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Turbulence Measurement in a Reacting and Non-reacting Shear Layer at a High Subsonic Mach Number

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ABSTRACT

The results of two component velocity and turbulence measurements are presented which were obtained on a planar reacting shear layer burning hydrogen. Quantitative LDV and temperature measurements are presented with and without chemical reaction within the shear layer at a velocity ratio of 0.34 and a high speed Mach number of 0.7. The comparison showed that the reacting shear layer grew faster than than without reaction. Using a reduced width coordinate, the reacting and non-reacting profiles were very similar. The peak turbulence for both cases was 20 percent.

1. INTRODUCTION

There is extensive work on the planar shear layer, but most of it has been at low velocities (at speeds less than 30 m/s). Single or two-stage-earth-to-orbit craft using airbreathing propulsion requires an understanding of the mixing and reaction for compressible flow at high-speed flight conditions. Major efforts are being carried out in supersonic flow to address this issue [Clemens, et. al 1991; Goebel & Dutton, 1990; Hall et. al. 1991]. This report addresses the high subsonic, compressible flow regime where no reacting data existed. The compressible Mach number M_c is 0.18, which is below the compressible transition at M_c of 0.3 for shear layers [Clemens, et. al 1991]. So one should obtain incompressible

results for the non-reacting flow. But with high heat release and density velocity differences, we expected to see an effect of chemical reaction. These data are especially applicable to gas turbine combustors and internal rocket flows.

Also in a turbulent reacting review edited by Strahle and Lekoudis [1985], they state the need for more turbulence and reacting data within a planar reacting shear layer at higher Reynolds number conditions, especially using non-intrusive laser diagnostics. The Reynolds number for this data based on the velocity difference and shear layer thickness at the end of the test section is 1.8×10^5 . Large differences were observed between the experimental data of Hermanson [1985] and computations using the standard two equation turbulence-reaction models [Farshchi, 1986]. The data set of Hermanson did not include the magnitude of the fluctuations which made it difficult to evaluate the cause of the difference. When the computer model was expanded to include generation terms from velocity/concentration coupling by adding eight more differential equations and eleven more constants, the comparison was much better [Farshchi, 1986]. The question was whether the constants in the additional equations were universal and would apply when the velocity was increased. Other reacting shear layer studies are Batt [1977] and Wallace [1981]. Batt studied a wall jet mixing into still air via dilute nitrogen tetroxide dissociation. Wallace studied a shear layer in a duct with dilute nitric oxide/ozone in inert gases of either helium, nitrogen, or argon.

