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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Liquid-Fuel Aeroramp Injector for Scramjets

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Introduction

ACHIEVING efficient scramjet combustion with hydrocarbon fuels is difficult and includes problems with injection and mixing. Work on gaseous fuel injection is reviewed by Schetz et al.[1] One promising scheme is the aeroramp,[2] which involves an array of angled jets that induce additional vorticity and enhance mixing.

There is also a large body of research on liquid injection in supersonic flow. The impinging jets in Ref. 3 were angled upstream and downstream at 60 deg to the wall and lay in a plane perpendicular to the wall. They were spaced at 5.0 equivalent jet diameters. This injector provided good penetration and atomization.

It was decided that an effective liquid-fuel injection system might be an impinging jet/aeroramp design. The impinging jets would help atomization while the aeroramp would induce additional vorticity and mixing. A study was done in a cold-flow supersonic facility at Mach 2.4 using kerosene as a safer alternative to JP7 fuel. Shadowgraphs and schlieren photographs were taken, and the penetration of the jet was determined. Sauter mean droplet size, D_{32}, measurements were obtained using a forward-scattering technique.[4]

Liquid-Fuel Aeroramp Injector

The new liquid-fuel injector was designed by looking at the advantages of impinging liquid jets and combining them with the advantages of an aeroramp. A nominal momentum flux ratio, $\bar{q} = (\rho U^2)_j/(\rho U^2)_\infty$, of 6.0 was selected for good penetration.

It was decided that the angles and the fuel flow rate for the liquid-fuel injector should be made close to those in an earlier gaseous-fuel aeroramp.[5] Two holes were used in the liquid-fuel aeroramp rather than the nine[2] or four[5] holes used for gaseous-fuel aeroramps, because the higher density of liquids leads to very small holes. The liquid-fuel injector consisted of two holes, each 0.533 mm in diameter spaced 4.34 mm apart while being angled downstream 40 deg and toed inward 60 deg. The equivalent jet diameter was 0.754 mm and the effective jet diameter, d_{eq}, including the discharge coefficient was 0.586 mm. A photograph of the injector in operation is shown in Fig. 1a.

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Facilities, Instrumentation, and Test Procedures

The experiments took place in the Virginia Tech 23 × 23 cm supersonic wind tunnel at Mach 2.4 with nominal stagnation pressure and temperature of 345 kPa and 292 K, respectively. Spark shadowgraphs and schlieren photographs were taken using a GenRad Strobotac type 1538-A. Longer duration (10^{-3} s) shadowgraphs were used for penetration measurements.

Droplet size measurements for Sauter mean diameter, or D_{32}, were made using a laser and a forward-scattering technique.[4,6] According to Dodge[6] a correction factor can be applied to the droplet size measurements for dense liquid sprays that cause multiple scattering, and such corrections were applied here.

The total standard deviation for the penetration measurements was estimated[7] as ±0.62 mm or $y/d_{eq} = \pm 0.82$. A calibration reticle with a reported mean value for D_{32} of 55 μ was used to test the drop size methods. Our setup and procedures resulted in D_{32} values ranging from 45 to 60 μ depending on where the laser beam was located on the calibration reticle. Based on this and the correction factor of Dodge,[6] it was estimated that the total uncertainty of the corrected droplets is roughly ±5 μ.[7]

More complete details on the facilities, instrumentation, and test procedures are available in Ref. 7.

