Penetration and Breakup of Slurry Jets in a Supersonic Stream

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Introduction

BY adding metal powders to liquid fuels, the energy of the fuels can be greatly increased. Ramjets that burn slurry fuels can be compact and yet possess high specific thrust, high speed, and high continuous thrust. The present study was directed toward examining the penetration and breakup behavior of transverse slurry jets. The suspended particles had an average diameter of 5 μm, which corresponds to the size of metal particles used in earlier NACA combustion studies (1-5 μm).

Apparatus and Procedures

Tests were conducted in the Virginia Tech 23×23 cm supersonic wind tunnel at Mach 3.0 and a stagnation pressure of 4.2 atm. The stagnation temperature was ambient.

The slurry was injected through a flat-plate model having dimensions of 10.0×15.25×0.9 cm. The model had a sharp leading edge and was attached to the bottom of the test section by a 5.0 cm tall support. The injection orifice was located 8.0 cm downstream of the leading edge. The orifice had a 1.6 mm straight run and a smooth conical entry passage. The diameter was 1.0 mm.

The high-energy fuels were simulated by a slurry formed by suspending silicon dioxide particles in water. The decision to use a simulated fuel was dictated by safety considerations. The silicon dioxide particles had an average diameter of 5 μm and a density of 2.35 g/ml. The particles were crude crystals in shape, with disorderly protrusions.

Two types of photographs were taken, streak and nanoflash. To measure the penetration, a time-averaged view of the continuously fluctuating jet was required. A flash duration of at least a millisecond producing a streak picture was necessary to capture such a view. For stop-action shots that reveal the structure of the jet, a very short flash duration of the order of 10 ns was required.

The "extinction" is the amount of light which is either absorbed or scattered when a beam of light passes through a suspension of particles or droplets. Through the Lambert-Beer law, the extinction can be related to the number of particles that the beam passed through. The extinction coefficient depends on the particle or droplet cross section, absorptive properties, and index of refraction. Due to the presence of both solid particles and liquid droplets in the path of the light beam, the Lambert-Beer law cannot be used in our case to give quantitative data on particle number, etc., but useful qualitative results can be obtained. A helium-neon laser (15 mW output) served as the light source for our extinction measurements and a photomultiplier tube was used as the light detector. The output of the photomultiplier tube was fed into a logarithmic amplifier and then into a data acquisition system.

Results

Penetration

The determination of the cross-stream penetration of the particle-laden liquid jet into a supersonic flow is complicated, since some of the solid particles separated from the liquid plume. Whereas all-liquid injection produces a rather definite and easily discernible penetration profile, slurry injection produces an indistinct profile whose outline could not be readily determined with great precision. The penetration height is usually defined as the vertical extent of the densest portion of the jet as viewed in streak photographs. For the slurry jets, this height corresponds to the penetration of the liquid part of the jet.

The penetration height for the liquid plume was measured at a distance 30 mm (30 orifice diameters) downstream of the injection orifice. In Table 1 the penetration height is given as a function of the momentum flux ratio, $\bar{q}=\rho_j V_j^2(\rho_\infty V_\infty^2)^{-1}$, and the loading defined as the percent of solid particles in the slurry by mass.

For a given loading, the penetration height follows the usual qualitative relationship with the momentum flux ratio: as $\bar{q}$ is increased, the penetration height increases as well. On the other hand, if $\bar{q}$ is held constant as the loading is in-

Table 1 Penetration height h/d as a function of loading and $\bar{q}$

$\bar{q}$	Loading, % 0	3	17	33	50
2	12.0	11.6	10.8	10.2	–
4	13.5	13.3	12.2	12.0	11.6
6	17.0	16.0	14.0	14.5	14.2
8	19.2	18.6	16.5	16.5	16.2
10	22.2	20.5	19.5	17.8	18.0
Density, g/cm^3	1.00	1.02	1.11	1.24	1.41

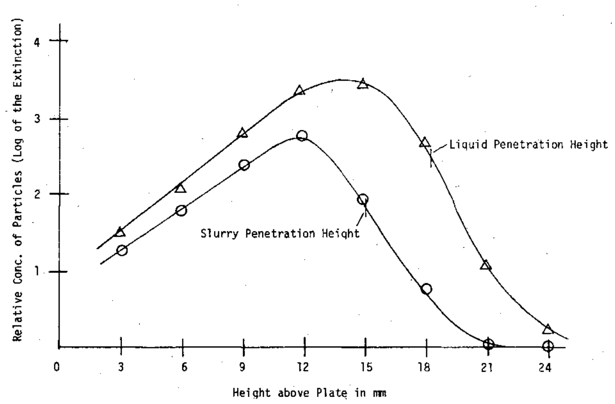

Fig. 1 Extinction curves for liquid and slurry jets.

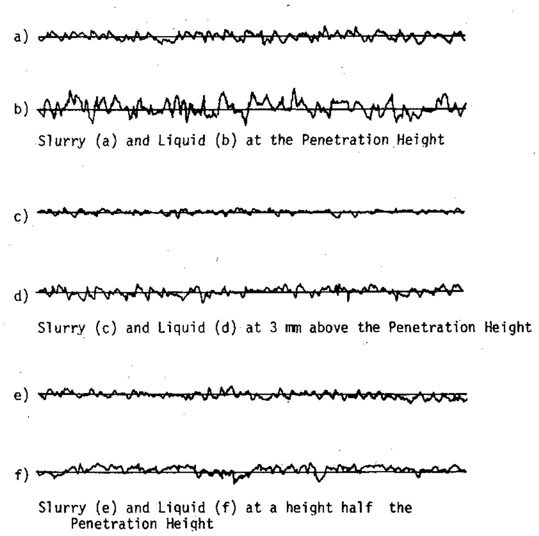

Fig. 2 Extinction data for various heights (all data taken 30 mm downstream of the injector at $\bar{q}=7$).

