Effects of Properties and Location in the Plume on Droplet Diameter for Injection in a Supersonic Stream

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The mean droplet diameter in the spray resulting from transverse injection of liquid jets into supersonic airstream was investigated in detail by the use of the diffractively scattered light method. The effects of viscosity, surface tension, jet/freestream dynamic pressure ratio, injector diameter, and location in the plume on the mean droplet diameter were determined. All tests were performed at $M_\infty = 3.0$, with $P_0 = 4.2$ atm and $T_0 = 300$ K. The injectants used were water, various solutions of glycerine and ethanol in water, and Fluorinert to produce wide variations in viscosity and surface tension. The important results can be summarized as follows: 1) the droplet size has an inverse relation with respect to jet/freestream dynamic pressure ratio, 2) the droplet diameter decreases as the measurement station moves downstream, 3) the smallest droplets are formed at the outer edge of the spray plume, 4) droplet size has a direct relation with respect to surface tension and viscosity of the injectant, and 5) at very high viscosities the jet does not break up into nominally spherical particles. For a certain range of viscosity and dynamic pressure ratio, the breakup of the jet is into ligaments rather than droplets.

Nomenclature

d	= injector diameter
D	= droplet diameter
D_{32}	= volume to surface mean diameter
h	= jet penetration height
$I(\theta)$	= normalized intensity of the scattered light
M_∞	= freestream Mach number
$N_r(D)$	= known distribution function of droplet diameters
P_0	= freestream stagnation pressure
$\bar{q}$	= ratio of dynamic pressure of jet ($\frac{1}{2}\rho_j v_j^2$) to dynamic pressure of freestream $\frac{1}{2}\rho_\infty v_\infty^2$
T_0	= freestream stagnation temperature
v	= velocity
x	= distance downstream of the center of the injection
y	= vertical distance from the surface
α	= size number
θ	= scattering angle
$\bar{\theta}$	= reduced scattering angle = $\pi\theta D_{32}/\lambda$
λ	= wavelength of incident beam
μ	= viscosity of the liquid injectant
ρ	= density
σ	= surface tension of the liquid injectant

Subscripts

j	= jet
∞	= free airstream

Introduction

THERE are a number of practical applications of transverse injection of a liquid jet into a high-speed gas stream, including fuel injection for ramjets, scramjets, and afterburners; thrust vector control in rockets; external control devices on missiles; cooling sprays in turbines; and localized cooling on re-entry bodies. In all of these applications, cross-stream penetration and the droplet sizes resulting from the breakup of the jet column are items of primary engineering interest.

The need for engineering information has stimulated considerable prior study of this general problem. Some of the major earlier works are listed as Refs. 1-15. The state of knowledge concerning penetration is now fairly advanced, with a general correlation containing most of the primary variables and parameters of interest having been developed (see Ref. 14). However, much less detailed information concerning breakup and especially droplet size is available. Waves grow on the jet surface, and these lead to the cross fracture of the jet column. The large "clumps" produced then break up further into droplets.

Weiss and Worsham[1] studied the atomization of molten Acrawax-C jets in a high-velocity airstream and obtained the diameter of the frozen particles. They found that the particles were almost uniformly spherical. Gooderum and Bushnell[10] conducted a study of droplet size and penetration for water injection at high-altitude re-entry conditions. The work employed the diffractively scattered light method (DSLM) developed in Refs. 16-18 to measure the mean droplet diameter of the particles. In Ref. 13, the DSLM was applied at high-density supersonic conditions to obtain mean droplet sizes in the plumes from jets with various port sizes and injection rates and at several locations across and along the plume.

In summary, it can be seen that while several studies of transverse liquid jet injection into supersonic flow have been presented, there is a scarcity of information available for droplet sizes in the spray over a broad range of conditions. In particular, the influence of wide variations of physical properties (viscosity and surface tension) and the variation of droplet size across and along the plume are of primary interest.