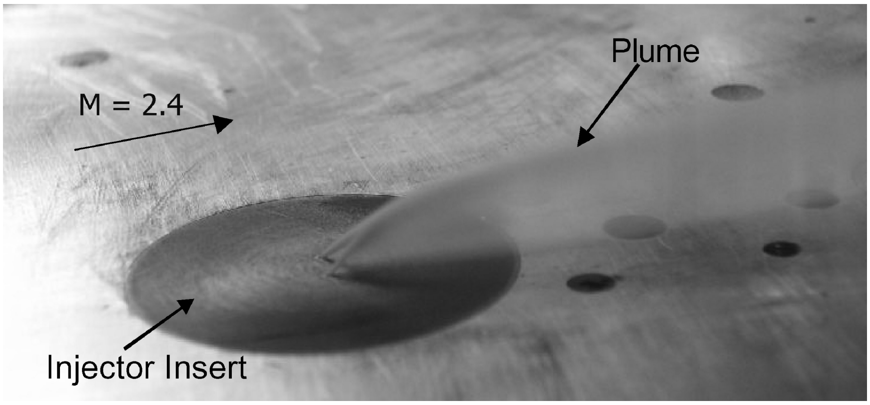
Results

Spark schlieren and shadowgraph pictures were taken of the liquid injector in a Mach 2.4 flow, and some examples are shown in Figs. 1b and 1c. One can note that the jets cause a weak shock wave, which will result in a low total pressure loss.

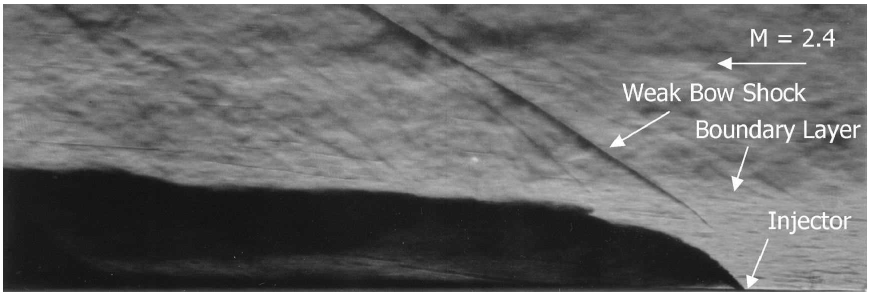
The penetration of the plume was measured directly off 10^{-3} s. shadowgraphs as the outer boundary of the visible plume. The results can be found in Fig. 2. The other curves and data points in Fig. 2 will be considered in the Discussion section.

Table 1 Vertical distribution of D_{32} in microns as a function of distance from the injector

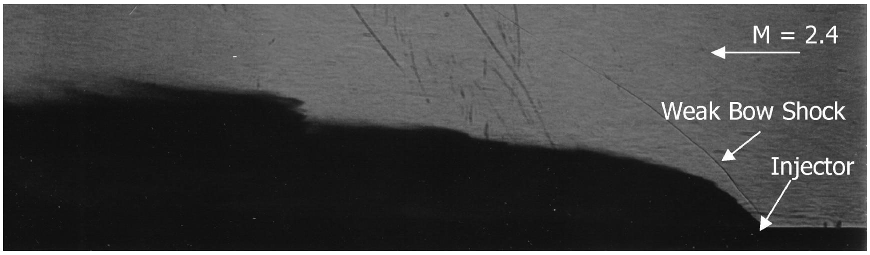
x/d_{eq}	y/d_{eq}	D_{32}, μ
23.3	3.4	27
23.3	6.7	29
23.3	10.1	28
23.3	13.5	21
46.7	3.4	31
46.7	6.7	——
46.7	10.1	33
46.7	13.5	23
70.0	3.4	29
70.0	6.7	33
70.0	10.1	——
70.0	13.5	32
101.1	5.1	33
101.1	6.7	37
101.1	8.4	——
101.1	10.1	34
101.1	11.8	34
101.1	13.5	32
101.1	15.2	——
101.1	16.8	23
101.1	18.5	24
101.1	20.2	22



a) Direct photograph



b) Spark schlieren, exposure 10^{-6} s



c) Spark shadowgraph, exposure 10^{-6} s

Fig. 1 Flow visualization of the liquid aeroramp injector in Mach 2.4 flow.

