Experiments on Reacting Gas Jet Penetration

D. W. Harvey,* D. F. Hopkins,† and R. Rosen*
McDonnell Douglas Astronautics Company, Huntington Beach, Calif.

Studies of reacting transverse gas jets were made in a shock tunnel under conditions of temperature, pressure, and Mach number corresponding to supersonic flight. Two jet nozzles were used: a circular nozzle and a 30° forward canted transverse slot nozzle, both converging-diverging and of area ratio two. Three jet compositions were involved: heated hydrogen, plus the exhausts of solid and liquid propellant motors, the latter at several oxidizer-to-fuel ratios. The test fluid was air, but in some cases duplicate runs were made using nitrogen to allow a measure of the effect of combustion of the jet with oxygen in the air. Measurements were made of the jet bow shock and of the separated region upstream of the jet. Concentration measurements were made at two stations downstream of the jet. Results are compared with data and correlations for jet penetration and mixing at lower temperatures, pressure, and Mach number. Dependence of the measured parameters on nozzle shape, on jet properties, and on combustion (or its absence) is also presented.

Nomenclature

d = nozzle diameter
E = rms error in shock-fitting procedure
h = penetration height
M Mach number
MW = molecular weight
P = pressure
q = dynamic pressure
T = temperature
x = streamwise distance
X = streamwise distance in units αh
x_{ref} = equivalent body nose location
α = penetration height correction factor
δ^* = boundary-layer displacement thickness

Subscripts

ex = exit location
j = jet conditions
L = local conditions
o, T = stagnation conditions
$*$ = sonic conditions
s = separated conditions

I. Introduction

THE interaction between a transverse jet of reactive gas and an airstream is of interest in many applications. The resulting flow is complex, involving chemical reaction and heat release, momentum and mass interchange between the jet and the stream, and viscous effects. Because of this complexity, the only analytical approaches available contain considerable empiricism, enough to raise questions when extrapolation is required.

One application of some interest is the use of a fuel-rich jet to provide a control force, or moment, on a vehicle flying in the atmosphere. This typically involves a sonic or supersonic jet of fairly high pressure and temperature injected into an airstream of high Mach number and, at low altitudes, of high dynamic pressure. Considerable work has been done on characterizing jet interaction under such conditions, but the experimental data needed to fill the gaps in the analysis have come almost exclusively from tests at low airstream Mach numbers and where no combustion occurred. The reason for this limitation on the available data is, of course, the cost and difficulty of testing at high Mach numbers and in the presence of combustion.

Received Jan. 12, 1976; revision received Sept. 3, 1976.
Index categories: Reactive Flows; Combustion in Gases.
*Senior Engineer/Scientist.
†Section Chief. Member AIAA.

This paper reports data on reactive jet penetration and mixing in an airstream at higher Mach numbers and lower equivalent altitudes than have heretofore been available. These data were taken as part of a program of shock tunnel tests which was conducted with the objectives of determining the feasibility of fuel-rich jet interaction as a control system, establishing its performance, and providing a data base for analysis and design. The tests produced model surface conditions equal to those that exist in flight over a representative range of Mach numbers and at altitudes as low as 15,000 ft. Injection of the fuel-rich gas was through the surface of a wedge model. Three injectants were used: heated hydrogen and the exhausts of a solid propellant motor and a liquid bipropellant motor. The solid propellant was Arcadene 246 B, a low-temperature, nonaluminized propellant from the Atlantic Research Corporation. The bipropellant was NTO/MMH, and three O/F ratios were run. A circular nozzle normal to the surface, and a 30° forward canted transverse slot nozzle of aspect ratio 10 were used. The throat area of both nozzles was 0.20 sq.in., and the exit area was 0.40 sq. in. Many of the test runs were repeated using nitrogen instead of air as the flowing gas, in order to allow, by comparison, a direct measure of the effects of combustion.

Forty-eight good runs were made. High-speed movies were taken in most of these runs. The movies included schlieren and other views of the jet interaction and combustion region and yielded data on shock shapes and on the upstream extent of the separated region. In 10 runs, a rake of 5 concentration probes was used to take samples from the flow. In the present paper, the shock shapes are correlated by establishing the dimension of a body that would produce the same shock; the upstream extent of the separated region is established; and the behavior of these measures is discussed. The measured concentration profiles are presented and compared with other data, and the effects of combustion, temperature, and molecular weight are considered.

II. Photographic Data

High-speed schlieren movies were taken in most runs. The result from a typical run was 12 to 20 half-frames of 16-mm film representing the steady test period. These frames show the jet shock resulting from the interaction of the jet with the local flow. They also show the model bow shock. The separation shock is generally visible, but in some runs it is obscured.

Plan view movies also were taken, and during the solid propellant runs a camera at a 45° angle to the plate was included. The films from these views show the upstream boundary of the light-emitting region. This boundary is approximately the upstream edge of the separated region in front of the jet and beneath the bow shock.

