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Mie Scattering Imaging of a Transverse, Sonic Jet in Supersonic Flow

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The structure of a nonreacting transverse sonic jet in a supersonic primary stream was visualized by single-shot planar Mie scattering and conventional spark schlieren photography. Sites for Mie scattering were provided by the condensation of ethanol vapor premixed with the transverse jet injectant gas. The planar, time-resolved Mie scattering technique readily reveals large-scale turbulent structure in the transverse jet that cannot be resolved using the schlieren method. The structure appears to be characterized by regions of unmixed gas that penetrate well across the jet centerline. The observed structure persists far downstream (at least 25 orifice diameters) of the jet injector site.

Nomenclature

C_D = injector orifice discharge coefficient
d = injector orifice diameter, corrected for discharge coefficient
d^* = actual injector orifice diameter
H_{top} = distance from wall to top of Mach disk
M = Mach number
P_0 = stagnation pressure
q = transverse jet to primary stream momentum ratio
r = radius of scattering particle
V = velocity
x = distance downstream of injector orifice
λ = frequency of laser illumination
ρ = static density

Subscripts
j = transverse jet
∞ = primary stream

Introduction

ACHIEVING a fundamental understanding of the mechanisms responsible for fuel dispersion and fuel/air mixing in compressible shear flows is vital to the success of supersonic ramjets. One research configuration of significant practical interest is the transverse jet in a supersonic stream. Successful application of this fuel injection strategy depends upon achieving adequate fuel penetration for satisfactory fuel distribution as well as rapid mixing. Numerous previous studies have examined the penetration, shock structure, and time-averaged mixing characteristics of both sonic[1-7] and supersonic[8-11] transverse jets issuing into supersonic primary streams. Experimental techniques used in these studies have typically included schlieren/shadowgraph flow visualization,[1-3,8-10] concentration measurements of the injected gas,[2-5,8,11] pitot/static pressure surveys,[2,4,5] and surface flow visualization.[5] These flow configurations have also been the subject of analytical[2,3,6] and computational[7] modelling efforts.

Although these investigative techniques have lead to useful correlations of jet penetration and growth for given injector and primary stream conditions, a detailed understanding of the physical mechanisms operative during jet penetration and mixing has yet to be achieved. By way of comparison, recent studies of compressible free shear layers have revealed the presence of large structures,[12-14] the nature of which evidently changes with convective Mach number.[12] The evolution of such structures and the degree to which they might dominate the mixing processes in transverse jets in compressible flow have yet to be fully explored.

Laser-based diagnostic techniques have allowed closer study of the mixing characteristics and flow structure in transverse compressible jets and other high-speed turbulent flows.[12,14-20] The focus of the current effort is the instantaneous visualization of the turbulent structure and mixing characteristics of a transverse sonic jet issuing into a supersonic freestream using planar Mie scattering. The Mie scattering images are supplemented by conventional spark schlieren photography. Efforts using the laser-induced fluorescence of biacetyl vapor for planar imaging in this flow have to date been less successful than Mie scattering due to the low fluorescence signal strength; that work is discussed in a previous paper.[20]

Experimental Setup

Flow Facility

Experiments were performed in a new, small-scale supersonic flow facility at United Technologies Research Center. The primary flow direction is vertically downwards, as shown in the schematic diagram of the experimental setup presented in Fig. 1. Dry nitrogen gas from compressed gas cylinders is supplied to the primary stream settling chamber via a high-flow rate regulator (Linde SG3882). The 64-mm-long settling chamber is housed in a 2-in. (51-mm i.d.) steel pipe, terminating with a section of honeycomb [3/32-in. (2.4-mm) cell size, 25-mm long] and a 24-mesh screen. The contraction and nozzle section is 135 mm in length. Two sets of fifth-order polynomial contraction contours provide a transition from the circular cross section of the settling chamber to the rectangular throat. The contours for the subsequent two-dimensional supersonic expansion to a nominal test section Mach number of $M = 2.0$ were generated using the method of Foelsch.[21]

