AD-A050 747 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 20/4
EFFECT OF INJECTOR GEOMETRY ON CHARACTERISTICS OF A LIQUID JET --ETC(U)
OCT 74 P B JOSHI, J A SCHETZ AFOSR-74-2584

UNCLASSIFIED AFOSR-TR-75-0468 NL

| OF |

AD
A050747

END
DATE
FILMED
4 -78
DDC

AFOSR - TR - 75 - 0468

AD A050747

Sponsored by—
American Institute of Aeronautics and Astronautics (AIAA)
Society of Automotive Engineers (SAE)

2
B.S.

AIAA Paper No. 74-1156

EFFECT OF INJECTOR GEOMETRY ON CHARACTERISTICS OF A LIQUID JET INJECTED NORMAL TO A SUPERSONIC AIRSTREAM

by
PRAKASH B. JOSHI and JOSEPH A. SCHETZ
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

See 1473 in back

AD NO.
DDC FILE COPY

DDC
RECEIVED
MAR 2 1978
A

AIAA/SAE 10th Propulsion Conference

SAN DIEGO, CALIFORNIA / OCTOBER 21-23, 1974

AFOSR-74-2584

~~For permission to copy or republish, contact the American Institute of Aeronautics and Astronautics, 1290 Avenue of the Americas, New York, N.Y. 10019~~

EFFECT OF INJECTOR GEOMETRY ON CHARACTERISTICS OF A LIQUID JET INJECTED NORMAL TO A SUPERSONIC AIRSTREAM

Prakash B. Joshi* and Joseph A. Schetz**
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Abstract

An experimental investigation concerning the effect of injector geometry on liquid jet characteristics is reported in this paper. The penetration and spread of the jet were given major emphasis in the present work. Attention was also directed to the jet structure, separation zone and liquid layers. Circular and rectangular injectors of four different port areas were tested in a Mach 3 air stream over a wide range of jet/free stream dynamic pressure ratio. For the rectangular injectors both aligned and transverse configurations with respect to the cross flow were studied. The penetration and spread data were obtained from streak photographs and the jet structure was examined using spark photomicrographs. Correlations for jet penetration and spread were developed by analyzing the jet as a blunt body in supersonic flow. The effect of injector geometry was incorporated through an experimentally obtained factor. The penetration correlation provided a good fit for the experimental data, however, the width correlation was less satisfactory. It was observed that the transverse configuration of the jet has the most pronounced jet breakup and the largest liquid surface layers.

Nomenclature

C	constant defined by Eqn. (2)
C_d	discharge coefficient of the orifice (injector)
C_D	drag coefficient of the jet body
d_{eq}	diameter of equivalent circular orifice
d_f	frontal dimension of the injector
d_s	streamwise injector dimension
h	penetration
M_∞	free stream Mach number
P_{eb}	effective back pressure behind the interaction shock
P_{oj}	total pressure of the injectant
P_∞	free stream static pressure
$\bar{q}$	jet/free stream dynamic pressure ratio
w	spread of the jet
ρ_j	density of the injectant liquid
ρ_∞	free stream static density

I. Introduction

Liquid injection into a supersonic air stream finds applications in supersonic combustion ramjets (scramjets), transpiration cooling of re-entry bodies and thrust rector control of rockets. Although gaseous injection has been previously considered for thrust vector control and supersonic combustion, liquid fuels of the kersene type will most probably be used as the energy source on scramjets. Liquid fuels are more attractive than gaseous fuels for thrust vector control since liquids are easier to handle and generally require a lighter control system for operation. The injector geometry will have a significant role in liquid injection applications. For instance, the mixing of liquid fuel with air in scramjets will be influenced by the injector characteristics such as size, shape and orientation with respect to the free stream. The injection of liquid into a supersonic air stream produces an interaction shock and a free stream boundary layer separation zone upstream of the injector. The separation zone plays an important role during combustion due to the high rate of heat transfer to the wall in this region. The shock system associated with each injector in a practical supersonic combustor has two important effects: (i) It reduces the total pressure of the free stream and thus adversely affects the overall performance of the engine; (ii) static temperature and pressure of the free stream rise through the injector shock system thus creating better conditions from the viewpoint of chemical reaction rates. In general, the shock system is a strong function of injector geometry. This shows that the role of injector geometry merits a detailed investigation.