Correlation of Bow Shock Using Penetration Height

The interaction of a gas jet with an external stream is a complex process. The bow shock produced as part of the interaction in a sense characterizes the interaction from the viewpoint of the force generated on the wall. This shock is also the most readily obtained result of a jet interaction experiment, as only schlieren or shadowgraph equipment is required to obtain it.

In view of the difficulty of calculating the bow shock and of the ease of measuring it, it seems useful to correlate the measurements in such a way as to allow prediction of the bow shock without calculating the entire interaction. If this is done, a simplified calculation of the interaction becomes possible, based on the bow shock rather than yielding it as a result of the calculation. The minimum result expected in this regard is that some of the features of the interaction field will scale in the same way as the shock.

In the present work, the scale length of the shock and its location are determined by finding the radius and location with respect to the nozzle of the sphere or cylinder that generates a shock that best fits the observed bow shock in the least-squares sense. The approximate expressions developed by Billig[1] are used; sphere shocks are used to fit circular nozzle shocks and cylinder shocks are used for the slot.

The radius of the sphere or cylinder that is "equivalent" in the foregoing sense to the gas jet, is expressed as a correction α to a calculated "penetration height" h. The particular penetration height used is a formulation due to Kallis,[2] assuming zero heat release and extended to a transverse slot jet by treating the equivalent obstacle as a cylinder with spherical ends. The use of a penetration height in presenting the results is intended to account as well as possible for the obvious effects of jet and stream dynamic pressure, fluid properties, and jet area, and is not intended to ascribe reality to the equivalent body beyond equivalence of the resulting shocks.

Evaluation of the use of a cylinder or sphere shock to represent the jet shock must be based on results produced. The fitting procedure yields values of rms error E that are very satisfactory; the largest value of E among all runs is 5.6%, and the average is 1.9%. No significant difference exists between fuel sources or nozzles. The average value of E over slot nozzle tests, for example, is 1.7%. These numbers cannot provide unequivocal proof of the validity of the method, but certainly amount to a strong indication of its usefulness.

Results (α and x_{ref}) of the shock shape correlation method described above are given in Tables 1 and 2, together with the calculated value of h and some run parameters, for easy reference. Local pressure and Mach number are shown; local and total temperatures are omitted, as no effect of these parameters appears to exist in the data. For reference, the test conditions noted as A through J are defined in Table 3 in terms of the nominal local flow parameters and corresponding flight parameters.

A substantial effect of nozzle configuration is apparent in the results (Tables 1 and 2). This is to be expected, on physical grounds as well as on the basis of the assumptions used in the analysis; other comparisons must be made with this effect in mind.

The circular nozzle data cover a wide range of local pressures. Figure 1 shows how α varies over the available range. There seems to be a trend towards higher values of α at both ends of the experimental P_L range, but more data and

Table 1 Results of shock shape correlation – hydrogen fuel source

Run	h (in.)	α	x_{ref} (in.)	Nozzle[a]	Condition	Type of Run	P_L (psia)	M_L	Injectant
4 (1)	0.725	1.79	0.26	C	A	Comb.	11.3[c]	3.79	H_2
4 (2)	0.725	1.71	0.34	C	A	Comb.	11.3[c]	3.79	H_2
5 (1)	1.103	1.29	0.32	C	B	Comb.	3.11	5.66	H_2
5 (2)	1.103	1.42	0.34	C	B	Comb.	3.11	5.66	H_2
12	1.379	1.52	0.34	C	D	Comb.	2.07	5.70	H_2
14	1.324	1.65	0.26	C	D	Inert	2.13	5.71	H_2
16	1.033	1.43	0.30	C	A	Comb.	7.58	3.81	H_2
19	0.723	1.14	0.19	C	F	Comb.	8.03	5.54	H_2
20	0.722	0.98	0.24	C	F	Inert	7.90	5.60	H_2
27	0.397	0.98	0.42	S	F	Comb.	8.20	5.56	H_2
24	0.637	1.35	0.20	C	F	Comb.[b]	8.34	5.54	H_2
29	0.375	1.01	0.44	S	F	Comb.[b]	8.72	5.54	H_2
31	0..404	0.96	0.51	S	F	Inert	8.52	5.60	H_2

[a]C = circular, S = slot. [b]Concentration run. [c]Calculated values.

Table 2 Results of shock shape correlation – solid propellant and bipropellant

Run	h (in.)	α	x_{ref} (in.)	Nozzle	Condition	Type of run	P_L (psia)	M_L	Injectant	Oxidizer/ Fuel Ratio
52	0.82	1.23	0.33	C	F	Comb.	7.77	5.55	Solid	
53	0.467	0.89	0.32	S	F	Comb.	8.62	5.54	Solid	
54	0.533	0.82	0.35	S	F	Inert	8.11	5.58	Solid	
59	0.453	0.86	0.33	S	H	Comb.	8.06	5.77	Solid	
60	0.465	0.85	0.38	S	H	Inert	8.20	5.80	Solid	
35	0.381	0.82	0.048	S	F	Inert	8.03	5.58	Bipropellant	0.60
40	0.394	0.78	0.17	S	F	Comb.	8.16	5.53	Bipropellant	0.59
43	0.512	0.87	0.27	S	J	Inert	8.90	4.36	Bipropellant	2.71
44	0.394	0.75	0.16	S	F	Comb.[a]	8.36	5.50	Bipropellant	0.59
46	0.379	0.79	0.46	S	F	Inert	8.38	5.56	Bipropellant	1.32
47	0.370	0.82	0.37	S	F	Comb.	8.39	5.51	Bipropellant	1.32
48	0.402	0.86	0.20	S	F	Comb.[a]	8.43	5.51	Bipropellant	0.58
50	0.750	0.85	0.14	C	F	Comb.[a]	8.14	5.52	Bipropellant	0.60

[a]Concentration run.