The test section is 12.7×12.7 mm in cross section over its 140-mm length, with the flush sonic injector orifice (diameter $d^* = 0.89$ mm) situated 22 mm downstream of the test section entrance. The walls of the injector orifice plenum consist of a 45-deg half-angle cone joined at its apex to a strait section 1 mm in length. Measurements of the actual injector gas flow rate yielded discharge coefficients in the range of 0.89–0.94 for this configuration. All four test section sidewalls were

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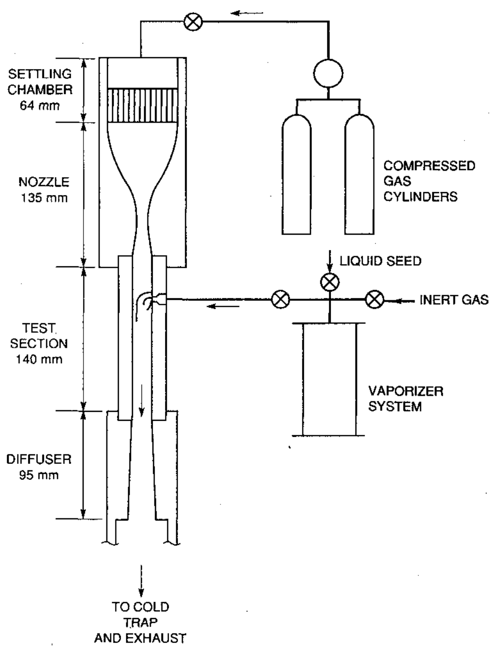

Fig. 1 Schematic diagram of flow facility.

fabricated from quartz plate to allow optical access to the flow; this also reduces the amount of elastic scattering from the walls. Pressure recovery is accomplished by a diffuser section (95 mm total length), which contains a divergent section 85 mm long formed by four walls, each at a ramp angle of 1.5 deg to the flow centerline. The exhaust gas is discharged to the atmosphere through a cold trap cooled by liquid nitrogen to condense out diagnostic seed materials.

The transverse jet was supplied with a mixture of inert gas (argon) and a diagnostic seed species (ethanol). Gas/seed mixtures are prepared prior to a set of runs by using a vaporizer system consisting of a heated aluminum pressure vessel 13-cm i.d. by 122 cm in height. The vaporizer vessel is packed with roughly 10 kg of five-mesh copper screen to minimize cooling as the mixture is discharged, thus preventing the condensation of ethanol upstream of the injector orifice. Before each series of runs, the vessel is evacuated, injected with a known quantity of liquid seed material and then charged with inert gas. This technique allows delivery of gas mixtures with a constant, precisely known seed concentration.

Diagnostic Techniques

Sites for Mie scattering were produced by seeding the transverse jet gas supply with ethanol vapor prior to injection. The ethanol vapor readily condensed in the test section due both to the expansion of the highly underexpanded sonic jet and to mixing between the injectant gas and the cold primary stream gas.[12,15] The diameter of the resulting ethanol particles were expected to be in the range of 0.2 μm to 0.05 μm based on measurements by Clemens and Mungal[15] under similar flow conditions; as such, they should easily follow the flow.[12] The ethanol concentration was typically 0.6%, which is 80% of the saturation concentration at the injection temperature of 310 K. A laser sheet of roughly 100 μm thickness by 15 mm in lateral extent was aligned with the midplane of the transverse jet. Laser illumination for the scattering experiments was provided by a frequency-tripled Nd:YAG laser ($\lambda = 355$ nm). This gave a high signal level because of the strong dependence of the scattering intensity on the incident wavelength in the regime $2r < \lambda$, where r is the physical radius of the scattering particle. The laser was pulsed at a rate of 20 Hz; each 10 ns pulse was sufficiently short to freeze the flow effectively.

The scattering signal was imaged onto a detector array to provide a two-dimensional image of the plane of the laser sheet. The images reported here were obtained by use of a Xybion CID camera (Model RSG-207-U3) with 512×512 elements. The image resolution of the array amounted to approximately 25 μm/pixel in physical space. Data were recorded using videotape and then subsequently transferred to a Macintosh II PC via a Data Translation frame grabber (Model DT-2255) for processing.

