAM USING A DELTA WING INJECTOR

by Louis A. Povinelli, Frederick P. Povinelli, and Martin Hersch

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1969

TECH LIBRARY KAFB, NM

0132323

A STUDY OF HELIUM PENETRATION AND SPREADING IN A MACH 2 AIRSTREAM USING A DELTA WING INJECTOR

By Louis A. Povinelli, Frederick P. Povinelli, and Martin Hersch

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

Experiments were conducted to determine if vortices could aid the penetration and spreading of helium in a Mach 2 airstream. A half-delta-wing injector, having a 30° semiapex angle and a 12° angle of attack, was used. This delta configuration was designed to produce leading edge vortices into which helium was injected. A flat plate of the same blockage area and at the same angle of attack was also run for comparison. Measured helium concentration profiles showed that the half-delta injector was more effective than the angled flat plate in achieving greater penetration along the vortex position. The spreading was also larger with the delta injector.

A STUDY OF HELIUM PENETRATION AND SPREADING IN A MACH 2 AIRSTREAM USING A DELTA WING INJECTOR

by Louis A. Povinelli, Frederick P. Povinelli, and Martin Hersch

Lewis Research Center

SUMMARY

The effect of vortex motion on jet penetration and spreading was investigated. Experiments were conducted in a Mach 2 airstream. Two injector configurations were used. The first was a half-delta wing with a 30° semiapex angle and a 12° angle of attack. Helium was injected from the upper surface in line with the mean position of the vortex. The second injector was a flat plate and had the same angle of attack and equal projected frontal area. Measurements of the helium concentration profiles at various downstream distances indicated that penetration into the free stream was at least twice as large with the delta injector at the vortex position. Comparison of the penetration at other angular positions may not yield the same degree of enhancement. The penetration was measured relative to the injection orifice.

The spread of helium in the lateral direction also occurred over twice the angular range with the delta injector as with the angled flat plate. The experimental measurement of the jet boundary was in reasonable agreement with the mean vortex position near the trailing edge of the injector.

The total pressure of the Mach 2 airstream was 0.92 atmosphere (93×10^{3} N/m^{2}), and the total temperature was 625° R (347 K). Helium at a total pressure of 15 psia (103×10^{3} N/m^{2} abs) was injected normal to the free stream at sonic velocity. The corresponding ratio of jet total pressure to free-stream total pressure P_j/P_{∞} was 1.11.

INTRODUCTION

Genesis of Problem

In recent years, much consideration has been given to the use of airbreathing ramjet propulsion systems for achieving hypersonic (>Mach 5) flight. In one type of ramjet engine, the combustion occurs in a supersonic flow stream. Supersonic combustion ramjets alleviate the high inlet losses and gas dissociation problems common to the subsonic combustion ramjet at high flight Mach numbers. In addition, the static pressures in a supersonic combustion ramjet are nominal in value, 0.1 to 3 atmospheres (0.10×10^5 to 3.03×10^5 N/m^2).

Although the supersonic combustion ramjet principles are generally understood and the system, in theory, should be workable, certain practical problems require attention. One of these problems is concerned with the injection, penetration, mixing, and burning of the fuel in the combustor to produce a uniform distribution of high-temperature combustion products at the nozzle entrance. The fuel must be injected in a manner so as not to cause large disturbances in the flow stream which lead to significant total pressure losses.

A variety of techniques have been considered for the injection process: (1) flush wall injection, (2) parallel wall injection, and (3) injection from a protrusion into the free stream out away from the wall.

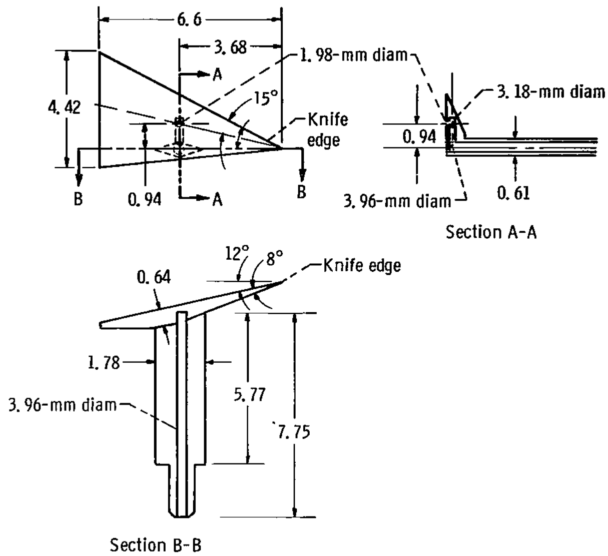
In the flush wall injection technique, jets of fuel are injected into the free stream from small holes in the combustion chamber walls, where the holes are alined normal to the wall. This method appears to be desirable because it minimizes physical blockage of the flow stream. However, a great deal of research on this type of injection (at sonic velocity) revealed, that for practical injection pressures with low molecular weight gases, penetration of the fuel is less than 5 to 10 orifice diameters (refs. 1 to 4). Theoretical work indicates that supersonic injection may enhance penetration with maximum penetration achieved at an injection Mach number of 2.2 (ref. 5). Some experimental data exist which show that the enhancement due to normal supersonic injection, as opposed to sonic injection, is 15 to 20 percent (refs. 3 and 6). Although this enhancement is a significant increase for annular-type combustors of small height, it does not contribute greatly to the penetration in large combustors. Thus, wall injection appears to be suitable only for thin annular-type combustors. The use of elliptical cross sections for the combustors has been proposed to alleviate the penetration problem (ref. 5). However, this use may introduce many matching problems between the combustor and inlet or nozzle in an engine system. Wall injection parallel to the stream has the disadvantage of poor spreading, which leads to long combustors.