The influence of injector geometry on penetration and spread of the jet were given major emphasis in the present investigation. Attention was also directed to the jet structure, the separation zone and the liquid layers. The purpose was to obtain experimental penetration and spread data suitable for engineering use and to seek theoretical correlations incorporating the governing parameters. The motivation for the present work comes from the work of Kush and Schetz[1] who observed that a liquid jet through a rectangular slot aligned with the flow gives significantly higher penetration than through a circular hole of the same area.

II. Experimental Investigation

Test runs were conducted in the VPI & SU 9" x 9" supersonic blowdown wind tunnel. The free stream Mach number was 3.0. The stagnation pressure was maintained at 80 psia and the stagnation temperature was at the ambient atmospheric value.

Liquid injection experiments were carried out over a 4" x 5" flat plate with sharp leading edge. The plate was mounted on a sting and located

* Graduate student, Department of Aerospace and Ocean Engineering, VPI & SU, Associate Member AIAA.
**Chairman, Department of Aerospace and Ocean Engineering, VPI & SU, Associate Fellow AIAA.

Copyright © American Institute of Aeronautics and Astronautics, Inc., 1974. All rights reserved.

approximately at the centre of the test section. The injectors were in the form of interchangeable brass inserts which fitted beneath the flat plate and the orifice was flush with the plate surface. The brass inserts made easier the use of injectors with different geometry and size. Each injector had a 1/16" straight run and a smooth conical entry passage. A 1" diameter plenum chamber was fitted to the plate underneath the injector using an O-ring to provide a seal. The plenum chamber size was large compared to the orifice size to keep the disturbances in the injectant small. The liquid was supplied to the plenum chamber by means of copper feed lines. The orifice was located 2" downstream of the leading edge of the plate. Injection over a flat plate rather than through the test-section walls minimized the effects of boundary layer thickness. Also, injection over a flat surface avoided any boundary layer effects over curved surfaces. Injectors of different geometries-circular, square and rectangular with rounded edges, were used. Table 1 contains a list of injectors used in the investigation.

Table 1 List of Injectors

Injector number	Rectangular			Circular	Square
	Width d	Length L	L/d	Diameter	Side
	in	in		in	in
1				1/8	
2					0.111
3	0.0665	0.199	3		
4	0.0506	0.253	5		
5				3/32	
6					0.0831
7	0.0622	0.124	2		
8	0.0498	0.149	3		
9	0.0426	0.171	4		
10	0.0380	0.190	5		
11				1/16	
12					0.0553
13	0.0415	0.083	2		
14	0.0332	0.0996	3		
15	0.0285	0.114	4		
16				1/32	

Water was used as the injectant throughout the investigation. The injectant was stored in a reservoir which was pressurized by means of compressed air. The air pressure was regulated and varied to obtain the desired mass flow rate through the injector. The injectant, under pressure, passed through a needle valve, then through a strain gauge type flowmeter and finally through a solenoid valve before entering the plenum chamber. This valve could be opened or closed remotely to start or stop injection. The flat plate was mounted vertically for lateral spread data and horizontally for all other experimental work.

The entire body of experimental data was obtained using photographic techniques. The penetration data were obtained from 1 millisecond exposure, back-lighted photographs of the jet. These pictures provide a time averaged appearance of the jet and clearly define the penetration of the jet into the cross flow. The lateral spread data was obtained from 1 millisecond exposure, front-lighted photographs of the jet. These pictures show the liquid trapped in the shock-boundary layer interaction region (liquid layer) but do not delineate the extent of spread very clearly. The jet structure was examined using spark shadowgraphs and photomicrographs. These pictures were back-lighted with an exposure time of 1 microsecond. Fig. 1 shows a typical spark shadowgraph. It shows a wide view of the jet including its instantaneous structur-, the interaction bow shock and the shock-boundary layer interaction region. An example of

