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Effect of Injection Angle on Liquid Injection in Supersonic Flow

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The aim of this experimental work was a study of the influence of injection angle on the penetration and breakup of liquid jets in a supersonic airstream. All tests were conducted in the VPI 23-cm Supersonic Wind Tunnel at $M=3.0$ with T_0 = ambient and $P_0 = 4.35$ atm. A particular goal was to incorporate injection angle into the penetration correlations previously developed at VPI. This was accomplished. A secondary aim of the work was to assess the performance of liquid fuel jet injection from the top of a strut. This is one method that has been suggested for the "mechanical" enhancement of penetration. The penetration behavior was found to be essentially the same as for injection from a flat plate. A result of interest was the discovery of waves with sharp crests on the windward side of the jets for downstream angled injection.

Nomenclature

d	= injection port diameter
d_f	= frontal dimension of noncircular injector
d_s	= streamwise dimension of noncircular injector
d_{eq}	= equivalent diameter of noncircular injector
h	= penetration height
$\bar{h}=h/d$	= dimensionless penetration
h^*	= defined in Eq. (4)
L_L	= upstream extent of liquid layer
$\bar{q}\equiv\rho_j U_j^2/\rho_\infty U_\infty^2$	= momentum flux ratio
U	= velocity
$\bar{x}_h = x/d$	= dimensionless streamwise distance
ρ	= density
θ	= injection angle

Subscripts

j	= initial injectant conditions
∞	= freestream conditions

Introduction

THE potential performance superiority of supersonic combustion ramjet (SCRAMJET) engines over other, more conventional types of engines for hypersonic flight within the atmosphere is a matter of established fact today. Liquid fueled systems will be attractive in applications where the system is volume-limited, and particularly where the structural cooling function of the fuel is not an essential requirement. Different methods of liquid fuel injection are under investigation, but one of the more common methods is normal injection from the wall. An important feature of the flowfield is the gross penetration of the jet into the flow. Intensive investigations of liquid injection have been carried out during the past, and a full review of the literature covering this problem was given in Ref. 1.

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The main aim of the present work was to study alternative methods of increasing liquid jet penetration. As was shown in Ref. 2, penetration may be increased if the injector angle is more than 90 deg, and a similar conclusion was made in Ref. 3. These qualitative suggestions need more quantitative data to develop methods of evaluating the penetration of liquid jets over a wide range of geometrical and gasdynamical parameters. In particular, it would be useful to generalize the penetration correlations given in Refs. 1, 4, and 5 to include the effects of injection angle. This is one of the aims of the present research. Another aim is to investigate "mechanical" methods of increasing the penetration, such as injection from the top of strut.

Experimental Equipment

Test Facility

The experimental test runs were conducted in the VPI 23×23 cm supersonic blowdown wind tunnel at Mach 3.0. The stagnation temperature was at ambient atmospheric value, and the stagnation pressure of the freestream was held at 440 KPa (or 4.35 atm).

Fluid Injection System

Most of the runs were conducted with water for safety reasons, but one set of runs used methanol as the injection liquid. These fluids have physical properties representative of liquid fuels, and some previous studies have indicated that penetration and breakup are not sensitive to properties.

The injectant was contained in a stainless steel reservoir pressurized by compressed nitrogen. From the reservoir, the injectant passed through a needle valve and then through a flowmeter.

Models and Injectors

Most of the experiments were conducted with a strut model machined from brass and wall-mounted parallel to the centerline of the test section. The strut had a diamond-shaped cross section with 9.5 deg half-angles and a flat top. A few runs were conducted with the flat plate model described in Ref. 4.

Two sets of injectors were used. The first set consisted of orifices, drilled at an angle of 90 deg to the flow direction, with diameters of 0.79, 1.59, and 3.2 mm (1/32, 1/16, and 1/8 in.). The second set of injectors included orifices drilled at different angles to the flow direction, but the diameter of all the injectors was the same—1.59 mm.

Photographic Techniques

Three kinds of photographic techniques were used during the set of experiments described. Direct and back-lighted streak photographs were of relatively long exposure time (2.5 ms) which gave time-averaged pictures of the highly unsteady flowfield. Back-lighted streak pictures were used for the measuring of penetration. To obtain small-scale details of the jet, stop action photographs are required. The light source in this case was a Nanolamp (exposure time of 15 ns).