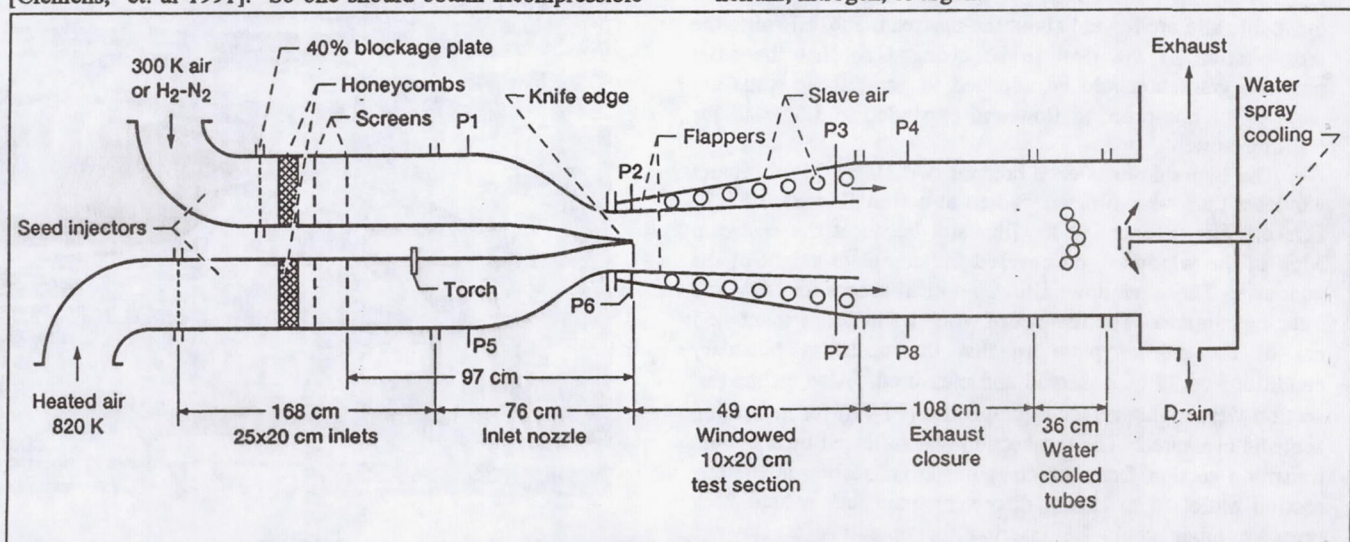


Figure 1. Planar reacting shear layer schematic.

A new continuous flow, reacting shear layer facility was built at Lewis, and a complete set of data, including boundary and initial conditions were obtained for computational modeling verification and development. This report highlights the turbulence data set that was compiled over a two year period. It does not attempt to explain all of the observations or the physics of turbulent combustion. We have compiled a complete set of data which is published in Chang [1993a].

2. DESCRIPTION OF THE EXPERIMENT - FACILITY

Figure 1 is the schematic of the experimental facility which was built to provide optical diagnostics of the reacting shear layer. A compressor supplying a non-vitiating heater provides up to 15 kg/sec of air rated at 820 K and 3 MPa pressure. In this study only 1.9 kg/sec of air was used for both the non-reacting and reacting conditions. This air flow is introduced into the test section below the horizontal splitter plate. The fuel/nitrogen stream is heated to 300 K using a steam heated exchanger and is introduced into the test section above the same plate. This stream consists of hydrogen with a flow rate of 0.032 kg/s diluted with nitrogen of 1.2 Kg/s. The two streams enter the test section horizontally and parallel to each other. The shape of the inlet nozzles approximated those of Hermanson [1985]. For the non-reacting case, air is substituted for the upper gases at the same velocity ratio and temperature. Flow conditioning is achieved by means of screens and honeycombs. We kept the inlet turbulence down so that any structures which formed would not be dissipated. Each stream first passes through a 40% blockage plate with 1.27 cm holes into a 25 x 20 cm rectangular duct. At 127 cm upstream from the end of the splitter plate (or knife edge), honeycomb grids with 0.63 cm squares were inserted to break up the large scales of turbulence. This was followed by two 30 mesh (wires/inch) screens at 107 and 97 cm upstream of the knife edge; they have 0.33 mm diameter wires. The flow area then undergoes a 5 to 1 contraction in a two dimensional nozzle which reduces the normalized turbulence intensity to 1% nominally. The two streams meet inside the test section past the splitter plate with a 2 degree convergence angle. The test section is 10 cm high by 20 cm wide at the knife-edge and extends 56 cm downstream. The upper and lower walls are moveable and are hinged about the upstream end, allowing the cross-section of the duct to be changed so that the axial pressure gradient could be adjusted to zero; these walls are parallel for non-reacting flow and expanded to 1.3° each for reacting flow.

The two sidewalls each contain two 10 by 20 cm quartz windows that were film air cooled at a film flowrate of 0.11 kg/sec. The 0.48 cm wide film slot began at the upstream edge of the windows and covered the complete height of the windows. These windows allowed optical access for LDV and imaging cameras. The first set of windows includes about 4.55 cm of the splitter plate so that the upstream boundary conditions could be observed and measured. Also on the test section were eight surface microphones (P1-P8) for measuring acoustic pressures. The test section was followed by a smooth transition section from a rectangular cross section at the test section outlet to a 45 cm diameter round area where back pressure tubes could be inserted for operating at elevated pressures. Slave air was introduced at a flowrate of 2.7 kg/sec each to cool the upper and lower walls to control the pressure,

and to dilute the exhaust gases. In the exhaust, water spray cooled the gases that were exhausted over the test cell roof.