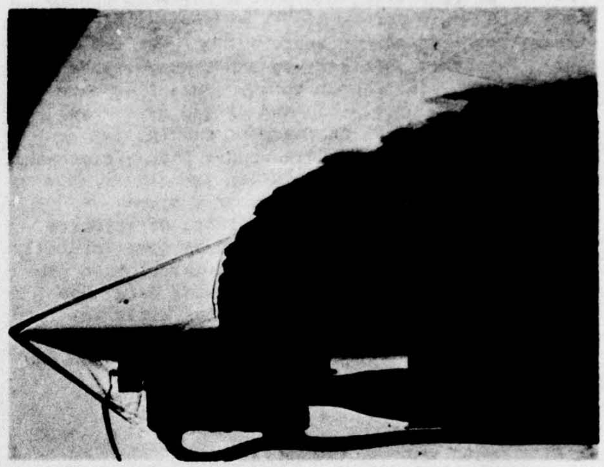


Figure 1 Typical Spark Shadowgraph

photomicrograph is shown in Fig. 2. The picture is a closeup view of the jet showing windward and leeward surface waves, fracture location and the interaction shock. The instantaneous jet structure

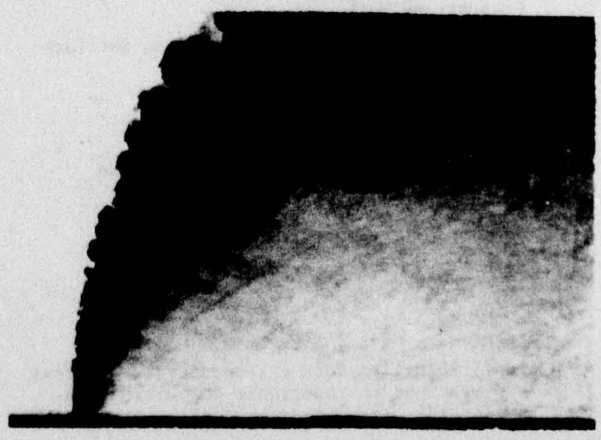


Figure 2. Example of Back-lighted Photomicrograph

seen in the back-lighted photomicrographs is, in fact, an integrated view over the width of the jet. In order to see the front surface of the jet, specifically with the purpose of determining whether the waves on the jet surface go around the jet, front-lighted photomicrographs were obtained. An illustration is shown in Fig. 3. The spark

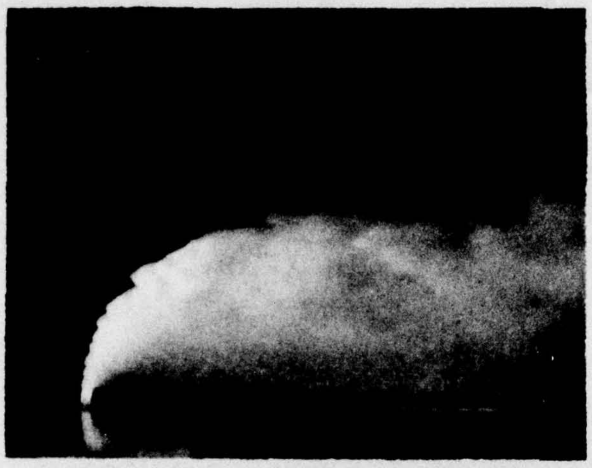


Figure 3 Illustration of Front-lighted Photomicrograph

duration was 1.2 microseconds. This picture also shows the waves on the jet surface and the downstream jet breakup in scattered light.

III. Correlation Analysis

The parametric correlations for jet penetration and spread were developed by analyzing the jet as a blunt body in supersonic flow. The liquid jet is considered to present an obstacle to the free stream and the effects of liquid vaporization are neglected. The jet is enclosed in a control volume enveloping the entire jet and liquid particles but not the interaction shock. Under this approach the gross aspects of jet characteristics are given the main consideration whereas the details of jet structure and unsteadiness are suppressed. The penetration correlation is obtained by equating the rate of change of streamwise momentum of the jet to the streamwise component of the total force on the jet (drag force). Here the frontal area is assumed to be proportional to the product of the asymptotic penetration height h with the frontal dimension d_f of the injector. The resulting correlation was

$$\frac{h}{d_f} = \text{const.}\ \frac{\rho_j}{\rho_\infty} (\bar{q})^{1/2} \frac{C_d}{C_D} (\frac{d_{eq}}{d_f})^2 \qquad (1)$$

