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Studies Of Hypersonic Boundary Layer Behavior

Covering the Period 12/1/92 through 11/30/94

Submitted by:

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ABSTRACT

Here, we present the final technical report on AFOSR Grant F49620-93-0064 "Studies Of Hypersonic Boundary Layer Behavior". The grant covered three interrelated research efforts: a study of the structure of hypersonic turbulent boundary layers and shock wave boundary layer interactions, a study of boundary layer transition at supersonic and hypersonic speeds, and the development and application of new optical techniques including filtered Rayleigh scattering and RELIEF to obtain multi-dimensional velocity and density data in the supersonic and hypersonic regimes. The research was performed using the existing facilities in the Applied Physics and Lasers Laboratory and at the Princeton University Gas Dynamics Laboratory. The construction of a new boundary layer facility was also partly supported under this contract. The new facility is designed to operate at Mach numbers from 2 to 8, with a range of Reynolds numbers so that the boundary layer can be laminar or turbulent, at all Mach numbers. It is primarily designed to operate with air (and possibly other gases including nitrogen and SF6) to exploit the new optical techniques and to help isolate specific Mach number and Reynolds number effects. It will be ready for its first trials in May, 1995.

1. INTRODUCTION

Here, we describe the progress made in the two years of this grant. A series of studies intended to investigate some basic questions regarding viscous flows at high speed were performed. In particular, we were concerned with (1) the effect of Mach number, Reynolds number, and heat transfer on transition, (2) the structure of a fully turbulent hypersonic boundary layer, with and without heat transfer, and (3) the structure of shock wave boundary layer interactions at high Mach number.

The experimental program was an integrated effort bringing together the members of the Gasdynamics Laboratory with the members of the Applied Physics Laboratory. Thus, experiments in transition and turbulence at hypersonic speeds were combined the development and testing of new, non-intrusive diagnostic techniques for this flow regime.

2. PROGRESS

As part of our experimental program, a new high Mach number boundary layer facility was built. Here, we report the progress on our research efforts, starting with the progress on the construction of this new facility.

2.1 Construction and Testing of the Mach 8 Boundary Layer Facility

This facility is designed specifically for the study of transition, turbulence and shock wave boundary layer interactions at supersonic and hypersonic Mach numbers. This tunnel, when operated with air as the working fluid, can operate from Mach 2 to 8. It has a circular test section with a diameter of 229mm (9 in), with an overall length of 1.5m (see Figure 1). A maximum temperature of 875K (1115F) at a maximum pressure of 107 Pa (1500 psia) is generated to allow running times of 2 to 13 minutes. The tunnel operating conditions give a Reynolds number range so that at the lowest Reynolds number the flow is laminar (even on the tunnel walls), and at the highest Reynolds number fully turbulent boundary layers are generated on a flat plate mounted in the test section. Even at Mach 8 a Reynolds number based on momentum thickness of about 12,000 seems possible, with natural transition and a highly cooled wall. The key parts of the installation are a storage heater which consists of a coil of heavy-walled stainless steel pipe which is preheated electrically to the desired stagnation temperature, and air ejectors driven by the existing high pressure air supply which provide low back pressures. The tunnel can be run with air or other gases (the mass flow rates are relatively small). A complete description of the facility was presented at the 1995 AIAA Aerospace Sciences Meeting (Baumgartner, *et al.* 1995). Further details were given at the 80th and 83rd Supersonic Tunnel Association Meetings in May 1993 and April 1995.

As part of the tunnel installation, our high pressure piping system was upgraded and extended. A new ejector system was installed to provide low back pressures, and our Low Turbulence Variable Geometry (LTVG) Mach 3 facility was connected to it. Tests of the ejector system have been very satisfactory, and Reynolds numbers as low as 2.3 x 10^6/m have been achieved in normal operation of the LTVG. The Mach 8 facility is almost ready for its first trials, and we expect to start performance tests in May 1995.

2.2 Study of transition to turbulence at Mach numbers from 2 to 8

The main difficulty with studying transition at supersonic and hypersonic speeds is the presence of tunnel noise, which makes the study of natural transition very difficult. The sources of noise are sound radiation from the tunnel wall boundary layers, and the turbulence convected into the test section from upstream. The convected noise can be reduced to arbitrarily small values by the use of a large settling chamber equipped with screens and honeycombs, and a well-designed contraction. However, the noise radiated from the wall boundary layers can only be eliminated by maintaining the layers laminar.

Our research efforts so far have concentrated on adapting the LTVG facility for the study of forced transition, that is, the formation of turbulent spots, at Mach 3. First, it was necessary to adjust the control system so that the required stagnation pressure could be set very precisely. That aim was achieved successfully by the end of 1993. Second, the ejectors were used to operate the LTVG at very low Reynolds numbers, so that the nozzle wall boundary layers were all laminar. This was successfully achieved by the summer of 1994. Third, the flow quality and turbulence levels were measured over a range of Reynolds numbers, including very low values (see Table 1). At each Reynolds number, the turbulence levels along the centerline of the test-section and the nozzle were obtained, and the boundary layer profiles on the test-section wall were measured. These were found to be of a superior standard, with turbulence levels in the freestream as low as 0.06% (which contrasts very favorably with the 0.8% mass flux turbulence level in our older 8in x 8in tunnel). In figure 2 we show the freestream turbulence levels on the centerline. It can be seen that the turbulence levels in the freestream increase with streamwise distance and generally decrease with stagnation pressure (that is, Reynolds number). Figure 3 shows some boundary layer profiles measured at a point 5 inches downstream of the nozzle exit. These results demonstrate that (1) the convected turbulence from the settling chamber is less than 0.06% (no corrections for electronic noise on the hot-wire signal were made so that these levels overestimate the true level); (2) the point of transition in the side-wall boundary layer moves downstream with decreasing Reynolds number. At a Reynolds number of 2.3 x 10^6/m, the point of transition is located approximately at the nozzle exit. A further, small decrease in stagnation pressure should result in a fully quite tunnel where the entire test section has laminar wall boundary layers.

2.3 Study of fully turbulent boundary layers at Mach numbers from 2 to 8

In the Mach 8 facility, the highest value of the unit Reynolds number will be 16 x 10^6/m. Now, Owen et al. found in their work that at x = 1.76m, the boundary layer was fully turbulent with Re_θ = 12,000. Under the same assumptions as before, with a cooled wall so that Tw/To = 0.5, and with natural transition at the highest unit Reynolds number, we could expect Re_θ = 12,000 at x = 1.2m. The boundary layer thickness will be about 15mm. In the experiment by Kussoy et al. (1991) at a Mach number of 8.2 and a unit Reynolds number of 5.1 x 10^6/m, with natural transition, it was found that Re_θ = 4,800 at x = 1.87m. At a unit Reynolds number of 16 x 10^6, and the same temperature ratio (0.27) and transition history, we would expect Re_θ = 8,540 at x = 1.2m. If a trip is used, then the experience of Stone and Cary (1972) at Mach 7.8 suggests that transition can be made to occur quite close to the leading edge of the plate. At a unit Reynolds number of 25 x 10^6, with Tw/To = 0.8, transition was complete at x = 0.127m, and they found Re_θ = 9823 at x = 0.455. Under similar conditions, we could expect to have Re_θ = 15,000 at x = 1.37.

Measurements in the zero pressure gradient, flat plate Mach 8 boundary layer will include:

> Mean flow: Pitot, stagnation temperature, wall pressure, wall heat transfer, schlieren, shadowgraph, maybe alcohol fog.
>
> Turbulence: Hot wire, high-speed schlieren. Regular Rayleigh is possible under some operating conditions. Filtered Rayleigh scattering is possible under all conditions, in the green, in a plane, to give density and velocity. RELIEF is also possible. Sodium seeding can be used into nitrogen, helium or other pure gases.

Progress on this task is awaiting the completion of the Mach 8 Boundary Layer Facility.

2.4 Studies of shock wave boundary layer interactions at Mach 8

A study of a "crossed- shock" interaction generated by two symmetrical sharp fins, each at an angle of attack to the incoming flow, has been completed (Forkey *et al.* 1993). Rayleigh scattering was used to image the three-dimensional shock structure and its interaction with the boundary layer.

