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TITLE AN EXPERIMENTAL INVESTIGATION OF THE PROPERTIES OF A
NON-REACTING SUPERSONIC SHEAR LAYER

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An Experimental Investigation of the Properties of a Non-Reacting, Supersonic Shear Layer

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ABSTRACT

A shear layer formed by the merging of two different mass density and velocity, supersonic, inert gas streams (Ar and He) was investigated using both intrusive (probes) and non-intrusive (laser-based) techniques. Interpretations based upon mean pitot pressure surveys, namely shear layer growth rate and compressibility agree with established data. An aspirating probe in conjunction with a mass spectrometer comprised a gas sampling system for ultimately obtaining concentration profiles. Rapid scanning of such flows is possible with such a technique but additional efforts are required to make quantitative concentration assignments. The technique does, however, provide a means of qualitatively assessing mixing rates. Finally planar laser-induced fluorescence (PLIF) was used to establish spatially and temporally resolved images of the shear layer. Obtained images demonstrate the usefulness of PLIF to qualitatively monitor turbulent mixing phenomena in supersonic flows.

INTRODUCTION

Advanced propulsion systems for vehicles capable of hypersonic speeds will utilize, at least over some part of the vehicle's flight envelope, a hydrogen fueled, air-breathing supersonic ramjet engine. With such scramjets, the air stream moves through the combustor as a supersonic flow. The fuel is injected at sonic or subsonic velocities into the oxidant stream forming a shear layer. Combustor efficiency is strongly dependent upon the degree of fuel-air mixing that occurs in these supersonic mixing layers. With increasing combustor Mach number, however, the growth rate of supersonic shear layers is small, due largely to the effects of compressibility¹. As a result, the fuel-air mixing rate is reduced leading to a decrease in combustion efficiency and ultimately propulsive thrust².

Efforts to develop efficient scramjet propulsion systems has prompted renewed interest in the properties of supersonic shear flows. Numerous experimental and theoretical investigations (e.g., ref. 3-7) have been undertaken to quantify these properties thereby establishing an effective predictive capability for supersonic shear flow behavior

over a wide range of conditions. An additional goal has been the development of mixing augmentation techniques to ultimately increase combustor effectiveness^{8,9}.

Our interest stems both from an initiative designed to investigate the interplay between chemistry and fluid dynamics in supersonic combustion processes as well as a need to understand the aero-optical phenomena associated with imaging through turbulent, high temperature shear flows. Computational fluid dynamic (CFD) calculations play an integral part towards understanding as well as predicting the phenomena and properties associated with such flows. Benchmarking CFD predictions through comparison with experimental measurements is critical in establishing the validity of models and techniques utilized in such calculations.

The primary (and initial) focus of the current study has been to investigate, experimentally, the properties of a non-reacting shear layer with large density gradients to provide a data base for CFD verification. Such a study removes the complication of chemically-driven processes and allows a means of assessing a CFD code's ability to predict fluid dynamic effects alone. Of secondary interest is the development of diagnostic techniques which would be appropriate for use in studying high temperature, reactive flow phenomena. This paper will cover the results of our experimental measurements only; a separate paper will cover the comparison with CFD predictions.

EXPERIMENTAL PROGRAM

Flow System Description

The shear layer is produced by the interaction of two inert gas streams, one helium and the other argon, expanded to supersonic speeds by a uniquely configured, rectangular nozzle assembly shown in Fig. 1. This two-dimensional, contoured, converging-diverging nozzle (width = 2.54 cm) was originally designed to produce shock free, Mach 2.4 flow with a monatomic gas. For the present study, this aluminum nozzle is split into two separate "half nozzles" by the addition of a 0.5 mm tungsten splitter plate. The splitter plate provides effective isolation of the two gas streams during their flow through the nozzle. The high degree of stiffness afforded by tungsten allows the plate to remain thin (reducing the wake size at the end of the plate) and eliminates difficulties with flow-induced vibration. The plate edge was filed to produce a (gradual slope) triangular shaped termination to avoid production of a strong shock wave in the argon and helium free streams.