The drag coefficient C_D in above equation is absorbed into a constant C which is a strong function of injector geometry but only a weak function of free stream conditions. C was determined experimentally to be

$$C = 5.75\ (\frac{d_f}{d_s})^{0.46} \qquad (2)$$

giving the following penetration correlation

$$\frac{h}{d_f} = 5.75\ (\bar{q})^{1/2}\ C_d\ (\frac{d_{eq}}{d_f})^2\ (\frac{d_f}{d_s})^{0.46} \qquad (3)$$

The above correlation was extended to include a wide range of free stream Mach numbers, giving the result

$$\frac{h}{d_f} = 0.127\sqrt{\frac{\rho_j}{\rho_\infty}}\ (\bar{q})^{1/2}\ C_d\ (\frac{d_{eq}}{d_f})^2 (\frac{d_f}{d_s})^{0.46} \qquad (4)$$

Or in terms of injection pressure,

$$\frac{hM_\infty}{d_f} = 0.152\sqrt{\frac{\rho_j}{\rho_\infty}}\ (\frac{P_{oj}}{P_\infty})^{1/2}\ C_d\ (\frac{d_{eq}}{d_f})^2\ (\frac{d_f}{d_s})^{0.46} \qquad (5)$$

The above equations are derived in detail in Ref. 2.

In a similar manner, in order to obtain a spread correlation, the rate of change of normal momentum of the jet was equated to the normal component of the total force on the jet. The projected area for the normal force balance was expressed as some function of the jet spread times downstream distance from the injector. The final form of the spread (or width) correlation was

$$\frac{w}{d_{eq}} = F\left\{\frac{1}{M_\infty^2}\left(\bar{q}C_d + \frac{1}{\gamma M_\infty^2}\frac{P_{eb}}{P_\infty}\right)\right\} \qquad (6)$$

The function F was determined experimentally, giving the spread correlation

$$\frac{w}{d_{eq}} = 11.2\left(\bar{q}C_d + \frac{1}{\gamma M_\infty^2}\ \frac{P_{eb}}{P_\infty}\right)^{0.19} \qquad (7)$$

IV. Results

Penetration data were obtained from streak photographs. Penetration was measured at a downstream distance $x/d_h = 25$ from the centre of the injector, where d_h is the hydraulic diameter of the injection port. Measured penetration was plotted against injection mass flow rate for different values of d_f/d_s, the ratio of transverse to streamwise injector dimension. Fig. 4 shows a typical plot for injectors having area equivalent to a 3/32" diameter orifice. This plot provides a comparison of circular and rectangular injectors having the same area. It is seen that for a given injectant mass flow rate the rectangular injector aligned (or transverse) with respect to the cross flow gives higher penetration than a circular injector of the same area. The maximum penetration occurs for the aligned configuration. This observation was confirmed for injectors of other areas as well. The penetration data for all injectors in Table 1 was plotted in terms of the correlation given by Eqn. (3). It is seen that the data

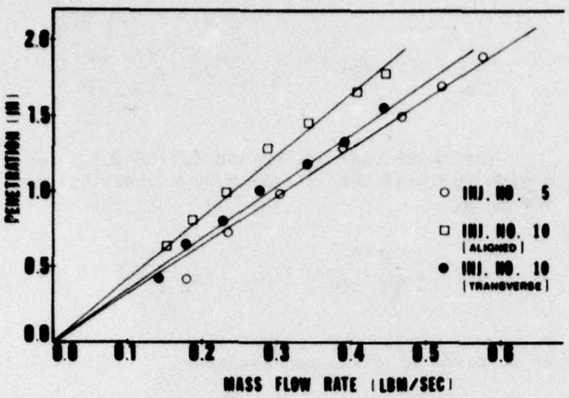


Figure 4 Comparison of Circular and Rectangular Injectors of the Same Area ($d_f : d_s$ = 1 : 2 and $d_f : d_s$ = 2 : 1)

points cluster around a single straight line (Fig. 5). The present penetration correlation agrees well with the purely empirical correlations developed by Kolpin et. al[3] and Yates and Rice[4] as shown in Ref. 2.