The most difficult practical problem has been to observe Rayleigh scattering in the presence of strong background from windows and walls, and to resolve the lineshift and linewidth of the Rayleigh scattered light. New work in the Applied Physics Group has shown that if a narrow linewidth laser is used, then a sharp cut-off molecular filter may be placed in front of the camera which records the scattering. By properly adjusting the laser frequency relative to the filter cut-off, background light from windows and walls can be eliminated, leaving only Rayleigh scattering from the flow field. This approach is particularly appropriate for high velocity, low density flows where the frequency shift between the light scattered from windows and walls and that scattered from the flow field is greatest and the signal-to-noise ratio is expected to be low. Using this technique, called "Filtered Rayleigh Scattering," we are able to resolve light scattered very close to surfaces. Consequently, boundary layer phenomena can be recorded without significant interference form nearby surface features.

For the three-dimensional visualization of the crossing shock interaction at Mach 3, filtered Rayleigh scattering images were obtained in planes perpendicular to the flow direction by using a 45^o mirror placed downstream of the interaction (see figure 4). By moving the laser sheet successively downstream, it was possible to reconstruct the three-dimensional flowfield (see figure 5). The crossing shock structure is clearly shown, as is the thickening of the low-speed boundary layer fluid on the centerline as the two vortex structures associated with each swept shock interaction come together and form a streamwise vortex pair. This flow field holds some promise as a form of fuel/air pre-mixing for high-speed inlets.

This summer, we expect to extend this work to study a similar crossed-shock interaction at Mach 8. We are particularly interested in the mixing of the incoming boundary layer as it interacts with the shock system. We will bleed helium seeded with sodium in the incoming boundary layer and observe the distribution of the sodium in the flow as it exits the interaction by using sodium fluorescence. This will indicate the level of molecular mixing, and the results will have important consequences for the design of hypersonic inlets. Progress on this task awaits the completion of the Mach 8 Boundary Layer Facility.

2.5 Development and Application of Non-Intrusive Diagnostics

In the study of high-speed boundary layers, we need to image low density turbulent flows close to a wall. Ultraviolet Rayleigh scattering is of limited utility in this region due to strong background scattering from the wall. Flow tagging by RELIEF can be used near walls since the observed molecules fluoresce in a portion of the spectrum far removed from either the tagging or interrogation lasers. A recently developed flow tagging laser source gives much stronger tagging than was previously achievable, so even at the very low densities associated with high Mach number flows, we expect to be able to see a marked line.

The application of Rayleigh scattering for flow visualization at the Gas Dynamics Lab has now become routine. We have completed some quantitative comparisons between the density signal as inferred from the Rayleigh image and the density signal inferred from a hot wire placed in the same flow at the same time (Nau 1995). The time traces of the hot-wire signal can be matched to the space contour of the density variation given by the image at the same distance from the wall by assuming a convection velocity of the motions in the boundary layer at that wall distance (the hot wire was always placed at the downstream extent of the imaging plane). The average convection velocity can be determined by finding the maximum in the correlation between the two signals. The results shown in figure 6 indicate the following: (1) the spatial information contained in the Rayleigh image is at least an order of magnitude better than the equivalent spatial information contained in the hot-wire signal, as deduced using Taylor's hypothesis; (2) the correlation of the two density signals peaks at values as high as 0.85 or 0.9 when the convection velocity is chosen correctly; (3) the correlation is reduced by the lack of resolution in the hot-wire signal compared to the Rayleigh signal, and (4) there exists a wide spread in the convection velocity of the large-scale motions.

The development of Filtered Rayleigh Scattering for flow visualization has already been demonstrated at Mach 3 in the crossing shock experiment described in Section 2.4. With existing laser sources, such as a frequency doubled Nd:YAG laser and simple filters, such as an iodine molecular vapor filter, the Filtered Rayleigh Scattering diagnostic approach can be done using visible light and standard optics and camera systems. Pulse laser outputs with durations on the order of 10 nsec are standard for this type of laser system. Thus, a single pulse will freeze the flow, allowing us to record instantaneous flow structure. During the first year of this project, we have also developed and tested such a filtered Rayleigh system with the capability of eliminating background light scattering using a double or multiple pulsed laser system (made available by a recent AFOSR supplement).

Thus it is possible to generate flow velocity information by measuring the displacement of flow features over a well calibrated time increment. This capability is most useful in observing boundary layer structure where the displacement of identifiable features can be recorded. Preliminary results at Mach 3 were reported by Cogne *et al.* (1993) and Forkey *et al.* (1993). See figures 7, 8 and 9. Work at higher Mach numbers awaits the completion of the new Mach 8 Boundary layer Facility.

2.6 Summary of Recent Work on Visible Filtered Rayleigh Scattering

Recent work has focused on developing and demonstrating the planar measurement capabilities of Filtered Rayleigh Scattering (FRS) for measuring velocity, temperature and pressure. In particular, we have verified the validity of our computer model of the scattering and detection processes. Also, we have determined and quantified the major sources of systematic uncertainties, many of which have now been reduced to a negligible level. Current work is focused on reducing the remaining major source of systematic uncertainty caused by an apparent non-linearity in our camera system.

In order to test and demonstrate the measurement capability of the Filtered Rayleigh Scattering technique, we have performed experiments under two test conditions. The first condition consists of ambient air at room temperature and pressure (nominally 0 m/s, 20°C and 760 torr). Although the air is not moving, this test is a good indicator of the absolute accuracy for the given temperature and pressure. The second test condition consists of a Mach 2 free jet pressure matched to ambient atmospheric pressure. The approach we used to measure flow parameters consisted of collecting Rayleigh scattered light through an absorption notch frequency filter for a number of different frequencies. This yields an intensity versus frequency curve, the shape of which is dependent on the local flow parameters. By fitting such a curve to our computer model, we are able to determine the flow velocity, temperature and pressure. By performing this procedure for each resolution element on the camera, planar measurements of velocity, temperature and pressure were achieved.

The configuration for these experiments is shown in figure 10. The laser beam was focused into a sheet and passed through the 6 inch by 6 inch vertical test section of a laboratory scale wind tunnel, at an angle of roughly 50 degrees to the vertical. The scattering was captured orthogonal to the laser sheet and an absorption cell containing molecular iodine, was placed in front of the camera lens. The ambient room air test condition was achieved by temporarily removing the windows on the test section before the experiment was performed. The Mach 2 test utilized a stagnation pressure of 100psig, and a stagnation temperature of 258 K. Isentropic calculations predict that the free stream velocity, static temperature, and static pressure at the exit of this jet should be 480 m/s, 143 K, and 753 torr, respectively. In order to achieve a significant Doppler shift, the Nd:YAG beam crossed the flow at an angle of 50°. This required that the measurement region in the flow be some 12 mm to 22 mm (2 to 4 nozzle diameters) downstream of the nozzle exit in order to keep the laser beam from hitting the nozzle.

A data run consisted of obtaining 50 camera frame averages at each of 110 different laser frequencies. The image data was binned into 10 by 10 superpixels corresponding to approximately 300 micron by 300 micron spatial resolution of the object plane. At each resolution element, the fitting procedure described above was performed. Figure 11 shows the experimental data (dots) and the best least squares fit (solid) for a single, representative resolution element of the ambient air case. Similar fits, one at each resolution element, yielded values for v, T, and P at each point in the flow.

The planar velocity profile from the first test case, which has a uniform velocity of 0 m/s, is shown in color figure 1. The laser sheet extends from the top right of the plot to the bottom left. Measured velocity values within the sheet range from -12 m/s to 31 m/s. A comparison of color figure 1 with color figure 2, which shows the laser sheet intensity, indicates that the variations in measured velocity are correlated with the spatial profile of the laser intensity. The velocity errors, therefore, are potentially due to a non-linearity of the detection system, which was neglected in this analysis. In particular, the region at the top of the laser sheet, with low laser energy (less than 75% of the peak), exhibits the largest discrepancy in the measured velocity. Neglecting this small portion of the laser sheet yields a measured velocity range between -12 m/s and 10 m/s. Current work is centered on investigating this potential non-linearity. According to a detailed error analysis which includes all other sources of systematic uncertainty, we expect that addressing the non-linearity issue will reduce the velocity uncertainty for these conditions to roughly 4 m/s.

Velocity values obtained with the Mach 2 free jet are shown in color figures 3 and 4. The core of the jet exhibits velocities between 192 m/s and 221 m/s, while the shear layers, apparent on either side of the core, exhibit velocities between 200 m/s and 0 m/s. The isentropic value is calculated to be 220 m/s. Points outside of the flow, but still within the laser sheet exhibit velocities of approximately 0 m/s. It should be emphasized that the measured velocity is the velocity component along the direction of FRS sensitivity, which is determined by the laser propagation direction, and the camera observation direction. When comparing the measured core velocities to the isentropic value, these angles were measured relative to the exit surface of the nozzle and the jet was assumed to issue perpendicular to this surface. If the direction of the jet differs from the perpendicular by 1°, the isentropic value changes by 8 m/s. As in the case of ambient air, a significant discrepancy is observed across the laser sheet, particularly in the low energy region. However, RELIEF measurements have exhibited velocity variations of ± 4 m/s in this region of the flow.

