Investigation of Injectant Properties on Jet Penetration in a Supersonic Stream

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The effect of liquid properties on secondary injection from a single small-diameter nozzle in a supersonic stream was investigated experimentally. Normal penetration of liquid jets was inferred from scattered-light and schlieren photographs. Primary flows of $M_\infty = 2.8$ and 4.0 were produced in a 4 × 4-in. blowdown wind tunnel. Data on normal penetration of room-temperature water were used to extend published correlations to lower injection pressure ratios. The effect of vapor pressure on penetration was investigated by injecting superheated water and acetone. Penetration height was correlated with injection pressure ratio for superheated liquid injection; these data were compared with room-temperature results. Vapor pressure breakup outside of the spray nozzle had little effect on the penetration height. Liquid viscosity and surface tension were varied over a wide range of conditions; neither property affected the penetration height for flow in the acceleration-wave breakup regime.

Nomenclature

d = nominal injector diameter, in.
d_e = equivalent jet diameter, in.
h = jet penetration height, in.
$\dot{m}$ = actual mass flow of rate of liquid, lb/sec
M = Mach number
p = pressure, psi
p_v = vapor pressure of liquid, psi
q = dynamic pressure, psi
T = temperature, °C
R = radius of vapor droplet, microns
Re = Reynolds number
V = velocity, fps
We = Weber number, $\rho_\infty V_\infty^2 d_e/\sigma$
x = coordinate axis in direction of freestream, origin at injector
α_l = thermal diffusivity of liquid, in.²/sec
β = dimensionless growth constant
ρ = density lb/in.³
τ_1 = nucleation time, sec
τ_2 = asymptotic growth time, sec
τ_3 = aerodynamic breakup time defined by Eq. (5), sec

Subscripts

j = liquid jet condition
0 = reservoir condition
∞ = freestream condition
2 = shocked condition

I. Introduction

A PLASMA sheath of ionized air surrounds a vehicle re-entering the atmosphere. This sheath reflects and absorbs rf signals and can interrupt radio communication. This communication blackout problem can be alleviated by localized injection of a coolant upstream of the antenna. Localized fluid injection is also of interest in the problems of supersonic combustion and liquid thrust vector control. To solve these problems, the prediction of jet penetration is required as a function of the injectant properties and the flowfield system. The process by which a liquid jet disintegrates in a supersonic cross flow is complex, and appropriate analytical models are difficult to formulate. Most of the experimental data to date on jet penetration into a supersonic flow are limited to injection of room-temperature water.[1–4] These data obey a simple correlation.[1]

The injection penetration problem may be further complicated if jet breakup is due in part to flashing. This situation is possible when a re-entry vehicle is in high-altitude flight. The liquid is then injected into a low-pressure environment where the local static pressure of the surrounding air is less than the vapor pressure of the injectant. Since the injectant is suddenly subjected to a pressure that is below the vapor pressure corresponding to the liquid temperature, the breakup characteristics of an otherwise well-collimated jet may be altered. Thus, flashing or flash vaporization of the injectant at large superheats may decrease the normal penetration of the jet in a supersonic cross flow. The rapid disintegration of liquids has been demonstrated in low-pressure vacuum chambers.[5–7] The only supersonic cross flow experiments with an appreciable amount of superheat were those of Newton and Dowdy[8] at the Jet Propulsion Laboratory (JPL). Liquid nitrogen was selected as an injectant to limit freezing in the wind tunnel at low static temperatures. Although the effective superheat was low (~25°C), flow meter measurements indicated that boiling had occurred within the nozzle. After d_e was corrected for the reduced mass flow rate, the normal penetration height did not correlate with the water data.[1] An empirical correction had to be applied to the JPL data to account for flash vaporization outside of the spray nozzle. These data suggest that flash vaporization of an injectant tends to decrease the jet penetration height. No data are available in the literature on penetration in a supersonic cross flow of injectants with large superheats.

This paper reports experimental data on the effect of superheated liquids on jet penetration of liquids injected normal to a uniform supersonic stream. Additionally, new room-temperature water data are presented for injection at low injection pressure ratios, and the effects of liquid viscosity and surface tension on penetration height are investigated for flow in the acceleration-wave breakup regime.

