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Technical Notes

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Dynamics of Supersonic Droplets of Volatile Liquids

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I. Introduction

THE breakup and vaporization of liquid droplets in supersonic flow is an interesting research problem with potentially important implications for supersonic combustion ramjets (scramjets). Noncryogenic, liquid hydrocarbons have substantial benefits as scramjet fuel [1], including higher energy density, lower cost, and ease of handling compared to liquid hydrogen fuel. The complications and time associated with the atomization and vaporization of liquid hydrocarbon scramjet fuel can, in principle, be avoided by injecting the fuel in the vapor phase. In some situations, however, such as a "cold start" in which the fuel is not preheated, hydrocarbon fuel may necessarily be injected while still in liquid phase. In this case, the rates and physical mechanisms associated with the disruption and vaporization of liquid droplets under supersonic flow conditions become critical issues to scramjet combustor performance.

One possible technique to increase the dispersion of liquid fuels is to exploit the accelerated vaporization made possible by superheating the liquid. Investigation of the vaporization of superheated droplets and sprays have to date been largely confined to incompressible flows [2,3], with the physics of superheated liquid droplet disruption and vaporization in supersonic flow not yet well established. Studies of droplet disruption in compressible flows that have been conducted [4–6] have generally not considered the effects of superheating. The numerical study of Joseph et al. [7] did suggest a flash vaporization mechanism in the disruption of liquid drops in steady, supersonic flow, arguing that superheating may occur over small regions of the droplet surface due to a local combination of low pressure and frictional heating.

The disruption of droplets in high-speed flow has often been studied by the sudden application of aerodynamic loads though the use of shock tubes [4,6,8–10]. Though this technique can produce liquid droplets under locally supersonic conditions, this is accomplished only after the passage of a shock wave through the droplets. Other droplet disruption studies have been conducted at subsonic speeds [11,12], for example, by droplets falling across a high-speed gas jet [13], droplet-bearing jets in cross flow [14], and in drop tubes [15]. In any case, these techniques do not typically result in the droplets achieving a significant degree of superheating.

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The research presented here investigated the dynamics of droplets consisting of volatile fluid smoothly accelerated to supersonic Mach numbers without passage of shock waves through the droplet. This was accomplished over a range of liquid vapor pressures using a compact, underexpanded supersonic jet configuration. This is an extension of a previous study of superheated droplet disruption with compressible, but subsonic, flow relative to the droplets [16]. One challenging aspect in the study of liquid drops in high-speed airstreams is the measurement of the drop velocity and acceleration [17]. Double-pulsed, planar laser imaging was employed here to determine the velocity of the droplets for various test fluids.

II. Approach

A. Flow Configuration and Diagnostics

Liquid droplet disruption under locally supersonic conditions was investigated using an underexpanded jet configuration, as shown schematically in Fig. 1. The underexpanded jet was discharged into a cubical test section with 76 mm sides connected to a vacuum tank with a volume of 30 m^3. The nozzle consisted of a conical convergent section 15.9 mm long with a 25.4-mm-diam entrance and a 3.2-mm-diam throat. Circular quartz windows with diameters of 40 mm allowed for flow visualization. Schlieren imaging indicated that the Mach disk was approximately 10.9 mm downstream of the nozzle exit. Conditions on the flow centerline were determined by a pitot probe inserted from the bottom of the tunnel, which gave, based on the uncertainty in the measured pitot pressure, an uncertainty in the flow velocity of approximately 4%. The airflow expanded to a measured Mach number of $M_{\text{flow}} = 3.9$ near the location of the Mach disk (only droplets upstream of the Mach disk are considered here). The nominal stagnation temperature and pressure were 293 K and 1 atm, respectively.

A *MicroFab* piezoelectric droplet-on-demand generator with a *MicroJet III* controller generated monodisperse 70-μm-diam droplets of each test fluid at a rate of 1000 droplets/s. This frequency was sufficiently low to preclude significant droplet–droplet interaction in the test section. The droplet generator tip was positioned 25 mm above the entrance of the convergent nozzle entrance, and was aligned with three-axis microstagers to ensure that the droplets were injected on the tunnel centerline. Experiments were conducted by first initiating the droplet stream, then opening the valve to the vacuum tank to initiate the supersonic flow. Additional details of the experiment are provided by Phariss [18].