Although the temperature and pressure data obtained from the Filtered Rayleigh Scattering experiments has not yet been fully analyzed, color figures 5 and 6 show preliminary plots of this data for the Mach 2 condition. Both show general behavior of the parameters as expected. The pressure of the free jet appears to be the same as that of the ambient surroundings, as expected from a pressure matched nozzle, although the pressure values vary significantly across the entire region of interest. These variations are believed to be due in part to variations in the jet, and in part to the non-linearities discussed above. The temperature of the free jet is seen in color figure 6 to be significantly lower than that of the ambient surroundings, as expected. Although the variation of measured temperature across the jet is ± 17 K, the average value of 142 K agrees with the isentropically calculated value of 143 K.

Finally, Filtered Rayleigh Scattering has the added capability of measuring the flow velocity by scanning the laser frequency relative to the filter cut-off. When the filter cuts off light scattered from the flow, a simple measurement of the frequency of the laser relative to the filter cut-off will give the flow velocity. Due to the finite width of the light scattered, the transmission of the filter does not change infinitely sharply, but has a slope which is indicative of the temperature of the flow field. Thus, with careful calibration and time-averaging, one can generate point resolved measurements of time-averaged temperature and velocity. Of course these measurements can be synchronized with periodic flow driving devices to give phase-selected velocity, temperature, and density measurements. With more sophisticated collection optics and several filters with slightly different cut-off frequencies, single-pulse, multiple images can be taken to yield instantaneous velocity, temperature, and density measurements. With multiple pulse sources, time-varying structures in the field can be observed, and, in the long run, with advanced source development to yield pulse-burst lasers and rapid data acquisition, full three-dimensional time-varying fields can be recorded.

The close collaboration between the development of new nonintrusive diagnostic instrumentation and the need for specific boundary layer or flow field measurements will serve to focus research on those approaches which have the highest payoff. Much fundamental development work remains to be done on the Filtered Rayleigh Scattering approach, including spectroscopy for filter selection and optimization, laser development, frequency calibration, and data collection and processing. Our preliminary experiments suggest, however, that the Filtered Rayleigh Scattering approach may be immediately implemented for qualitative imaging of flow structures in supersonic flows.

The accurate timing which is possible with laser systems make them particularly appropriate for introducing externally driven perturbations in the flow field. The Applied Physics and Lasers Group has been working on the development of far ultraviolet sources for use in flow field diagnostics. These sources have the capability of generating significant light flux far enough in the ultraviolet that it is strongly absorbed by air. As a consequence, these sources may be used to selectively perturb air flows by heating. These sources can be focused to single points or more complex patterns to examine force phenomena in the flow field. By varying the spectral output, the depth at which the energy is absorbed in the flow can be controlled. For example, these techniques can provide a "clean," two- or three-dimensional disturbance to initiate transition. In conjunction with a laser diagnostic system, the timing can be selected on a microsecond or, potentially, a submicrosecond timescale so that driven structures can be repeatedly observed.

2.7 Additional Activities

2.6.1 AASERT Activities

Under the connected AASERT Grant F49620-93-1-0476, we are studying the flowfield generated by a generic hypersonic vehicle shape. This investigation will provide data on a complex three-dimensional flowfield which is expected to contribute new insight into the physics of shock-shock interactions, the generation of vorticity in compressible flows (by the action of pressure gradients acting on boundaries as well as by baroclinic torques, the surface pressure and heat loading, the steadiness of the flowfield and the onset of separation in high-speed three-dimensional flows. This detailed information on the flowfield behavior will also be used to generate an important test case for code validation. In the original proposal, we proposed a study of a delta wing with rounded leading edges at a 30° angle of attack (designated "Problem 7" in Abgrall et al. 1992). Following recent discussions with the Program Manager, Dr. L. Sakell, we will now be studying the flowfield around a 4:1 elliptical cone at Mach 8. This is the same body that is being used in computational transition studies by Thorvald Herbert at Ohio State University, and experimental transition studies by Steve Schneider at Purdue University. We are now designing the body and its support system for mounting in the Mach 8 facility, and we expect construction to be completed by the beginning of the summer.

2.6.1 Aerothermochemistry Activities

Under the aegis of the AFOSR/URI Aerothermochemistry Program we are developing the capability to conduct combustion experiments at Mach 3. That facility, the Princeton Supersonic Combustion Tunnel, uses the same heater, diffuser, cooler and ejector system as the Mach 8 facility. Therefore the addition of the hypersonic tunnel also represents a major factor in broadening the scope of our capabilities at Princeton. The design work on the combustion facility will be completed this summer, and we anticipate that the facility will be ready to perform non-reacting flow experiments by the Spring of 1995.

Under the same grant, we are also studying a number of pre-mixed combustion experiments where the fluid mechanics is laminar. Preliminary work will be performed in the LTVG, once we have established that it is possible to operate that facility with laminar flow on the nozzle walls. The candidate flow is the laminar flow over a diamond-shaped airfoil, which, in the absence of combustion, can be computed very accurately. Comparisons with computations represent a cornerstone of this effort.

3. PERSONNEL

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4. PUBLICATIONS ACKNOWLEDGING GRANT F49620-93-1-0064

Baumgartner, M.L., Smits, A.J., Nau, T. and Rowley, C.W., "Design and testing of a new hypersonic boundary layer facility," 80th Supersonic Tunnel Association Meeting, Buffalo, NY, April 10 - 12, 1993.

Baumgartner, M.L., Smits, A.J., Nau, T. and Rowley, C.W., "A New Hypersonic Boundary Layer Facility." AIAA Paper #95-0787, 33rd AIAA Aerospace Sciences Meeting, Reno, Nevada, January 9 - 12, 1995.

Baumgartner, M.L. and Smits, A.J., "Progress report on the construction of the Princeton Mach 8 blowdown facility," 83rd Supersonic Tunnel Association Meeting, NSWC, Md, April 2 - 4, 1995.

Debiève, J.F., Dupont, P., Smith, D.R. and Smits, A.J., "The Response of a Supersonic Turbulent Boundary Layer to a Step Change in Wall Temperature." Submitted AIAA Journal.

Dussauge, J.-P., Fernholz, H.H., Finley, P.J., Smith, R.W., Smits, A.J. and Spina, E.F., "Turbulent Boundary Layers in Subsonic and Supersonic Flows," NATO-Advisory Group for Aerospace Research and Development AGARDograph, #335. To appear 1995.

Dussauge, J.P. and Smits, A.J., "Characteristic Scales for Energetic Eddies in Turbulent Supersonic Boundary Layers." Tenth Symposium on Turbulent Shear Flows, Pennsylvania State University, University Park, PA, August 14-16, 1995.

Evans, T. and Smits, A.J., "Measurements of the Mean Heat Transfer in a Shock Wave Turbulent Boundary Layer Interaction." To appear Experimental Thermal and Fluid Science.

Forkey, J., Cogne, S., Smits, A.J., Lempert, W. and Miles, R.B., "Time-sequenced and spectrally filtered Rayleigh imaging of shock wave and boundary layer structure for inlet characterization," AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Monterey CA, June 28 - 30, 1993.

Forkey, J., Finkelstein, N.D., Lempert, W.R. and Miles, R.B., "Control of experimental uncertainties in filtered Rayleigh scattering measurements," AIAA Paper #95-0298, 33rd AIAA Aerospace Sciences Meeting, Reno, Nevada, January 9 - 12, 1995.

Konrad, W., Smits, A.J. and Knight, D., "Mean Flow Field Structure of Mach 3 Shock-Free Three-Dimensional Turbulent Boundary Layer." Submitted AIAA Journal.

Nau, T.A., "Rayleigh scattering as a quantitative tool in compressible turbulent boundary layers," MSE Thesis, Department of Mechanical and Aerospace Engineering, Princeton University, 1995.

Poggie, J., Evans, T., Poddar, K. and Smits, A.J., "A Wavelet Analysis of Intermittent Pressure Fluctuations in a Supersonic Flow over a Blunt Fin." In preparation.

Schuitevoerder, C., "Turbulence and transition measurements in the LTVG supersonic wind tunnel," MSE Thesis, Department of Mechanical and Aerospace Engineering, Princeton University, 1994.