Injectors that protrude into the combustor would overcome the problem of fuel penetration but may be limited in application because of problems arising from (1) the high stagnation temperatures associated with the flow, and (2) flow blockage and drag. Unfortunately, at least two conflicting requirements must be satisfied in the injection process; namely, high fuel penetration and low total-pressure losses.

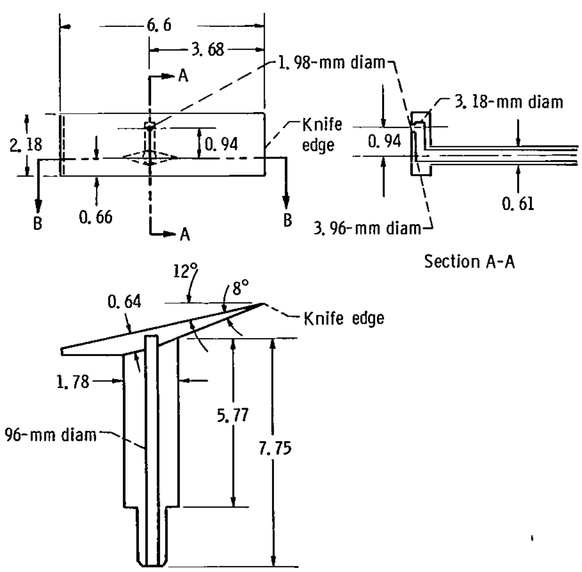
This report presents a novel approach to the problem of fuel injection into large-diameter combustors where struts would be required to ensure more uniform injection and mixing.

Objective of Present Study

The use of vortices to enhance fuel mixing has been proposed previously (refs. 7 and 8) but has not been experimentally verified. The purpose of this study was to investigate the effect of vortex flow on jet penetration and spreading in supersonic flow. Two models were used. The first was the half-delta injector shown in figure 1(a). This in-



(a) Delta injector.



(b) Angled flat-plate injector.

Figure 1. - Experimental models. (Dimensions are in cm except where noted.)

jector gives rise to vortex motion resulting from the circulation from the underside, or high-pressure region, to the top side, or low-pressure region. Injection of fuel into the vortex region may lead to greater penetration and spreading. The second model was a flat plate injector shown in figure 1(b). This injector had the same angle of attack and projected frontal area as the delta injector but did not give rise to vortex motion. Comparison of the penetration and spreading from these two models should indicate if any advantage is gained by the vortex.

In designing a delta injector, it is desirable to optimize the shape so as to obtain minimum drag and maximum vortex strength and size. Although such an optimization was not carried out in this work, it would be a necessity in the development of supersonic combustor hardware.

SYMBOLS

a	semispan
d	orifice jet diameter
M	Mach number
P_j	jet total pressure
P_∞	free-stream total pressure
T_∞	free-stream total temperature
V_j	jet exit velocity
V_∞	free-stream velocity
x	streamwise coordinate
y	vertical coordinate
z	lateral coordinate
α	angle of attack to flow
γ	specific heat ratio
ϵ	semispan apex angle
θ	angular distance from injection orifice in x, z-plane

APPARATUS AND PROCEDURE

Experimental Models

Two models were used in the experimental testing. The first was a half-delta-wing configuration having a 30° semiapex angle and a 12° angle of attack (see fig. 1(a)). A sonic orifice, 0.078-inch (1.98-mm) diameter, was located along a line 15° from the leading edge of the wing surface and 1.45 inches (3.68 cm) from the apex of the delta. The 15° line corresponds to the mean position of the vortex flow field as observed experimentally in reference 9. Only half a delta was used because a full delta would not allow the tunnel to start. The change in the flow characteristics over half a delta compared with that over a full delta is discussed later in the Model and Tunnel Effects section.

The second test model (fig. 1(b)), a flat plate with the same projected frontal area as the delta wing, was also mounted at a 12° angle of attack. With this mounting, the flow field over the top surface simulated the expansion over the delta surface. Helium was injected at sonic velocity through an 0.078-inch (1.98-mm) diameter orifice. Injection was always normal to the model surface.