Table 3 Achieved local and equivalent flight conditions

		Local Conditions				Flight Conditions[a]				
Run No.	Test Condition	T_T (°R)	T_L (°R)	P_L (psi)	M_L	Temperature (°R)	Pressure (psi)	Altitude (Kft)	Mach Number	Angle of Attack (deg)
3	A	5,974	1,799	7.94	3.80	400	0.36	83	9.1	19.4
5	B	5,487	916	3.11	5.66	400	0.36	83	9.0	9.2
6	C	5,447	739	0.91	6.16	416	0.17	99	8.5	6.2
10	E	5,692	455	0.70	8.25	397	0.41	80	8.9	-1.5
11	D	4,513	689	2.11	5.68	397	0.41	80	7.8	6.9
18	F	4,618	736	8.16	5.56	366	1.19	58	8.3	8.5
34	G	2,905	637	7.23	4.46	365	1.39	55	6.3	9.9
38	H	2,764	389	5.45	5.80	448	5.45	26	5.8	-5[b]
41	J	2,055	452	8.58	4.35	489	8.58	15	4.4	-5[b]
58	H'	2,957	421	8.25	5.77	486	8.25	16	5.8	-5[b]

[a]Vehicle cone half-angle = 5 deg and 1963 PAFB reference atmosphere.
[b]Flight conditions determined for α = -5 deg and pressure equivalence.

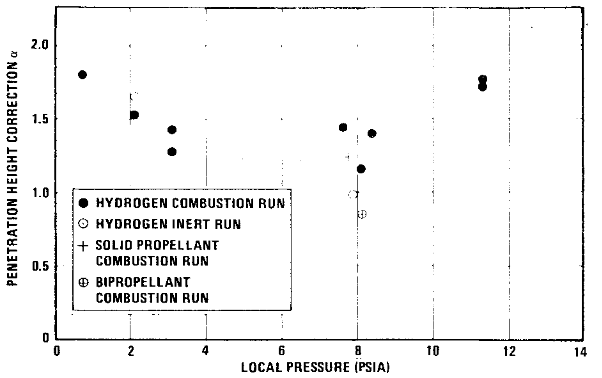

Fig. 1 Penetration height correction resulting from shock shape correlation – circular nozzle.

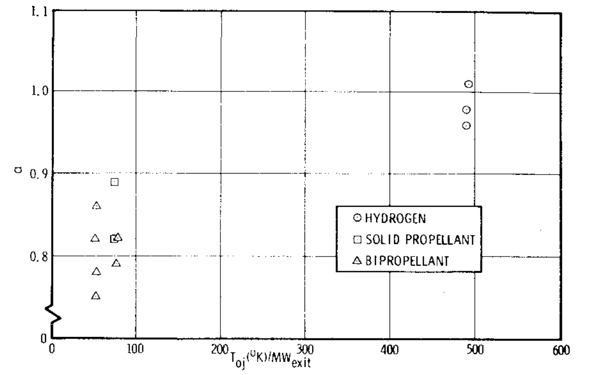

Fig. 3 Effect of temperature and molecular weight of injectant on penetration height correction – slot nozzle, condition F.

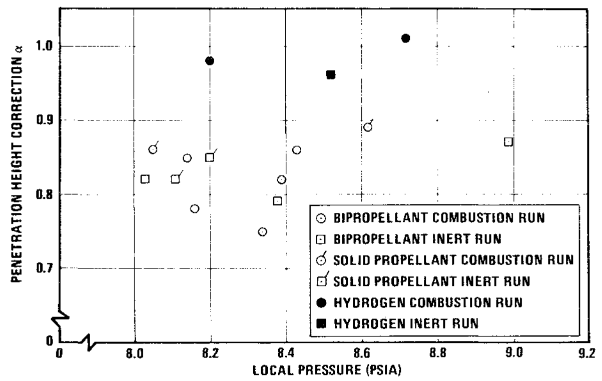

Fig. 2 Penetration height correction resulting from shock shape correlation – slot nozzle.