No observable vibration of the optic components was noticed. The optic table was examined with accelerometers and was found to have no detectable displacement. The vibration of the rig itself was barely noticeable by physical touch, and the amplitude was judged to be less than 0.5 mm in the 30 Hz range.

3. DIAGNOSTICS AND RESULTS

3.1 Imaging

Imaging lends itself to a qualitative description of the flow, looking for patterns and length scales. Quite often it leads to an insight into what is occurring. Figure 2 is a photograph of the facility with the laser beams on. The upper beam is the second harmonic of a pulsed ND:YAG laser which enters through the top of the test section as a sheet for flow visualization. This data will not be discussed here. The beams from the front side window are LDV argon ion beams.

A large Schlieren system was used to take movies through the side windows. We did not see the domination of large scale structures which are considered to be important for transport, see figure 3. Some oscillation was evident in the movie frames which appeared to be two dimensional with some axial vorticity superimposed. With reaction more oscillation appeared to be present. When the speeds were very low, then coherent structures were visible.

The spectral density curves from the microphones are given in figure 4. This is for non-reacting flow. For wake

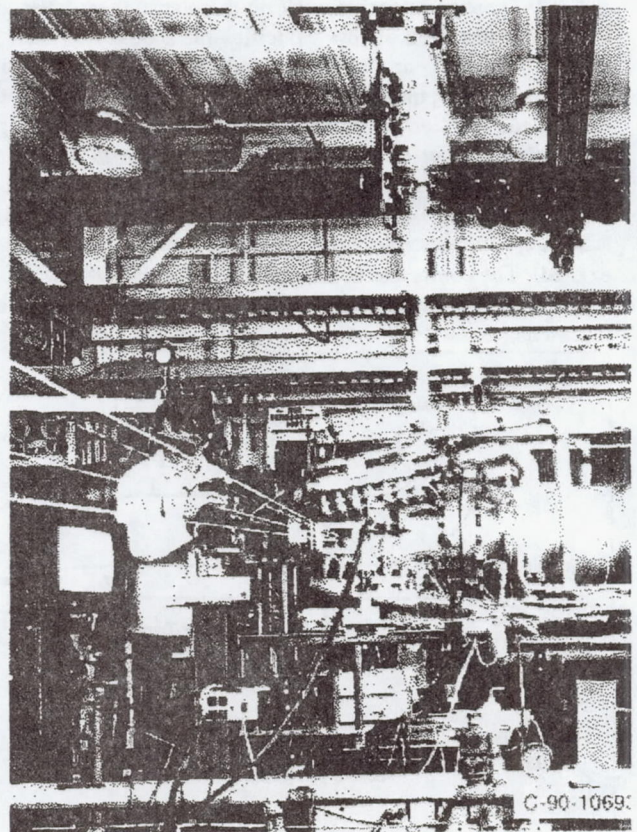
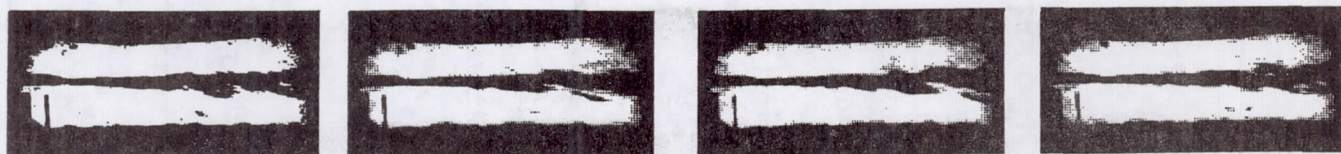


