Liquid Jet Injection into a Supersonic Flow

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Theme

THE study of a liquid jet injected normal to a supersonic gas crossflow is one of significant practical import and stimulating theoretical interest. There has been, however, a relative scarcity of experimental data pertaining to many details of the process, particularly the primary decomposition mechanism. The immediate stimulus and sources of the initial direction for this study were the experiments of Sherman and Schetz, wherein the presence on the jet of large axial waves, which appeared to create the dominant means of jet decomposition by gross detachment of large masses, was noted.

Contents

Test procedures: Liquid jet behavior was studied at Mach numbers of 2.4 and 4.0 with ambient stagnation temperature and stagnation pressures from 40 to 140 psia using a sting-mounted, flat plate model having removable injection port inserts. The injectants included water, carbon-disulfide, a 30% glycerin-water solution and Freons 12 and 21.

The primary observations were microphotos at 10^{-6} sec, "Streak" photos at 10^{-3} sec, high-speed motion pictures up to 44,000 pic/sec and spark shadowgraphs.

Fracture location: Representative microphotos of the jet break-up process are shown in Fig. 1. The high-mass flow case shown in Fig. 1a clearly illustrates the large amplitude, axial waves that lead to a fracture of the liquid column. The total length until fracture decreased with $\bar{q}$ ($\equiv \rho_j U_j^2/\rho_\infty U_\infty^2$), but curvature increased, so that the location of fracture remained always somewhat beyond the sonic angle on the centerline of the bow shock. Thus, the fact that the external gas stream was supersonic appears to play an important role in the break-up process. The locally supersonic flow over the "wavy-wall" surface of the jet produces significantly more drag on the elevations than does a subsonic flow, and this force apparently becomes sufficient to fracture the jet.

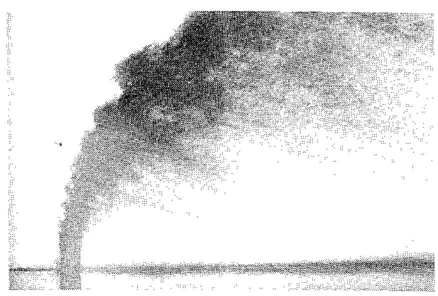
The location of the sonic angle of the shock was determined from the microphotos which displayed a shadowgraph effect. The small arrow in Fig. 1a indicates the sonic angle location on the shock.

The transition from subsonic to supersonic flow over the jet surface produced an important effect on the waves themselves. Beyond the sonic point, waves increased in wavelength and decreased in amplitude/wavelength ratio and remained in this mode until fracture.

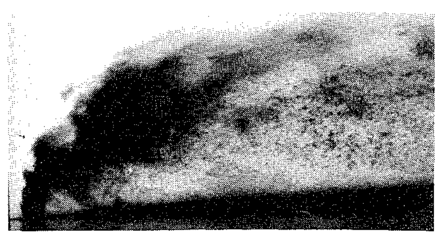
Regimes of jet configurations: A very important feature of normal liquid jet decomposition in supersonic crossflow that was observed is the existence of three regimes of jet behavior, determined by $\bar{q}$. The dividing values of $\bar{q}$ can be reasonably well-defined, but there is a gradual transition from one regime to the next.

What we have called regime 3 corresponds to cases with a $\bar{q}$ greater than about 6. As would be expected, the penetration in this regime is high. The jet forms a smooth curve as it is turned downstream and the waves form perturbations to the basic jet shape. The growth of the waves is regular, and the jet spreads fairly gradually out to the point of fracture (see Fig. 1a). Clump detachment is regular both in size and frequency, and the over-all jet body is reasonably steady.

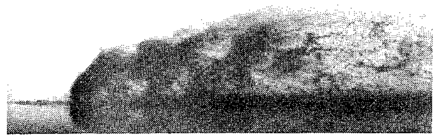
Regime 2, which ranges from about $\bar{q} = 1.5$ to 6, differs from regime 3 basically in that the waves here actually determine the jet shape and are not simply perturbations. Large, steep waves appear early in the jet development and influence the turn downstream and the clump size and fracture location (see Fig. 1b). The jet shape in this regime is not a smooth curve but is usually stepped or serpentine. The clump break-off is



a) Regime 3 case—$\bar{q} = 10.9$, $M = \frac{1}{16}$ in., H_2O



b) Regime 2 case—$\bar{q} = 3.8$, $M = 2.4$, $d = \frac{1}{32}$ in., H_2O



c) Regime 1 case—$\bar{q} = 1.1$, $M = 2.4$, $d = \frac{1}{32}$ in., H_2O

Fig. 1 Microphotos of jet break-up.

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Index categories: Multiphase Flows; Wave Motion and Sloshing; Hypersonic Airbreathing Propulsion.