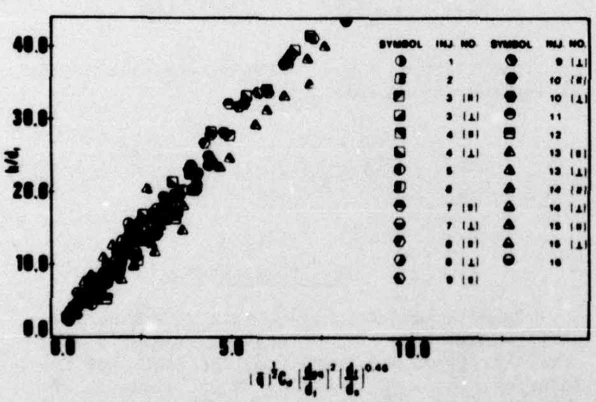


Figure 5 Penetration Correlation

Jet Spread

Fig. 6 shows a plot of spread correlation for circular injectors. The jet spread could not be determined sufficiently accurately and appeared to be sensitive to lighting conditions. In Eqn. (7) the contribution of the pressure term to $\bar{q}C_d$ is small, especially at high injection pressures. It is therefore concluded that the nondimensional spread is only a weak function of the dynamic pressure ratio or the injection pressure.

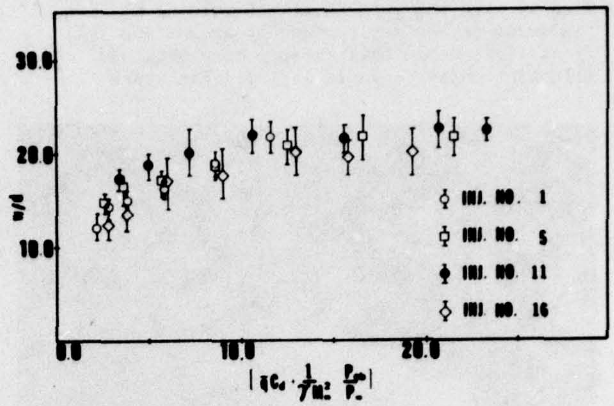


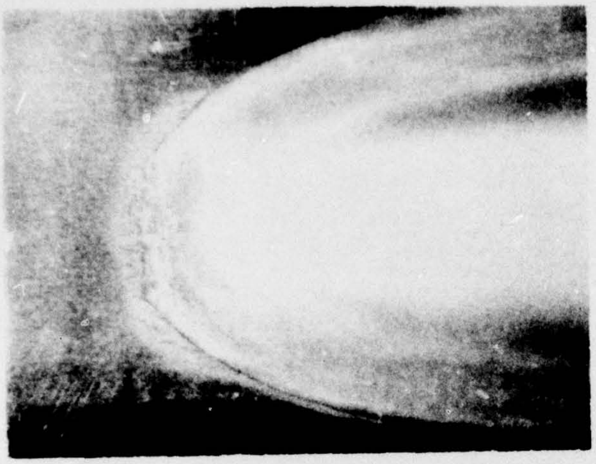
Figure 6 Spread Correlation for Circular Orifices

The effect of injector shape on the jet spread can be qualitatively assessed from Fig. 7a, b, c. The transverse configuration has the largest spread and the aligned configuration has the smallest.

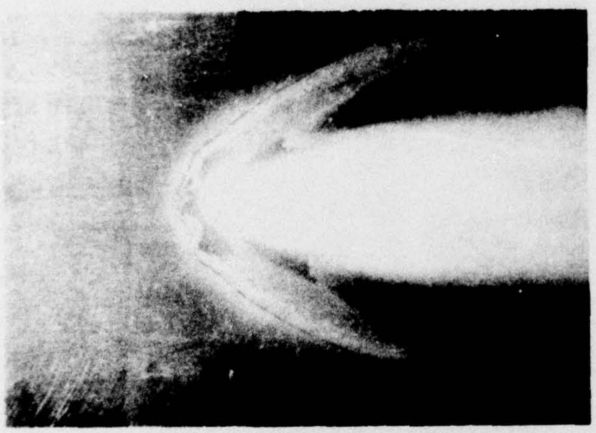
Liquid Layers

Fig. 7 clearly shows the existence of liquid layers around the jet. These layers are believed to be due to the liquid trapped in the interaction region of the enveloping shock surface and the flat plate boundary layer. The surface layers are of particular importance in combustion applications because pilot ignition may occur in this region, resulting in increased heat transfer to the wall. It was found during the present investigation that the injector geometry and injection pressure influenced the extent of the liquid layers very significantly. Fig. 7 illustrates the influence of injector geometry. For given injector area the largest liquid layer occurs for the transverse configuration and the smallest occurs for the aligned case. The extent of the layer for a circular injector is intermediate between the above two cases. A close examination of Fig. 7(b) shows that inside the two major branches of the liquid layer (primary layer) there are two distinct smaller layers (secondary layers) on either side of the jet. The secondary layers appear to originate under the jet and then merge with the primary layer downstream of the injector.