Results

The presentation of the results is divided into two main parts—data on penetration and that on a liquid layer existing upstream of the injection nozzle.

Jet Penetration

Comparison with Previous Flat Plate Injection for Normal Injection

Considerable work has been undertaken on liquid jets injecting into a supersonic gaseous stream from both a flat plate and a nozzle wall, but liquid injection from the top of a strut investigated here has no precedent. It is, therefore, necessary to compare the penetration data obtained both for flat plate and strut injection. It is convenient to make this comparison for the well-investigated case of normal (90 deg) injection.

The penetration correlation formulae obtained by Yates,[5]

$$\bar{h} = h/d_j = 1.15(\bar{q})^{1/2} \ln(1+6\bar{x}_h) \quad (1)$$

was used for comparison with the current experimental data. Notice that for $\bar{x}_h = 30.0$ and a circular nozzle the following formula

$$\bar{h} = 5.98(\bar{q})^{0.49} \quad (2)$$

which was developed in Ref. 4, gives the same results as Eq. (1). Comparisons of the present experimental data with Eq. (1) are shown in Fig. 1 for $\bar{x}_h = 30.0$, and in Fig. 2 for three values of $\bar{q}$. Good agreement between previous results for a flat plate and the present data for strut injection allows one to conclude, that, first, there are no differences in physical phenomena for both cases and, second, it is possible to use well-known correlations to predict the penetration of liquid jets injected in supersonic flow from the top of a strut.

Downstream Injection

Data available in the literature show that the effect of injection angle is strong,[2,3] but these data are mainly qualitative. For design and preliminary calculations of SCRAMJET combustion chambers and other applications, it is necessary to have reliable correlations for evaluating the penetration of liquid jets as a function of injection angle.

A set of nine runs conducted at the same conditions was carried out. Injection angle was the new parameter which was changed from 30 to 150 deg with a step size of 15 deg. Direct photographs of strut injection at $\bar{q} = 3.65$ with different downstream angles are shown in Fig. 3. The main qualitative result from these pictures agrees with that of previous investigations, i.e., with increasing injection angle, penetration increases. This result was confirmed and quantified here by other tests including ones for different diameters of the injection port, various downstream distances, and another injectant (methanol). For obtaining detailed quantitative information about the angle effect on the penetration, the experimental program included measurements of penetration as a function of the parameter $\bar{q}$ for each angle of injection using back-lighted streak photos. Reduction of these data allows us to obtain the results shown in Fig. 4 for $\theta = 60$ and 75 deg as typical examples. The solid lines on the figure represent a new correlation formula obtained, which will be discussed later.

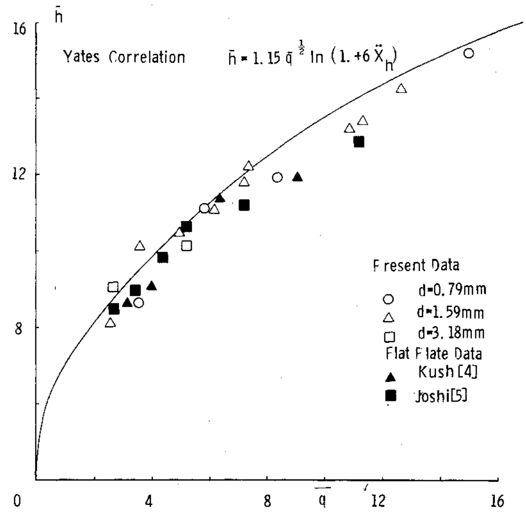


Fig. 1 Comparison of penetration vs $\bar{q}$ from top of strut with flat plate correlation and data at $x/d = 30$.

