Effects of Viscosity and Surface Tension on a Jet Plume in Supersonic Crossflow

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Abstract

LIQUID injection into a high-speed crossflow has been considered in a number of aerospace systems. Recent developments in engine design and new hybrid fuels with large viscosity and surface tension ranges and the lack of data relating the behavior of the jet to physical properties were the motivating forces behind this study.

In a crossflow the jet is deformed and bent downstream by the main flow. Several types of waves appear on the windward edge leading to breakup. Some are capillary disturbances and waves caused by turbulence, and some are aerodynamically induced waves which are primarily responsible for the decomposition of the jet. The viscosity and surface tension of the injectant have a direct effect on the spray plume, both internally and at the surface.

Contents

Apparatus

The study was conducted at Mach 3.0 with the stagnation pressure at 4.2 atm and the stagnation temperature ambient. The injection was through a flat-plate model with a sharp leading edge. The injector had a diameter of 0.96 mm and a 1.3 cm run.

For stop-action photography a very short duration spark (9×10^{-9} s) was utilized. The penetration of the jet was measured from streak shadowgraph pictures (10^{-3} s).

To investigate the effects of surface tension and viscosity on the jet structure the following plan was adopted: 1) water was used as the reference with a surface tension of 72 dyne/cm and viscosity of 1.0 cP, 2) ethyl alcohol was added to water to reduce the surface tension to 33.5 dyne/cm with viscosity $1.0 \leq \mu \leq 2.7$ cP, 3) glycerine was added to water to increase viscosity while holding surface tension nearly constant $66 \leq \sigma \leq 72$ dyne/cm. Some tests were run with a low surface tension liquid Fluorinert ($15 \approx$ dyne/cm and 1.5 cP).

Results

The parameter $\bar{q}$ was used to describe all tests. The study of the jet in a crossflow has led to division of the range of $\bar{q}$ into three regimes. Regime 1 corresponds to injection at $\bar{q} \leq 3$, which results in very low penetration. Regime 2 corresponds to $\bar{q}$ ranging between 3 and 12, which is suitable for fuel injection. Regime 3 corresponds to injection at $\bar{q} > 12$.

Figure 1a contains a photograph of a water plume in regime 2. The aerodynamically induced waves grow in wavelength and amplitude to the point of first cross fracture, while capillary waves stay superimposed on these waves. The jet rapidly spreads to several times its base diameter in a short distance along the jet. The spray formation zone contains large liquid clumps.

Figure 1b is a higher viscosity spray. The process of atomization and jet decomposition has now changed. The cross diameter of the spray plume remains virtually constant. The jet behaves as a very long, thick ligament while continuously shedding smaller subligaments into the crossflow. The large waves of the aerodynamically induced wave zone show an inconsistent pattern, and are of lesser magnitude in length and amplitude than the cases of lower viscosity spray plumes. The space between the main jet body and the flat plate is at first sparsely populated with liquid particles. There are no spherical particles, and the time for complete atomization has increased greatly.

Figure 1c shows a water/alcohol spray in regime 2. Breakup and atomization is very rapid and starts immediately near the injector surface. The coherent zone of the jet body has vanished. The capillary waves first grow into large-amplitude waves, then increase in wavelength and finally result in the cross fracture of the jet. The space between the flat plate and the spray plume is filled with spherical droplets, with an increase in concentration near the jet. Due to low surface tension of the injectant, jet disintegration is faster and the resultant droplet diameters are smaller and more uniform.

Figure 1d is a spark photograph of the low surface tension Fluorinert injectant in the same regime as Figs. 1a-c. Here the atomization is even more rapid than for the water/alcohol plume. Also, the spray is much finer, i.e., the droplet sizes right after breakup are smaller. The breakup mechanism is by wave growth and column fracture, but the intermediate stage of large clump formation is almost completely suppressed.

The effects of viscosity and surface tension on atomization processes of liquid jets, injected in regimes 1 and 3, were found to be similar to the patterns described for regime 2.

Penetration measurements were made from the streak photographs at $x/d = 26$ and 52. The water/glycerine data points all collapsed around a single line, and consistently show a higher penetration than water. At $\bar{q} = 20$, viscous liquid jets penetrate 22% more than water. The surface tension of water/alcohol mixture is 65% lower than that of water, but there was not a significant difference between the penetration heights.