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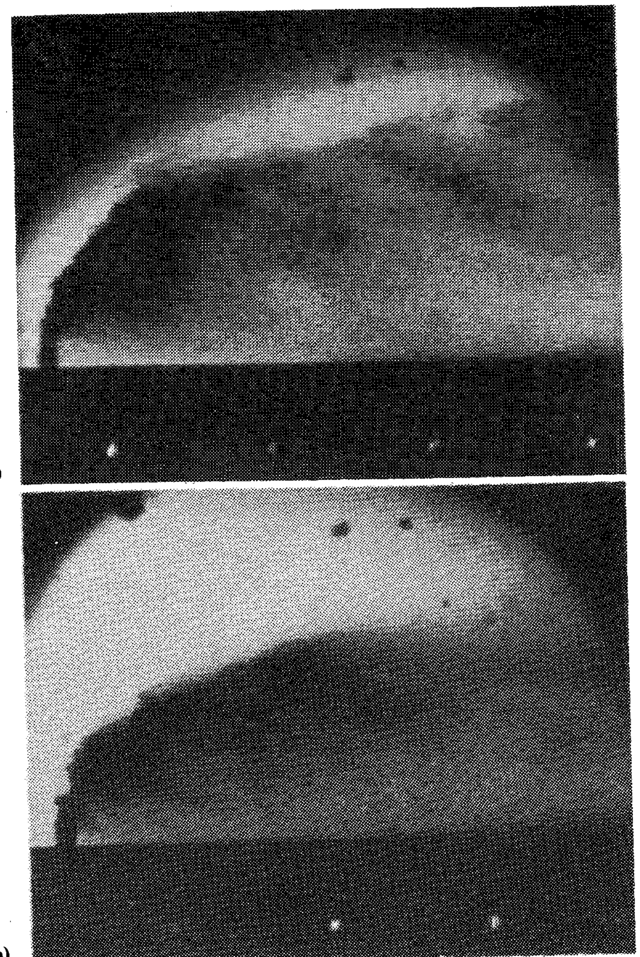

Fig. 3 Nanoflash photographs for various loadings: a) loading = 16%, $\bar{q} = 4.2$; b) loading = 52%, $\bar{q} = 4.2$.

creased, the penetration decreases. This latter relationship can be attributed to the combined factors of particle/liquid interactions and the definition of $\bar{q}$ for slurries. The momentum flux ratio $\bar{q}$ depends explicitly on the density of the slurry. This dependence upon the density is noteworthy since two jets with the same $\bar{q}$ but with different loadings (densities) will possess different jet velocities.

Further studies of the penetration were performed by light extinction methods. An all-liquid jet and a slurry jet of 40% loading were surveyed. The momentum flux ratio of both jets was 7.0. A transverse survey of each jet was performed at a location 30 mm downstream of the orifice.

In Fig. 1, it can be seen that the liquid jet penetrated further and had a higher extinction than the slurry jet. Furthermore, the extinction profiles for the two jets are similar except for the slopes on the upward part of the jets. The all-liquid jet has a slightly steeper slope (i.e., the extinction decreased more rapidly), which corresponds to a sharper penetration profile on the streak pictures.

The extinction experiments also raised some questions concerning the definition of penetration. The penetration as measured from the streak photographs is marked on Fig. 1 for both jets. Based on the extinction curves, the penetration height found from the streak photographs does not correspond directly to any physical phenomenon. However, since the penetration heights presented in this and other reports are primarily for comparison purposes only, the ambiguity about the penetration height does not adversely affect the stated results.

Jet Breakup

The breakup process of the slurry jet was noticeably less violent than its all-liquid counterpart. The lessening of the violence can be seen in the raw data for the extinction tests which consisted of the time variation of the undiffracted beam intensity. Both of the jets showed unsteadiness in the curves, as is evident in the sample curves presented in Fig. 2. The amplitudes of the fluctuations for the slurry jet are dramatically less than those for the all-liquid jet. Examination of the nanoflash pictures suggests that the slurry jets do indeed become more steady as the loading is increased. Compare the jets depicted in Fig. 3.

The maximum amplitudes in the fluctuations occurred 3 mm above the point of maximum extinction for each jet. The maximum amplitudes, in terms of the streak photographs, occurred at the penetration height of each jet.

Phase Separation

From the nanoflash photographs, the particles are shown to penetrate 40-45% farther into the airstream than the liquid portion of the jet. The particles that separated were actually agglomerates of particles. These clumps were 25-40 μm in diameter. The particles agglomerated or flocculated due to the interparticle attraction of small wetted particles. Smaller agglomerates can be seen within the liquid plume.

Water was contained within the separated agglomerates. In several nanoflash pictures, water can be seen being sheared away from the particles. The shearing is visible in the comet-like structures: the "head" of the comet is the agglomerate and the "tail" is formed by the water as it was being sheared away.

Conclusions

The behavior of the agglomerated particles found can be compared with the behavior of particles in particle-laden gas jets. Small clumps remain within the confines of the liquid jet, but are shifted toward separation. Clumps with diameters greater than 25 μm separate from the jet, following paths dictated by their mass and momentum. About one-eighth of the particles separate, and they penetrate up to 45% further into the cross stream than the liquid phase.

The separation of the phases results in reduced penetration of the liquid portion of the injectant as the loading is increased.

The slurry jets are more stable than all-liquid jets. In the present study, the stability was noted as a decrease in fluctuations in the jet.

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Further Experiments on Shock Tube Wall Boundary-Layer Transition

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Nomenclature

M = Mach number
p = pressure
Re_T = $\rho_2 U_2 X_T / \mu_2$, transition Reynolds number

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