Tunnel Configuration

The models were mounted in a Mach 2 wind tunnel, 3.84 inches (9.75 cm) by 10 inches (25.4 cm) (ref. 10). The tunnel had an air supply with a stagnation pressure and temperature of 0.92 atmosphere (93.1×10^3 N/m^2) and 625° R (347 K), respectively. The models were mounted as shown in figure 2, with the origin of the coordinate system located at the injection hole (see fig. 2).

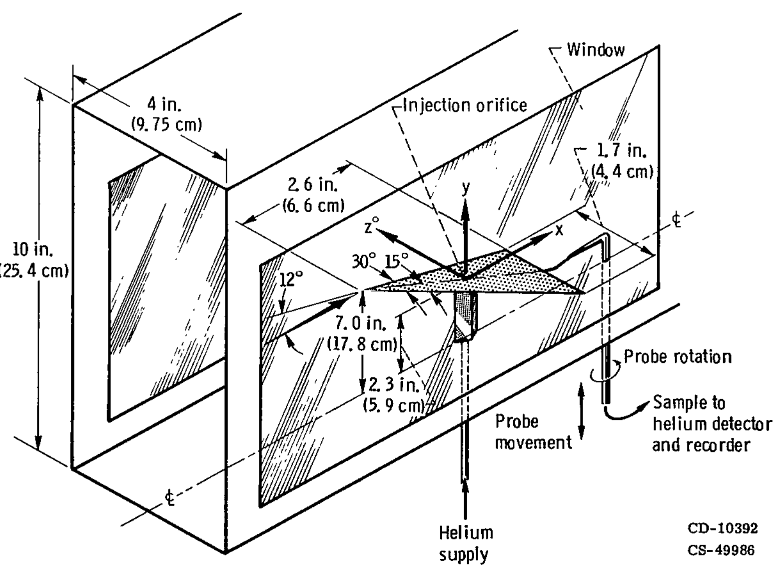
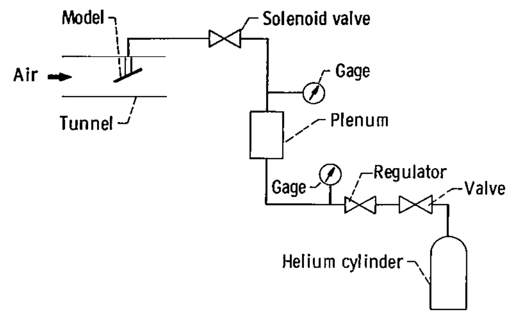


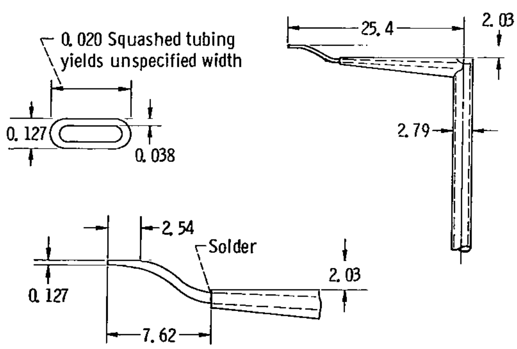
Figure 2. - Delta injector installation for jet penetration study. Free-stream Mach number, 2.0; stagnation pressure, 0.92 atmosphere (93×10^3 N/m^2); stagnation temperature, 625° R (347 K).

Helium Injection and Detection

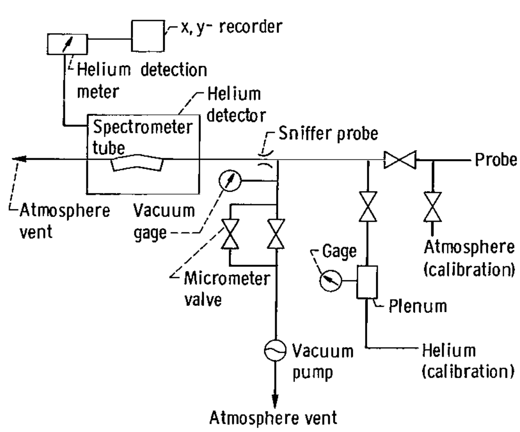
Helium was injected at a total pressure of 15 psia (103×10^3 N/m^2 abs) at ambient temperature. A schematic diagram of the helium injection system is shown in figure 3(a). Vertical traverses (y-direction) were made at various x/d positions (downstream



(a) Helium injection system.



(b) Gas sampling probe. (All dimensions are in mm.)



(c) Helium detection system.