II. Supersonic Wind-Tunnel Experiments

A. Description of Experiments

The experiments reported were performed in the 4 × 4-in. supersonic blowdown wind tunnel at the Naval Postgraduate

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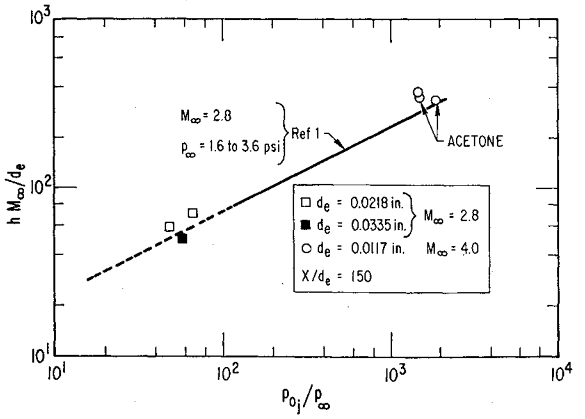


Fig. 1 Normal penetration vs ratio of jet reservoir pressure to freestream static pressure for room-temperature water.

School in Monterey, Calif., using a sharp-edge, flat-plate model at Mach numbers of 2.8 and 4.0. This model design limited the boundary-layer thickness to $\sim 10^{-2}$ in. The apparatus and test procedure for the room-temperature water injection tests were similar to those detailed in Ref. 1. Either schlieren photographs, scattered-light photographs, or both were taken of the jet spray. For the scattered-light photographs, two electronic flashes (120 w-sec) were used with exposure times of 10^{-4} sec.

In the superheated liquid experiments, a 500-cc accumulator was submerged in a hot oil bath; the connecting tubing and manual fast-acting valve were wrapped with a regulated heating tape.[9] The temperature of the bath was varied between 90 and 190°C by regulated diffusion-pump heaters.

The preinjection temperature of the superheated liquid was estimated from the bath temperature and the vapor pressure of the injectant. The temperature rise was monitored by a thermocouple near the injector plenum. A heat-transfer analysis indicated that the temperature of the liquid in the injector was within 4°C of that in the accumulator. As a final precaution in establishing a steady-state temperature, the superheated liquid was injected for a few seconds before each photograph was taken. In this series of tests, the injectants were distilled water and chemically pure acetone. Measured volumetric flow rates indicated no detectable change in the discharge coefficients of the superheated and the room-temperature injections. Thus no boiling occurred within the nozzles in these experiments.

The injectors (Table 1) were tested to ensure a well-collimated jet for injection of room-temperature water. The spreading of the jet was measured, as in Ref. 1, by injection into still air at 1 atm. The equivalent jet diameter is defined by $d_e = (4\dot{m}/\pi V_j \rho_j)^{1/2}$.

The ranges of the primary and secondary flow conditions explored in this study of normal injection are: $M_\infty = 2.8$ and 4.0; $p_\infty = 0.9$–6.5 psi; $q_\infty = 9$–36 psi; $T_\infty = 113$ and 69°K; Re_∞/in. $\cong 6 \times 10^5$; $W_e = (\rho_\infty V_\infty{}^2 d_e/\sigma) > 400$; $p_{0j} = 100$–2900 psi; and $T_{0j} = 20$, 90, and 190°C.

B. Extension of Normal Penetration Correlation for Room-Temperature Water

The correlation in Ref. 1 of penetration height with injection pressure ratio p_{0j}/p_∞ was based in part on JPL liquid nitrogen data[8] for the low injection pressure ratio regime. The penetration height is defined as the upper boundary of the visible spray at the station $x/d_e = 150$. This correlation is shown in Fig. 1; the dashed line represents the domain where the JPL liquid nitrogen data were used. The curve is given by

$$hM_\infty/d_e = 6.77(p_{0j}/p_\infty)^{0.51} \tag{1}$$

In the correlation, an empirical correction was applied a priori to the JPL data to account for flashing outside of the spray nozzle since the vapor pressure for liquid nitrogen was greater than the static pressure of the wind tunnel. (The reduced mass flow due to boiling within the nozzle was taken into account by d_e.) This correction was based on the ratio of the vapor pressure of liquid nitrogen to the static pressure p_2 behind a normal shock. This p_2 was chosen since this was the highest static pressure that could exist within the shock system that was supported by the free liquid jet near the injection point. The room-temperature water data and the LN_2 data reduced to a single correlation when the LN_2 data were plotted in the form