The splitter plate is terminated at the nozzle exit permitting the two streams to interact and form the mixing layer. Creation of this shear layer occurs in an expansion

chamber which contains four window ports for optical diagnostic access (i.e., Schlieren, laser-based schemes). The expansion chamber is coupled to a 1500 scfm vacuum system (two Kinney model 2700 blower/backing pump combinations operating in parallel) as well as a large blowdown tank. For the flow rates generated in the present study, the vacuum system pumping capability is sufficient for continuous operation. A manually controlled throttle valve is positioned between the expansion chamber and the primary evacuation line leading to the pumps. Background pressure in the expansion chamber is regulated by adjusting this valve. A diagram of the overall flow system is shown in Fig. 2. Gas is supplied to the system from high capacity (30,000 ft³) tube trailers. Pressure reduction and control of gas flow is accomplished by regulator-dome loader combinations in conjunction with a series of both manual and automatic valves. Such an arrangement provides stable pressure and gas flow control during the course of an experimental run. Flow rates for each gas are monitored by a bank of Tylan 300 slm flow meters connected in parallel. Full control of pressure and vacuum system components is possible from a central station.

Pressure monitoring is done at several critical points along the system path. Mechanical gauges are used to measure pressures in the helium and argon supply lines. Nozzle stagnation pressures are monitored by 10,000 torr capacitance type manometers as well as appropriately rated, silicon diaphragm, Kulite and or Endevco fast response transducers. Such transducers use a four-arm, Wheatstone bridge strain gauge arrangement, embedded in the diaphragm material, to facilitate pressure measurement with fast frequency response (the resonance frequency varies from 70 khz for low pressure devices, to over a megahertz for the higher range transducers). These silicon diaphragm transducers are also used to record pressures at two positions in both the helium and argon nozzles. Pressures in the expansion chamber are monitored by both a 100 and 1000 torr capacitance manometer.

Diagnostic Techniques

Pitot Tube: The pitot tube represents a common diagnostic probe which has been used in experimental investigations of supersonic shear layer properties^{6,10,11}. For the present study, mean impact pressure profiles were determined with a circular, 0.41 mm OD, stainless steel pitot tube. The actual sampling tube is sealed inside of a 0.634 mm OD high pressure (thick wall) tubing which provides structural support and ensures against any movement of the probe in the flow. The sampling tube line length is kept short to minimize gas volume and increase probe response time. Both the sampling and outer support tube are terminated in a small volume coupling which also contains a fast response pressure transducer of the type described earlier. Output

from the transducer is processed with a Measurements Group model 2310 strain gauge conditioner and amplifier which in turn provides a proportional output voltage for recording. The pitot probe is coupled to a motor-driven scan system positioned on top of the expansion chamber. With this scan system, it is possible to move the probe vertically across the nozzle face at variable positions downstream of the nozzle exit. A precision resistor coupled to the drive shaft provides a means of establishing the vertical displacement of the probe.

Local Concentration from Gas Sampling: Generally, calculation of parameters such as local velocity from experimentally-measured mean flow quantities in a shear layer formed by streams of different gases (i.e., N_2 and He, or Ar and He) requires a knowledge of the local ratio of specific heats and the gas constant. Determination of these quantities can be made knowing the local gas composition.

A gas sampling system was built using an aspirating-type probe to measure the local mean gas composition in the shear layer and surrounding free streams. Our goal was to design a gas sampling system which exhibited adequate frequency response to allow fairly rapid vertical traverse of the probe across the mixing layer. Rapid scanning as opposed to pointwise measurements were desirable to minimize excessive gas loss during an experimental run. In general, supersonic wind tunnels operate in a blowdown mode and have only several minutes of constant flow time. Thus, measurement techniques which exhibit long response times can not be effectively utilized in such systems.