Studies to date of droplet dynamics in high-speed flow have largely relied on some form of high-speed imaging to measure drop displacement vs time [17]. In the current work double-pulsed laser imaging was employed for this purpose. Imaging of droplets was accomplished using a *Princeton Instruments* PI Max 2 ICCD camera with a VZM 300 video microscope lens. Illumination was provided by a *New Wave Research* Solo PIV 120 double-pulsed Nd:YAG laser, which fired two pulses with a duration of 5 ns each with a typical pulse separation of $\Delta t = 10$ μs. The laser light was formed into a vertical sheet 50 mm tall by 2 mm thick. The droplet velocities were determined from the measured droplet displacement and the pulse separation time, that is, $V_d = \Delta z/\Delta t$. This method is similar to particle image velocimetry (PIV); however, in this case the droplets did *not* follow the flow (precisely the point of the current study). The calculated velocities had an estimated error of approximately 8%.

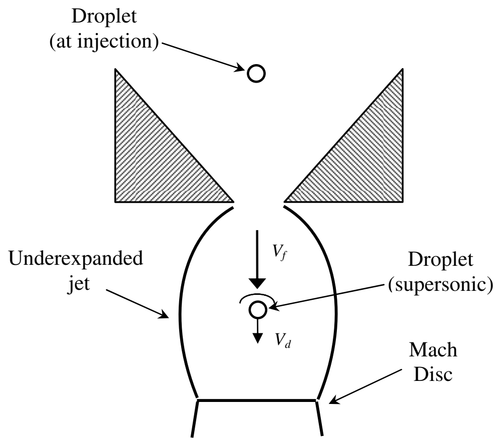

Fig. 1 Schematic diagram of droplet injection and acceleration process using an underexpanded jet configuration.

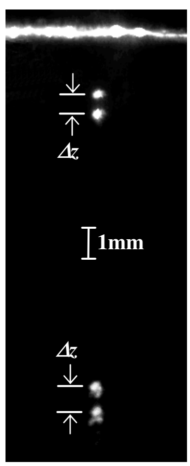

Fig. 2 Double-pulsed images of 1-propanol droplets in supersonic flow. The bright horizontal line at the top of the figure is the nozzle exit.

Representative double-pulsed images of droplets in supersonic flow are shown in Fig. 2. The apparent centers of the bright droplets were used to determine the positions for the velocity calculation, as shown in the figure. Though some features of droplet deformation and disruption were apparent in many cases, the wide field of the images, combined with bright scattering of the laser light from the droplets, did not allow for the detailed examination of the features of droplet disruption in this work.

B. Test Fluids and Droplet Superheating

The test fluids employed were 1-hexanol, 1-propanol, and ethanol. The fluids have similar surface tensions but significantly different vapor pressures. The vapor pressure of these liquids at 20°C are, respectively, 0.048, 2.0, and 5.9 kPa; the corresponding surface tensions are 22.4, 23.8, and 26.2 mN/m. Hexanol served as a nonvolatile control liquid to determine the potential effects of droplet volatility on the dynamics and disruption behavior. The low static pressure in the supersonic airstream has the potential to give rise to superheating of the droplet fluid, as the static pressure can become significantly lower than the vapor pressure of the droplet [7].

The droplet fluids were not heated before their injection into the supersonic flow. The calculated Fourier number of the droplets was $Fo = 4\alpha t/d_0^2 \approx 0.013$ for all test fluids. Here t is the total time for which droplets were subjected to cold static temperatures in the nozzle (more than 1 K below ambient) and in the underexpanded jet up to the Mach disk. The low value of the Fourier number suggests that whereas there may have been some cooling very near the droplet surface, cooling of the bulk droplet fluid was negligible in the supersonic flow owing to the very short droplet lifetimes. It has suggested that, in fact, the liquid temperature can increase due to the viscous heating resulting from rapid droplet deformation in high-speed flow [7].