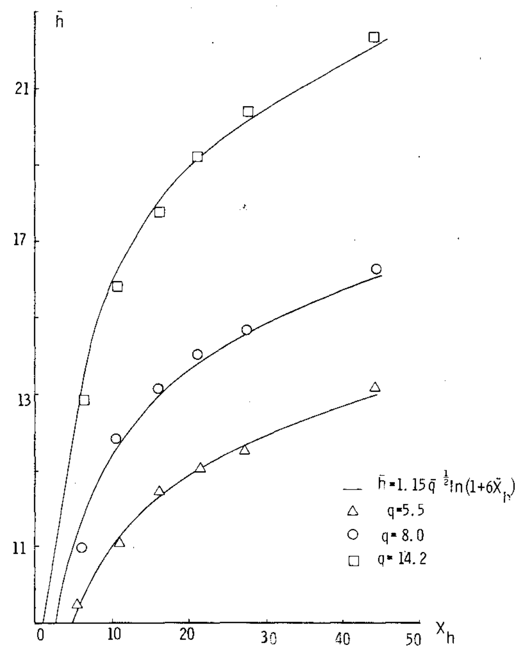


Fig. 2 Comparison of penetration vs x/d from top of strut with flat plate correlation.

Upstream Injection

Pictures of upstream liquid injection show that the flowfield in this case is more complicated than for downstream injection. Some direct photographs are shown in Fig. 5 and back-lighted nanosecond photographs are presented in Fig. 6, with close-ups of the front portion of the jet plume in Fig. 7. There is a large separation zone ahead of the jet and a liquid layer on the wall extending upstream from the injection nozzle, and its extent depends upon the parameter $\bar{q}$. The general behavior of the jet into a supersonic crossflow is the same as for normal injection—unsteady pulsations of the outer boundary but still a regular dependence of penetration upon the parameter $\bar{q}$.

Reduction of the data from the streak pictures for three injection angles (90, 105, and 120 deg) allowed one to obtain the penetration data shown in Fig. 8.

General Correlation for Penetration

We have from Refs. 1, 4, and 5 correlation formulas that include all the major jet and freestream parameters except

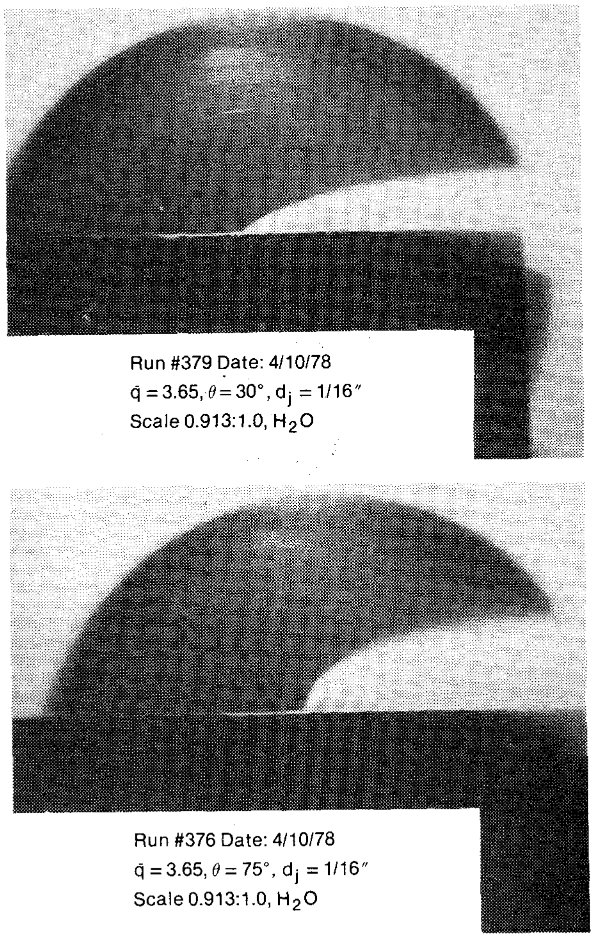


Fig. 3 Direct-streak photographs of downstream-angled injection.