The aspirating probe concept has been employed by several investigators primarily for gas composition measurements¹²⁻¹⁴. The current concentration measurement system uses a probe similar in construction to the aforementioned pitot tube. The pressure transducer, once attached to the small volume coupler, is replaced by a tee type fitting. One side of the fitting is attached to a throttled mechanical pump by a flexible line. The other side is connected via a double valve arrangement (Nupro double pattern metering valve in series with a Nupro micrometer needle valve) and a short section of flexible line to a UTI model 300 mass spectrometer system (consisting of an ionizer, mass filter, and electron multiplier) evacuated by a mechanical pump-backed turbomolecular pump vacuum system. The probe, along with the series-connected metering valves, is attached to the motor-driven vertical scan system and the entire assembly is traversed. Proper adjustment of the metering valves is required for each nozzle stagnation pressure setting, prior to a set of scans, to prevent saturation of the mass spectrometer pumping system. The mass spectrometer is operated in a DC mode where the quadrupole mass filter is set to transmit only a specified mass. At each position

downstream from the nozzle exit, two scans are made; one scan to measure the helium distribution and another to examine the argon distribution. The output from the electron multiplier is processed by an amplifier unit on the mass spectrometer control unit and then recorded using an XY plotter.

Schlieren Flow Visualization: A Schlieren arrangement comprised of two 10 cm diameter, f/3.6 lenses, knife edge, white light source, and CCD camera is used to provide real time imaging during flow surveys. The output from the camera is fed through a video camera recording system for storage and future playback.

Advanced Diagnostics: The use of laser-based schemes provides a means of probing high speed shear flows in a non-intrusive fashion. Flow visualization using CCD camera imaging of spatially resolved planar laser-induced fluorescence (PLIF), offers a means of qualitatively assessing both average and time-resolved shear layer mixing patterns as well as concentration (since the intensity of fluorescence is related to the concentration of the emitting species). Use of this technique in shear flow investigations requires that either one of the free stream gases fluoresce upon laser excitation or that a suitable tracer be seeded into the either flow. Time-resolved imaging is provided by a combination of short pulse excitation lasers and short-lived species fluorescent times.

The experimental arrangement used to obtain PLIF images is shown in Fig. 3. A tracer species, NO_2 , is seeded into either the helium or argon flow well upstream of the nozzle plenum. Frequency doubled Nd:YAG laser light, at 532 nm (300 mj), was used to excite the NO_2 . The NO_2 emits in the red portion of the visible spectrum when excited by such a wavelength of light. The excitation beam was formed into a sheet of light (10mm X 1mm) by passage through a cylindrical telescope and then transmitted through the free streams and shear flow region at variable distances downstream of the nozzle exit. The emitted light is captured by an intensified Cohu CCD camera coupled to a Poynting frame grabber board to obtain a two-dimensional image. A single image is recorded for each laser pulse. A detailed description of the PLIF-based flow visualization methods used and results obtained in the current study is given elsewhere¹⁵. Only a summary review will be provided here.

EXPERIMENTAL RESULTS AND DISCUSSION

Half Nozzle Performance

As noted previously, the original nozzle was designed for Mach 2.4 flow. Performance of each half nozzle configuration, however, had to be established before the

shear layer measurements were initiated. Several methods were employed to establish the operating properties of each nozzle. First the VNAP2 computer code¹⁶ was used to predict flow parameters for each nozzle half. Well behaved, laminar flow profiles, with the expected Mach number distributions, were calculated to exist during operation. Such predictions were verified with actual experimental measurements. Each half nozzle contains two static pressure ports located at the same positions downstream of the nozzle throat. Static pressure measurements coupled with a measurement of the nozzle stagnation pressure can be used to estimate the local Mach number at the pressure sensor location. Several Mach numbers calculated by such a method are displayed in Fig. 4 as a function of nozzle stagnation pressure. At the downstream sensor location, the half nozzles are producing the expected Mach number flow (within 10%). Impact pressure measurements at the nozzle exit provided a means of measuring exit Mach number. The Mach numbers determined from such measurements agree well with the design exit value of 2.4 (1 atm: $M_{He} = 2.35$, $M_{Ar} = 2.41$; 10 atm: $M_{He} = 2.39$, $M_{Ar} = 2.33$). A total temperature probe (copper-constantan thermocouple, projected recovery factor of 99% at $M=2.4$) was used to check the nozzle exit temperatures. In the free streams the nozzles appear to be functioning efficiently recovering approximately 90-95% of the initial stagnation temperature (~300 K). The corresponding local static temperatures, based upon measured local Mach numbers, fall between 98 to 105 K, in good agreement with anticipated values.