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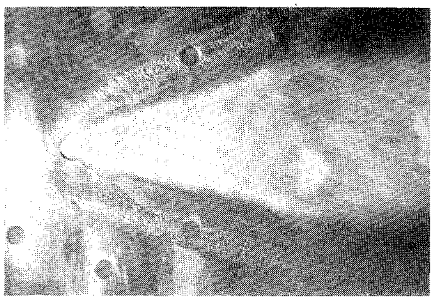
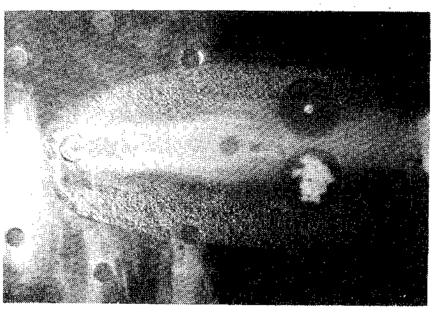


a) $q = 4.1$, $M = 2.4$, $d = \frac{1}{32}$ in., H_2O



b) $q = 1.6$, $M = 2.4$, $d = \frac{1}{32}$ in., H_2O

Fig. 2 Top-view microphotos showing liquid surface layers.

quite unsteady in size, shape, and frequency, and the entire jet is often seen to whip in the movies as a clump is detached.

Regime 1, which corresponds to $\bar{q}$ less than about 1.5, is characterized by the jet being chopped off very shortly after entrance and curving downstream quickly and smoothly with very low penetration (see Fig. 1c). The Regime 1 process is very unsteady; the entire jet moves constantly, and the clump size and frequency are very random.

Another important aspect of liquid jet injection was the liquid surface layers observed from top-view microphotos such as given here in Fig. 2. The jet is the light area in the center of the picture, with flow from left to right. The surface layers appear as rippled bands emerging from the injection port and extending downstream to either side of the jet trajectory. The size, shape, and depth of these surface layers was found to vary strongly with $\bar{q}$. For the high $\bar{q}$, regime 3, jets only thin, shallow layers were observed, while at low $\bar{q}$, wide and rather deep layers were produced. The existence and behavior of these surface layers have important implications for thermal protection and ignition processes.

Penetration: The penetration of the jet liquid into the free-stream is of primary practical importance, and it depends principally on $\bar{q}$ for a given orifice size and shape. Streak photographs were used to assess the average jet penetration which was defined as the normal distance from the wall to the

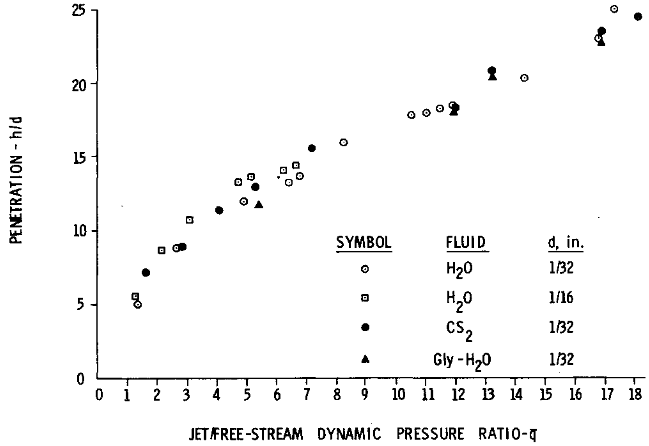


Fig. 3 Penetration of circular jets.

outer edge of the main body of jet flow after it had turned parallel to the wall; this occurred by about $x/d = 30$.

The measured penetration heights for circular ports are given in Fig. 3. Features to be noted are the apparent insensitivity of the penetration to the type of liquid, the somewhat higher nondimensionalized penetrations of the $\frac{1}{16}$ in. jets relative to the $\frac{1}{32}$ in. jets, and the local flattening in slope of the curves for both size jets near $\bar{q} = 5$, which is in the transition region from regime 2 to regime 3. The data formulate into the average empirical relation $h/d = 6\bar{q}^{0.49}$.

The jets produced by a 4 to 1 aspect ratio slot aligned parallel to the crossflow achieved penetrations substantially greater than those of comparable $\frac{1}{32}$ in. circular jets at corresponding $\bar{q}$'s, due to the lower frontal area presented to the airstream. The comparison is shown in Fig. 4 for the low $\bar{q}$'s at which the slot was tested.

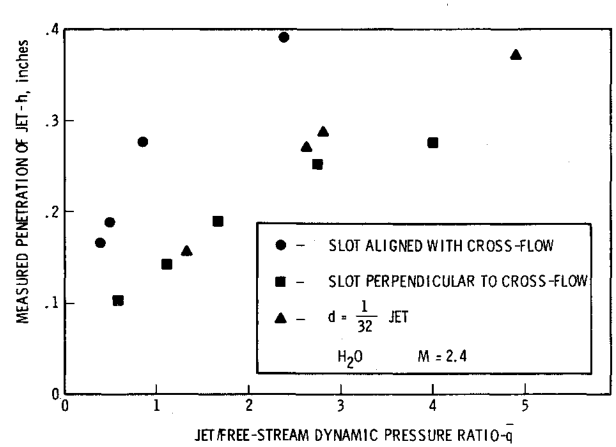


Fig. 4 Penetration of slot orifice jets.