The Mie scattering technique was supplemented by conventional spark schlieren photography. A spark-discharge source of 1/3 μs duration provided illumination for the f/10 schlieren system; images were recorded using a 35-mm camera. A breakdown spark resulting from strongly focusing the laser beam in air was also employed as a schlieren light source. The knife edge was positioned "horizontally," that is, parallel to the supersonic primary stream. The difference in optical density between the argon injectant and the nitrogen primary stream for the conditions of this experiment resulted in improved schlieren images over those obtained using nitrogen injectant.

Flow Configuration and Conditions

A simplified diagram[3] of the principal features of the flowfield is shown in Fig. 2. For the case of an underexpanded transverse jet, a barrel shock and Mach disk are normally formed downstream of the injector orifice. The interaction of the transverse jet with the supersonic primary stream results in the former being swept downstream and the barrel shock structure becoming inclined relative to the primary flow. In addition, the injected gas serves to obstruct the primary stream, giving rise to a bow shock upstream of the transverse jet. This shock wave can lead to separation and thickening of the boundary layer upstream of the injector orifice.

The transverse sonic jet stagnation pressure in this investigation ranged from 3 atm to 20 atm at a temperature of typically 300–315 K. The supersonic primary stream was run with stagnation pressures from 2.2 to 4.3 atm at stagnation temperatures typically of 273–283 K. The primary stream stagnation pressure was sufficiently high to prevent unstarting of the supersonic flow by the transverse jet. The turbulent boundary-layer thickness at the injector site was estimated from schlieren photographs to be 0.8 mm. Wall static pressure measurements for the case without injection (i.e., primary flow only) indicated an actual Mach number at the test section entrance of M = 1.84. The Mach number decreased roughly 6% over the length of the test section due to boundary-layer growth.

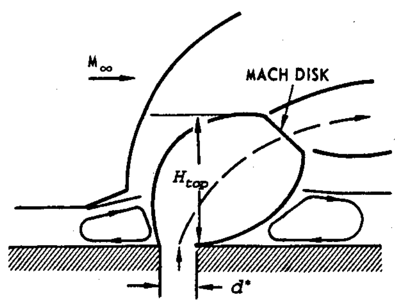

Fig. 2 Flow configuration (adapted from Ref. 3).

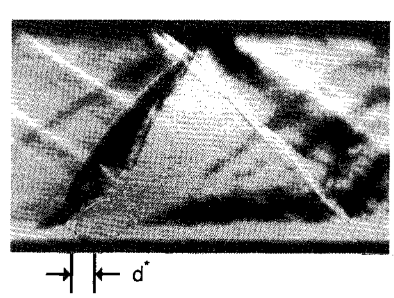

Fig. 3 Spark schlieren photograph (flow is from left to right).

Results and Discussion

Schlieren Photography

A spark schlieren photograph of the injectant flowfield is shown in Fig. 3. In all cases presented here, the flow is from left to right with the injector wall at the bottom of each image. The location of the injector orifice is shown in the figure. The stagnation pressure of the transverse jet was $P_{0_j} = 20.4$ atm; that of the primary stream, $P_{0_\infty} = 4.3$ atm. Many of the flow features sketched in Fig. 2, such as the bow shock, boundary-layer thickening, Mach disk, and barrel shock can be seen from schlieren photographs such as Fig. 3. It can, however, be considerably more difficult, using the schlieren technique, to determine the actual location of the injectant fluid or to study the details of the mixing of the injectant with the primary stream.

The penetration of the transverse jet, as indicated by the height of the Mach disk above the tunnel wall, is plotted in Fig. 4. The normalized heights represented correspond to the edge of the Mach disk farthest from the wall. The solid line in the figure is based on a correlation developed by Cohen et al.[8] using results of Zukoski and Spaid[2]:

$$\frac{H_{\text{top}}}{d} = 1.51\left[\frac{(\rho V^2)_j}{(\rho V^2)_\infty}\right]^{0.5} = 1.51\bar{q}^{0.5}$$