Figure 2

Nonreacting, $T_{lower}=460^{\circ}\text{K}$, $T_{upper}=300^{\circ}\text{K}$



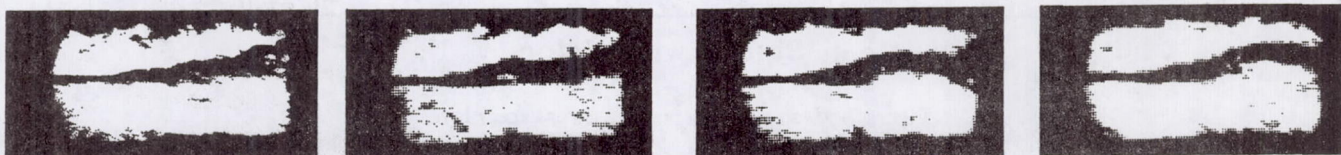
Time = 0

100 msec

200 msec

300 msec

Reacting, $T_{lower}=800^{\circ}\text{K}$, $T_{upper}=400^{\circ}\text{K}$



Time = 0

100 msec

200 msec

300 msec

Figure 3. Schlieren Movies at 10,000 frames/sec, $M_{lower}=0.8$, $M_{upper}=0.4$

flow the upper and lower velocities were the same with the lowest acoustic level. For shear flow the acoustic level was 142 dB (approx 700 pa) with the intensity growing in the frequency range from 150 to 1500 Hz. With the upper flow set to zero recirculation occurred and a broad band spectrum was obtained.

Visually and with Schlieren using a fast CCD TV camera, one could not see a difference with and without reaction. A

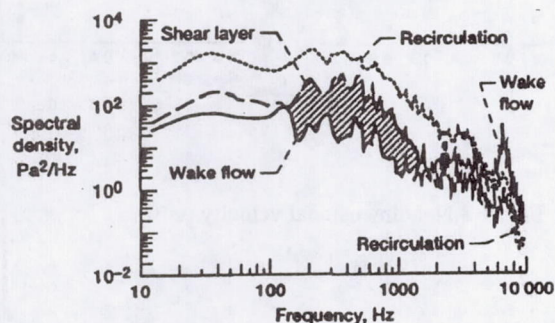


Figure 4. Spectral density curves for high speed flow with $M_1=0.7$. Shear $U_2/U_1=0.35$, wake flow $U_2/U_1=1$, recirculation $U_2/U_1=0$.

Xybion CCD camera was placed at right angles to the flow. The total ground state emission of hydroxyl as visualized by a UV intensified CCD camera with 306 nm interference filter is shown in figure 5. This shows that burning was occurring in the shear layer. This picture was taken with an upstream torch

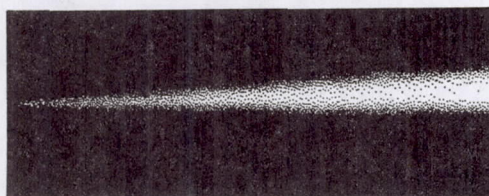


Figure 5. OH emission at 306 nm

burning seven percent of the total hydrogen used. Without the small hydrogen torch in the air side (see Figure 1), no ignition occurred in the shear layer. Initial ignition was by a spark in the torch with continuous flow of hydrogen. Blowout occurred when the torch flow was stopped.

3.2 Temperature measurement

Platinum thermocouple traverses were made at 300 mm as shown in Figure 6 for non-reacting flow, with the torch added, and finally for reacting flow. These temperatures have been corrected for radiation loss (a maximum of 80 K at the peak). The torch was used to bring the gases to ignition at 925 K. The non-reacting temperature profile can be represented by an error function Erf. An equilibrium temperature profile was computed using the equilibrium code of reference 10 with the assumption that the point concentration followed an Error function with the width of the thermal profile. The results show that combustion is very efficient in the mixing layer. The peak temperature was not obtained probably because of unmixedness. A peak appeared for the equilibrium because the extra nitrogen lowered the temperature enough to reduce dissociation of the species.