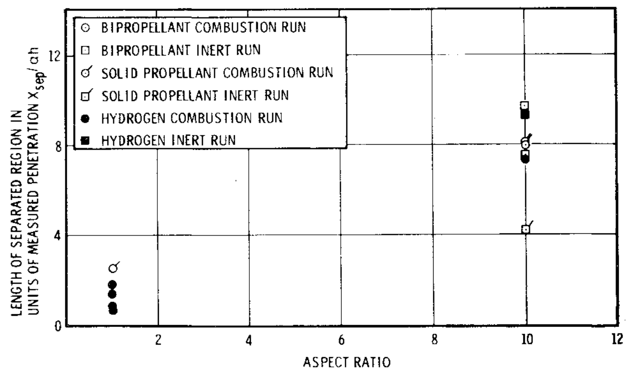

Fig. 4 Effect of nozzle aspect ratio on upstream extent of the separated region.

some reasonable explanation would be needed before it could be asserted that such a trend really exists.

Figure 2 shows α over the much smaller available range for the slot nozzle. Little or no variation in α appears over this range, but an interesting feature is the difference between the results for hydrogen and for the other propellants. Hydrogen is distinguished both by its low molecular weight and its high available heat release as a result of combustion. However, if heat release were responsible for the increase in α for hydrogen that is shown in Fig. 2, it might be expected that some systematic difference would appear between combustion and inert runs. No such difference appears in Fig. 2.

If the difference between hydrogen and solid propellant-bipropellant results in Fig. 2 is not caused by heat release, it may be caused by molecular weight (or by the difference in T/MW, where MW= molecular weight, as the effect of temperature is generally equivalent to the inverse of molecular weight). Figure 3 shows this possibility by making comparisons with the same nozzle (slot) at the same condition (F). In view of the apparent independence of combustion, combustion and inert results both are included in Fig. 3.

It can be concluded that sufficient data exist to allow correlation of the shape of shocks produced by jets from circular and slot nozzles under the conditions tested. A substantial difference exists between penetration heights for circular and slot nozzles. The data show little or no effect of combustion, which neither is included in the calculation of penetration height nor appears in the measurements. An uncompensated effect of T/MW appears, with the correction increasing with increasing value of that ratio. No clear trends with pressure or Mach number appear.

Upstream Extent of the Separated Region

The size of the jet-induced separated region is of some importance to the efficiency of momentum transfer from the jet to the external stream. This is because for fixed jet and stream conditions an increase in height of the separated region decreases the amount of gas processed by the strong part of the jet shock, and, as a result, the net entropy rise of the external stream is lower and its deflection is more efficient.

Measurements and Data Reduction

Measurement of the upstream extent of the separated region is the easiest way to characterize the size of the region, but even so, only relatively few good data resulted. The location of the upstream edge of the separated region was available from the three camera views: schlieren, plan, and 45°, the latter in the solid propellant runs only. In principle, this information also could be taken from the pressure measurements. However, transducer spacing on the upstream centerline was insufficiently close to provide more than an approximation to the separation point. Thus, only the film data were used.

The length of the separated region was taken to be the streamwise distance from the nose of the effective body to the farthest upstream indication of emission in the plan views, or to the intersection of the separation shock with the model surface in the schlieren. When more than one indication was available, the farthest upstream indication was used. In all cases of this type this procedure resulted in use of the schlieren data, which are probably the most reliable. The use of the nose of the effective body x_{ref} instead of the nozzle location to determine the downstream end of the separated region is intended to properly include effects to expansion of the jet as it leaves the nozzle, and of upstream injection in the slot nozzle case. The resulting length is reported in units of measured penetration height. Denoting the distance from the nozzle center to the farthest upstream indication of separation as x_s, the dimensionless length of the separated region is given by $X_s = (x_s - x_{ref})/\alpha h$.

Table 4 Upstream separation – test conditions and results

Run	Injectant	Oxidizer Fuel Ratio	Nozzle	Condition	Type of Run	$X_s = \frac{x_s - x_{ref}}{\alpha h}$
4	H_2		Circ.	A	Comb.	0.7
5	H_2		Circ.	B	Comb.	0.8
12	H_2		Circ.	D	Comb.	1.1
16	H_2		Circ.	A	Comb.	1.8
29	H_2		Slot	F	Comb.	7.4
31	H_2		Slot	F	Inert	9.3
35	Biprop	0.6	Slot	F	Inert	7.4
52	Solid prop		Circ.	F	Comb.	2.5
53	Solid prop		Slot	F	Comb.	8.1
54	Solid prop		Slot	F	Inert	4.3
59	Solid prop		Slot	H'	Comb.	8.2

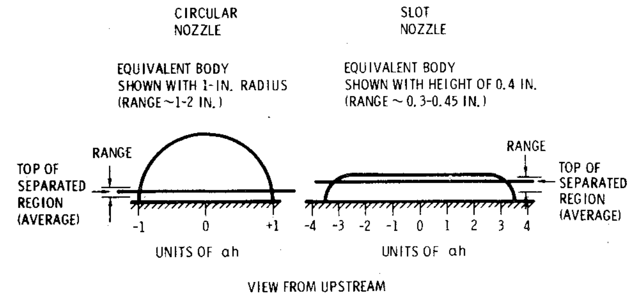

Fig. 5 Size of separated region compared to equivalent body.

Results and Discussion

Results are shown in Table 4. The data show a great deal of scatter, so much so that any effect of combustion or of change in conditions is masked. The one effect unequivocally disclosed by the data is that the slot nozzle results in approximately an order of magnitude greater separation than does the circular nozzle, in units of penetration height. This effect is shown as a function of aspect ratio in Fig. 4.