Pitot Tube Measurements

A series of measurements were made with the pitot probe for nozzle stagnation pressures, p_0 , of one and ten atmospheres. Runs at stagnation pressures of ten atmospheres were done in an attempt to increase the Reynold's number along the splitter plate thereby generating a turbulent boundary layer. The shear layer would then be fully turbulent past the nozzle exit and avoid a laminar to turbulent flow transition which is difficult to model computationally. For all measurements, the expansion chamber pressure was adjusted to approximately equal the nozzle exit pressure, thereby producing a "matched" flow. Schlieren images as well as pitot tube scans indicate, however, the presence of expansion fans at the nozzle edges so the main flow appears to be somewhat underexpanded. A shock wave is also noted in the argon and helium free streams originating from the splitter plate. The shock wave strength is apparently quite weak as it does not cause any noticeable deflection in the impact pressure profiles.

Pitot tube scans were made at several distances downstream of the nozzle exit. A three dimensional reconstruction of the impact pressure profiles recorded for a one atmosphere nozzle stagnation pressure is displayed in Fig. 5. The

shear layer is evident as the trough or valley region between the argon and helium free streams. The impact pressure profiles offer one means of estimating the shear layer width. The width is defined as suggested by Papamaschou¹¹, namely as the distance between the 95% values of pitot pressure on each side of the measured shear layer pressure defect. A plot of the shear layer width as a function of position downstream of the nozzle exit is shown in Fig. 6. As expected the shear layer growth is smaller than observed with subsonic flows. The growth rate (db/dx) is approximately linear and equal for both the 1 and 10 stagnation pressure cases. Such a result is not surprising in view of the approximate equality of the free stream Mach numbers (and stream temperatures) for both values of p_0 .

The low spreading rate observed with supersonic mixing layers is due largely to compressibility effects. A parameter which correctly scales this compressibility is the convective Mach number¹. The convective Mach number is defined for each stream as:

$$M_{C1} = (U_1 - U_C)/a_1; \quad M_{C2} = (U_C - U_2)/a_2, \quad (1)$$

where U_1 , U_2 , and a_1 , a_2 are the free stream velocities and speeds of sound respectively. The subscript 1 refers to the higher speed stream. The quantity U_C defined as

$$U_C = (a_2 U_1 + a_1 U_2)/(a_1 + a_2) \quad (2)$$

is the convective velocity and represents the axial velocity of large scale, coherent, vortical structures in the shear layer. Such structures, common to incompressible shear layers, have been observed in compressible (supersonic) shear layers as well using spark-source schlieren systems¹⁷.

Papamaschou and Roshko¹ proposed that the growth rate of an incompressible shear layer, b_c' , normalized by the growth rate of an incompressible shear layer, b_i' , could be expressed in terms of the convective Mach number. Such a representation would be applicable over a wide range of free stream velocities and temperatures. Figure 7 shows several sets of normalized free shear layer growth rates (b_c'/b_i') along with data obtained through the present investigation as a function of the convective Mach number. The strong effect of compressibility on shear layer spread rate is noted as the convective Mach number decreases from zero to a value of unity. For M_C greater than one, the normalized spread rate approaches a constant. The normalized shear layer spread rate values obtained for nozzle stagnation pressures of 1 and 10 atmospheres are in relatively good agreement with the convective Mach number for each free stream essentially equivalent.