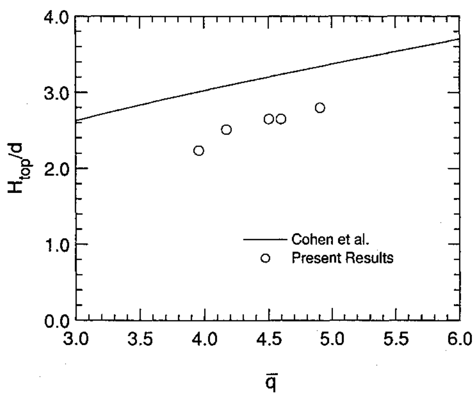

Fig. 4 Comparison of jet penetration.

where $\bar{q}$ is the ratio of the momentum flux of the transverse jet to that of the primary stream. The quantity d denotes the effective orifice diameter obtained by scaling the actual orifice diameter by the square root of the experimentally determined discharge coefficient. The momentum flux of the transverse jet is based on conditions at the jet exit; the momentum flux of the primary stream, on conditions in the primary flow upstream of the bow shock. The penetration in the current work is seen to be roughly 20% lower than that observed by Zukoski and Spaid.[2] The somewhat lower penetration in the current configuration was largely due to confinement by the tunnel walls, as suggested by criteria developed by Wu and Aoyama.[6]

Planar Mie Scattering

Single-shot Mie scattering images of the transverse jet are shown in Fig. 5. Each image is a composite obtained by merging images obtained at two different downstream locations during separate runs; each composite image extends a total of 25 actual jet diameters downstream of the injector orifice. The injector wall is situated along the bottom edge of each image, with the location of the injector orifice as shown. The images are presented using a gray scale, where white corresponds to the highest recorded scattering intensity; all images have been background subtracted.

The condensation of ethanol is seen in Fig. 5 to commence very rapidly after the underexpanded flow exits the jet orifice, with significant condensation occurring well upstream of the Mach disk (for these flow conditions, the results shown in Fig. 3 indicate that the top of the Mach disk is roughly 2.2 jet orifice diameters above the injector wall). The rapid onset of condensation is also apparent in the 10-shot average shown in Fig. 6 for the same flow conditions as Fig. 5. That the observed signal strength does not show a systematic decrease downstream of the Mach disk, as would be expected in the presence of dilution only, suggests that additional condensation is being brought about by the mixing of the jet fluid with the much colder supersonic primary stream gas.

The large structure of the flow is readily revealed by the single-shot Mie scattering images. For the conditions shown in Fig. 5, large structure continues to be apparent for normalized distances of up to at least $x/d \approx 25$, where x is the distance