Upstream separation can modify and improve the efficiency of the jet obstacle in deflecting the external flow away from the body. To help clarify the differences between the circular and slot nozzles in this regard, the height of the separated region is of interest. This can be calculated from the length of the region by utilizing the empirical observation that the top of the separated region generally is oriented at 11° to the freestream. The reason this orientation is approximately constant and independent of Mach number is not understood entirely, but it is related to the pressure rise needed to separate the boundary layer.

When the height of the separated region thus is calculated, it is about 0.1 (in units αh) for the circular nozzle and about 0.75 for the slot nozzle. The significance of these values is made clear in Fig. 5, which shows the jet obstacles and the height of the corresponding separated regions as seen from upstream. The jet obstacles are shown to the same comparative scale, approximately correct for condition *F*. The assumption is made, in the absence of data, that the circular nozzle separated region height in units of αh for condition *F* is in the range measured (0.7 to 1.8) for conitions *A*, *B*, and *D*.

The results shown in Fig. 5 are interesting in view of the comparative performance of circular and slot nozzles. Results of the control-force part of this study showed that better overall performance was produced by the slot nozzle, but that the combustion increment was higher for the circular nozzle. By reference to Fig. 5 it is clear that the slot nozzle with its associated separated region is a more efficient way of turning the external flow away from the wall. This would have been anticipated on general fluid mechanical considerations.

The reason for the overall performance improvement resulting from the use of the slot nozzle is thus clear. The question remains, why is the combustion contribution lower? The separated region can be considered as an obstacle to the flow, as no substantial amount of mass flow exhausts from its downstream end. As such, it interferes with mixing between the jet and the external stream. Viewed simplistically, only the jet perimeter protruding above the top of the separated region is available to the external stream for mixing purposes. Some numbers may clarify matters, although the model implied is so oversimplified that the results should be viewed with caution. From Fig. 5, if no separation occurred, the jet surface area in contact with the external flow to a distance 1 in. downstream of the nose would be 3.14 sq. in. for the circular nozzle and 3.7 sq. in. for the slot nozzle. The ratio of areas, slot to circular, would be 1.2; the surface area of the slot nozzle obstacle is about 20% greater than the surface are of the circular nozzle obstacle. If, on the other hand, only the portions above the average location of the top of the separated region are considered, the circular nozzle yields a surface are of 2.6 sq. in., whereas the slot nozzle yields an area of 2.2 sq. in., for a ratio of 0.85. The effect of separation is thus to decrease the initial surface area available for mixing to perhaps 15% less for the slot than for the circular nozzle. This differential is likely to become greater with distance downstream, as the mixing process may be more efficient in the case of the circular nozzle jet.

III. Concentration Measurements

Concentration measurements were made in the present experimental program during 20 runs, of which seven were made using the hydrogen fuel source and three the bipropellant; one hydrogen run was a checkout run. The measurements were made by taking samples during the runs, using quick-operating probes which opened and closed within a period of approximately 2 ms during the steady portion of the run. The collecting probes were arranged in a five-probe rake. In all tests, the probe farthest from the plate was inoperative. The data for each run thus consist of four samples, taken in the plane of flow symmetry normal to the surface. The probe apertures were 3/8, 1-1/8, 1-7/8, and 2-5/8 in. from the surface. Two downstream locations were used: 4 and 8 in. downstream of the nozzle center.

The collected samples were analyzed subsequently by mass spectrometry. A careful analysis of the error involved in analysis of the data showed that the hydrogen data were accurate to ±10% absolute or better. The bipropellant data accuracy was considerably worse, so that their value is only qualitative. This section is concerned exclusively with the concentration data taken during the hydrogen runs.

Hydrogen Concentration Data

The hydrogen concentration runs are listed in Table 5. All runs were made at condition *F*. Nominal local flow and injectant conditions also are shown in Table 5. Duplicate combustion runs, 21 and 25, were made with the circular nozzle and the probes at the 4 in. downstream location. An inert run, 26, was made at the same condition. In view of the substantial similarity shown between combustion and inert runs both in terms of shock shape and of concentration, these three runs were taken as representing as single condition.

Results of runs 21, 25, and 26 therefore are shown together in Fig. 6. The error bars include all effects of inaccuracy in analysis but they do not include the effects of rapid variations, either directly temporal or convected spatial, about the mean value of concentration at the sampling location. These postulated variations are a probable cause for the failure of the error analysis to account entirely for the scatter of data at 1-1/8 in. above the plate surface. Thus, the area outlined by connecting the ends of the error bars in Fig. 6 with straight lines cannot be expected to include all data that would result from a large number of repetitions of runs 21, 25, and 26, but it should include most of them.