Gas Sampling Measurements

Gas sampling measurements were recorded at several positions downstream of the nozzle exit for both a one and ten atmosphere nozzle stagnation pressure. The aspirating probe was traversed vertically through the free streams and shear layer starting and ending in the background regions of the expansion chamber. Figure 8 depicts the uncorrected voltage signal corresponding to a scan very close to the nozzle exit and two recorded somewhat further downstream. It is quite evident from this raw data that close to the nozzle exit little to no mixing has occurred but further downstream, as the shear layer develops, evidence of mixing becomes apparent. The helium signal tends to track the pitot pressure distribution recorded at the same downstream condition. In a similar comparison, the argon signal corresponds well to the measured pitot pressure except in the middle portion of the free stream. The flat response most likely indicates a saturation effect apparently due to insufficient pumping capacity of the aspirating probe's vacuum pump. The argon signal response in and near the shear layer (on the argon slope) appears to be free from such difficulties, however, and is satisfactory for mean concentration determination.

The aspirating probe used in these experiments was not designed to operate in a choked configuration. A normal shock was observed standing off the probe's entrance orifice. Thus, the tube is not capturing a stream tube equal in area to the probe opening. Such an operating condition admittedly introduces some degree of sampling error but the recorded signal should still be proportional to the local species concentration (as long as saturation is avoided).

System response time is limited by how quickly a gas sample entering the aspirating probe entrance can be "flushed" through the system and be recorded by the mass spectrometer. The scan speed of the probe traverse system was adjusted to match the frequency response of the sampling system. The aspirating probe is very useful as it allows fairly rapid scanning across the shear layer. The need for considerably slower point by point measurements is eliminated.

The gas sampling system was calibrated by placing the probe in the middle portion of both the helium and argon stream at the nozzle exit. Nozzle operating characteristics, as a function of nozzle stagnation pressure, are well defined at the exit static pressure is known. By varying p_0 , it is then possible to characterize sampling system response and record output voltage as a function of measured local pressure (and density).

Helium molar concentration profiles are shown for three different axial stations in Fig. 9 and 10 corresponding to $p_0 = 1$ and 10 atmospheres. With the exception of scans very close to the nozzle exit, the profiles in the vicinity of

the shear layer are smooth and gradually varying. Such profiles allow for a determination of the gas constant distribution and the ratio of specific heats as well. With such information, it is then possible to determine other mean flow data such as the local mean velocity distribution. A reduced density profile can be determined directly from the gas sampling data. Two such profiles are shown in Fig. 11 for both p_0 equal to one and ten atmospheres ($x=1.1$ cm).

To examine the extent of the mixing across the shear layer, the molar concentration profile width (Δz) was calculated as the distance between the 5% and 95% points and compared with the shear layer widths determined from the pitot pressure profiles. The results are displayed in Fig. 12 for the $p_0 = 1$ atmosphere runs and in Fig. 13 for the $P_0 = 10$ atmosphere case as a function of increasing downstream distance from the nozzle exit. Striking differences are observed between the two nozzle stagnation pressures data sets. For one atmosphere, the width of the helium profile matches the shear layer width (b) at approximately $x = 1$ cm and then continues to grow at a considerably faster rate. Such rapid growth may indicate increased free stream turbulence which is transporting helium into the argon stream and argon into the helium stream. Schlieren images appear to indicate a free stream transition to turbulent flow between 1 to 2 cm downstream of the splitter plate. For ten atmospheres, the width of the concentration profile matches the shear layer width at approximately $x = 1.5$ cm and then continues to grow at the same rate as the shear layer. Apparently, the majority of the mixing is confined to the region of the shear layer itself.

The aspirating probe, mass spectrometer-based sampling system allows for rapid characterization of the concentration distribution in the supersonic shear layer. Additional efforts are required, however, to improve the accuracy of the obtained concentration profiles. For example, design and use of a choked aspirating probe would eliminate bow shock sampling interference.

