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FINAL TECHNICAL REPORT

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"DEVELOPMENT AND APPLICATION OF OXYGEN FLOW TAGGING FOR VELOCITY MEASUREMENTS AND FLOW VISUALIZATION IN TURBULENT THREE-DIMENSIONAL SUPERSONIC FLOWS"

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August 30, 1989

ABSTRACT

Over the past three years, work supported by this grant has led to several major advances towards the full characterization of three-dimensional compressible turbulent flows. Flow tagging by Raman Excitation plus Laser-Induced Electronic Fluorescence (RELIEF) and ultraviolet Rayleigh scattering have been developed to measure instantaneous velocity profiles, temperatures, and density cross sections in air. In order to establish the feasibility and utility of these new diagnostic techniques, experiments have been undertaken in supersonic free jets and supersonic boundary layers. In these experiments lines have been written into air to give the first direct images of velocity structure in supersonic free shear layers, and UV Rayleigh scattering has been used to achieve the first measurements of instantaneous two-dimensional density cross sections in free jets and in supersonic boundary layers. Computer software has been developed to analyze the data to generate new statistical information on high-speed turbulent flow. For example, two-dimensional correlations of the density cross sections have yielded the size and shape of turbulent structure and regions

of correlated shock motion. Similar analysis of the two-dimensional images of the displaced lines show regions of coupled motion in the flow field. By quantifying the displacement of the tagged lines, instantaneous and averaged velocity profiles, turbulent velocity intensity, and velocity correlations have been derived.

A. INTRODUCTION

The goal of the research effort was to develop a new flow diagnostic technique involving laser tagging and subsequent laser interrogation of oxygen molecules in air. The capability of following flow fields at a speed of approximately Mach 3 was of particular interest so that the technique could be implemented in the Mach 3 supersonic facility at the Princeton Gas Dynamics Laboratory. Over the last three years, the RELIEF and UV Rayleigh diagnostic systems have been developed and tested at the Princeton Applied Physics Laboratory in a small axisymmetric supersonic facility with high optical access and a wide range of operating conditions. Initial experiments in that facility were done using an underexpanded 1/4" diameter sonic free jet which could be run with a stagnation pressure of approximately 150 psi into an atmospheric or lower pressure exhaust chamber. This produced a range of flow conditions up to approximately Mach 4, and a variety of interesting flow features including a Mach disk, slip lines, reflected and barrel shocks, and turbulent free shear layers. The initial demonstration of RELIEF flow tagging was accomplished with the tunnel in this configuration, and measurements of the centerline flow velocity, velocity profiles, turbulence intensity, and velocity correlations were made.

Since the interrogation step involves illumination of the flow field with an argon-fluoride laser, ultraviolet Rayleigh scattering was simultaneously observed to record the gas density. With the argon-fluoride laser expanded into a thin, two-dimensional sheet, a cross-sectional image of the gas density was recorded. These images were taken simultaneously with the line interrogation to give a time-frozen image containing one or more velocity profiles and the density.

Following those initial experiments, a small supersonic tunnel was inserted into the flow facility. This tunnel allowed boundary layers and shock wave boundary layer interactions in a Mach 2.5 flow to be observed. Lines have not yet been marked in the boundary layer due to the high intensity of the laser beams, but two-dimensional UV-Rayleigh scattering images have been taken to generate cross-sectional images of the turbulence and the shape and extent of turbulent structure. By adding a 16° angle wedge to the flow field, shock wave boundary layer interactions have also been imaged. The fact that the UV-Rayleigh images can be taken close to a boundary layer with pulse energies on the order o[illegible] mJ suggests that this is a promising and versatile technique for flow diagnostics. By integrating flow tagging with the UV-Rayleigh scattering, instantaneous images of density and velocity can be recorded.

An analysis of many images has led to average pictures of the density cross section and the average velocity profile. By comparing each individual image with the average, two-dimensional spatial correlations were constructed. In these correlations a point in the two-dimensional image is chosen and a new image is generated which shows the correlation of the brightness of the other points in the two-dimensional images with the selected point. This leads to a quantitative mapping of the size and shape of turbulent structures, plus an image of the correlated regions of flow motion.

The lasers which have been used include an injection-locked and stabilized Nd:YAG laser, a narrow linewidth tunable dye laser, and an injection-locked argon-fluoride laser. These lasers are all highly sensitive to noise and vibration, so that operating them close to a large-scale supersonic facility such as that at the Gas Dynamics Laboratory will be exceedingly difficult. Consequently, we have focused on developing simpler systems for flow tagging and UV-Rayleigh scattering. These include a high-pressure, oxygen-filled stimulated Raman cell which is expected to replace the tunable dye laser and operate with a noninjection-locked Nd:YAG laser, and a far-UV, high-intensity flashlamp which is expected to replace the argon-fluoride laser. Research will continue with follow-on support to develop these systems and complete the installation at the Forrestal Campus.