Table 5 Hydrogen concentration runs

Run	Type of Run	Nozzle	Probe Location (in. downstream of nozzle center)	Nominal Conditions
18	Combustion	Circular	27 (checkout run)	P_L = 8.3 psia
21	Combustion	Circular	4	T_L = 750 R
24	Combustion	Circular	8	M_L = 5.5
25	Combustion	Circular	4	P_{oj} = 400 psi
26	Inert	Circular	4	T_{oj} = 1,700 R
29	Combustion	Slot	4	M_j = 2.2
30	Combustion	Slot	8	

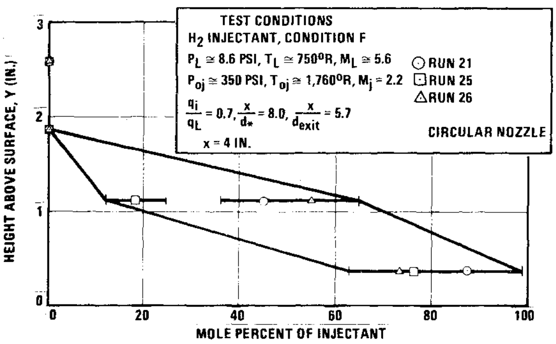

Fig. 6 Hydrogen concentration profile.

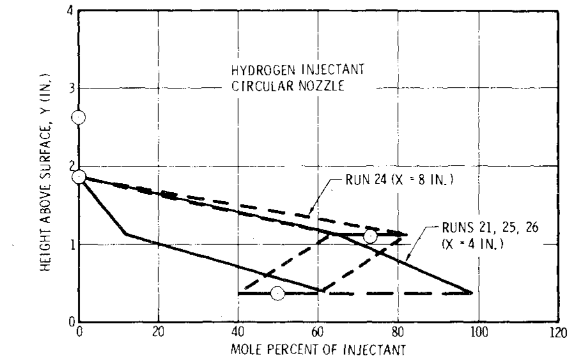

Fig. 7 Effect of downstream distance on concentation profiles.

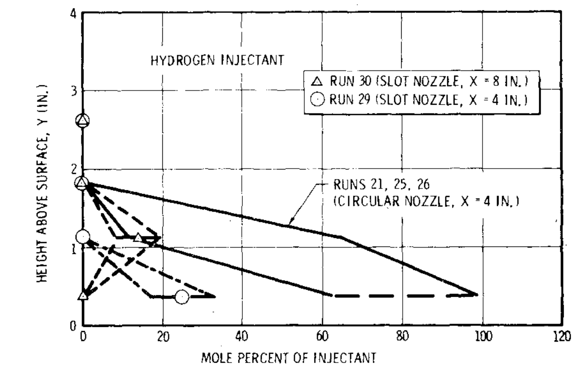

Fig. 8 Effect of nozzle geometry.

Three other hydrogen runs were made, and some instructive comparisons are possible. Figure 7 shows the effect of downstream distance on the concentration profile. At 8 in. downstream, the plume appears to have lifted off the surface. This is of course not a buoyancy effect; not only are the pressure forces involved much greater than gravitational forces, but the jet is injected downwards, so that a buoyant jet would tend to move towards the plate.

Figure 8 shows the effect of nozzle shape on the concentration profiles at 4 in. downstream. It also shows the effect of downstream distance for the slot nozzle. The injectant plume from the slot nozzle is nearer to the surface at the 4 in. downstream location than is the circular nozzle plume. Values of penetration height deduced from the measured shock shapes can be found as αh from Table 1. Representative circular nozzle runs are 19, 20, and 24, and an average value of αh for these runs in 0.82 in.; representative slot nozzle runs are 27, 29, and 31, with an average αh of 0.39 in. This implies a decrease in the profile height of approximately a factor of 2 for the slot nozzle, if the change in penetration height is the only factor involved. The profiles shown in Fig. 8 are not resolved sufficiently to determine the decrease in plume height for the slot as compared to the circular nozzle, but a factor of 2 is consistent with the data. Thus, the observed decrease in plume height at the 4 in. downstream location can be attributed, at least approximately, to the decrease in jet penetration seen from analysis of the jet shock shapes.

Figure 8 also shows the effect of downstream evolution on the slot nozzle plume. The tendency shown in Fig. 7 for the circular nozzle plume to lift off the surface is accentuated in the slot nozzle case. Several possibilities exist to explains this effect. These incude the fact that the 8 in. downstream location is farther downstream in units of penetration height for the slot than for the circular nozzle. This should however be qualified by noting that, viewed from sufficiently far away, any disturbance is independent of the nozzle causing it. Therefore, the scale length properly used for scaling downstream distances should include both penetration and spreading half-width of the jet. Since the circular nozzle penetration height is the same as the spreading half-width, the value of h calculated for a circular nozzle with the area ratio of the actual nozzle is probably the best available unit of length for far-field distrubances caused by a jet from any actual nozzle. It also may be conjectured that the forward component of injection involved in use of the slot nozzle may increase the ability of the airstream to penetrate beneath the plume, despite the larger obstacle of the separated region, as shown in Fig. 5.

Comparison with Other Data

Comparison of experimental data with other experimental data is often difficult since exact matching conditions of one experiment ususally are not available in another. Two sources of data on hydrogen injection exist, with sufficient similarity in jet-to-freestream dynamic pressure ratio and in sampling location so that comparison is possible.