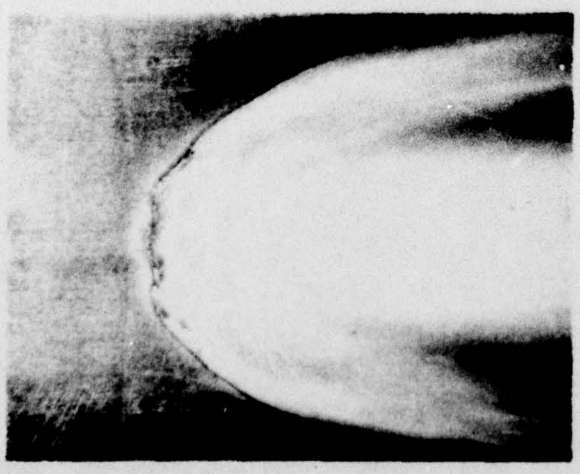
An increase in the injection pressure (or $\bar{q}$) was observed to have the following effects: (a) the upstream extent and the width of the primary layer branches decreases (b) the secondary layers move upstream and finally merge with the primary layer. (c) after a certain value of injection pressure the primary layer breaks up into small streaks of liquid which appear to merge downstream. Fig. 8 shows the effect of increasing the injection pressure.



(a) Inj. No. 4 (Transverse), P_{oj} = 30 psia

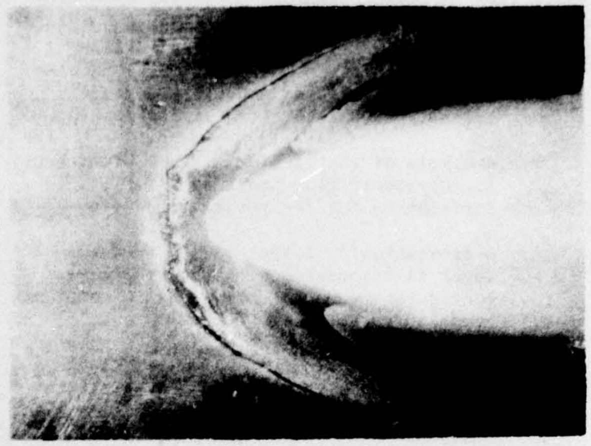


(b) Inj. No. 4 (Aligned), P_{oj} = 30 psia

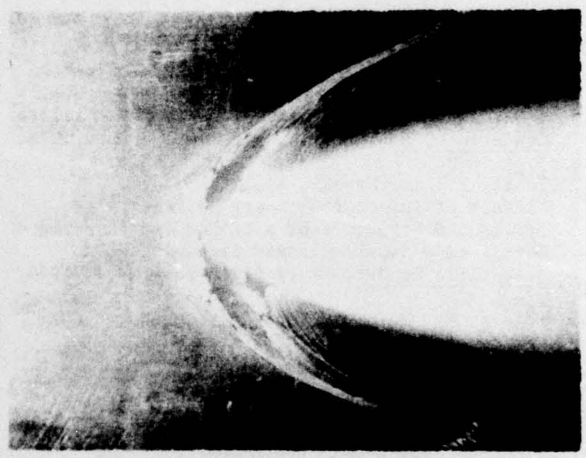


(c) Inj. No. 1 (Circle), P_{oj} = 30 psia

Fig. 7 Effect of Injector Geometry on Liquid Layers



(a) $\bar{q}$ = 3.8



(b) $\bar{q}$ = 6.1

Fig. 8 Effect of Increasing $\bar{q}$ on Liquid Layers (Inj. No. 1)

Jet Breakup

A qualitative study of the effect of injector geometry on jet breakup and structure was made. It was observed that the jet breakup is more pronounced for the transverse configuration than for the aligned configuration. The front-lighted photomicrographs show that the waves on the jet surface appear to go around the jet (Fig. 3). Mixing fluorescent paints and metal pastes with water to improve the light scattering from the jet surface did not show any noticeable improvement in the quality of the front-lighted pictures.