Smith, D.R. and Smits, A.J., "The Effects of Successive Distortions on the Behavior of a Turbulent Boundary Layer in a Supersonic Flow." To appear Journal of Fluid Mechanics, 1995.

Smits, A.J., "Mach and Reynolds Number Effects on Turbulent Boundary Layers." AIAA Paper #95-0578, 33rd AIAA Aerospace Sciences Meeting, Reno, Nevada, January 9 - 12, 1995.

Wang, Q., Brasseur, J.G., Smith, R.W. and Smits A.J., "Multi-Dimensional Continuous Wavelet Transforms and Applications to Turbulence Data," Submitted to Experimental Thermal and Fluid Science.

REFERENCES AND BIBLIOGRAPHY

Abgrall, R., Désidéri, J.-A., Glowinski, R., Mallet, M. and Périaux, J. (editors), "Hypersonic Flows for Reentry Problems," Volume III. Proceedings of the INRIA-GAMNI/SMAI Workshop on Hypersonic Flows for Reentry Problems, Part II, Antibes, France, 15-19 April, 1991.

Bartlett, R. P. 1981, "A study of the mean and fluctuating properties of a turbulent hypersonic boundary layer," Ph. D. Thesis, Imperial College, University of London, London, England.

Baumgartner, M.L., Smits, A.J., Nau, T. and Rowley, C.W. 1993, "Design and testing of a new hypersonic boundary layer facility," 80th Supersonic Tunnel Association Meeting, Buffalo, NY, April 10 - 12. Submitted for presentation at 33rd Aerospace Sciences Meeting, Reno NV, Jan 9 - 12, 1995.

Berg D. E. 1977, "Surface roughness effects on the hypersonic turbulent boundary layer," Ph. D. Thesis, CALTECH, Pasadena, CA (University Microfilm 77- 17260).

Fernholz, H. H. and Finley, P. J. 1977, "A critical compilation of compressible turbulent boundary layer data," AGARDograph No. 223.

Fernholz, H. H. and Finley, P. J. 1981, "A further compilation of compressible turbulent boundary layer data with a survey of turbulence data," AGARDograph No. 263.

Forkey, J., Cogne, S., Smits, A.J., Lempert, W. and Miles, R.B. 1993, "Time-sequenced and spectrally filtered Rayleigh imaging of shock wave and boundary layer structure for inlet characterization," AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Monterey CA, June 28 - 30, 1993.

James, C. S. 1958, "Observations of turbulent-burst geometry and growth in supersonic flow," NASA TN 4235.

Jedlicka, J. R., Wilkins, M. M. and Seiff, A. 1954, "Experimental determination of boundary layer transition on a body of revolution at M = 3.5," NACA TN 3342.

Kussoy, M. I., Kim, K. and Horstman C. C. 1991, "An experimental study of a three-dimensional shock wave boundary layer interaction at hypersonic speed," AIAA Paper 91-1761.

Mikulla, V. and Horstman, C.C. 1975, "Turbulence stress measurements in a non-adiabatic hypersonic boundary layer," AIAA J. 13:1607-1613.

Mikulla, V. and Horstman, C.C. 1976, "Turbulence measurements in hypersonic shock-wave boundary layer interaction flows," AIAA J. 14:568-575.

Miles, R., Connors, J., Howard, P., Markovitz, E. and Roth, G. 1988a, "Proposed Single-Pulse, Two-Dimensional Temperature and Density Measurements of Oxygen and Air," Optics Letters 13, pg. 195.

Miles, R., Connors, J., Markovitz, E., Howard, P. and Roth, G. 1988b, "Instantaneous Supersonic Velocity Profiles in an Underexpanded Jet by Oxygen Flow Tagging," (Accepted for publication in Physics of Fluids).

Morkovin, M. V. 1962, "Effects of compressibility on turbulent flows," Int. Symp. on the Mechanics of Turbulence 367. C.N.R.S., Paris.

Owen, F. K., Horstman, C.C. and Kussoy, M. I. 1975, "Mean and fluctuating flow measurements of a fully developed, non-adiabatic hypersonic boundary layer," J. Fluid Mech. 70, 393.

Pope, A. and Goin, K. L. 1978, "High Speed Wind Tunnel Testing," Krieger, Huntington NY.

Seiff, A. and Short, B. J. 1958, "An investigation of supersonic turbulent boundary layers on slender bodies of revolution in free flight by use of a Mach-Zehnder interferometer and shadowgraph," NASA TN 4364.

Settles, G. S. and Dodson, L. J. 1990, "Hypersonic shock/boundary-layer interaction database," Dept. Mech. Engin., Penn. State Univ. Rept. PSU-ME- 90/91-003.

Smith, M. W., Kumar, V., Smits, A. J. and Miles, R. B. 1989, "The Structure of Supersonic Turbulent Boundary Layers as Revealed by Line Profiles and Density Cross Sections," to be presented, Seventh Symposium on Turbulent Shear Flows, Stanford University, Stanford, CA.

Smith, M. W. and Smits, A. J. 1988, "Cinematic visualization of coherent density structures in a supersonic turbulent boundary layer," AIAA Paper 88- 500.

Smits, A. J., Hayakawa, K. and Muck, K. C. 1983, "Constant-temperature hot- wire anemometer practice in supersonic flows. Part I - The normal wire," Experiments in Fluids 1, 83.

Stone, D. R. and Cary, A. M. 1972, "Discrete sonic jets used as boundary layer trips at Mach numbers of 6 and 8.5," NASA TN D-6802.

van Driest, E. R. 1951, "Turbulent boundary layer in compressible fluids," Journal of Aeronautical Sciences 128, 283.

Wegener P. P. and Stein, G. D. 1968, "Light-Scattering Experiments and Theory of Homogeneous Nucleation in Condensing Supersonic Flow," 12th International Symposium on Combustion, 1183-119.

Zarin, N. A. and Vas, I. E. 1963, "The development of a small Mach 10 hypersonic wind tunnel," Princeton Univ. Dept. Mech. and Aerosp. Engin. Rept. 666.

P_0 (Psia)	T_0 (K)	Re / m
4.3	290.0	2.31×10^6
5.0	291.0	2.67×10^6
10.5	288.0	5.71×10^6
17.0	281.0	9.60×10^6
24.6	282.0	1.38×10^7
100.0	273.5	5.88×10^7

Table 1. Flow conditions for turbulence measurements in the LTVG.