$$hM_\infty/d_e = f[(p_{0j}/p_\infty)(p_2/p_v)^{1/4}] \tag{2}$$

when $p_v/p_2 > 1$. All normal penetration data were represented by $f[\ \ ] = 6.77[\ \ ]^{.51}$. The reduction in penetration height for the flashing case with a fixed injection pressure ratio, freestream pressure, and Mach number becomes

$$\Delta h/h \simeq 1 - (p_2/p_v)^{1/8} \tag{3}$$

where Δh is the decrease in h due to flash vaporization outside of the spray nozzle. For high vapor pressures, and hence large superheats, Eq. (3) implies that the penetration height can be greatly reduced over zero superheat injection.

The data points for room-temperature water injection, represented by squares in Fig. 1, were obtained by operating the wind tunnel at high static pressures ($p_\infty = 6.5$ psi). These data for water correlate with Eq. (1) in the low range of p_{0j}/p_∞ and hence verify the correlation for room-temperature water that was originally obtained using the JPL liquid nitrogen data with the empirical correction. Several data points for injection of room-temperature acetone into a $M_\infty = 4.0$ flow with large p_{0j}/p_∞ ratio are also shown in Fig. 1. These data exhibit a general agreement with the correlation derived from the water data.

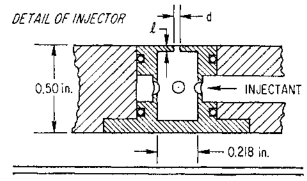
C. Normal Penetration of Superheated Injectants

When the vapor pressure of a liquid injectant is much greater than the external pressure environment, a well-collimated jet will break up or shatter because of flash vaporization.[5–7] Gooderum and Bushnell[7] found that the resultant mean drop size depends on the temperature of the injectant and the orifice diameter only. The JPL data[8] suggest that flash vaporization outside of the spray nozzle of a secondary injectant tends to decrease the jet penetration. For room-temperature water injection, the static pressure of the primary flow must be well below 10^{-2} atm for flash vaporization to be significant. Since the Naval Postgraduate School wind tunnel did not operate in this pressure range, room-temperature water injection was equivalent to zero superheat ($p_2 > p_v$).

Table 1 Injector characteristics

NOMINAL INJECTOR DIAMETER, in.	d_e, in.	ℓ/d	θ^a, deg
0.0145	0.0117	4.0	5
0.0210	0.0175	2.5	8
0.0280	0.0218	2.0	10
0.0400	0.0335	1.4	12

DETAIL OF INJECTOR



^{a}JET CONE ANGLE θ DETERMINED BY INJECTION INTO STILL AIR AT 1 atm AND p_{0j} = 2000 psig

The low-pressure restriction could be removed if heated liquids were injected. Figure 2 shows the saturation pressure for water, acetone, and nitrogen as a function of liquid temperature. The shaded areas represent the nominal static pressure range for the wind-tunnel tests in the facility used in this study and the JPL wind-tunnel conditions. For water or acetone temperature $\gtrsim 125°C$, the vapor pressure is at least an order of magnitude greater than the static pressure of the primary flow. This ratio is comparable to the one experienced in the JPL LN_2 tests.

Most of the previous work[6–7] concerning the effect of vapor pressure on flashing of liquid jets has been confined to injection into low-pressure vacuum chambers where the Weber number of the flow is low. In the present supersonic cross flow experiments with $We > 400$, the aerodynamic forces greatly exceed the surface tension forces. All experiments were performed in the acceleration-wave regime as defined by Adelberg.[10]

Typical scattered-light photographs of normal penetration are shown in Fig. 3 for room-temperature and superheated acetone injections under identical flow conditions. The scattered light from the liquid spray indicates the penetration height of the jet is about the same for the three cases. At a downstream station of $x/d_e \gtrsim 50$, the density of the droplets appears to decrease in the superheated cases (Fig. 3b and 3c). This decrease must be a result of droplet evaporation. Similar results were observed in the case of superheated water injection. Photographs of the superheated water injection show that the intensity of the scattered light was less than that recorded for acetone injection. The greater intensity in the acetone case was attributed to the smaller droplet size and to the increased droplet density expected from low surface tension liquids.[11–12] The schlieren photographs show a bow shock ahead of the collimated jet and a small oblique shock very near the injection point.