CD-10410-14

Figure 3. - Experimental apparatus.

distance dimension normalized with respect to orifice diameter) downstream from the injection hole by using a probe fabricated from hypodermic tubing (see fig. 3(b)). Lateral traverses (z-coordinate) were also made at various x/d positions by a rotation of the probe (see fig. 2) with subsequent bending of the probe tip in the flow direction (see insert in figs. 6 and 7). At the larger angular positions relative to the tunnel centerline, the probe was not directly in line with the flow. Probe samples were withdrawn from the flow stream and analyzed with a helium leak detector, as illustrated in figure 3(c). Helium and air mixtures of various concentrations were used to calibrate the leak detector. The output of the leak detector was linear with helium concentration for a fixed sampling pressure. Hence, the pressure at the entrance to the detector was regulated to maintain a constant pressure of 4 millimeters of mercury (5×10^2 N/m^2), by two valves in a dump line located upstream of the main vacuum pump. The reproducibility of a concentration measurement for a typical sampling condition was determined to be ±1.5 percent.

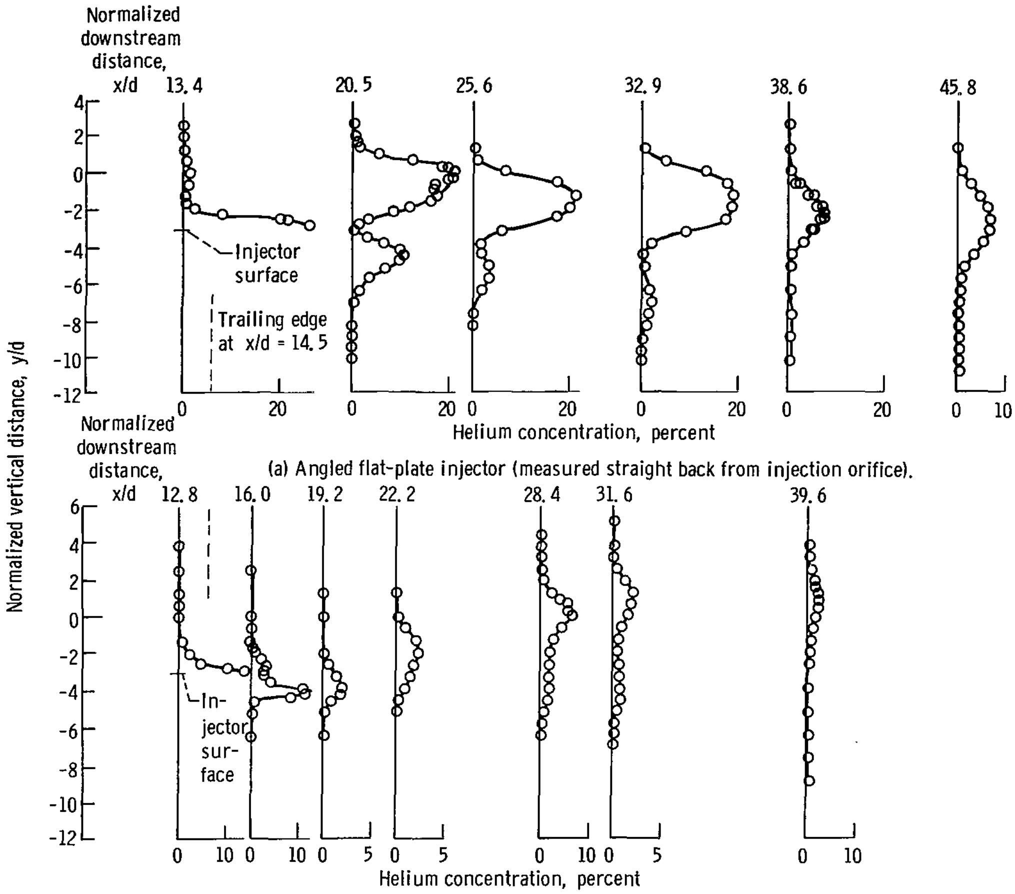
Pressure Measurement

The change in total pressure caused by the two test models was measured with a pitot probe. The pitot measurements were corrected by assuming a specific heat ratio γ of 1.4 and a Mach number M of 2. Also assumed was that a normal shock existed in front of the probe and that the total pressure was 0.92 atmosphere (93×10^3 N/m^2). Measurements were made on the vertical centerline of the tunnel at an x/d position of 138.

RESULTS

Helium Concentration Profiles

The concentration profiles obtained at various x/d positions for both the angled flat plate and the delta injectors are shown in figure 4. All these data, with the exception of the first x/d station for each model (13.4 for the plate and 12.8 for the delta), were obtained downstream of the trailing edge of the model. Profiles for the flat plate were obtained straight downstream of the injector hole, whereas, with the delta injector, the measurements were made in line with the vortex flow at 15° from the leading edge of the wing.



(a) Angled flat-plate injector (measured straight back from injection orifice).

(b) Delta injector (measured along 15° line).

Figure 4. - Helium concentration profiles at various axial stations.