Experimental Methods and Apparatus

Diffractively Scattered Light Method

The primary experimental tool used in this study was the DSLM. This method was selected over other methods based on short duration microphotographs because of the many practical difficulties associated with those techniques: 1) the difficulties related to sufficient resolution, 2) the small depth of focus required, 3) the small number of particles usually present within the focal plane and the question of whether these particles constitute a representative statistical sample, 4) the differentiation between film grain and droplet images, 5) the problem of deciding between single droplets or clumps, and 6) perhaps most important, the very tedious process of counting and measuring the droplet sizes one by one. The same difficulties apply to the use of short duration holograms. We have also not adopted some of the more

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elaborate methods based on scattered light, because a method simple and reliable enough for routine use over a study involving many individual tests was required.

The investigation of the DSLM was first conducted by Chin et al.,[16] using a theory by Gumprecht and Sliepeevich[17] which describes the scattering properties of a polydispersion. This theory requires very low droplet concentrations to constitute a small optical depth. It further requires that both particle size and refractive index fall within given intervals. The formation of a theory for the scattering properties in the more general case of particles of arbitrary size and arbitrary refractive index occurring in a polydispersion of finite optical depth has been discussed by Dobbins et al.[18]

A distribution function $N_r(D)$ is defined in such a way that the integral of $N_r(D)$ over a given diameter interval represents the probability of occurrence of particles within the specified interval. This function determines the relative frequency of occurrence of particles of a given diameter D. The expression for the intensity of scattering due to a polydispersion is normalized by dividing by the intensity of diffractively scattered light in the forward direction ($\theta=0$, centerline). The normalized, integrated intensity of forward scattered light $I(\theta)$ due to a polydispersion of particles is given as

$$I(\theta)=\int_0^D [2J(\alpha\theta)]^2 N_r(D)D^4\mathrm{d}D\Big/\int_0^D \infty\,[N_r(D)D^4]\mathrm{d}D \qquad (1)$$

A problem arises from the fact that one does not know what distribution function is a good representative of the particle sizes being investigated. Roberts and Webb[3] studied the accuracy of the DSLM in measuring particle size by using many different distribution functions. They concluded that the value of the volume/surface mean diameter, D_{32}, may be determined from the intensity of diffractively scattered light from a polydispersion of spherical particles to a good degree of accuracy for an extremely wide range of distributions without a knowledge of general distribution type. They developed a mean theoretical illumination profile for all distributions investigated, which can be regarded as a universal illumination profile, and which has been utilized in the current study in obtaining mean droplet diameter.

Optical Arrangement

A schematic diagram of the final optical setup is shown in Fig. 1. A helium-neon laser was used as the light source. A spatial filter located directly in front of the light source produces a larger diameter and more uniform light beam. Two circular high-quality glasses 5.1 cm in diameter and 1.3 cm thick were used as windows, one on each side of the test section. A plano-convex lens, 5.1 cm in diameter with a focal length of 50 cm was used as the condensing lens. This lens focused the unscattered light beam on a 0.15-mm aperture located directly in front of a photomultiplier tube.

The photomultiplier assembly was mounted on a traverse mechanism which allowed scanning of the scattered light illumination profile. We required the illumination profile intensity vs the scattered angle θ. Since the output signal of the photomultiplier varied greatly in magnitude, it was processed through a logarithmic amplifier.

Accuracy of the Diffractively Scattered Light Method

The accuracy of our experimental implementation of the DSLM was investigated for two separate cases. These two cases were selected to be representative of our actual experimental conditions. First, the mean droplet diameter of water particles produced by a commercial atomizer was measured by both the DSLM and the direct microphotographic technique. Second, the mean diameter of a mixture of known-sized glass beads was measured by the DSLM. The microphotographic technique revealed an average droplet diameter in the atomizer spray of 24.6 μm,

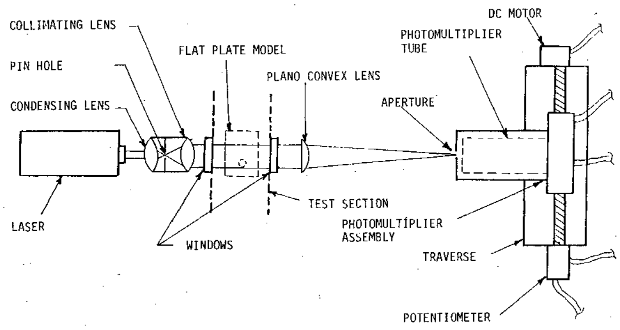


Fig. 1 Schematic of light scattering optical setup.

and the DSLM gave a mean droplet diameter of 26 μm. This amounts to an error of 5.7%. The glass bead diameter size range was from 48-53 μm. The DSLM measured a mean diameter of 48 μm, which is again within about 5% accuracy.