V. Conclusions

The following conclusions were reached as a result of the present experimental investigation.

A. For a given injectant mass flow rate the greatest penetration occurs for an aligned rectangular slot, and the least value occurs for a circular injector of the same area. The value of penetration for the transverse configuration is intermediate.

B. Analysis of the liquid jet as a blunt body in supersonic flow provides a satisfactory correlation for the penetration data.

C. A substantially larger liquid surface layer is associated with the transverse configuration of a rectangular injector as compared to the aligned case.

The width and upstream extent of liquid layers depends strongly on the injection pressure, decreasing with increase in the injection pressure.

D. The jet breakup appears to be more pronounced in the case of transverse configuration than in the case of aligned configuration.

References

1. Kush, E. and Schetz, J., "Liquid Jet Injection into a Supersonic Flow," AIAA Paper No. 72-1180, AIAA/SAE, 8th Joint Propulsion Specialist Conference, New Orleans, La., Nov. - Dec. 1972.

2. Joshi, P., Jakubowski, A., and Schetz, J., "Effect of Injector Geometry on Penetration, Spread and Structure of a Liquid Jet Injected Normal to a Supersonic Air Stream," AFOSR Scientific Report, TR-74-0149, September, 1973.

3. Kolpin, M., Horn, K., and Reichenbach, R., "Study of Penetration of a Liquid Injectant into a Supersonic Flow," AIAA Journal, Vol. 6, No. 5, May 1968.

4. Yates, C. and Rice, J., "Liquid Jet Penetration," Research and Devekopment Programs Quarterly Report, U-RQR/69-2, Applied Physics Lab., Johns Hopkins University, 1969.

ACCESSION for
NTIS White Section
DDC Buff Section
UNANNOUNCED
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. AVAIL. and/or SPECIAL
A

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR - TR - 75 - 0468
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): EFFECT OF INJECTOR GEOMETRY ON CHARACTERISTICS OF A LIQUID JET INJECTED NORMAL TO A SUPERSONIC AIR STREAM
5. TYPE OF REPORT & PERIOD COVERED: INTERIM
6. PERFORMING ORG. REPORT NUMBER: AIAA Paper No74-1156
7. AUTHOR(s): PRAKASH B JOSHI, JOSEPH A SCHETZ
8. CONTRACT OR GRANT NUMBER(s): AFOSR-2584-74
9. PERFORMING ORGANIZATION NAME AND ADDRESS: VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY, DEPARTMENT OF AEROSPACE ENGINEERING, BLACKSBURG, VIRGINIA 24061
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 681308, AF-9711-02, 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, 1400 WILSON BOULEVARD, ARLINGTON, VIRGINIA 22209
12. REPORT DATE: Oct 1974
13. NUMBER OF PAGES: 7
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

PROCEEDINGS
AIAA/SAE Propulsion Conference 10th pp1-6 San Diego, CA 21-23 Oct 1974

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

LIQUID FUEL INJECTION
JET MIXING
SUPERSONIC COMBUSTION RAMJETS
LIQUID FUEL JET PENETRATION
RE-ENTRY BODY COOLING
THRUST RECTOR CONTROL

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental investigation concerning the effect of injector geometry on liquid jet characteristics is reported in this paper. The penetration and spread of the jet were given major emphasis in the present work. Attention was also directed to the jet structure, separation zone and liquid layers. Circular and rectangular injectors of four different port areas were tested in a Mach 3 air stream over a wide range of jet/free stream dynamic pressure ratio. For the rectangular injectors both aligned and transverse configurations with respect to the cross flow were studied. The penetration and spread data were obtained

over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

406 922 JB

from streak photographs and the jet structure was examined using spark photomicrographs. Correlations for jet penetration and spread were developed by analyzing the jet as a blunt body in supersonic flow. The effect of injector geometry was incorporated through an experimentally obtained factor. The penetration correlation provided a good fit for the experimental data, however, the width correlation was less satisfactory. It was observed that the transverse configuration of the jet has the most pronounced jet breakup and the largest liquid surface layers.