Jet Penetration Comparison

The trajectories of both the zero and maximum concentration points downstream of the plates are plotted as a function of x/d in figure 5. At x/d values of less than 24, the delta injector shows less penetration than the angled flat plate. When x/d exceeds 24, a crossover occurs, and jet penetration becomes greater with the delta. With increasing downstream distance, the difference in penetration increases and appears to level off at an x/d value of 45. The important finding is that the penetration, defined in terms of either the zero or the maximum concentration, is 2 to 3 times larger with the delta injector than with the angled flat plate. This comparison was made by using the injection orifice as a reference point and is based on measurements at the vortex position. Comparison of the penetration at other angular positions may not yield the same

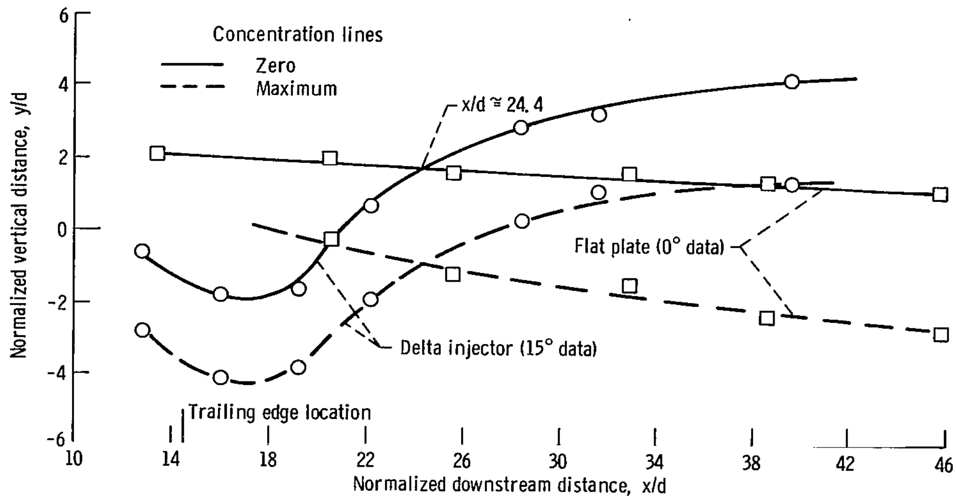


Figure 5. - Helium jet trajectories for delta and flat-plate models.

degree of enhancement. However, if long swept struts at the angle of attack were used for injectors, the major portion of the flow over the strut may be at the vortex angle. Therefore, the increased penetration (i.e., 2 to 3 times larger) would probably exist along most of the strut length.

Lateral Jet Spreading Comparison

Concentration surveys were made in the lateral z and vertical y directions to determine the extent of spreading. The results are shown in figure 6. These measurements, made upstream from the trailing edge, show that the lateral spreading with the delta injector is distributed over at least 40°. The spread in helium is seen to be dependent on the vertical position and appears to be composed of two regions. The first region is in the vicinity of 0° and represents the normal penetration of a jet into a stream in the absence of vortex flow. The second region exists to the right of the main peak and extends to the larger positive angular positions. This portion represents the helium carried across the half delta as a result of the velocity and pressure fields created by the vortex flow. Both regions contain high concentrations of helium. The resulting flow picture, therefore, appears to be similar to normal jet penetration, which produces a symmetrical peak around 0°; but in addition, a secondary peak exists at the larger angular positions. This second peak is a result of the vortex flow direction and the spanwise pressure gradient set up by the vortex motion.

Measurements made downstream from the trailing edge are shown in figure 7.