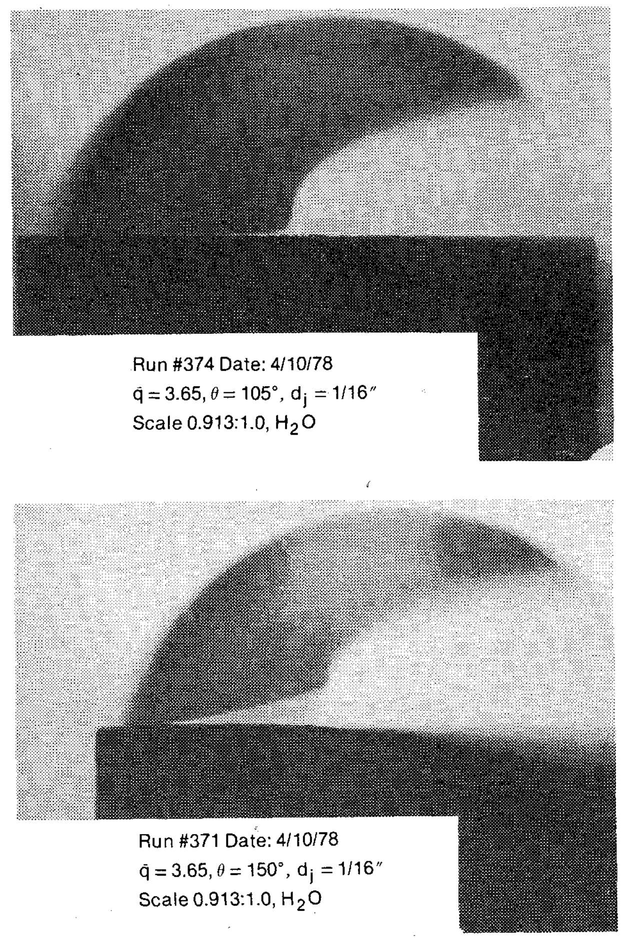


Fig. 5 Direct-streak photographs of upstream-angled injection.

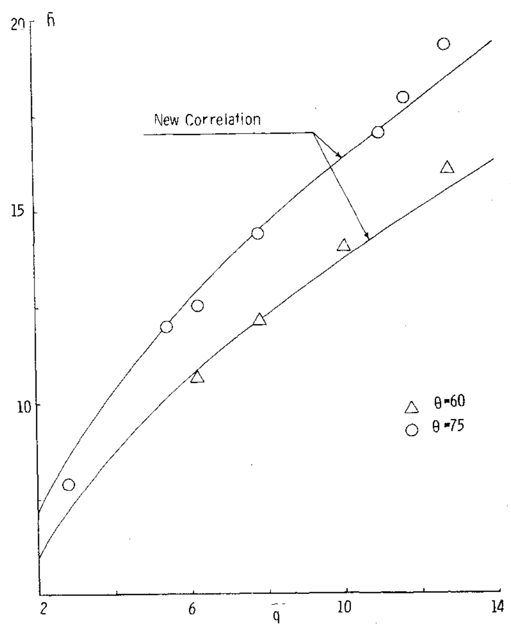


Fig. 4 Typical penetration results for downstream injection.

injection angle. It is our purpose here to extend the previous results to include that parameter and thus generate a master correlation formula that can be used for design.

Leaving aside the effects of injector shape for the moment, we take the dependence on $\bar{q}$ from Ref. 4 and the dependence on x/d from Ref. 5. We have found it possible to account for the effect of injection angle by inserting the last factor in Eq. (3) and modifying the constant appropriately.

$$\bar{h} = 1.32(\bar{q})^{1/2} \cdot \ln(1+6\bar{x}_h) \cdot \sin(2/3\theta) \tag{3}$$

For $\theta = 90$ deg, this reduces to the well-known correlation (1) and for the still more special case, where $\theta = 90$ deg and $\bar{x}_h = 30.0$, it becomes equivalent to correlation (2). Comparison of Eq. (3) with experimental data is shown in Fig. 9. The slope of this curve confirms the conclusion of Ref. 2 that the maximum penetration takes place at $\theta = 135$ deg.