Test Facility

The study was conducted in the Virginia Tech 23 m$\times$23-cm supersonic wind tunnel at Mach 3.0. The stagnation temperature was ambient (roughly 25°C) and the stagnation pressure was controlled at 4.2 atm $\pm$2%.

Model

The liquid injection was carried out through a flat plate model with a sharp leading edge. The flat plate had dimensions of 15.2 m$\times$25.4 cm, with the orifice of the injector located 5.1 cm downstream of the leading edge. Three circular injectors were used with diameters of 0.46, 0.96, and 1.50 mm. Each injector had a 1.3 cm straight run.

Injectants

Since an understanding of the influence of injectant physical properties such as surface tension or viscosity upon the spray plume characteristics was one of the main objectives of this investigation, there arose a need for plentiful and safe liquid injectants with variable surface tension and fixed viscosity or vice versa. The following plan was adopted:

1) Pure water was used as the reference injectant with a surface tension of 72.0 dyne/cm and viscosity of 1.0 cP at 20°C.

2) Ethyl alcohol was added to water to change the surface tension while viscosity remained nearly constant, $1.0\leq\mu\leq2.7$ cP.

3) Glycerine was added to water to change the viscosity of the injectant, while its surface tension remained essentially constant, $66\leq\sigma\leq72$.

4) Some tests were run with Fluorinert (C_8F_{18}) cooling fluid which has a low surface tension of 15 dyne/cm and viscosity of 1.5 cP. The specific gravity is 1.78.

Results

The values of the physical properties and the parameters and conditions of the experiments were made dimensionless in terms of three groupings:

$$\bar{q}\equiv\rho_j v_j^2/\rho_\infty v_\infty^2$$

$$Re_j\equiv\rho_j v_j d_j/\mu_j$$

$$We_j\equiv\rho_j v_j^2 d_j/\sigma_j$$

The droplet sizes were measured at several locations across and along the jet. These locations are specified by an x/d value denoting downstream distance measured in port diameters and a location y/d above the plate referenced to the value h/d of the penetration of the outer portion of the plume at the same x/d. Long-exposure (10^{-3} s) back-lighted streak photographs of the jet in the airstream were obtained, and the

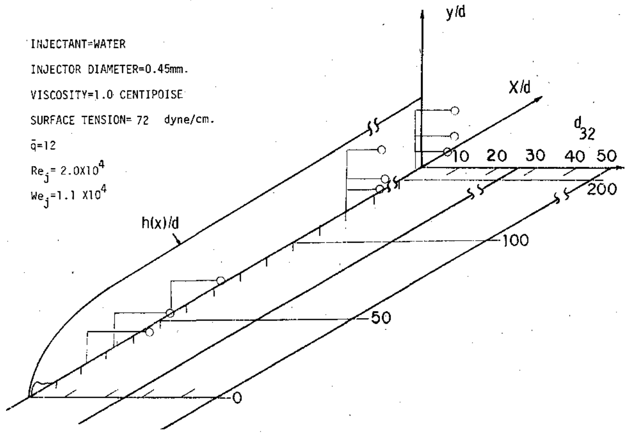


Fig. 2 Droplet size distribution in the plume for water injectant at $\bar{q}=12$, $d=0.45$ mm.

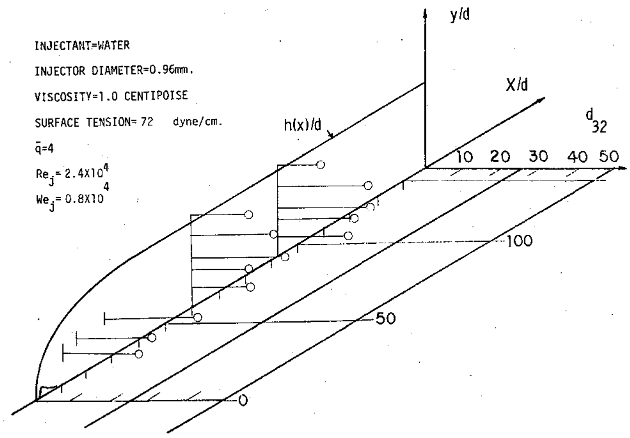


Fig. 5 Droplet size distribution in the plume for water injectant at $\bar{q}=4$, $d=0.96$ mm.