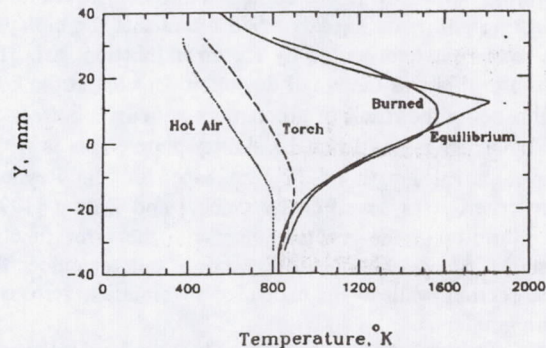


Figure 6. Temperature distribution at 300 mm.

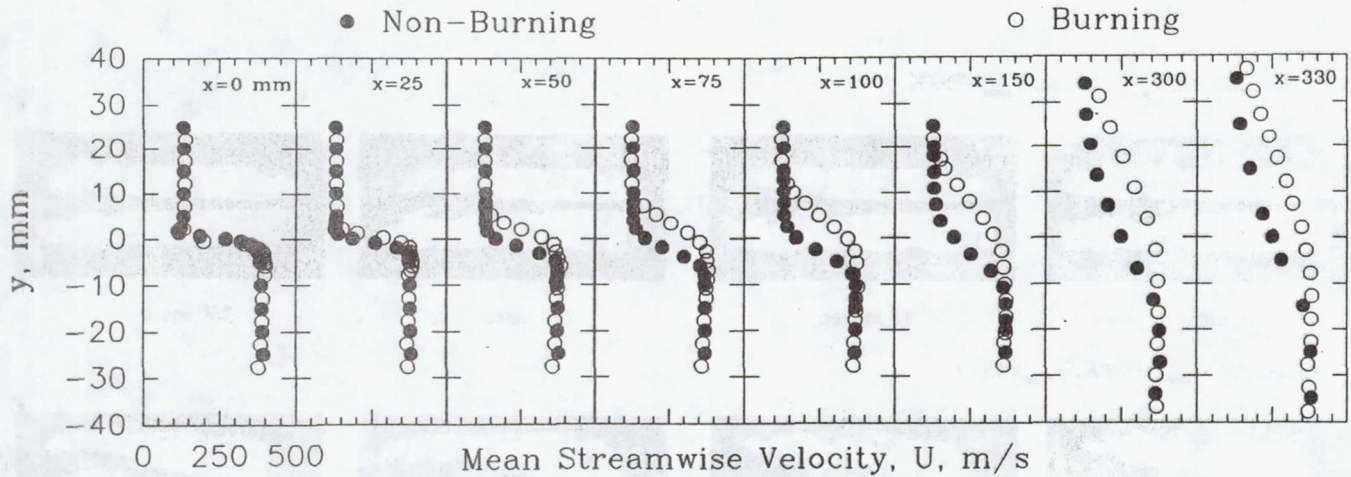


Figure 7. Mean Velocity profiles across shear layer

3.3 Velocity measurement

A two-component, forward-scatter heterodyne laser Doppler velocimeter system was used to measure the streamwise and cross-stream flow components in the planar reacting shear layer duct. A TSI Model 9100-7 four beam counter system with modified optics was used to acquire the signal. The analog signal was processed by a Concurrent 5600 computer. A 5 W Coherent Innova 90 argon ion laser operating in the multiline mode provided the illumination. Various types of seeds were used to scatter the incident laser beams, but a mixture of 20% fumigated silica and 80% alumina of nominally 1 micron diameter was eventually adapted as standard. Attempts at using titanium dioxide formed from titanium tetrachloride and steam reaction at a temperature above 700 K were unsuccessful and the technique was abandoned. The total mapping cycle covering the two sets of windows took about 30 minutes.