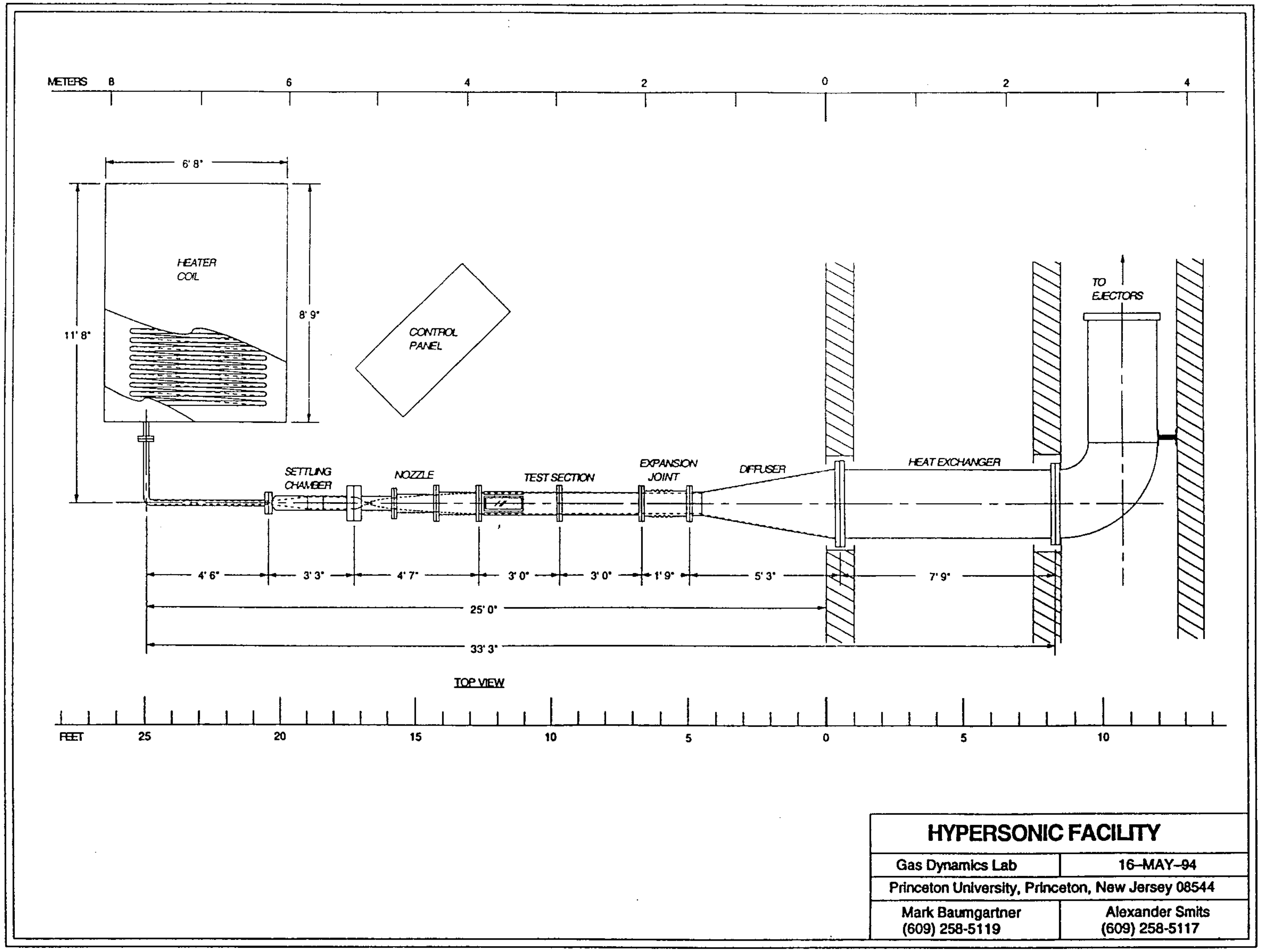
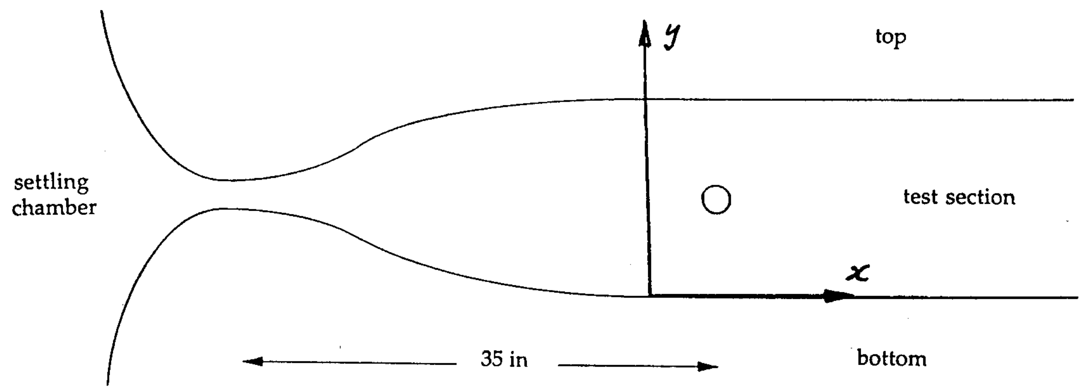


Figure 1. Mach 8 Boundary Layer Tunnel.



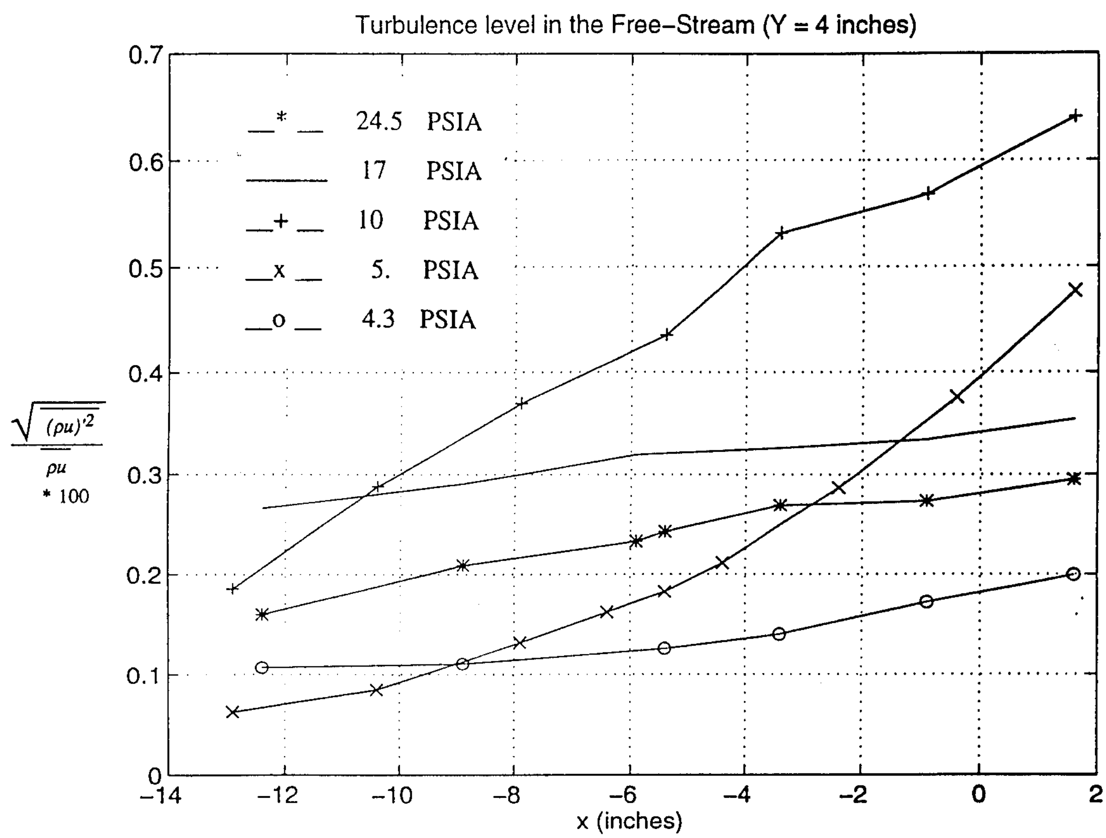


Figure 2. Turbulence levels on the centerline of the LTVG working section.

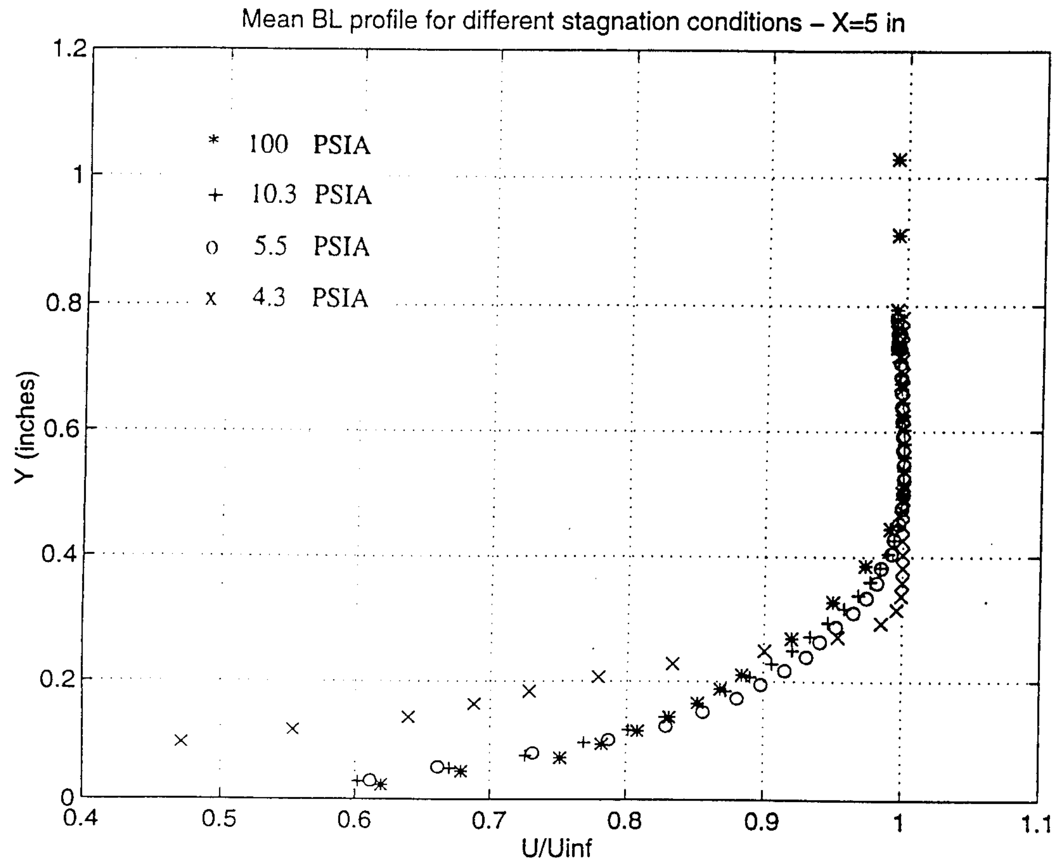


Figure 3. Mean velocity boundary layer profiles on the wall of the test section at a position 5 inches downstream of the nozzle exit.