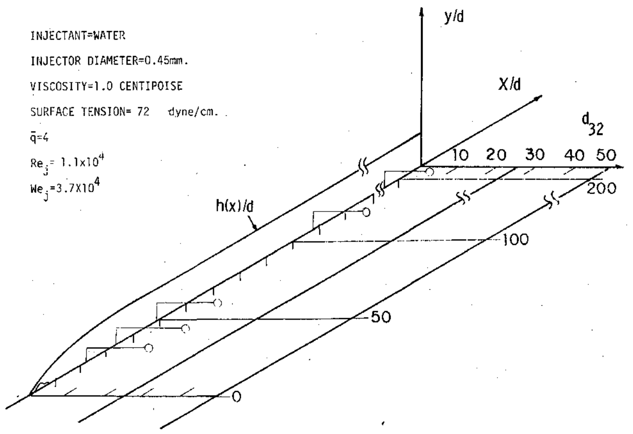


Fig. 3 Droplet size distribution in the plume for water injectant at $\bar{q}=4$, $d=0.45$ mm.

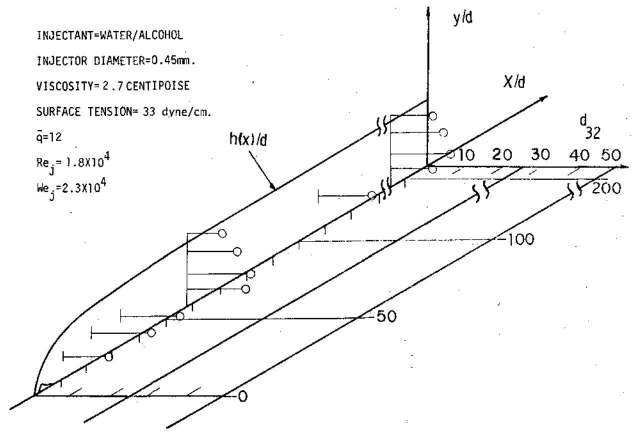


Fig. 6 Droplet size distribution in the plume for water/alcohol injectant at $\bar{q}=12$, $d=0.45$ mm.

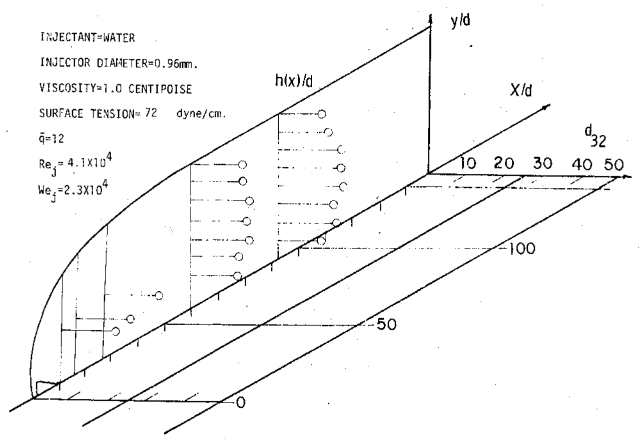


Fig. 4 Droplet size distribution in the plume for water injectant at $\bar{q}=12$, $d=0.96$ mm.

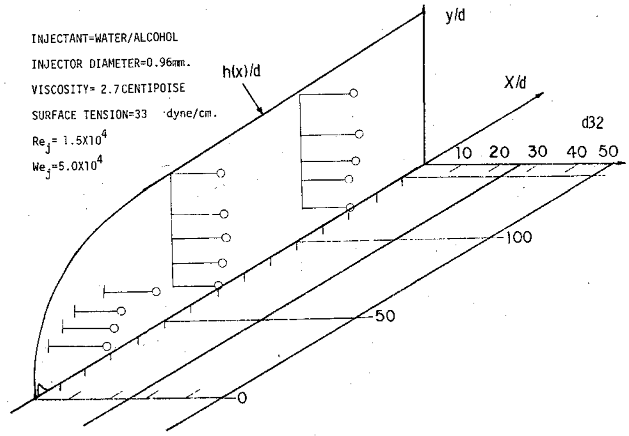


Fig. 7 Droplet size distribution in the plume for water/alcohol injectant at $\bar{q}=12$, $d=0.96$ mm.

solid black portion of the spray image was measured to reveal the jet penetration height.