III. Results

The measured absolute velocities (i.e., relative to lab-fixed coordinates) are shown in Fig. 3 for hexanol and ethanol droplets. Only droplets within 1 mm of the tunnel centerline were considered. The hexanol droplets exhibited an initial measured velocity of approximately 40 m/s immediately downstream of the nozzle, increasing to a velocity of approximately 100 m/s near the downstream location of the Mach disk ($z = 10.9$ mm). The velocities of the ethanol droplets were similar to those of hexanol, reaching a typical velocity of approximately 85 m/s at the Mach disk. The velocity data for the propanol droplets were very similar to those of the hexanol droplets. The similar velocity histories between ethanol (the most volatile fluid considered here) and hexanol (the nonvolatile fluid) suggest that any superheating of the droplet fluid does not strongly impact the droplet velocity. The initial droplet acceleration is of the order of 10^6 m/s^2; such high levels of droplet

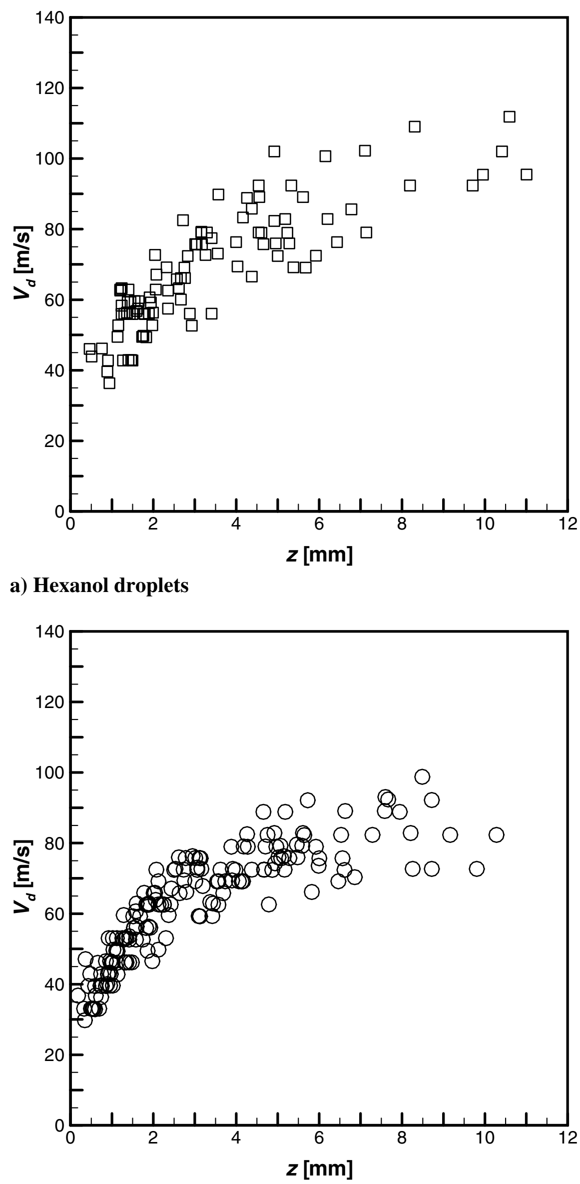

Fig. 3 Measured absolute (lab-fixed coordinates) droplet velocities in supersonic flow. z is the distance downstream of the nozzle throat.