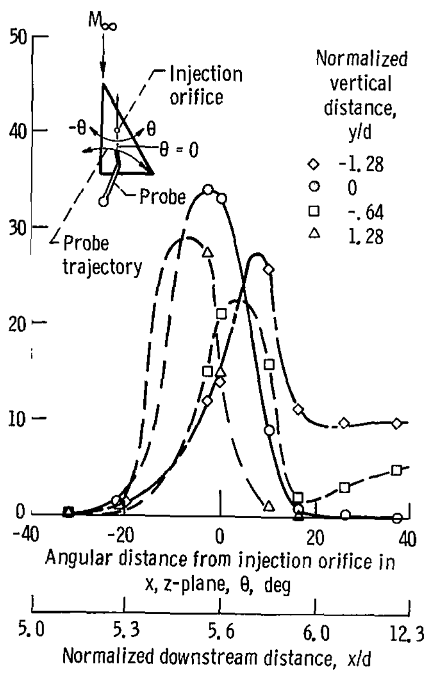
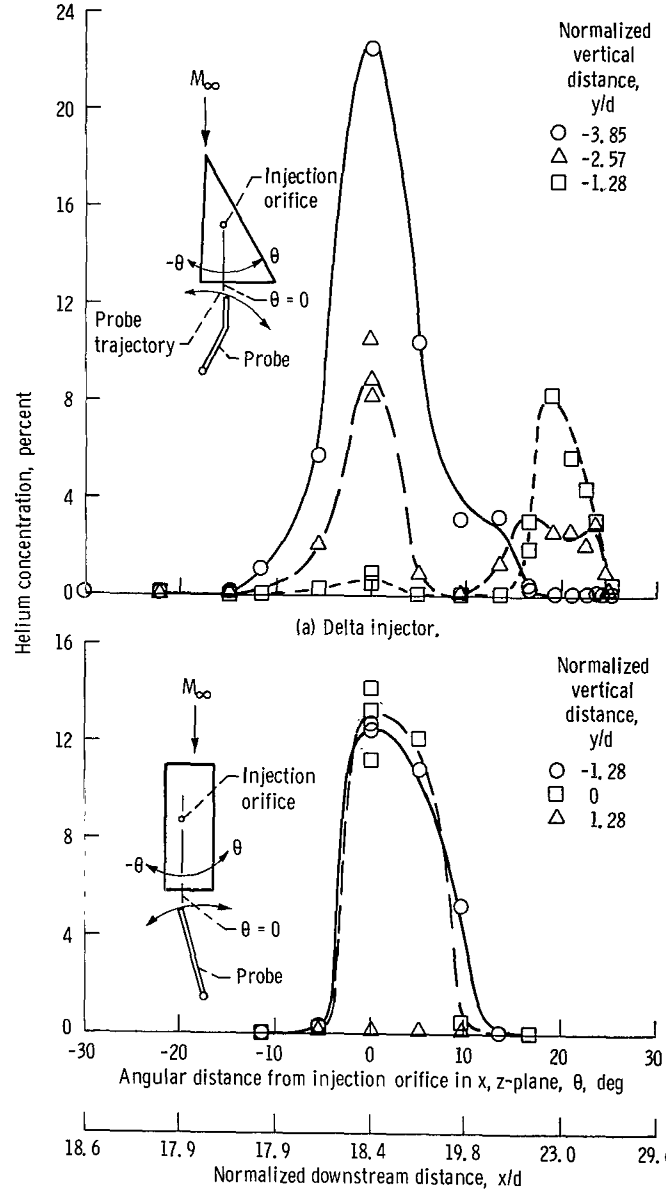


Figure 6. - Jet lateral spreading behavior for various normalized vertical positions on delta injector. Measurements made upstream of trailing edge.



(a) Delta injector.

(b) Flat-plate injector.

Figure 7. - Jet lateral spreading behavior. Measurements made downstream of trailing edge.

Again, the spreading exists over 40^{o}. The flat plate data, however, show that spreading is restricted to 20^{o}. Hence, the delta injector spreads the helium considerably farther than the angled flat-plate injector.

Figure 7 shows that the spread of helium with the delta injector depends on the vertical position y. At low y/d values, a high concentration of helium is found straight back from the injection hole. At y/d values corresponding to positions above the plate, the highest helium concentration is found along the vortex position. This downstream behavior of the helium is quite different from the upstream behavior, which indicates a strong wake effect. The downstream concentration behavior with y/d changes (fig. 7) indicates that the delta penetration at other angular positions besides 15^{o} may not yield the same degree of enhancement noted previously. However, as mentioned in the previous section, a major part of the leeward flow from a swept strut at the angle of attack may be along the vortex path.

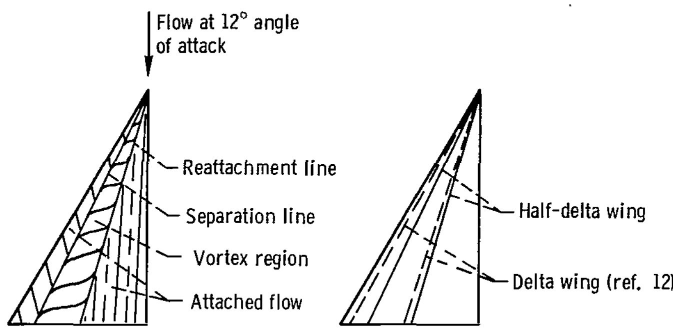
Model and Tunnel Effects

Existence of large vortices on the surface of the angled flat plate was not considered likely because of the relatively thick edges of the plate. However, water injection tests were made to verify the absence of large-scale vortices. These tests were run with a flat-plate model, both with and without side fences attached to the plate. In the absence of the fences, most of the injected water penetrated directly out of the orifice into the free stream. Some of the water was observed moving laterally on the plate surface to the side edges of the plate where it accumulated. The absence of water being carried out into the free stream from the plate is considered a confirmation of the absence of large vortices on the plate surface.

When the side fences were attached to the flat-plate model, water was still observed moving laterally outward and up the sides of the fences. Again, most of the water penetrated directly into the free stream. No significant differences in jet behavior were observed with or without the side fences.

Oil-streak studies of the flow lines over the leeside of a half-delta-wing injector were made. No helium was injected during these studies. The flow lines followed the typical delta-wing pattern (see fig. 8(a)). Comparison of the separation and reattachment lines for the half-delta model with those of the full-delta-wing data shows some differences in their locations (see fig. 8(b)). However, the qualitative features of the flow remain unchanged. Note that extrapolation of the half-delta data to full-delta behavior may not be entirely valid.