The variation of droplet diameter in the plume for the case of water injectant at $\bar{q}=12$ with $d=0.45$ mm ($Re_j=2.0\times10^4$, $We_j=1.1\times10^4$) is shown in Fig. 2. Measurements were taken along the jet from $x/d=10.9$ to 207.7. The droplet diameter decreased as one moved downstream. For example, $D_{32}=19$ μm at $x/d=54.4$, $h/d=23.0$, which decreased to 14 μm at $x/d=207.7$, $h/d=24$. The cross-plume measurements of droplet size revealed the fact that droplet diameter decreases to its smallest value near the boundaries of the plume. At $x/d=109.4$, y/d was changed from 6.6 to 21.9 and the droplet diameter increased in size from 10 to 14 μm and then decreased to 13 μm.

Figure 3 shows the variation of droplet diameter in the jet plume for the case of water injectant at $\bar{q}=4$, $d=0.45$ mm ($Re_j=1.1\times10^4$, $We_j=3.7\times10^4$). The most important result is the general increase in mean droplet diameter compared to that found at $\bar{q}=12$. The droplet diameter again decreases in size as one moves downstream of the injector. Because of the

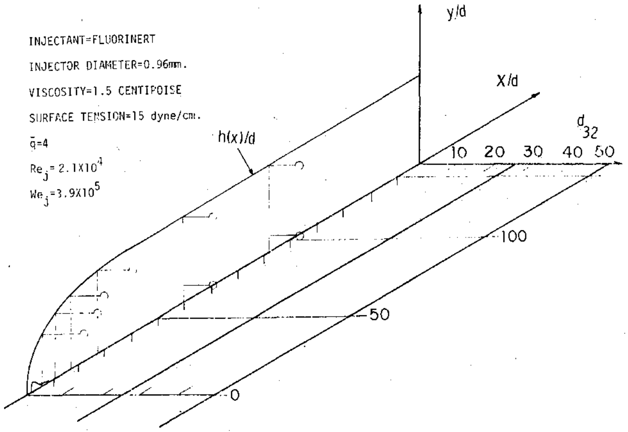


Fig. 8 Droplet size distribution in the plume for Fluorinert injectant at $\bar{q}=4$, $d=0.96$ mm.

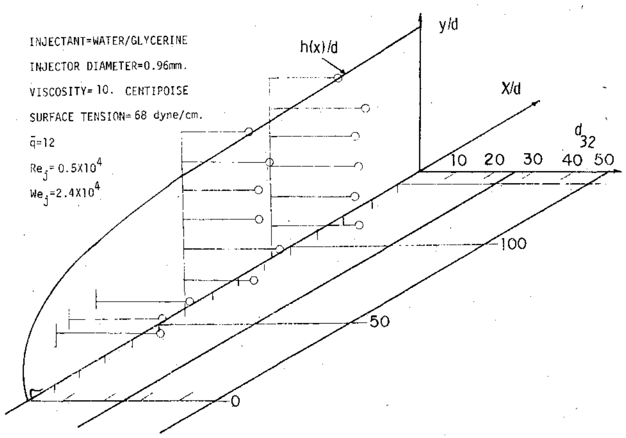


Fig. 9 Droplet size distribution in the plume for water/glycerine injectant at $\bar{q}=12$, $d=0.96$ mm.