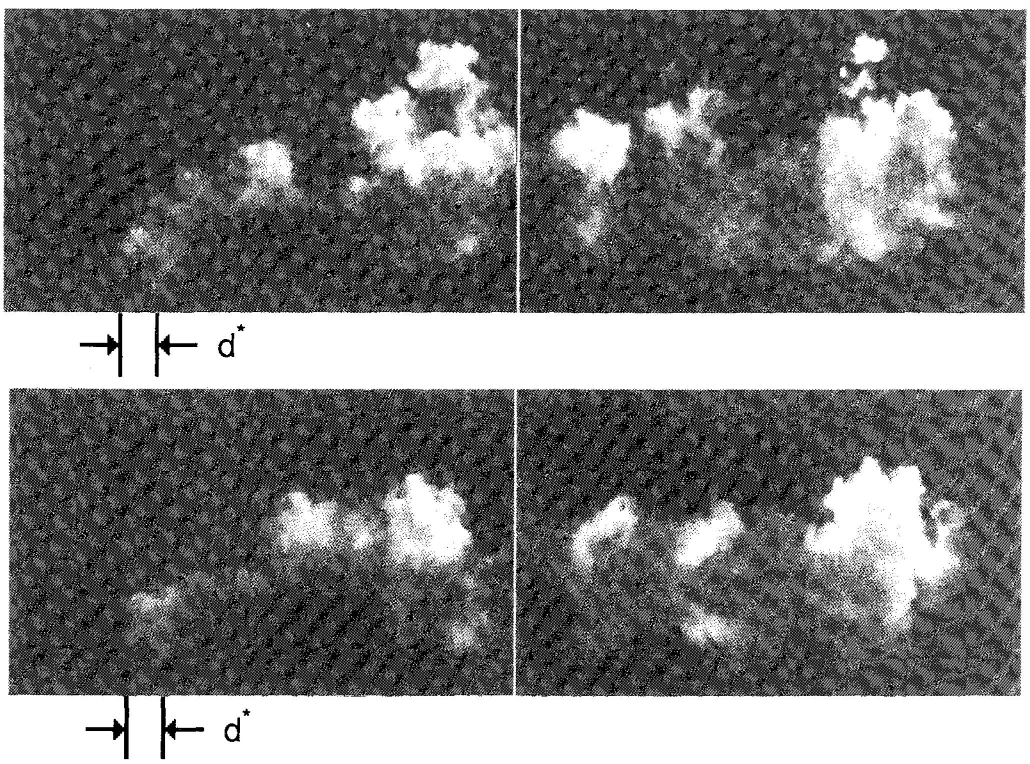

Fig. 5 Composite single-shot planar Rayleigh/Mie scattering images. $P_{0_j} = 12.1$ atm, $P_{0_\infty} = 3.4$ atm.

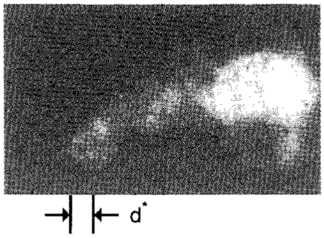

Fig. 6 Ten-shot average planar Rayleigh/Mie scattering images. $P_{0_j} = 12.1$ atm, $P_{0_\infty} = 3.4$ atm.

downstream of the injector site. The images in Fig. 5 suggest that the jet achieves essentially its maximum penetration at a normalized downstream distance of $x/d \approx 6$–8. These distances are consistent with the value $x/d \approx 8$ reported by Papamoschou et al.[10] Distinct regions of condensed fluid (light) are seen to be interspersed by (dark) regions of primary stream gas throughout the flowfield. The regions of unmixed gas appear to penetrate well across the profile of the transverse jet, especially in the region of the jet where the penetration height is most rapidly increasing (i.e., $x/d < 8$).

The time-resolved images presented here demonstrate the applicability of the Mie scattering technique to this flow configuration. Important advantages of this diagnostic technique vs laser-induced fluorescence imaging include a relatively high signal strength and the ability to avoid using seed materials that are toxic, corrosive, or odoriferous; the Mie scattering technique also avoids complications due to quenching.

Although the planar Mie scattering technique presented here can easily be employed to obtain useful information on jet penetration, growth, and turbulent structure, the technique does not directly provide quantitative information on the amount of dilution or mixing. Estimation of these quantities requires separate knowledge of the particle sizes and number densities. This information is not unambiguously provided by Mie scattering, as the signal strength is proportional to the product of the particle number density and the scattering cross section. To obtain quantitative estimates would thus require some understanding of the nucleation process, which in turn necessitates knowledge of the temperature field. The potential for quantitative measurements of dilution and mixing has recently been explored by Messersmith et al.[19] using Mie scattering of droplets in a compressible mixing layer either as a passive scalar or as an indicator of molecular mixing. In the latter case, where condensation results from mixing, a simple model was employed to estimate the nucleation and growth of droplets as a function of the mixture fraction in the mixing layer. This permitted the use of the measured scattering intensity, within certain limits of detection sensitivity, to infer the local mixture fraction.

Summary

The turbulent, compressible flow structure of a sonic, transverse jet issuing into supersonic flow was visualized by planar single-shot Mie scattering and spark schlieren photography. Planar imaging using Mie scattering of ethanol is easily accomplished in this type of flow. Turbulent structure of the injectant fluid not apparent in schlieren photographs is clearly revealed by the planar, time-resolved Mie scattering technique. This laser-based technique reveals the existence of large structures in the flowfield that persist at least 25 jet diameters downstream of the injector site. The turbulent, compressible flowfield is also characterized by the presence of inclusions of unmixed, primary stream fluid that penetrates across the centerline of the transverse jet.

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