Measurements of the helium penetration and spreading were made relatively close ($x/d < 40$) to the trailing edge of the delta injector to avoid shock reflection regions.



(a) Flow lines on half-delta wing.

(b) Comparison of separation and reattachment lines.

Figure 8. - Delta-wing flow pattern (leeside).

The bow shock from the delta model, however, intersected the boundary layer on the tunnel sidewall. The reflected shock wave crossed the measuring stations at an x/d position of 28. Hence, three of the measuring stations lie downstream of the reflected shock. The effect of the reflection on the measured penetration was determined by mounting the delta injector on the tunnel sidewall in a position where Schlieren photographs showed that the measuring stations were free of shock reflections. Spot checks on the zero concentration boundary at two x/d stations (28.2 and 41.0) yielded values that were approximately 20 percent lower than those shown in figure 5. However, these lower values have only minor significance relative to the objective of this study, since the increased penetration with the delta injector becomes 2.4, rather than 3, times greater than that of the flat-plate model. These values of the penetration distance were measured relative to the injection orifice.

Henry (ref. 11) showed that jet spreading is not influenced by the presence of shock waves.

Pressure Loss

The total pressure drop caused by the two models was measured along the vertical centerline of the tunnel at an x/d of 138, a position slightly upstream of the tunnel diffuser. The total pressure in the absence of any test model was also measured, as shown in figure 9. These measurements were corrected by using the standard pitot tube expression. The influence of the relatively thick boundary layer is shown in the no-model case. With both the angled flat-plate and delta injectors, an average drop of 4 psia (27.6×10^3 N/m^2 abs) occurs. The integrated pressure loss with both models was nearly identical. Hence, the two models, having the same angle of attack and projected frontal area, caused the total pressure in the stream to undergo an equivalent change (when the

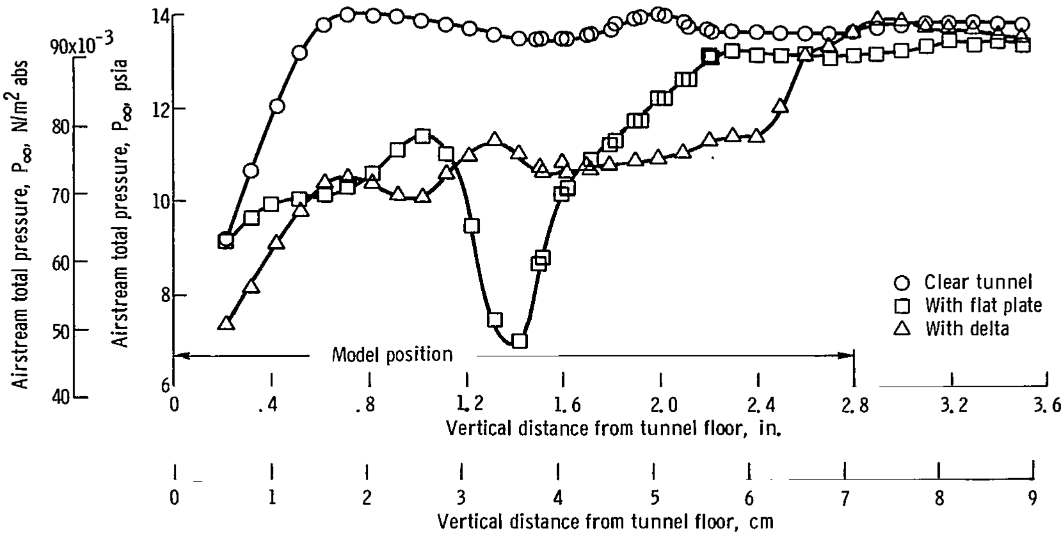


Figure 9. - Total pressure profiles at tunnel centerline with and without injectors at normalized downstream distance of 138.

centerline pressure measurements are assumed representative of the flow losses). The distances spanned by the models, including the supports, are indicated along the abscissa of figure 9.

Comparison of Jet Penetration with Vortex Position

The experimental data obtained in this study were compared with the mean vortex position as determined in reference 12. Penetration data for the delta injector (along the 15° line) were plotted in nondimensional form as shown in figure 10. An additional data point was also obtained at an x/d position of 5.9. Both jet boundaries are shown along with the potential solution of Pershing (ref. 12). The experimental data are seen to follow the mean vortex position over the plate and for some distance into the wake region