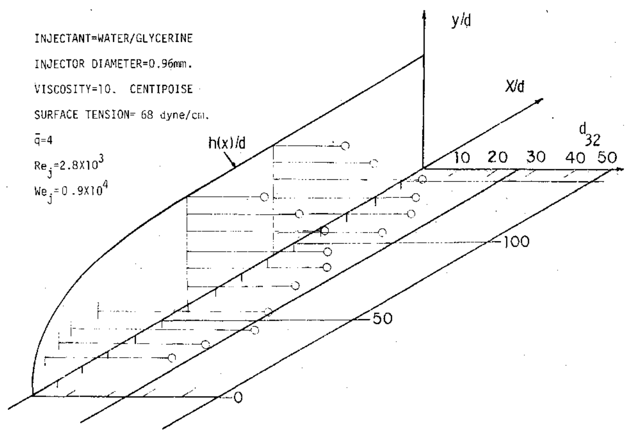


Fig. 10 Droplet size distribution in the plume for water/glycerine injectant at $\bar{q}=4$, $d=0.96$ mm.

small penetration of the jet at $\bar{q}=4$ with respect to the size of the injectant beam, it was not possible to check the variation of mean droplet diameter across the plume.

The results of a study of droplet distribution across and along the jet plume for water at $\bar{q}=12$, but now with a larger diameter injector $d=0.96$ mm ($Re_j=4.1\times10^4$, $We_j=2.3\times10^4$), are given in Fig. 4. It appears that, at high values of $\bar{q}$, the jet plume breaks up fully and the droplet diameters reach a limiting size which is only weakly dependent on the injector diameter in this size range.

Droplet distributions throughout a water spray injected at $\bar{q}=4$ through the bigger injector $d=0.96$ mm ($Re_j=2.4\times10^4$, $We_j=0.8\times10^4$) are plotted in Fig. 5. Here, there is an increase in droplet diameter as compared to that in Fig. 4.

Figure 6 displays the variation of droplet diameter across and along the jet for injection of the lower surface tension water/alcohol solution at $\bar{q}=12$ through the smallest injector $d=0.45$ mm ($Re_j=1.8\times10^4$, $We_j=2.3\times10^4$). The surface tension of this injectant is roughly one-half of the surface tension of pure water, while it has the same viscosity. Again, the droplet diameter decreases in size as one moves downstream from the injector port. The process of atomization seems to be more complete than that for pure water, as there is not a great variation in droplet diameter throughout the plume. A direct comparison with results of Fig. 2 shows that, due to a lower surface tension, complete atomization of the jet takes place earlier downstream of the injector port, roughly at $x/d=33$ for water/alcohol rather than $x/d=109.9$ for pure water. Also, the droplet diameters appear to be smaller for the case of lower surface tension, keeping other variables constant.