Orth, et al.[3] injected room-temperature hydrogen through a circular sonic nozzle into a Mach 2.72 free air jet. The difference in stream conditions between that work and this are large but may be assumed, consistent with the penetration height concept discussed above, to scale with the ratio of dynamic pressure, q_j/q_L. Based on this assumption, downstream distance to the probe location can be expressed in nozzle diameters. The correct nozzle diameter to use in the present tests to compare results with Ref. 3 is not clear; exit and throat diameters differ. Thus, an exact comparison with Ref. 3 is not possible, although results at two values of x/d_* in the range of interest of the present data were chosen for comparison.

Results of this comparison are shown in Fig. 9. The data of Ref. 3 fall generally in the same region as the present data. In fact the data are as consistent as their scatter allows. This is especially interesting in view of the fact that the sample analysis accuracy claimed in Ref. 3 is ±2%. The scatter can result only from large directly temporal, convected spatial or fixed spatial variations; and it can only be the latter if the apparent scatter of the data of Ref. 3 is not scatter, but is reproducible. This not only appears unlikely on general

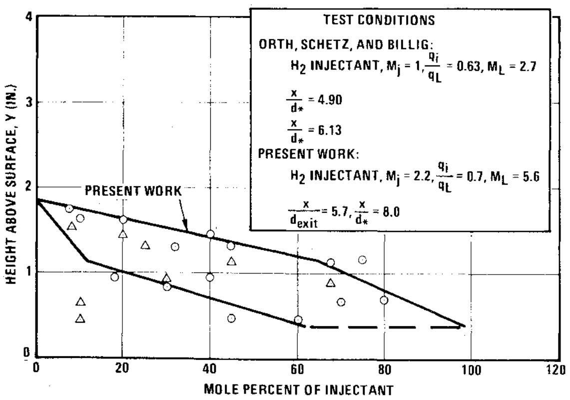

Fig. 9 Comparison with hydrogen injection data of Orth et al.[3]

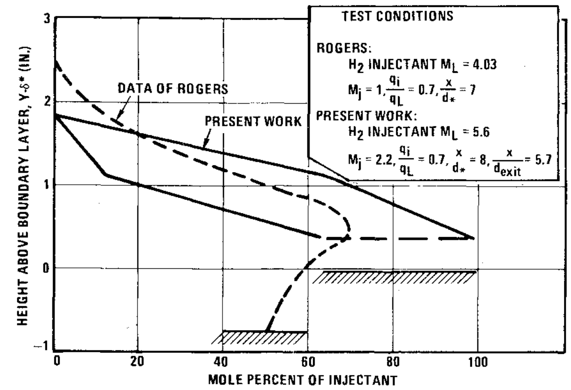

Fig. 10 Comparison with hydrogen injection data of Rogers.

grounds (as well as from the present data) but is disclaimed implicity in Ref. 3 by drawing a smooth curve throught the data. It therefore may be concluded from the comparison with Ref. 3 that within the accuracy possible, simple dynamic pressure and penetration height considerations satisfactorily scale mixing. Measurements of great accuracy are not needed until either sufficiently long collection time can be provided for true temporal or convected spatial averaging, or until the mixing process is better understood. The existence of extreme spatial variations in concentration, convected with the stream, which is by far the most likely explanation of the scatter (which are therefore really convected local concentration fluctuations) is of greater importance to the combustion process than long-time-average profiles.

A second source of useful data is the work of Rogers.[4] Here a circular sonic nozzle is used to inject hydrogen into an airstream at $M_L = 4.03$, $P_0 = 200$ to 300 psi, and $T_T = T_{0_j} \simeq$ 300K. Relatively little data scatter exists in this reference, perhaps because of long collection times, and a correlation is presented which allows interpolation to the same value of dynamic pressure ratio q_j/q_L used in the present tests. However, because of a particular interest in supersonic combustors, a thick boundary layer was involved; at the injector $\delta/d^* = 2.7$ and $\delta^*/d_* = 1.1$, in contrast to the present work in which $\delta^*/d_* = 0.04$. In order to make a comparison, the correlation of Ref. 4 and the present data is plotted in Fig. 10 in terms of height above the boundary-layer displacement thickness.

Although the comparison is quite good, it is only roughly valid. There is no real reason why mixing should remain exactly similar in the presence of a thick boundary layer. The existence of appreciable injectant farther from the boundary-layer displacement thickness in Ref. 4 than in Ref. 3 or the present work may result from the presence of the boundary layer. It is also very likely that upstream separation is different in Ref. 4 than in the present work.