Laser-Induced Fluorescence Imaging

A typical image obtained during these experiments is shown in Fig. 13. The nozzle stagnation pressure was equal to one atmosphere. The flow is from left to right with the splitter plate marking the beginning of the shear layer. For this image the NO_2 tracer was seeded into the helium stream. The distance across the captured image is approximately 2 cm. For a short distance downstream of the splitter plate, the shear layer looks to be laminar but then transitions to a turbulent flow at approximately 1 cm. This is the same downstream distance where the helium concentration profile width equals the shear layer width. Images obtained at increasing distances from the nozzle show increasing turbulence levels indicating enhanced mixing

which again is supported by the one atmosphere concentration profile data.

With the experimental arrangement, the stagnation pressure was limited to 3 atmospheres (exit pressure $\approx$ 200 torr) because collisional quenching reduced emission intensities to undetectable levels. The present experiments, however, demonstrate the capability of planar LIF (PLIF) for visualizing turbulent, supersonic flows. Proper calibration of the technique can be used to provide quantitative concentration information. As noted previously, a more detailed description of the PLIF technique and obtained results for the current shear layer study is provided in reference.

SUMMARY

An investigation of the properties of a non-reacting, supersonic shear layer has been done with both intrusive and non-intrusive techniques. Measurements from pitot tube pressure profiles agree with existing data compiled by several investigators. Concentration measurements obtained using an aspirating probe/mass spectrometer-based gas sampling system provide a semi-quantitative interpretation of actual gas mixing rates in the shear layer. With further refinement of experimental technique quantitative assessments will be possible. Cold flow imaging experiments demonstrate the utility of planar LIF for monitoring the progression of turbulent mixing processes in supersonic shear flows.

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Figure Captions

- Fig. 1. Nozzle Assembly for Shear Layer Generation.
- Fig. 2. Flow System.
- Fig. 3. Experimental Arrangement for Obtaining Plana LIF Images of Supersonic Shear Layers.
- Fig. 4. Calculated at Downstream Static Pressure Ports as a Function of Nozzle Stagnation Pressure.
- Fig. 5. Three-Dimensional Reconstruction of Pitot Tube Pressure Profiles, $P_0 = 1$ Atmosphere.
- Fig. 6. Shear Layer Width as a Function of Distance from Nozzle Exit.
- Fig. 7. Normalized Shear Layer Spread Rate vs M_C (original figure from Ref. 6).
- Fig. 8. Helium Mass Spectrometer Signal from Aspirating Probe-Gas Sampling System across the Shear Layer.
- Fig. 9. Helium Molar Concentration Profile for $p_0 = 1$ Atmosphere.
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- Fig. 11. Reduced Helium Density Profile; $p_0 = 1$ and 10 atm.
- Fig. 12. Shear Layer and Molar Concentration Profile Width vs Distance Downstream from Nozzle Exit, $p_0 = 1$ Atmosphere.
- Fig. 13. Shear Layer and Molar Concentration Profile Width vs Distance Downstream from Nozzle Exit, $p_0 = 10$ Atmosphere.
- Fig. 14. Planar Laser-Induced Fluorescence Image of a Ar/He Supersonic Shear Layer.

Cold Flow Nozzle

Fig. 1

Cold Flow System Layout

P = Baratrons, TC, fast response pressure transducers

S = Schlieren

I = Imaging system

Fig 2

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Fig. 3

Experimental arrangement for obtaining time-resolved LIF images of cold flows at the Los Alamos Aerochemistry Facility.

Fig 4

Fig. 5

Fig. 6

Fig. 7

Electron Multiplier Output vs Z (cm)

1 Atm., $x = 0.018''$

Fig 8a

Electron Multiplier Output vs Z (cm)

1 Atm, $x = 0.428''$

Fig. 86

Profiles of Three Downstream Locations
Helium Molar Concentration, $P_0 = 1 \text{ atm}$.

Fig. 9

Helium Concentration Profiles at Three Downstream Locations, $P_0 = 10 \text{ atm}$

Fig. 10

Fig. 11a

Fig. 11b

Fig. 12

Fig. 11

Fig. 13

Fig. 14

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