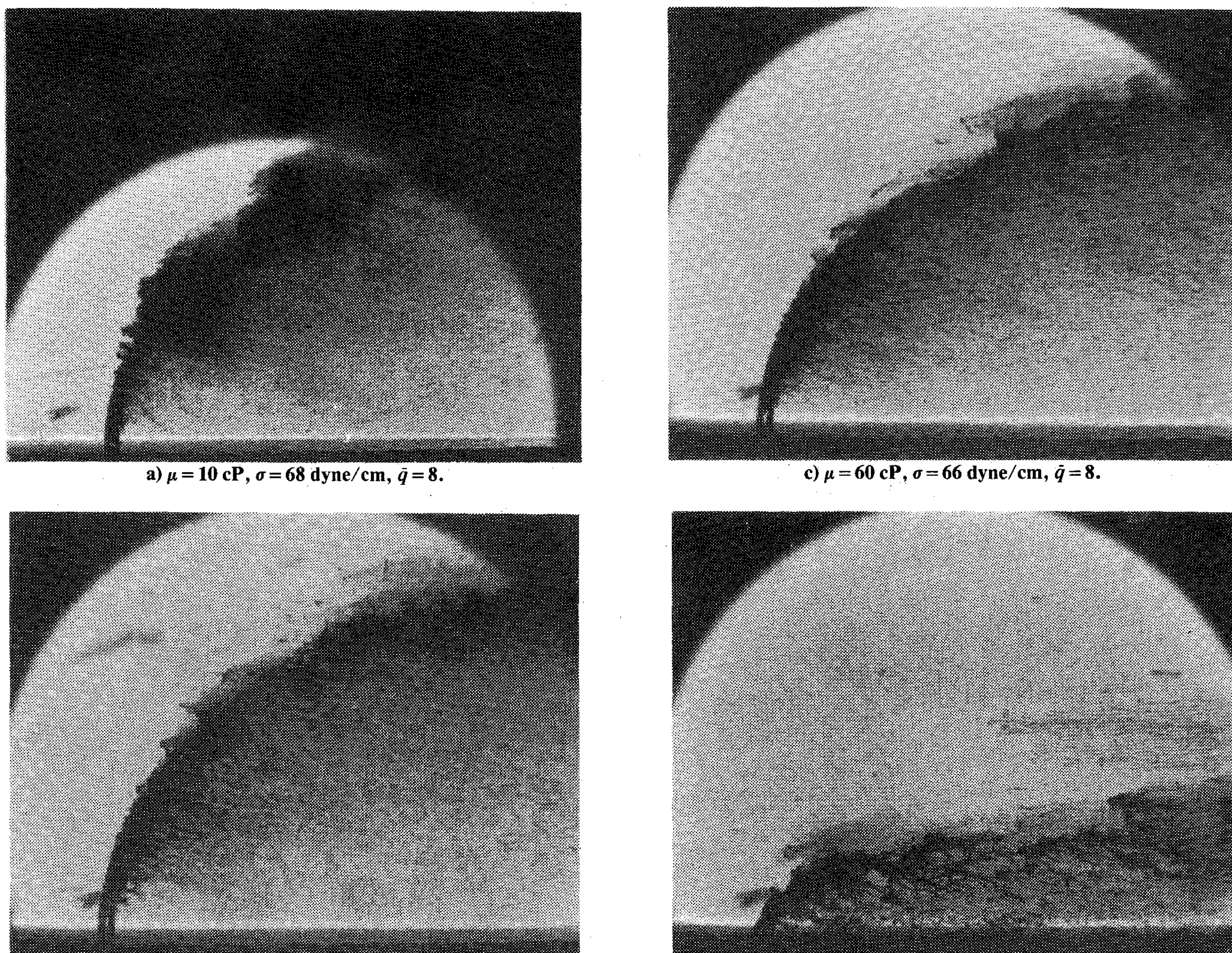
Figure 7 shows the droplet diameter variation in a water/alcohol jet plume injected at $\bar{q}=12$, $d=0.96$ mm ($Re_j=1.5\times10^4$, $We_j=5.0\times10^4$). The results clearly show that atomization is almost instantaneous at $x/d=54$. The droplet diameter stays almost constant as one moves downstream, and the variation of droplet diameter across the jet plume is not great. A direct comparison with the results of Fig. 4 shows that the water/alcohol spray is finer, but more importantly the atomization is more uniform throughout the jet plume.

The mean droplet diameter variation results from atomization of the very low surface tension Fluorinert at $d=0.96$, $\bar{q}=12$ ($Re_j=2.1\times10^4$, $We_j=3.9\times10^5$) is shown in Fig. 8. Due to extensive atomization, the light absorption by the spray particles at stations deep inside the spray was greater than 20%, clearly suggesting multiple scattering of the light. Therefore it was only possible to obtain droplet size information for stations very near the spray edge with the DSLM. The results indicated extreme atomization. The droplets at stations $x/d=5.2$, 10.4, 15.6, and 28 were all 7 μm in diameter. At $x/d=60$ and 93 the droplets were reduced in diameter to 5 μm. The small droplet diameter near the spray plume edge together with the excessive light absorption suggests that atomization is rapid and complete.

Figure 9 gives the variation in droplet diameter in a higher viscosity water/glycerine jet plume injected at $\bar{q}=12$, $d=0.96$ mm ($Re_j=0.5\times10^4$, $We_j=2.4\times10^4$). The viscosity of this injectant is ten times greater than that of water with about the same surface tension. Comparison with the data of Figs. 4 and 8 (water/alcohol) shows that an increase in viscosity, while holding other properties constant, increases the droplet diameter. Further, the process of atomization across the jet is not as uniform.

The droplet sizes found at several stations along and across the same water/glycerine mixture injected at $\bar{q}=4$, $d=0.96$ mm ($Re_j=2.8\times10^3$, $We_j=0.9\times10^4$) are graphed in Fig. 10. The atomization of the jet is slow, and throughout the plume the particles are large. The droplet size decreases at first from 47 μm at $x/d=15.6$, $y/d=7.0$ to 36 μm at $x/d=60$, $y/d=9.3$. However, after $x/d=60$, the droplets stay constant in size.