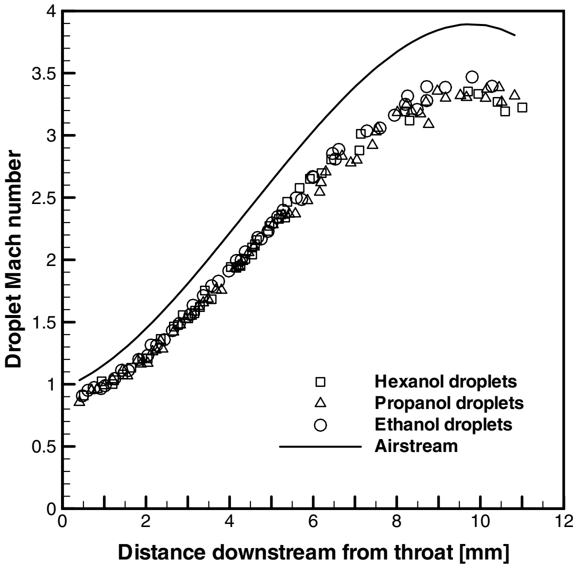

Fig. 4 Mach numbers of droplets relative to the surrounding supersonic airstream. The solid line is the Mach number of the air flow. The Mach disk is located 10.9 mm downstream of the nozzle throat.

acceleration have been observed previously in compressible flow [6,8].

The measured droplet velocity was used to determine the Mach number of the droplets relative to the surrounding stream as follows: $M_r = (v_f - v_d)/a_f$, where v_f and v_d are, respectively, the lab-fixed velocities of the supersonic flow and the droplet, and a_f is the speed of sound at the droplet location. The local flow conditions (air velocity and speed of sound) were determined from the pitot probe measurements mentioned earlier. The Mach numbers relative to the droplet are shown in Fig. 4 for all three liquids (the data points have been thinned to improve the readability of the figure). A maximum relative Mach number of approximately 3.3 was achieved for all three test liquids, demonstrating the capability of this under-expanded-jet technique to produce droplets at high Mach number, without the impulsive loading and shock passage that occurs in shock tube experiments [4–6,9,11]. The similar Mach numbers for the three fluids is in part a consequence of the large difference between the high flow velocity and the significantly lower droplet velocities.

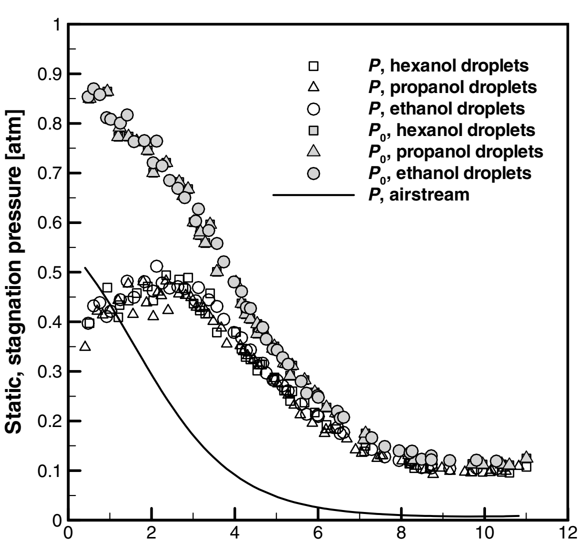

Fig. 5 Static and stagnation pressures in the vicinity of the droplets, based on normal shock conditions. The solid line is the static pressure in the shock-free surrounding airstream.

In previous research in smoothly accelerated droplets in a supersonic wind tunnel [16], where the droplets were at a high subsonic Mach number (0.6–0.8) relative to the surrounding flow, a more noticeable difference in droplet velocities was reported for fluids of different vapor pressures (hence different levels of superheating). The difference in droplet velocities did not appear to be as substantial in the current work, where the droplets were at supersonic Mach numbers. The total residence times of the droplets over the region considered were comparable in that study to those of the current investigation.

