Effect of Injector Shape on Penetration and Spread of Liquid Jets

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Theme

LIQUID injection into a supersonic air stream finds applications in supersonic combustion ramjets (scramjets), transpiration cooling of re-entry bodies and thrust vector control of rockets. The injector geometry will have a significant role in liquid injection applications. The injection of liquid into a supersonic air stream produces an interaction shock and a freestream 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: 1) it reduces the total pressure of the freestream and thus adversely affects the overall performance of the engine; 2) static temperature and pressure of the freestream rise through the injector shock system thus creating better conditions from the viewpoint of chemical reaction rates. The shape and strength of the shock also affect the forces on the liquid column and thus penetration. In general, the shock system is a strong function of injector geometry.

The influence of injector geometry on penetration and spread of the jet were given major emphasis in the present investigation. The purpose was to obtain experimental penetration and spread data suitable for engineering use and to seek theoretical correlations incorporating and 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.

Contents

Experimental Methods: Test runs were conducted in the VPI&SU 9 in. × 9 in. supersonic tunnel at Mach number 3.0. The stagnation pressure was 80 psia, and the stagnation temperature was ambient.

The model was a 4 in. × 5 in. flat plate with sharp leading edge. The injectors were interchangeable brass inserts which fitted beneath the flat plate, and the orifice was flush with the plate. Each injector had a 1/16 in. straight run and a smooth conical entry passage. A 1 in. diam plenum chamber was fitted to the plate underneath the injector. Injectors of different geometries—circular, square, and rectangular with rounded edges, were used (Table 1).

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Water, used as 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 entire body of experimental data was obtained using photographic techniques. The penetration data were obtained from 1 msec exposure, back-lighted photographs of the jet. The lateral spread data was obtained from 1 msec exposure, top-lighted photographs of the jet. The jet structure was examined using spark shadowgraphs and photomicrographs, back-lighted with an exposure time of 1μ sec.

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 freestream 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

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

where ρ_j = density of liquid, ρ_∞ = freestream static density, $\bar{q}$ = jet/free stream dynamic pressure ratio, C_d = discharge coefficient of the injector and d_{eq} = diameter of equivalent circular injector.

The drag coefficient C_D in Eq. (1) is absorbed into a constant C which is a strong function of injector geometry but only a weak function of freestream conditions. C was determined experimentally to be

$$C = 5.75 (d_f/d_s)^{0.46} \tag{2}$$

where d_s is the streamwise dimension of the injector, giving the following penetration correlation

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

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

$$\frac{hM_\infty}{d_f} = 0.152 \left(\frac{\rho_j}{\rho_\infty} \right)^{1/2} \left(\frac{P_{oj}}{P_\infty} \right)^{1/2} \times C_d \left(\frac{d_{eq}}{d_f} \right)^2 \left(\frac{d_f}{d_s} \right)^{0.46} \tag{4}$$

In a similar manner, to obtain a spread correlation, the rate of change of normal momentum of the jet was equated to the

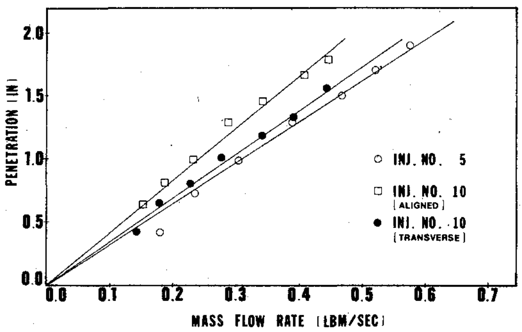

Fig. 1 Comparison of circular and rectangular injectors having the same area (d_f:d_s = 1:2 and d_f:d_s = 2:1).

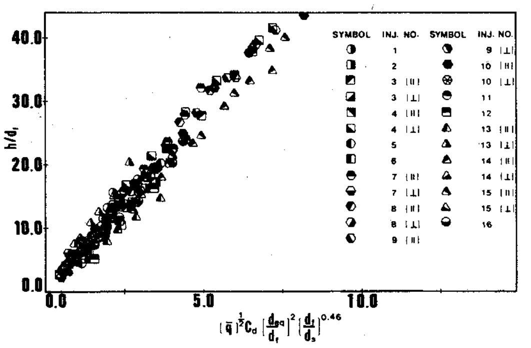

Fig. 2 Penetration correlation for circular, square, and rectangular injectors of various sizes.

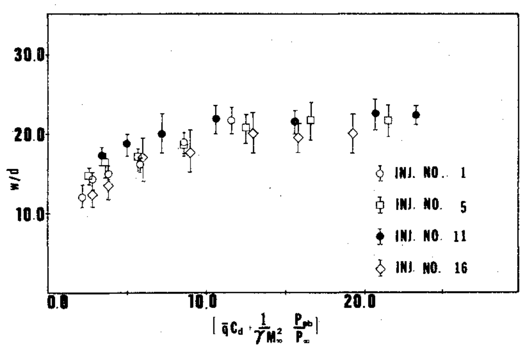

Fig. 3 Nondimensional width data for circular injectors.

normal component of the total force on the jet. The projected area for the normal force balance was expressed as some function F of the jet spread times downstream distance from the injector.

The function F was determined experimentally, giving the spread correlation

$$\frac{w}{d_{eq}} = 11.2\left(\bar{q}C_d + \frac{4}{5}\,\frac{1}{\gamma M_\infty^2}\,\frac{P_{eb}}{P_\infty}\right)^{0.19} \qquad (5)$$

where P_{eb} is the effective back pressure behind the interaction shock. It is the pressure downstream of a normal shock with upstream Mach number M_∞ in Eq. (5). The coefficient 4/5 is a correction factor.

Results: Penetration was measured at a downstream distance $x/d_h = 25$ from the center 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. Figure 1 shows a typical plot for injectors having area equivalent to a 3/32 in. diam 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 Eq. (3). It is seen that the data points cluster around a single straight line (Fig. 2). The present penetration correlation agrees well with the purely empirical correlations developed by Kolpin et al.[2] and Yates and Rice,[3] when reduced to circular injectors only. Of course, here we include the important effects of orifice geometry. The details of these comparisons are given in Ref. 4.

Table 1 List of injectors

	Rectangular			Circular	Square
Injector no.	Width d (in.)	Length L (in.)	L/d	diameter (in.)	side (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	

Figure 3 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. The agreement between the present experimental results for jet spread with the results of Ref. 5 is not good. This may be because the jet spread is not clearly delineated in the pictures and is sensitive to lighting conditions. In Eq. (5) 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.

Top view photographs of the jet show the existence of liquid layers around the jet.[4] 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. For given injector area, the largest liquid layer occurs for the aligned case. For details, Ref. 4 should be consulted.

References

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