In summary, it can first be said that droplet diameter is inversely related to jet/freestream dynamic pressure ratio ($\bar{q}=\rho j v_2^2/\rho_\infty v_\infty^2$). Therefore, for given freestream conditions, increasing jet velocity decreases droplet diameter, or vice versa. Droplet diameter was also found to increase or decrease monotonically with jet diameter, viscosity, and surface tension of the injectant. Therefore increasing surface tension, viscosity, or jet diameter increases the resultant droplet diameter in the spray plume and vice versa. It has been suggested that simple interrelations of these parameters, such as Reynolds and Weber numbers, are capable of correctly



a) $\mu = 10$ cP, $\sigma = 68$ dyne/cm, $\bar{q} = 8$.

c) $\mu = 60$ cP, $\sigma = 66$ dyne/cm, $\bar{q} = 8$.

b) $\mu = 40$ cP, $\sigma = 66$ dyne/cm, $q = 8$.

d) $\mu = 60$ cP, $\sigma = 66$ dyne/cm, $\bar{q} = 2$.

Fig. 11 Spark photomicrographs of various glycerine/water jets.

correlating the mean droplet diameter to the experimental conditions. In the present test program the injection Reynolds and Weber numbers had a range of $(2.8\text{-}41.2)\times 10^3$ and $3.7\times 10^3\text{-}1.7\times 10^6$, respectively. This is due to jet diameter, jet velocity, injectant viscosity, and surface tension variations programmed into the test plan. Both Reynolds and Weber numbers increase as a result of increasing jet diameter and jet velocity. Decreasing viscosity and surface tension of the injectant also increases both nondimensional parameters. In-depth study of our results shows that mean droplet diameter does not follow the trends predicted by either Reynolds or Weber numbers by themselves. For example, from a comparison of the results of Fig. 10 ($Re_j = 2.8\times 10^3$) and Fig. 5 ($Re_j = 2.4\times 10^4$) it can be concluded that increasing the Reynolds number by decreasing viscosity has, while holding the Weber number constant, resulted in smaller droplet diameters. However, the opposite conclusions can be drawn by comparison of two tests both with water at $Re_j = 3.6\times 10^4$ and 2.4×10^4. This time, increasing the Reynolds number by increasing the diameter increased the droplet diameter. The same type of argument holds true for Weber number effects. Therefore it is clear that the effects of surface tension, viscosity, injector diameter, and jet velocity on the mean droplet diameter are more complex than can be expressed through a simple Reynolds and Weber numbers correlation.

A study of the effects of a very high viscosity injectant upon droplet diameter was not possible. From very short duration (10^8 s) spark photographs of the jet plume, it was found that higher viscosity injectants behave very differently from the lower viscosity injectants. As can be seen in Fig. 11, the combination of high injectant viscosity and low $\bar{q}$ produces a breakup into ligaments rather than droplets. For high enough $\bar{q}$, even the high viscosity injectants break up into droplets. The boundary between the two situations is rather sharp, and it is near $\bar{q} = 10$. However, for the present effort, the occurrence of ligaments rather than droplets renders the DSLM (at least in its present, simple form) unusable.

Conclusions

Our results can be summarized as follows:

1) The droplet size decreases as one moves downstream from the injector port.

2) The largest droplets are formed in the middle of the jet plume.

3) The droplet diameter decreases as the dynamic pressure ratio $\bar{q}$ increases and vice versa.

4) A decrease in surface tension at lower dynamic pressure ratios decreases the droplet diameter.

5) The lower surface tension injectants produce a more uniformly atomized jet spray.

6) The lower surface tension injectant spray plume gets atomized fully at a shorter distance downstream of the injector orifice.

7) An increase in viscosity of the injectant increases the droplet diameter and delays the atomization of the jet to larger values of x/d.

8) For very high-viscosity injectants and low $\bar{q}$, the breakup is into ligaments rather than droplets, at least over the range of x/d studied here.

9) Reynolds and Weber numbers do not correlate the results in any simple way. The correlation of Ref. 1, for example, was found to be inadequate.

Acknowledgment

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