In Fig. 4, the superheat data for hM_∞/d_e are plotted as a function of the injection pressure ratio p_{0j}/p_∞. Most of the data agree well with the correlation derived from the room-temperature water injection. Only the data for the largest injector diameter ($d_e = 0.0335$ in.) are below the room-temperature water curve. As shown in Fig. 4, improvement in the correlation results if these data are replotted using the vapor-pressure correction of Eq. (2).

These data suggest that the vapor-pressure correction for breakup outside of the nozzle is applicable only for large injector diameters, as was the case in the JPL LN_2 experiments. The rationale for applying such a correction can be explained in terms of competing flashing and aerodynamic breakup times.

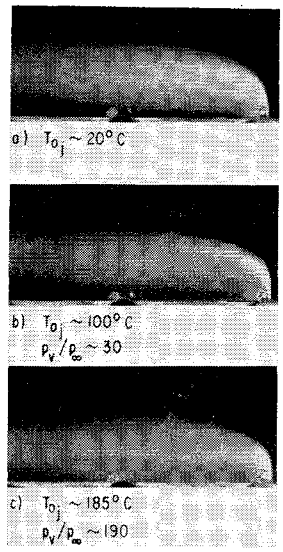


Fig. 3 Effect of vapor pressure on normal penetration (p_∞ = 1.7 psi; p_{0j} = 2000 psi, d_e = 0.0117 in.; medium, acetone).

When a liquid jet is suddenly subjected to a pressure that is below the vapor pressure corresponding to the liquid temperature, a metastable equilibrium state exists.[13–14] After the liquid adjusts to the new low-pressure environment, a two-phase equilibrium condition of saturated vapor and liquid results. If such an adjustment to equilibrium occurs rapidly as the liquid leaves the injector orifice, the effective breakup time of a normally well-collimated jet may be decreased, while the observed penetration height will be reduced. The breakup of a liquid jet in low-pressure environments is influenced by flash vaporization, as illustrated in Ref. 5. Such flashing is dependent on the formation and the subsequent growth of vapor bubbles within the liquid jet. Transition to the ultimate two-phase equilibrium state is controlled by two rate phenomena. When the vapor bubble size is of the order of the metastable radius R_0, hydrodynamic and surface tension forces determine the slow growth rate, whereas the asymptotic bubble growth rate is controlled by energy transfer to the liquid-vapor interface. The nucleation, or first transition, time τ_1 is $\sim 10^{-4}$ to 10^{-5} sec.[13–14] This characteristic nucleation time is strongly dependent on the decompression period, possible nucleation sites, and degassed state of the liquid. The asymptotic growth time can be related by[15]

$$\tau_2 \sim R^2/(4\beta^2\alpha_l) \tag{4}$$

The dimensionless growth constant β is a function of the latent heat of vaporization, the specific heat, and the degree of superheat.

For flashing near the injector orifice, the characteristic aerodynamic breakup time of a well-collimated jet should be longer than $\tau_1 + \tau_2$. Conventionally, τ_1 equal zero referred to

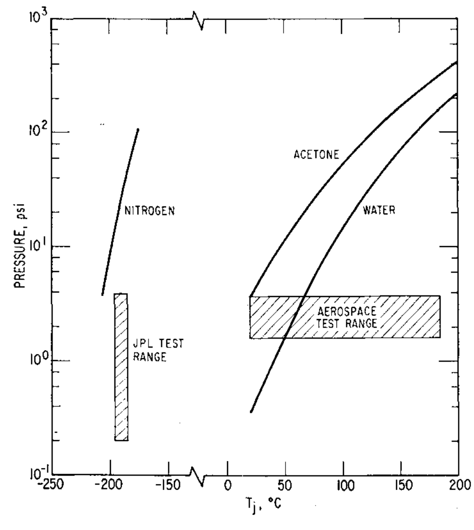


Fig. 2 Comparison of vapor pressure of several injectants with range of static pressure conditions.