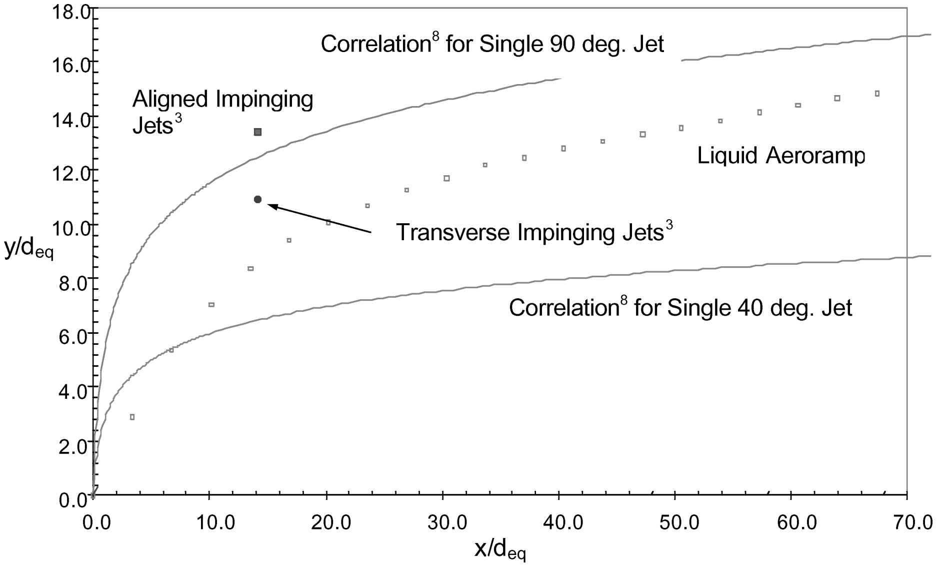


Fig. 2 Penetration of the top of the plume as a function of distance downstream from the injector for $\bar{q} = 6.0$ (data points from Ref. 3 are for $\bar{q} = 6.1$ and 6.2).

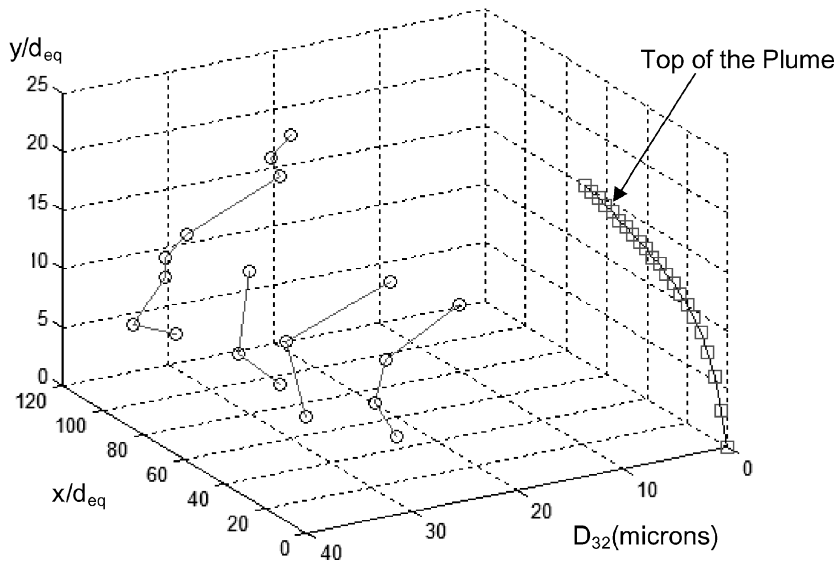


Fig. 3 Liquid aeroramp droplet size distribution and penetration for $\bar{q} = 6.0$.

Vertical profiles of the mean droplet diameter, D_{32}, were obtained as a function of distance from the liquid-fuel aeroramp injector. The locations for droplet measurements were 17.6, 35.2, 52.8, and 76.2 mm downstream from the injector or 23.3, 46.7, 70, and 101.1 effective jet diameters, respectively. The results are given in Table 1 and Fig. 3. In correcting the droplet data for multiple scattering, it was found that as the transmission decreased to 9% the correction increased the droplet size by as much as 11 μ. The values indicated with a dash are illumination profiles with so much absorption and scattering, due to multiple droplets in a small area, that almost all light was absorbed and no useful data could be obtained. From Table 1 and Fig. 3, it can be seen that the droplet diameter ranged from 21 to 37 μ. As the height increased, the droplet size first increased, but then it decreased toward the top edge of the plume. There was little further reduction in droplet size between 23.3 and 101.1 effective jet diameters.