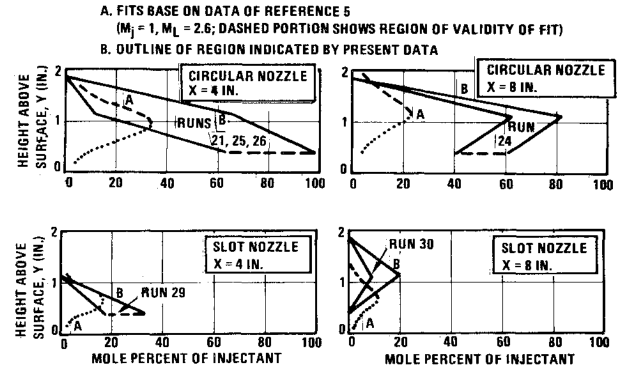

Fig. 11 Comparison of present hydrogen data with fits to argon data of Spaid et al.[5]

Finally, it is of interest to compare the present results with data for other injectants. This is done in Fig. 11, in which comparison is made with concentration profile fits derived from experimental data of Spaid et al.[5] using injectants of moderate molecular weight, mostly argon. The fits are not valid between their maximum and the plate, shown in Fig. 11 by dotted lines, but they correctly represent the experimental profiles and at the point of maximum concentration. They are governed by calculated penetration height rather than by the value determined from the jet shock, i.e., by h rather than αh; but as shown in the foregoing, the correction is rarely greater than 20% and would not affect significantly the comparison shown in Fig. 11. It is clear that for the circular nozzle, Fig. 11 shows the maximum value of injectant concentration to be much greater for hydrogen than for argon injectant, but the vertical extent of the injectant is very similar in both cases. Since the same number of moles of injectant must pass the probe station in a given times, by conservation of mass, one may speculate that the smaller apparent area under the argon data implies greater lateral spreading for that injectant than for hydrogen.

Fair correspondence exists between the slot nozzle fits and hydrogen data. This comparison probably has limited physical significance, however, as no slot nozzle argon results were included in the data of Ref. 5. Further, because of the possibility of substantial increases in lateral spreading with the slot nozzle, no use can be made of this approximate correspondence.

IV. Conclusions

Experimental data on jet penetration and mixing and on the upstream extent of the separated region are presented for conditions equivalent to those that would be produced on a vehicle flying in the atmosphere at high Mach number (4 to 9) and reasonable altitudes (15,000 to 100,000 ft).

Interaction between the jet and the airstream was evaluated by measuring the bow shocks produced by the jet of injectant, as recorded on schlieren film, and reducing each measured shape to a single scale length, representing the radius of the obstacle which would produce the same shock. This length is the experimental penetration height, which is expressed as a correction α times the calculated penetration height. Each measured shock shape was reduced to an experimental penetraton height, and thus to value of α. Results show a clear dependence of α on nozzle, shape, a possible dependence on injectant temperature and molecular weight, but no clear dependence on combustion.

Measurements also were made from the films of the upstream extent of the separated region. This extent was measured from the farthest upstream optical indication to the position of the equivalent body that would produce the jet shock, thus eliminating the effect of jet geometry and differential expansion, caused, for example, by molecular weight differences. The length of the separated region was measured in units of the experimenal penetration height. Results showed that the only factor exerting a clear control over the extent of the separated region is nozzle geometry. The combined effect of nozzle geometry and separation on the interaction between the jet and the stream was considered. It was shown that the jet from the slot nozzle protruded only slightly above the top of the separated region, whereas in the case of the circular jet, the height of the separated region was small compared to the jet penetration. It was concluded that a decrease in mixing could result in the slot jet as opposed to the circular jet.

The concentration measurements provided a better understanding of jet mixing under flight conditions and in the presence of combustion. Comparison of these measurements with those of other investigators at different conditions, but with the same injectant (hydrogen), showed that the difference in conditions could be accounted for by use of a calculated penetration height. The comparison also showed that the effect of combustion on jet penetration and mixing was negligible for the slot nozzle, although it possibly caused a significant increase in the case of the circular nozzle. However, a change in injectant molecular weight and temperature resulted in changes in jet penetration and mixing considerably larger than those predicted by the penetration height calculation.

Acknowledgments

This work was done under contract to the U. S. Army Missile Command, Redstone, Arsenal, Ala. The contract monitor was R. G. Rhoades. The concentration probes were provided by K. E. Woodgrift of the Marquardt Co. The tests were conducted at Calspan Corp. under the direction of C. E. Rogers. The authors acknowledge these contributions with thanks.

References

[1]Billig, F.S., "Shock-wave Shapes Around Spherical- and Cylindrical-Nosed Bodies," *Journal of Spacecraft and Rockets*, Vol. 4, June 1967, pp. 822-823.

[2]Kallis, J.M., "Equivalent Solid Obstacle for Gas Injection into a Supersonic Stream," *AIAA Journal*, Vol. 10, Oct. 1972, pp. 1342-1344.

[3]Orth, R.C., Schetz, J.A., and Billig, F.S., "The Interaction and Penetration of Gaseous Jets in Supersonic FLow," NASA CR-1386, July 1969.

[4]Rogers, R.C., "A Study of the Mixing of Hydrogen Injected Normal to a Supersonic Air Stream," NASA TN D-6114, March 1971.

[5]Spaid, F.W., Zukoski, E.E., and Rosen, R., "A Study of Secondary Injecion of Gases into a Supersonic Flow," TR 32-834, Aug. 1966, Jet Propulsion Laboratory.