If the penetration is written in the form:

$$h^* = h/[1.32 \cdot d_j \cdot \sin(2/3\theta) \cdot \ln(1+6\bar{x}_h)] \tag{4}$$

All experimental data will fit the very simple correlation:

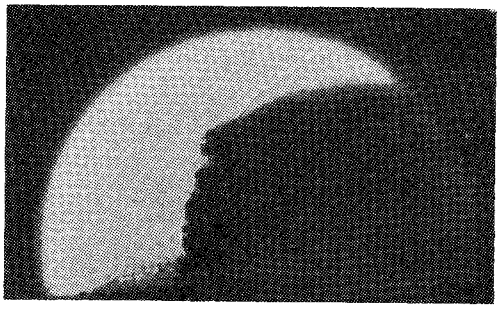
$$h^* = (\bar{q})^{1/2} \tag{5}$$

This correaltion is shown in Fig. 10. Detailed information about the parameters corresponding to each symbol is available in Ref. 6.

Analysis of the earlier experimental results, obtained at VPI[1,4] for injectors having noncircular shapes, shows that it is possible now to obtain a very general correlation for liquid jet penetration, including the effect of injector shape. In fact, from these investigations, it is known that penetration depends upon the shape and the orientation of the injector as follows:

$$\bar{h} = K(\bar{q})^{1/2} C_d \cdot \left[\frac{d_{eq}}{d_f}\right]^2 \cdot \left[\frac{d_f}{d_s}\right]^{0.46} \tag{6}$$

In the limit, this correlation for a circular injector ($C_d \approx 1.0$; $d_{eq} = d_f = d_s$) becomes the equivalent of Eq. (2), which is a special case of the general Eq. (3). Finally, a general



a) Run #223 Date: 3/1/78
$\bar{q} = 7.3, \theta = 135°, d_j = 1/32''$
Scale 3.4:1.0, H_2O

b) Run #224 Date: 3/1/78
$\bar{q} = 11.35, \theta = 135°, d_j = 1/32''$
Scale 3.4:1.0, H_2O

Fig. 6 Back-lighted nanosecond photographs of upstream-angled injection.

correlation including all these effects may be written as:

$$\bar{h} = 1.32(\bar{q})^{1/2} \cdot C_d \cdot \left[\frac{d_{eq}}{d_f}\right]^2 \cdot \left[\frac{d_f}{d_s}\right]^{0.46}$$
$$\cdot \ln(1+6\bar{x}_h) \cdot \sin(2/3\theta) \qquad (7)$$

Good agreement between this correlation and experimental data allows one to recommend Eq. (7) for evaluating liquid jet penetration in supersonic gas flow for liquid injectors over the following ranges of parameters:

$$\bar{q} = 2.0\text{-}18.0,\ \theta = 15\text{-}150 \text{ deg},\ \bar{x}_h = 5.0\text{-}45.0$$

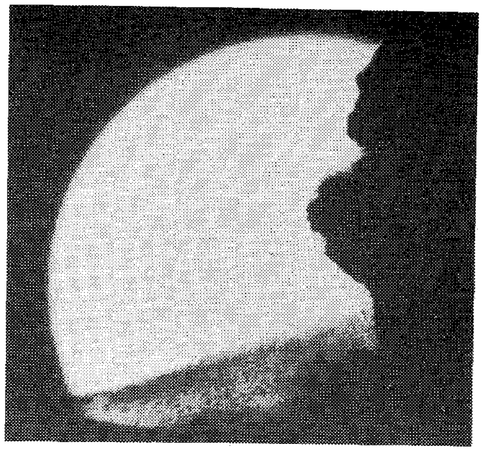
$$d_j = 0.79\text{-}3.20 \text{ mm},\ M_\infty = 2.0\text{-}4.0,\ d_f/d_s = 0.20\text{-}5$$

Liquid Layer Upstream of Injector

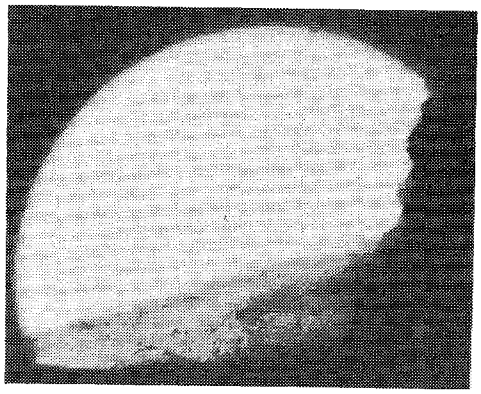
Top-view photographs of liquid jets injected at $\theta = 90$ deg from a flat plate obtained in previous investigations[1,4] show that around the nozzle on the surface of the flat plate there is a liquid layer. The side-view photographs for upstream injection (e.g., Figs. 6 and 7) indicate that the formation of such layers will be enhanced under those conditions. The extent of this layer can be important for heat transfer and combustion applications. The maximum upstream extent of this layer was studied as a function of injection angle for several values of $\bar{q}$ and the results are shown in Fig. 11. There is an apparent weak maximum at $\theta = 135$ deg.