Flow speeds at various locations from the splitter plate tip to 330 mm downstream were measured and are shown in Figure 7. The mean streamwise velocity component, U , for the two shear layers at the same initial flow speeds are superimposed. The maximum error in velocity is estimated to be 0.5 percent. A more complete discussion of error is given in Chang [1993a]. In the reacting case the hot gases have moved upward into the cold fuel stream.

Velocity profiles for both cases are self-similar when reduced by the velocity difference and the layer thickness δ , see Figure 8. The magnitudes collapsed into two curves for the non-reacting and reacting data. We found that the collapsed curves were best represented by the error function, Erf. The exception to this was the small deviation detected at the knife edge, this being the result of momentum deficiency introduced by the boundary layers from the splitter plate. This is within the development length of 12 mm based on the Reynolds number criterion as specified by Goebel and Dutton [1990]. The conformity of the reacting data with the error function suggests little acceleration with reaction, but remember that the test section walls were expanded to maintain zero axial pressure gradient.

The velocities for the transverse directions are shown in Figure 9. The axial velocity width was used to normalize the transverse direction. The torch flow from the nozzle may have

had an effect on the reacting profile, however the data at x equals zero shows good agreement between the non-reacting and reacting data.

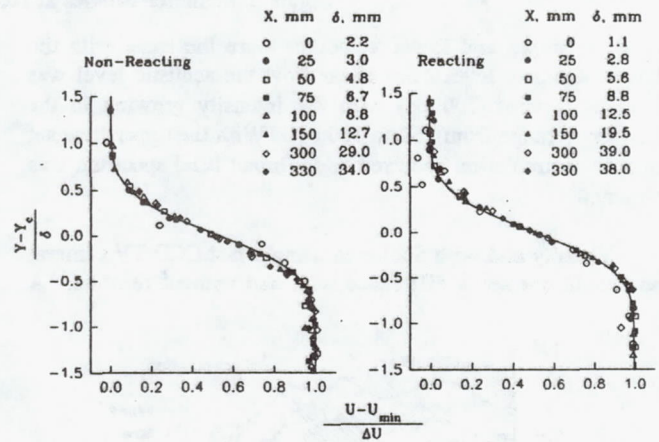


Figure 8. Nondimensional velocity profiles

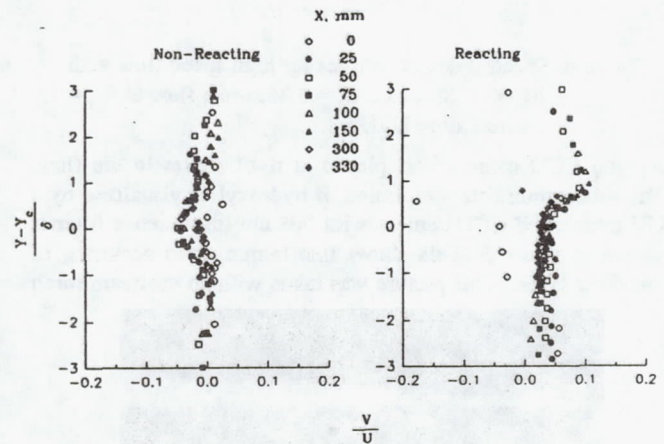


Figure 9. Normalized transverse velocities

4. ANALYSIS AND DISCUSSION

4.1 Turbulence and diffusion

The distribution of normalized turbulence intensities for the streamwise direction, u' , and that for the cross-stream direction, v' , are shown in Figures 10 and 11 respectively. Both the non-reacting and reacting turbulence profiles exhibit bell-shaped curves about the shear layer. The non-reacting and reacting intensities are surprising close even with the large amount of heat release present. The maximum turbulence intensity for both cases is 23 percent. The turbulence intensities in the lower air duct is much higher in the reacting case, partially attributed to the presence of the small hydrogen torch upstream of the nozzle.