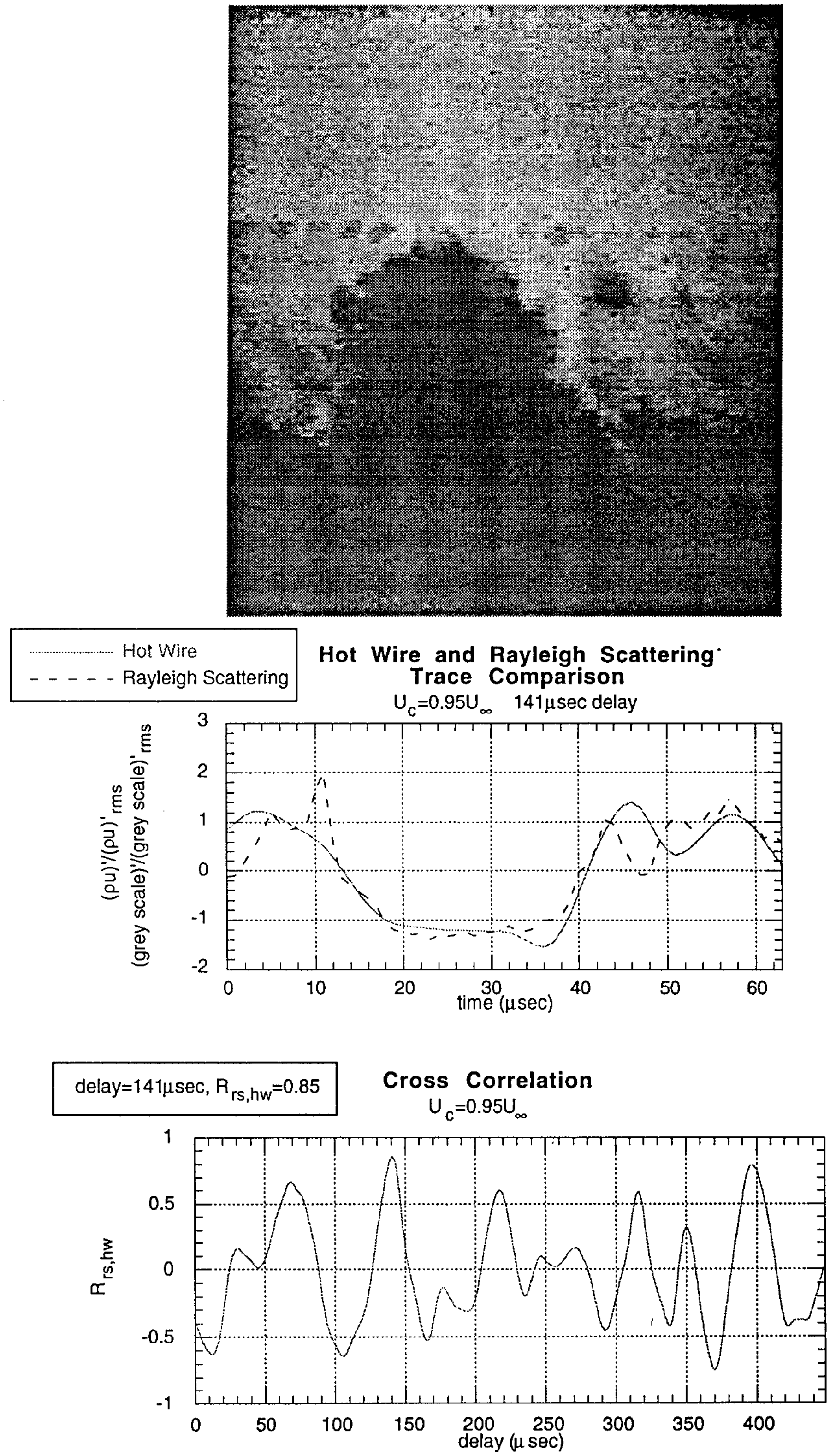


Figure 4. Comparison of hot wire trace and corresponding Rayleigh scattering trace for $y/\delta = 0.5$

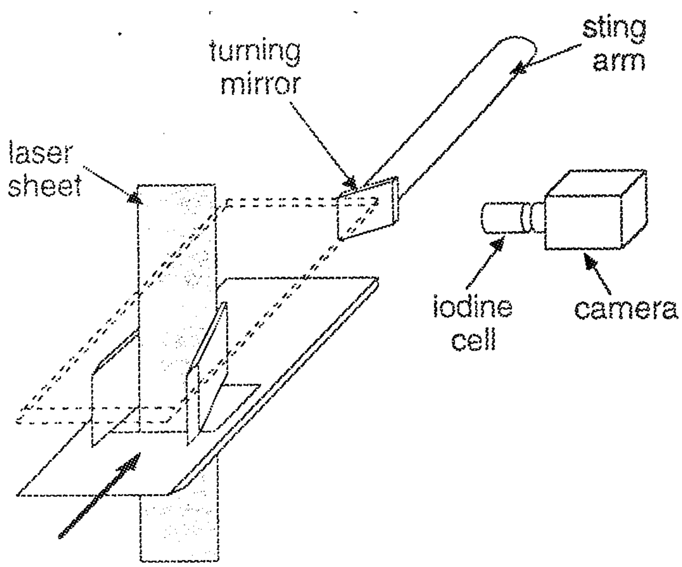


Figure 5. Technique for obtaining Filtered Rayleigh scattering images in planes perpendicular to the flow direction by using a 45° mirror placed downstream of the crossing shock interaction.