Wave Phenomenon on Jet Column

Let us now look more deeply into a physical phenomenon that occurs when a liquid jet is injected in the downstream direction to the main supersonic gas flow. A clear illustration of typical wave patterns is shown in Fig. 12. The existence of an oblique shock before the jet and the highly unsteady wave pattern on the jet plume are well-known and have been



a) Run #231 Date: 3/6/78
$\bar{q} = 7.3, \theta = 150°, d_j = 1/16''$
Scale 3.4:1.0, H_2O



b) Run #227 Date: 3/6/78
$\bar{q} = 7.3, \theta = 135°, d_j = 1/16''$
Scale 3.4:1.0, H_2O

Fig. 7 Back-lighted nanosecond, closeup photographs of region ahead of injection port for upstream-angled injection.

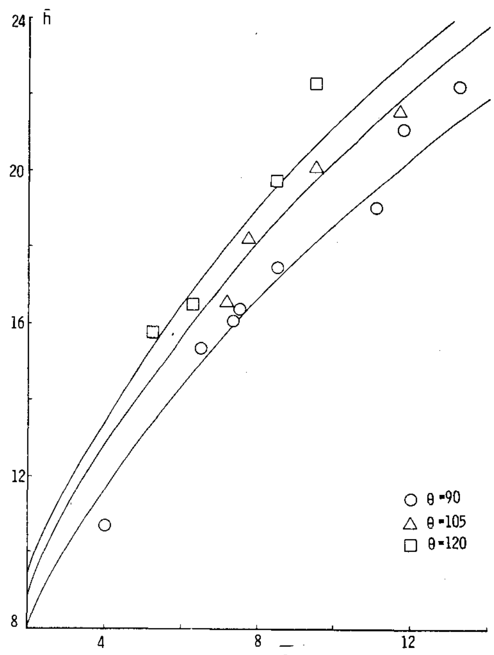


Fig. 8 Typical penetration vs $\bar{q}$ for downstream injection.

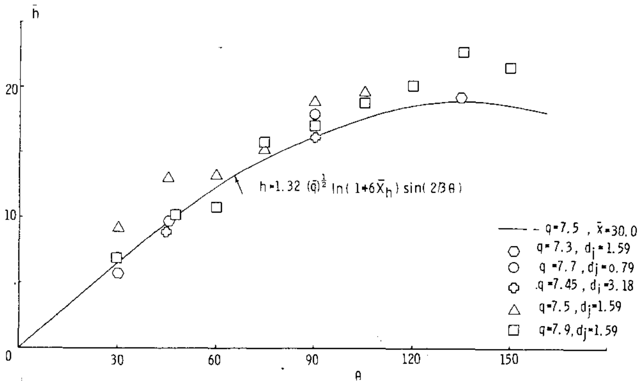


Fig. 9 Penetration correlation for circular injectors.

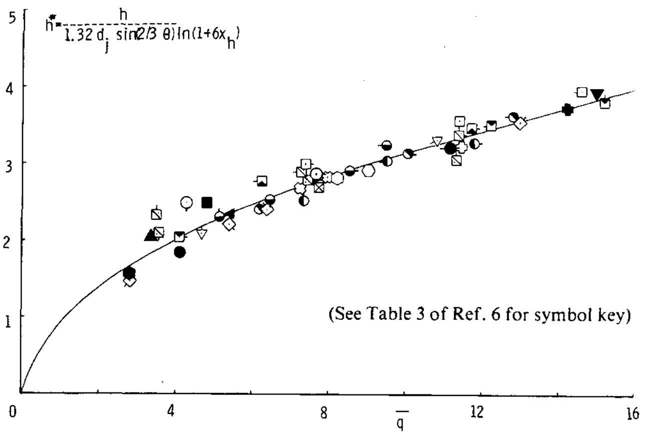


Fig. 10 "Reduced" penetration correlation for circular injectors.