The effects of surface tension and viscosity on the wave formation phenomena were measured from the spark photos. The wavelength and wave amplitude were found to be independent of the injection rate expressed as $\bar{q}$. Injection throughout the three regimes resulted in average nondimensional (divided by jet diameter) wavelengths and amplitudes of 1.4 and 0.4 diameters for water. Regime 1 resulted in formation of 2 to 3 waves on the jet body, which increased to 8 waves in regime 2, and to 11 waves in regime 3. The

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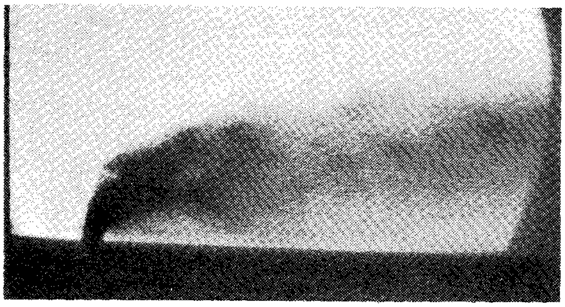

a) Water: viscosity = 1.0 cP, surface tension = 72 dyne/cm.

b) Glycerine/water: viscosity = 27.6 cP, surface tension = 68 dyne/cm.

c) Alcohol/water: viscosity = 2.7 cP, surface tension = 33.5 dyne/cm.

d) Fluorinert: viscosity = 1.5 cP, surface tension = 15 dyne/cm.

Fig. 1 Spark photographs of transverse liquid jets at $\bar{q}$ ($\equiv \rho_j V_j^2 / \rho_\infty V_\infty^2$) = 4, regime 2.

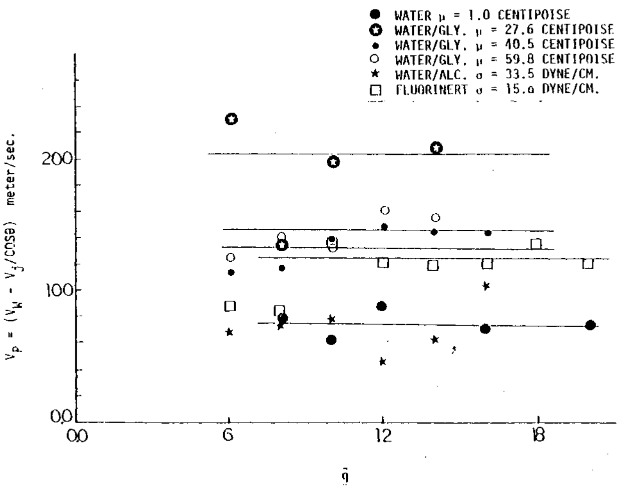

Fig. 2 Wave propagation velocity on the cohesive jet body vs dynamic pressure ratio for different surface tension and viscosity.

capillary wave region varied from 1.3*d* in regime 1 to 4.2*d* in regime 2, and finally to 6.8*d* in regime 3.

For the case of more viscous water/glycerine, the average nondimensional wavelength increased to 1.4 which corresponds to a 70% increase compared to water. The wave amplitude averaged 0.7, a 60% increase over water.

For the low surface tension water/alcohol the average value for the wavelength on the jet surface was 1.7*d*, a 24% increase over water. The wave amplitude had a value of 0.7*d*, a 55% increase over water. The number of waves on the cohesive jet body increases from 3 waves in regime 1 to a maximum of 12 waves in regime 3.

In summary, it can be said that increasing viscosity decreases the wavelength and increases the wave amplitude. These two effects together result in deep square-looking waves. Decreasing surface tension increases both the wavelength and wave amplitude which intensifies the process of jet breakup.

A multiexposure photographic technique with the time between the exposures (10^{-5} s) was used to determine the velocity of the waves along the jet. The measured wave speeds were converted to apparent propagation speeds by subtracting out an estimated value of the local bulk velocity. Figure 2 shows the results on the cohesive body of the jet. Clearly, the absolute precision of these deduced values is not great, but the effects of the major variables can be discerned easily. First, the effect of $\bar{q}$ on the propagation speed is very small. Second, either increasing viscosity or decreasing surface tension increases the propagation speed.

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