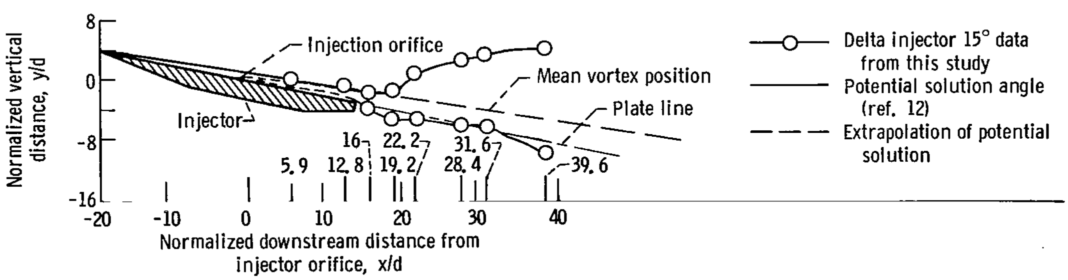


Figure 10. - Comparison of experimental jet boundaries with predicted result. Zero concentration lines.

($x/d = 20$) at which point the data show a rapid increase. Beyond an x/d of 20, the wake phenomena appear to exert a controlling influence on the behavior of the helium dispersion, and the vortex prediction is not valid. The lower jet boundary appears to follow the extended plate line.

CONCLUSIONS

An experimental study of helium penetration and spreading in a Mach 2 airstream was performed with a delta-wing injector. For comparison, a flat-plate injector with the same projected frontal area and angle of attack as the delta was also tested. The delta injector, which gives rise to vortex motion, gave approximately 2.5 times greater penetration than the angled flat plate, as measured from the injector orifice and along the vortex position. Comparison at other angular positions may not yield the same degree of enhancement. The angular spreading with the delta injector was twice as large as that of the angled flat plate. These results indicate that the presence of vortex flow in the vicinity of the injection orifice can lead to increased penetration and spreading in supersonic flow.

Comparison of the experimental data from the delta injector (as measured along the 15° line) with the vortex position obtained from a potential solution revealed that the helium jet boundary follows the mean vortex position. This agreement was good over the delta injector surface and in the vicinity of the trailing edge. At larger downstream distances ($x/d > 20$), wake phenomena lead to large differences between theory and experiment.

The data presented in this report may have practical application in supersonic ramjet combustors in that swept-strut injectors at an angle of attack could be used to enhance penetration and spreading of the fuel into the supersonic airstream.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 9, 1969,
722-03-00-06-22.

REFERENCES

1. Zukoski, Edward E.; and Spaid, Frank W.: Secondary Injection of Gases into a Supersonic Flow. AIAA J., vol. 2, no. 10, Oct. 1964, pp. 1689-1696.

2. Torrence, Marvin G.: Concentration Measurements of An Injected Gas in a Supersonic Stream. NASA TN D-3860, 1967.

3. Orth, Richard C.; and Funk, John A.: An Experimental and Comparative Study of Jet Penetration in Supersonic Flow. J. Spacecraft Rockets, vol. 4, no. 9, Sept. 1967, pp. 1236-1242.

4. Schetz, Joseph A.; Hawkins, Paul F.; and Lehman, Harry: Structure of Highly Underexpanded Transverse Jets in a Supersonic Stream. AIAA J., vol. 5, no. 5, May 1967, pp. 882-884.

5. Schetz, Joseph A.; and Billig, Frederick S.: Penetration of gaseous Jets Injected into a Supersonic Stream. J. Spacecraft Rockets, vol. 3, no. 11, Nov. 1966, pp. 1658-1665.

6. Schetz, Joseph A.; Weinraub, Robert A.; and Mahaffey, Raymond E., Jr.: Supersonic Transverse Injection into a Supersonic Stream. AIAA J., vol. 6, no. 5, May 1968, pp. 933-934.

7. Townend, L. H.: Ramjet Propulsion for Hypersonic Aircraft. Rep. TM-AERO-917, Royal Aircraft Establishment, Jan. 1966.

8. Swithenbank, J.; and Chigier, N. A.: Vortex Mixing for Supersonic Combustion. Presented at the Twelfth Symposium (International) on Combustion, Poitiers, France, July 1968.

9. Werlé, H.: The Separation and Reattachment of Fluid Flows. Rech. Aéro., no. 79, Nov./Dec. 1960, pp. 9-26.

10. Brinich, Paul F.: Boundary-Layer Measurements in 3.84- by 10-Inch Supersonic Channel. NACA TN 2203, 1950.

11. Henry, J. R.: Recent Research on Fuel Injection and Mixing and Piloted-Ignition for Scramjet Combustors. Presented at the Twelfth Symposium (International) on Combustion, Poitiers, France, July 1968.

12. Pershing, Bernard: Separated Flow Past Slender Delta Wings with Secondary Vortex Simulation. Rep. TDR-269 (4560-10)-4, Aerospace Corp. (SSD-TDR-64-151, DDC No. AD-607442), Aug. 24, 1964.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

06U 001 26 51 3DS 69178 00903
AIR FORCE WEAPONS LABORATORY/AFWL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 87117

ATT E. LOU BOWMAN, ACTING CHIEF TECH. LI.

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546