The transverse turbulence intensities are about one third

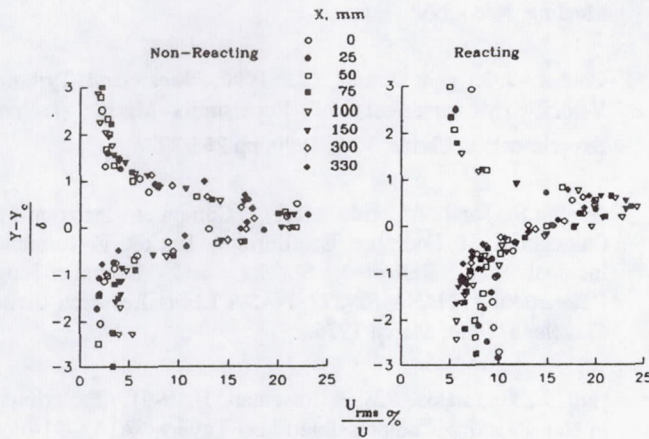


Figure 10. Axial turbulence intensities

of the axial values, figure 11. The reacting and non-reacting levels agree very well. The nonisotropic nature of the flow is clearly evident as is expected for shear layers.

Figure 12 shows the normalized Reynolds stress data. Large differences are present in this transport property, but the levels are much lower than is typically reported. Since this work is the exploration of an uncharted flow range, confirmation of this data is required, possibly through the use of computational analysis.