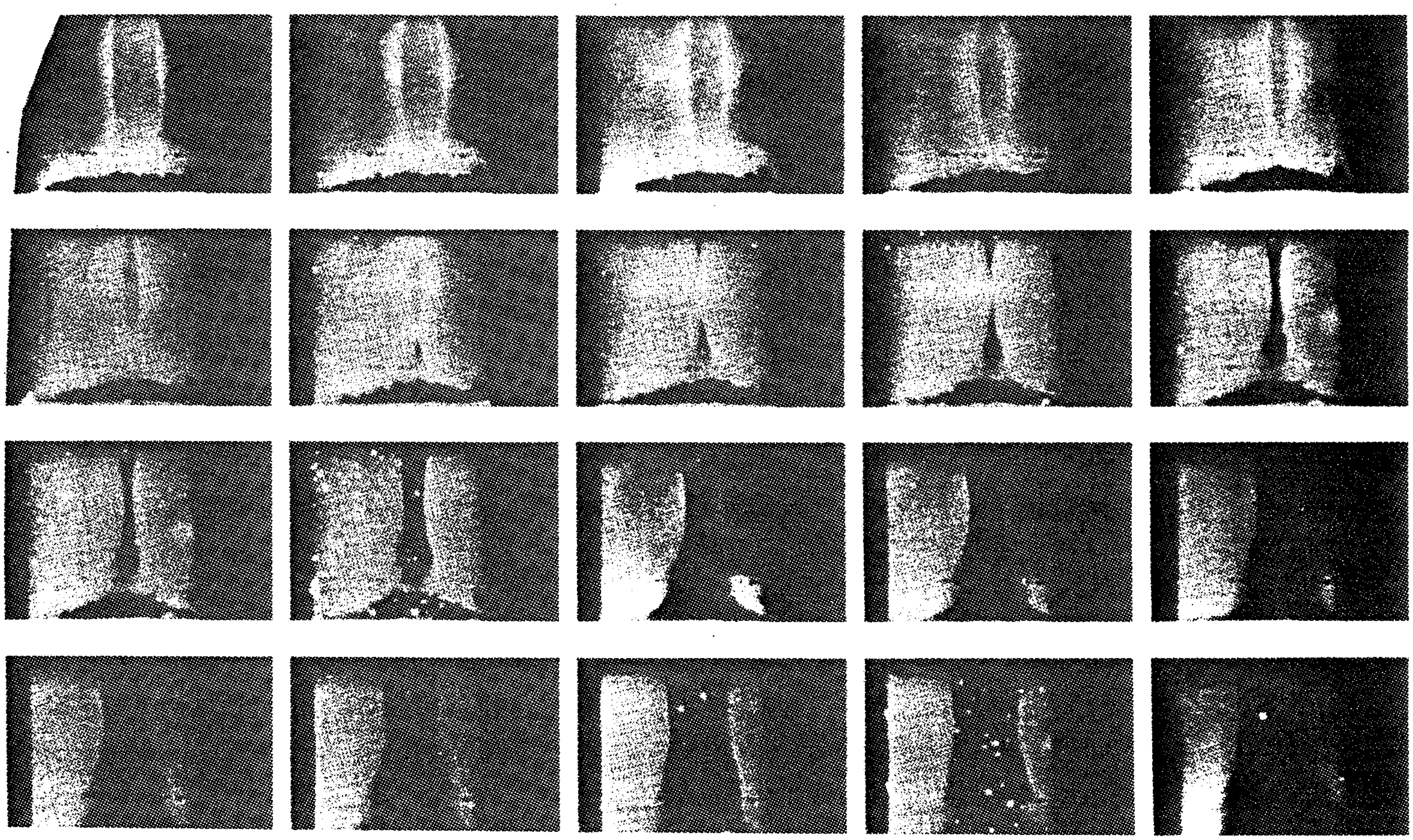


Figure 6. Cross-sectional Filtered Rayleigh Scattering images taken at sequential 0.1 in intervals moving downatream through the three-dimensional flowfield of the crossing shock interaction. The shock structure is clearly shown, as is the thickening of the low-speed boundary layer fluid on the centerline as the two vortex structures associated with each swept shock interaction come together and form a streamwise vortex pair.

Fig. 7. Double pulsed Rayleigh image pair of a Mach 3 high Reynolds number boundary layer. The lower image was taken 20μs after the upper image and flow is from right to left. The images were taken with two separate cameras.

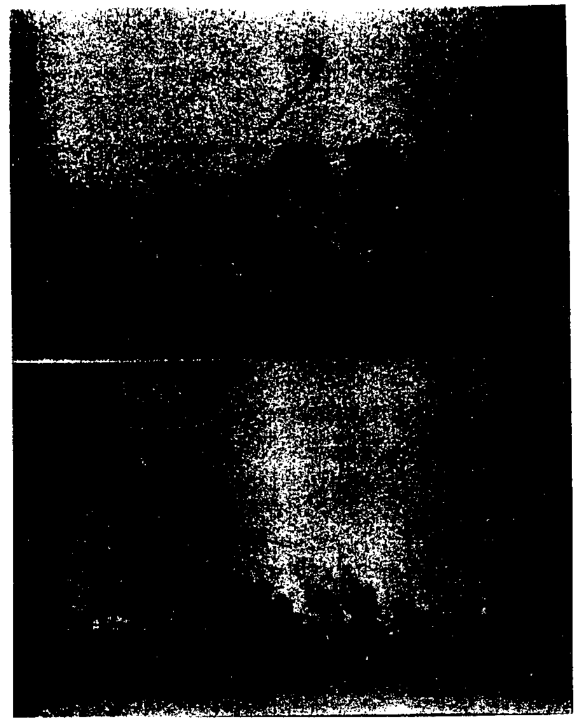


Fig. 8. Double pulsed Rayleigh image pair of a Mach 3 high Reynolds number boundary layer. The lower image was taken 60μs after the upper image and flow is from right to left. The images were taken with two separate cameras.

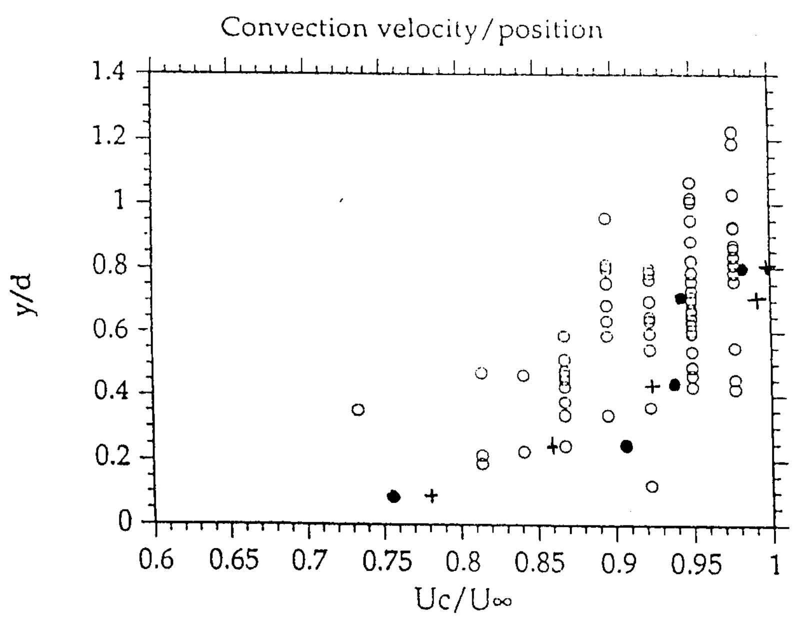


Fig. 9. Normalized convection velocities across the boundary layer determined by double pulsed Rayleigh imaging (open circles),[4] RELIEF flow tagging (solid circles) and pitot survey (crosses).[3]

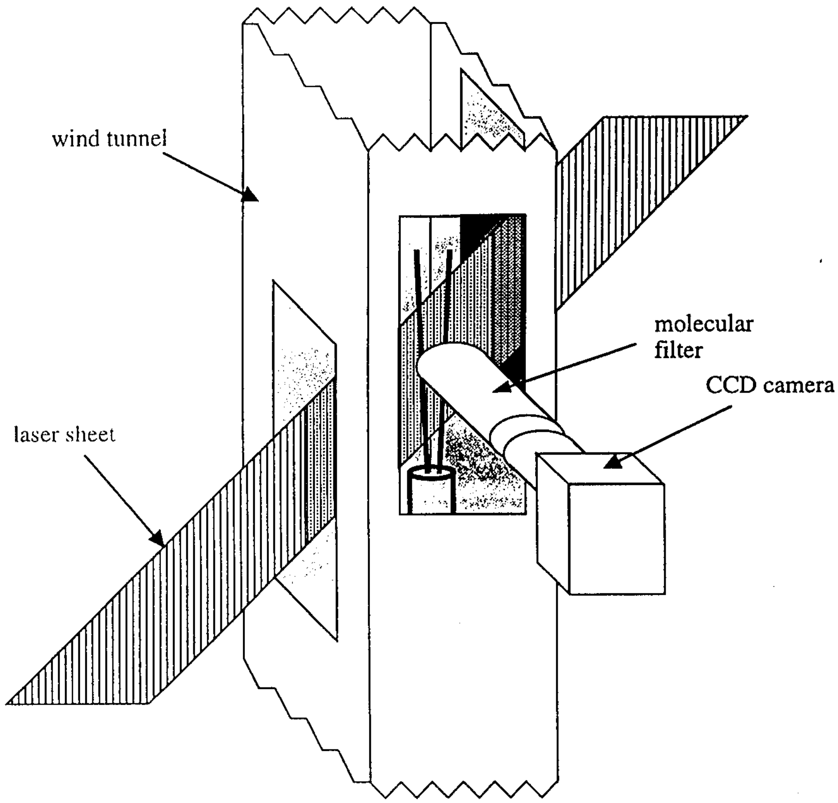


Figure 10. Experimental configuration for Filtered Rayleigh Scattering Experiments.