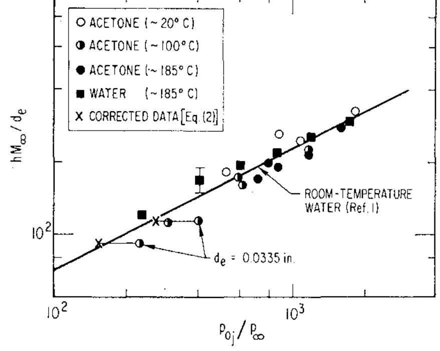


Fig. 4 Normal penetration vs ratio of jet reservoir pressure to freestream static pressure for various superheats (M_∞ = 2.8 and x/d_e = 150).

the nozzle exit. The aerodynamic breakup time can be defined as the ratio of the penetration height to the jet velocity. Since the jet velocity can be expressed in terms of the injection pressure ratio, the aerodynamic breakup time can be estimated by

$$\tau_3 \sim 4.8 d_e \rho_j^{1/2}/(M_\infty p_\infty^{1/2}) \quad (5)$$

The characteristic breakup times for the superheated injectants were compared for the flow conditions of the JPL and present experiments. The details of these calculations are shown in Ref. 9. The calculated asymptotic growth time was very short; one can conclude that flashing effects are normally governed by the nucleation time, which unfortunately is not well known. No significant decrease in the jet penetration height was observed; therefore, τ_1 must be comparable to τ_3 in the present experiments, except possibly in two cases where d_e was large. One would have expected similar results in the JPL experiments. However, the turbine flowmeter in the JPL experiments recorded a reduced mass flow rate ($\Delta\dot{m}_j/\dot{m}_j \lesssim 20\%$). The smaller discharge coefficient indicates that nucleation and boiling occurred within the injector, and hence τ_1 was completed while the LN_2 was still in the injector. Since τ_2 is short, the free jet should rapidly disintegrate by the formation of vapor bubbles. In the experiments reported here, where no boiling was noted, either τ_1 was exceedingly long or the heat-transfer model that predicts τ_2 is invalid for large superheats. The recent work of Hooper and Abdelmessih[16] tends to substantiate the latter statement. In their static bath experiments, as the superheat was increased, the observed bubble growth rates fell well below those predicted by Eq. (4).

D. Effect of Viscosity and Surface Tension of Normal Penetration

Data obtained from the experiments using superheated injectants may be compared with the data from Ref. 1 to ascertain the effect of fluid viscosity and surface tension on normal jet penetration. The comparison is valid for aerodynamic breakup times shorter than the flashing time. Thus, only the data for small d_e and large p_∞ could be used. The viscosity of water ranged from $\sim$0.16 to 1 centipoise, and the surface tension varied from 40 to 73 dyne/cm. In the case of acetone, the viscosity varied from 0.08 to 0.33 centipoise, and the surface tension varied from 5.4 to 24 dyne/cm.

The normalized penetration height was independent of the fluid properties. This result is in agreement with the recent conclusions of Castle.[17] In Castle's experiments, secondary penetration was measured using room-temperature heptane and a glycerine-water solution as injectants. The results of Castle and this study substantiate the analytical results of Adelberg[10] on his acceleration-wave jet breakup model (large Weber number). The acceleration-wave breakup is independent of the liquid surface tension; viscosity enters only in a relatively minor way by producing damping.

III. Concluding Remarks

The new room-temperature data for water injection at low injection pressure ratios are in good agreement with the correlation curve in Ref. 1. Since this correlation was based in part on liquid nitrogen data, the new data greatly strengthen the correlation.

Data on superheated acetone and water show that normal penetration can be relatively insensitive to superheat. As long as the aerodynamic breakup time is less than the flashing time, the penetration height obeys the room-temperature water correlation. For large-diameter jets normal penetration correlates with the room-temperature scaling if the empirical correction of Ref. 1 is used. This correction is based on the ratio of the vapor pressure to static pressure behind a normal shock. The vapor-pressure correction was applied to only two data points, those corresponding to the largest injector diameter. For all other data, no correction was necessary, which suggests that the over-all breakup process was controlled by the aerodynamic breakup.

The effect of viscosity and surface tension on normal penetration was studied. As suggested by analytical models, these properties do not affect the normalized penetration height at large Weber numbers.

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