Conclusions

The aeroramp liquid injector was found to function as originally intended. Good penetration and atomization compared to single and simple impinging jet injectors with a weak interaction shock were documented. The maximum shock angle observed near the injector is about 50 deg, which corresponds to a wedge deflection of 23 deg or a conical deflection of 35 deg. The maximum total pressure loss would be 20%, and that is confined to a small area of the airflow.

The penetration correlation for single, round jets found by Baranovsky and Schetz[8] can be used for comparison. In Fig. 2, a comparison is made between the two-jet, liquid-fuel aeroramp, which is angled 40 deg downstream with 60 deg toed in, and the correlation given by Baranovksy and Schetz[8] for a single 40-deg jet with no yaw. The aeroramp injector penetrates considerably more than a 40-deg jet, demonstrating that the liquid-fuel aeroramp performs as hoped. By impinging the two jets, a vertical liquid sheet is formed so that the fluid tends to penetrate farther into the flow and perhaps the aeroramp portion of the liquid-fuel aeroramp induces additional vorticity and lifts the liquid plume as has been proven for gaseous aeroramps.

One can attempt to compare the current results to those in Ref. 3 for the tranverse and aligned impinging injectors studied there. In the aligned impinging jet case of Ref. 3, the front jet is angled 60 deg up from the wall, whereas the back jet is angled 30 deg into the direction of the flow or 120 deg with respect to the wall. Both jets are in a plane perpendicular to the wall. In the transverse case of Ref. 3, the injector was rotated 90 deg so that the impinging jets are in a vertical plane aligned perpendicular to the flow. In making such comparisons, it is important to recall that the data in Ref. 3 are for water injection into a Mach 3.0 airstream, whereas that here is for kerosene injection into a Mach 2.4 airstream.

Figure 2 also shows a comparison between the penetration of the liquid-fuel aeroramp at $\bar{q} = 6.0$ and the aligned and transverse impinging jet injectors studied by Hewitt and Schetz[3] for $\bar{q} = 6.1$ and 6.2. The penetration measurement by Hewitt and Schetz[3] was done at 20 jet diameters or 14.1 equivalent jet diameters. One can notice that the impinging jets of Ref. 3 penetrate farther into the flow than the liquid-fuel aeroramp at this location, with the aligned, impinging jet arrangement penetrating farthest. The spacing between the impinging jets of Ref. 3 is slightly different than the spacing for the liquid-fuel aeroramp. This difference in spacing could result in better penetration, but this is difficult to determine without further research. The liquid-fuel aeroramp and the impinging jet injectors are both toed in 60 deg, and so the results shown in Fig. 2 are a function of the downstream angle and the difference in spacing, and the other differences in test media and conditions noted earlier. Both the aligned and the transverse impinging jet injectors studied by Hewitt and Schetz[3] present a more erect obstacle to the main airstream than the liquid-fuel aeroramp, and so they can be expected to produce greater total pressure losses. The magnitude of the difference in total pressure losses will have to await further experiments.

The droplet size measurements showed effective atomization for the liquid-fuel aeroramp injector. The kerosene was atomized to droplet sizes that are favorable for ignition and combustion in a hot flow. In a hot flow, there will also be substantial evaporization, which will further reduce the droplet size. One can also compare the current droplet size results to those in Ref. 3 for the tranverse and aligned impinging injectors. That reference also provides data for an equivalent 90-deg, circular injector. Unfortunately, Ref. 3 gives droplet size data only for $\bar{q} = 4$ and 12, whereas that here is for $\bar{q} = 6$. That fact and the other differences in test media and conditions make a direct comparison difficult. One more complication is that the droplet size data in Ref. 3 were not corrected for absorption and multiple scattering, whereas the current data were. Recall that such corrections increase the measured droplet size. With all those caveats, it would appear that the more erect impinging jet injector of Ref. 3 produces somewhat smaller droplets than the current liquid-fuel aeroramp. The atomization of the liquid-fuel aeroramp is judged as adequate for combustion in a hot flow, but that can only be proven by testing under hot-flow conditions.

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