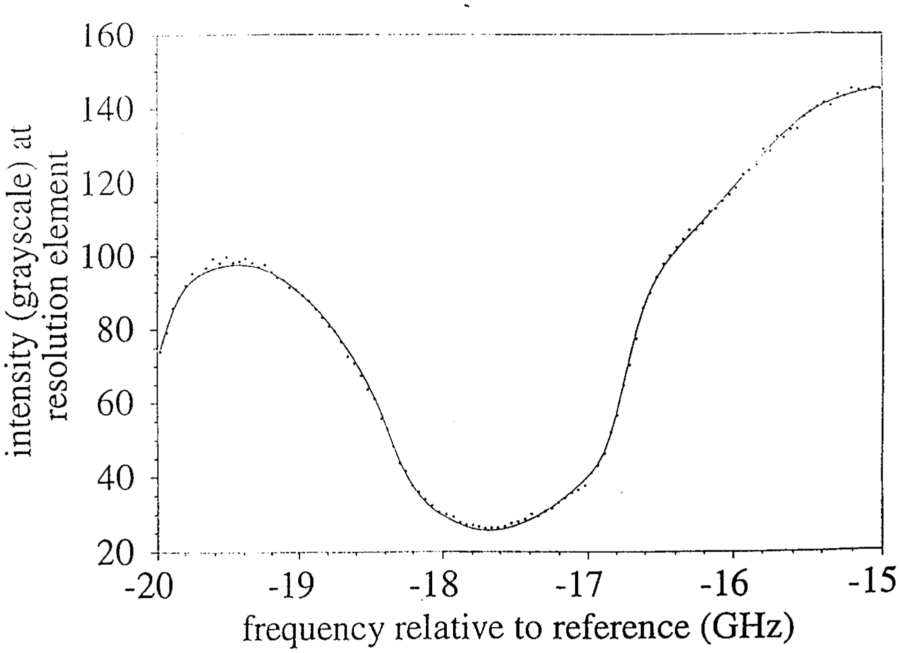
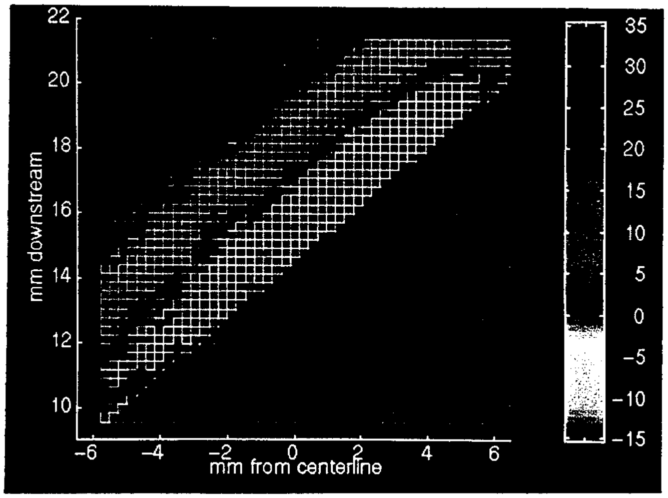
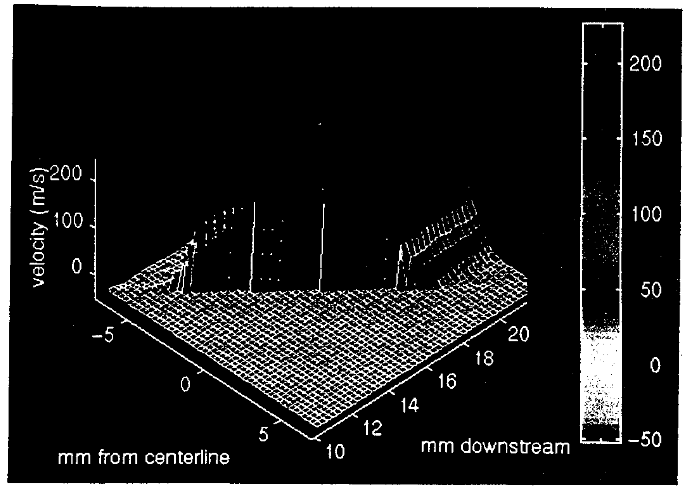


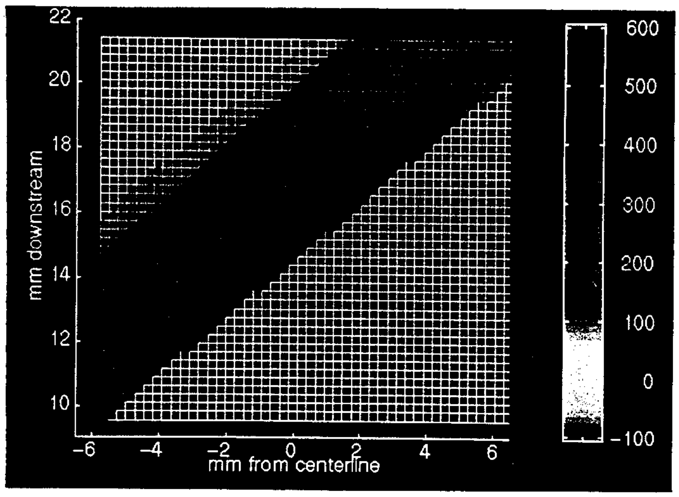
Figure 11. Fit of grayscale data values at one resolution element (points) to computer model (line).



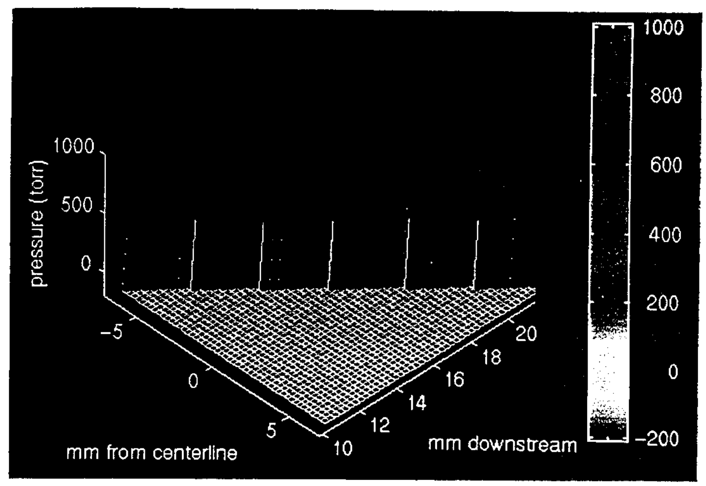
C. Fig. 1: Measured velocity in the direction of FRS sensitivity, of ambient air. Large values at the top of the laser sheet are due to low laser energy.



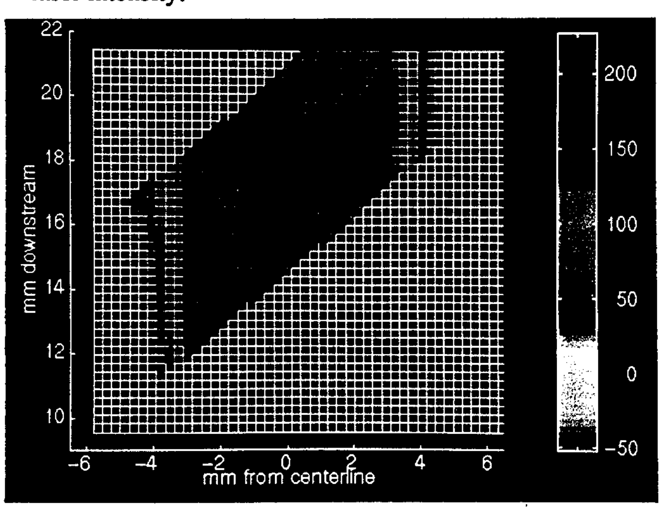
C. Fig. 4: 3-D plot of velocity in direction of FRS sensitivity, of Mach 2 free jet



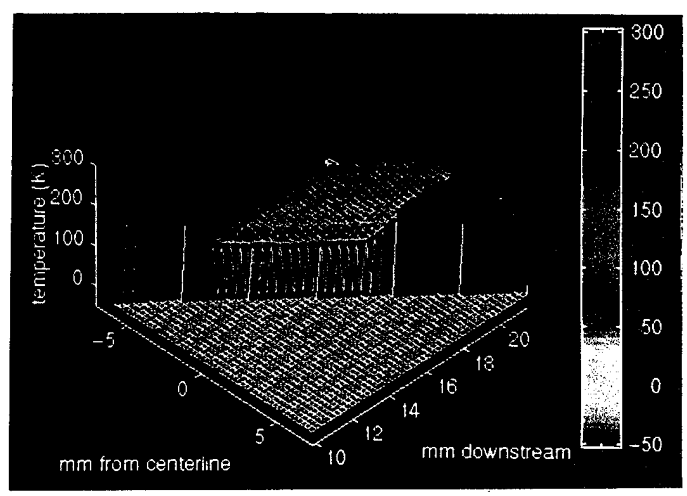
C. Fig. 2: Calibration of R for ambient air. Variation of R across laser sheet is an indication of the variation in laser intensity.



C. Fig. 5: Measured static pressure of Mach 2 free jet.



C. Fig. 3: Measured velocity in direction of FRS sensitivity, of Mach 2 free jet.



C. Fig. 6: Measured static temperature of Mach 2 free jet.