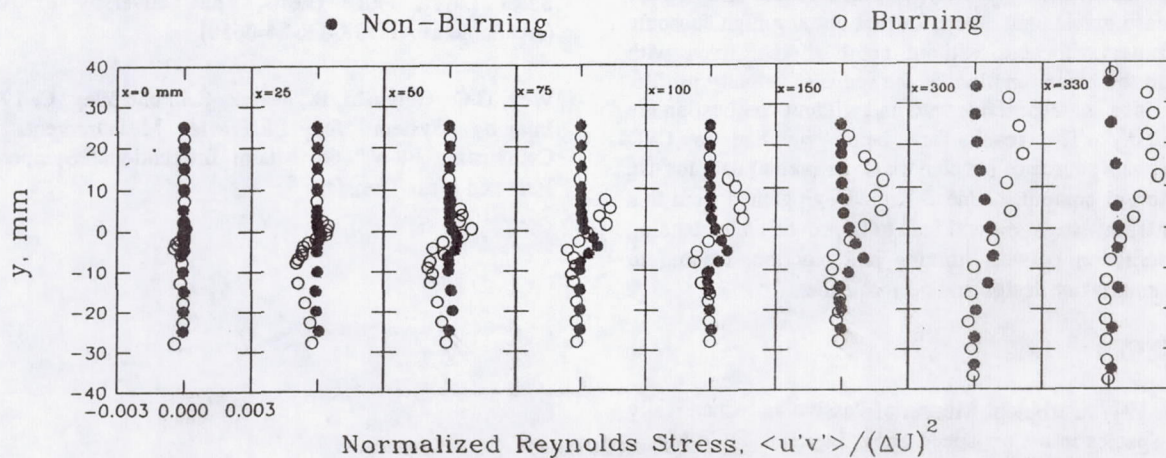


Figure 12. Normalized Reynolds stress

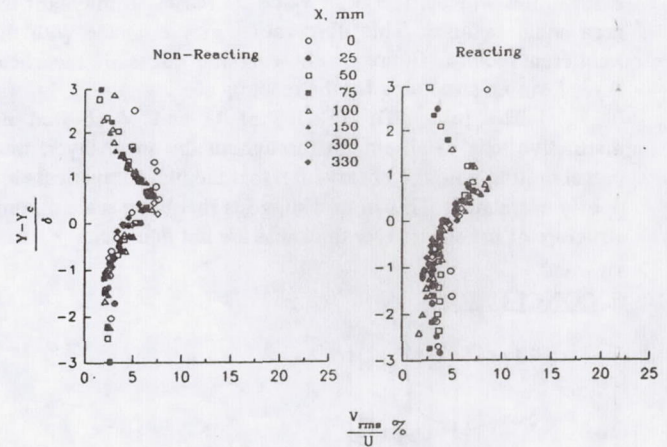


Figure 11. Transverse turbulence intensities

4.2 Layer growth rate

The mixing layer widths based on the 10 and 90 percent velocity level are tabulated in figure 8. The angle for the non-reacting and the reacting cases are about 4.9 and 7.3 degrees, respectively. The former compares favorably with the prediction based upon the formulation of Hermanson, et al. [1985] at 5.5 degrees. The predicted growth angle for the burning case, 5.4 degrees, however, was much smaller than that which was observed. The difference may be that our flow and density range is outside the data range of the correlation.

The thermal layer thickness for the non-reacting case is twice that of the velocity layer thickness thus indicating that the turbulent Prandtl is about 0.5. This agrees with the formulation of Hermanson et al [1985].

Whether the flow scales were changed significantly is indeterminant since the maximum 20 kHz data rate is only able to resolve length scales over 4 cm at 400 m/s mean flow speed. This size is larger than the mixing layer thickness for the first 200 mm of the layer, and so is not meaningful in shedding information regarding scales inside the layer itself.

4.3 Probability density function

Probability Density Functions (PDF) at 100 mm are shown in figure 13 a and b. The axial velocity distribution is narrower for the non-reacting than the reacting case. As the

distribution widens, the peak value decreases to maintain the area equal to one. This observation may coincide with the Schlieren picture, figure 3, showing the edges of the shear layer forming structures for the reacting case.

The joint PDF (JPDF) of U and V showed no distinctive axis of alignment throughout the shear layer, thus corroborating with the observation that the two components are poorly correlated. This in turn suggests that large scale mixing structure of the shear layer thickness are not dominant.

5. CONCLUSIONS

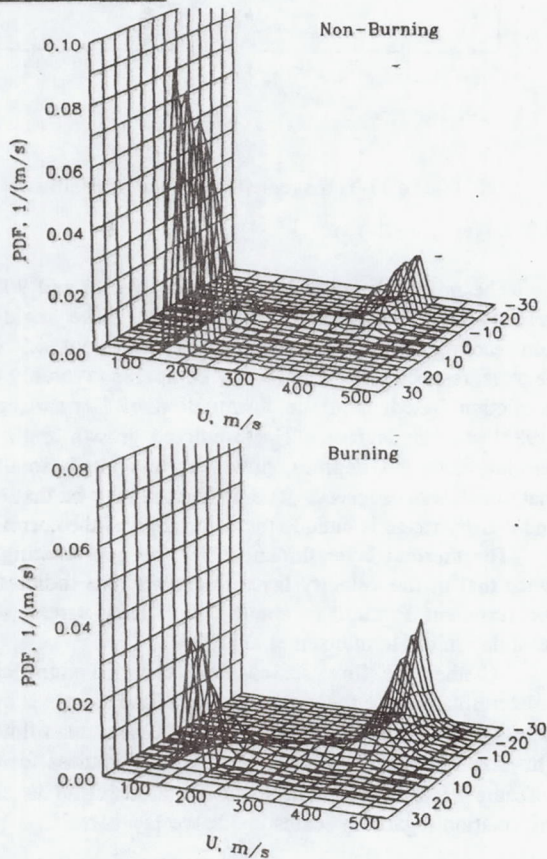


Figure 13. Streamwise velocity (U) Probability Density Distribution at $x=100$ mm.

Flow visualization, velocity, turbulence, and temperature profile measurements have been carried out at a high subsonic Mach number with and without combustion. Even with combustion the error function fit the reduced velocity profile. The turbulence characteristics with and without combustion are very similar. The results are being supplied to CFD researchers as a source of benchmark experimental data for use in validation of computer codes. Knowledge gained from this experimental investigation will lead to improved understanding of the interaction between mixing and reaction, leading to improved combustor design and performance.

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