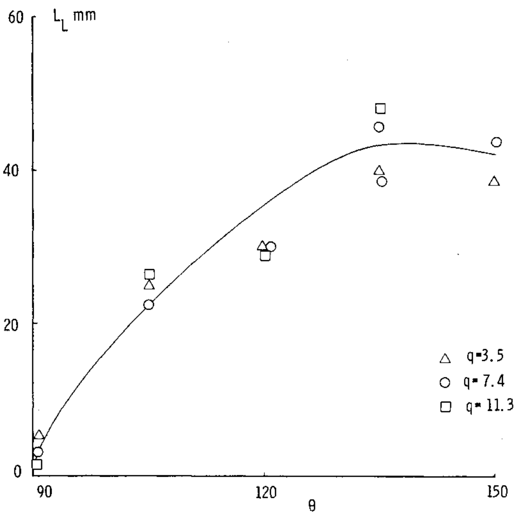
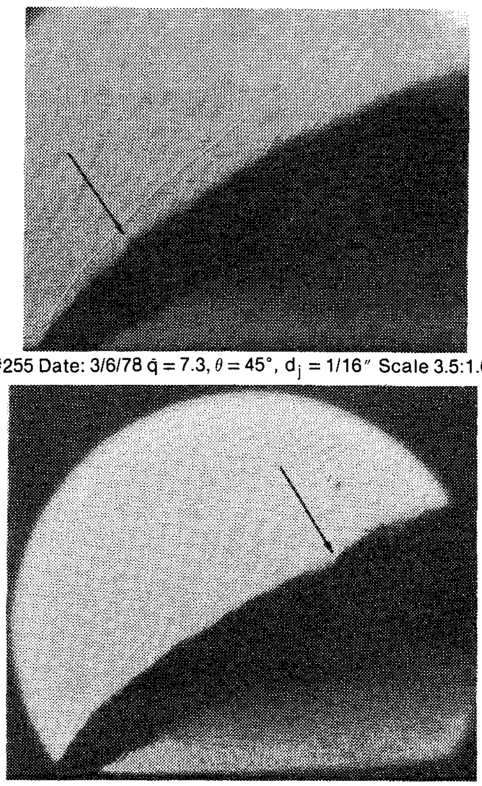


Fig. 11 Upstream extent of liquid surface layer vs injection angle.



a) Run #255 Date: 3/6/78 $\bar{q} = 7.3$, $\theta = 45°$, $d_j = 1/16''$ Scale 3.5:1.0, H_2O

b) Run #205 Date: 3/1/78 $\bar{q} = 11.4$, $\theta = 45°$, $d_j = 1/16''$ Scale 3.4:1.0, H_2O

Fig. 12 Back-lighted nanosecond photographs of downstream-angled injection showing sharp wave crests.

described in the literature (e.g., Refs. 1 and 4), but the sharp upstream face of the waves encountered here is new. Some of the waves appear as if they were solid, upstream-facing steps. Indeed, a close examination of some of the original photographs suggests that there is a separation region after the edge of the "step." This exaggerated sharpness was not found for normal or upstream-angled injection.

Conclusions

The present experimental investigation of liquid jet injection into supersonic flow over a wide range of geometrical and gasdynamical parameters allows one to make the following conclusions:

1) From a basic gasdynamic point of view, injection from the top of a strut is essentially equivalent to that for flat plate or wall injection.

2) It was possible to develop a new correlation formula which allows one to evaluate the penetration of a liquid jet into a supersonic flow in very general situations, including the effects of different nozzle diameters and shapes, angles of injection, distances from injector, freestream parameters, and injectant flow rate.

3) Upstream injection of liquid fuel may be used as a method to increase penetration and residence time of a liquid fuel into a SCRAMJET combustion chamber.

4) Some unusual, sharp-edged wave patterns were found on the main jet column for downstream-angled injection.

Acknowledgment

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