Different droplet dynamics for supersonic vs subsonic droplets might be expected owing to the shock waves that presumably occur in the vicinity of the droplets in the supersonic case. The supersonic relative Mach numbers were used to calculate the expected changes in static pressure and stagnation pressure using standard normal-shock relations. The calculated stagnation and static pressures on the droplet center immediately downstream of the bow shock are shown in Fig. 5 for ethanol, propanol, and hexanol droplets. The stagnation pressure in the vicinity of the droplet changes due to the bow shock as well as the changing droplet velocity. Also shown for reference is the low static pressure in the supersonic freestream. Based on the freestream static pressure, the ethanol and propanol droplet fluids would be expected to become superheated at downstream distances of approximately 4.5 and 6.4 mm, respectively. Both the calculated stagnation pressure near the droplets and the static pressure, however, significantly exceed the static pressure in the supersonic flow. The high stagnation pressure in the vicinity of the droplet would effectively suppress droplet superheating near the windward surface of the droplet. Near the flanks of the droplet, by contrast, it has been suggested that the static pressure can be significantly lower than both the centerline static pressure, amounting to less than 10% of the stagnation pressure [7]. Even lower static pressures may occur on the leeward side of the droplet. The current research suggests that although there may be some droplet superheating over some regions of the droplets for the volatile test fluids and flow conditions considered here, such superheating does not appear to strongly impact the dynamics of the droplets as reflected by the droplet velocity and acceleration.

The disruption of droplets due to aerodynamic forces is frequently characterized in terms of the Weber number, $We = \rho_\infty v_r^2 d_0/\sigma$, where ρ_∞ is the static density of the air, v_r the velocity of air relative to the droplet, d_0 the initial diameter of the droplet, and σ the surface tension of the liquid. The relative velocities determined from these experiments suggest a Weber number near the nozzle throat of approximately $We \approx 90$ for all liquids. This value of Weber number would expected to be near the transition from bag-and-stamen breakup to sheet stripping [19]. There are numerous correlations in the literature for droplet disruption times as a function of the Weber number. Part of the reason for the different correlations are differences in the definition of breakup time, such as whether that refers to the start of droplet instability [6], a specific degree of droplet deformation [4], or droplet fragmentation [19]. One correlation based on the last condition was given by Pilch and Erdman [19]: $\bar{t} = 14.1(We - 12)^{-0.25}$, where the nondimensional breakup time $\bar{t} \equiv [tv(\rho_f/\rho_d)^{0.5}]/d_0$ is based on the physical time t, the gas velocity v, and the ratio of the gas flow to liquid densities ρ_f/ρ_l. For the current work this suggests a characteristic breakup time of approximately 40 μs, compared to the approximate residence time for droplets between the nozzle throat and the Mach disk of approximately 150 μs. This suggests that a significant degree of droplet deformation and disruption occurred between the nozzle exit and the Mach disk, though it should be pointed out that the correlation presented by Pilch and Erdman is for a uniform high-speed flow (as opposed to the accelerating flow in the underexpanded jet), and does not explicitly address the effects of compressibility at the high droplet Mach numbers of the current study.

The stability of droplets under high acceleration can also be characterized in terms of the Bond number, $Bo \equiv \rho_l a r_0^2/\sigma$, where a is the droplet acceleration and r_0 the initial droplet radius. The Bond numbers for the droplets in this investigation were approximately $Bo = 40$ immediately downstream of the nozzle exit. This value of

Bond number is not sufficiently high to result in droplet shattering due to inertial instability at the windward front surface [20].

IV. Summary

Droplets of three liquids with a range of vapor pressures were injected along the axis of a freely expanding supersonic jet. This underexpanded jet configuration is seen to be capable of smoothly injecting discrete droplets and accelerating them to a high supersonic droplet Mach number, relative to the surrounding flow, in excess of $M_r = 3$, without impulsive loading or shock passage over the droplet that occurs in shock tubes.

For the volatile and nonvolatile fluids considered here, the droplet dynamics (the velocity and acceleration) do not appear to be impacted significantly by liquid superheating. Consideration of the bow shock under locally supersonic conditions suggests that the static and stagnation pressures in the vicinity of the droplet leading edge significantly exceed the low static pressure in the supersonic flow, thus effectively suppressing superheating of the liquid over much of the droplet. Though some droplet superheating may occur in the lower-pressure regions along the flanks and in the wake regions of the droplets, for the volatile test fluids and flow conditions considered here, such superheating does not appear to significantly impact the dynamics of the droplets.

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