B. PROJECT ACCOMPLISHMENTS

1. Development of the RELIEF Flow Tagging Technique

The physical principles behind the RELIEF technique are outlined in the paper entitled, "Velocity Measurements by Vibrational Tagging and Fluorescence Probing of Oxygen," (Optics Letters 12, p. 861, November 1987). A copy of this paper is included as Appendix 1. Oxygen tagging is accomplished using a high-power Nd:YAG laser and a Nd:YAG laser pumped dye laser. These generate light in the green at 0.532μ and in the orange at 0.58μ, respectively. The frequencies of these two lasers differ by the vibrational frequency of the oxygen molecule, so when they are both focused tightly, oxygen is driven into its first vibrational state by stimulated Raman scattering. Due to the very long lifetime of oxygen, the molecules stay vibrationally excited until they are interrogated by an argon-fluoride excimer laser, which excites them into the Schumann-Runge band from which they immediately fluoresce. The fluorescence is recorded by a camera. In this paper, the tagging lasers overlap each other in a line above a small oxygen jet. By delaying the interrogation, the displacement of that line was used to observe the velocity profile and measure the centerline velocity of the jet.

The details of the stimulated Raman pumping and the character of simultaneously collected coherent anti-Stokes Raman scattering were examined and reported in a paper entitled, "Coherent Anti-Stokes Raman Scattering (CARS) and Raman Pumping Lineshapes in High Fields," published in the SPIE Vol. 912, "Pulsed Single-Frequency Lasers: Technology and Applications," 1988. This paper is included as Appendix 2. Here, again, pure oxygen was used. The laser intensities were varied to examine saturation phenomena in both coherent anti-Stokes Raman scattering and stimulated Raman pumping. To do this work, the Nd:YAG laser was injection-locked so that high resolution Q-branch spectra associated with the vibrational transition could be examined. These spectra reflect populations of oxygen in the various rotational states and can be used to determine the temperature of the oxygen. At very high pumping intensities, the spectra are distorted by saturation phenomena. Although the mechanism is the same, the distortion of the spectrum is different depending upon whether coherent anti-Stokes Raman scattering or stimulated Raman pumping is observed. In the case of coherent anti-Stokes Raman scattering, a large peak due to the real part of the nonlinear susceptibility begins to appear. In the stimulated Raman pumping spectrum, this large peak is not there. Line-broadening of the individual rotational lines also occurs. A simple theoretical model was generated to explain these observations.

The RELIEF tagging method was then extended to observations of high-speed air using the small supersonic facility which was constructed for this project. The results of that work are reported in two papers, "Instantaneous Supersonic Velocity Profiles in an Underexpanded Jet by Oxygen Flow Tagging," (Physics of Fluids A 1, p. 389, 1989) which is included as Appendix 3, and "Instantaneous Profiles and Turbulent Statistics of Supersonic Free Shear Layers by Raman Excitation Plus Laser-Induced Electronic Fluorescence (RELIEF) Velocity Tagging of Oxygen," to be published in Experiments in Fluids, which is included as Appendix 4. The tunnel facility was operated with an underexpanded free air jet which generated a supersonic expansion reaching approximately Mach 4 at the Mach disk. Lines were written across the supersonic jet at various locations, both before and after the Mach disk, and allowed to move for one or two microseconds before interrogation. The displaced line profiles were recorded and analyzed using a computer. Instantaneous velocity profiles were found and compared with standard plume models to show the accuracy of velocities measured at the centerline, and turbulent structure in the free shear layer was analyzed to give average velocity profiles, turbulence intensity, and lateral velocity correlations. In the second paper, the tagging laser beams were refocused through the jet so that line pairs could be marked and longitudinal velocity correlations could be made. Preliminary comparisons of free shear layers at supersonic and subsonic speeds were also made in that paper.

Detailed measurements of the evolution of the free shear layer as a function of distance downstream of the nozzle were made and reported in a Master's thesis by Edward Markovitz entitled, "Measurements of Turbulence Quantities in the Near Field of an Underexpanded Sonic Jet by Raman Excitation and Laser-Induced Electronic Fluorescence," (November 1988). The abstract of this thesis is included as Appendix 5. At locations downstream of the nozzle beginning with x/d=0.5, up to the Mach disk at x/d=2.03, ensemble axial velocity averages, variances of the velocity, and lateral velocity correlations were taken. From this data were found the width of the shear layer, the integral scale of the turbulence, and the Taylor microscale as a function of distance from the nozzle. This work also reported the capability of marking small shaped points by crossing the laser beams so that three-dimensional velocity and vorticity can be tracked.

From the above work it is clear that the RELIEF method can be used as a tool for instantaneously observing flow structure and velocity profiles in high-speed air. Lines can be tagged and easily seen up to Mach 4, at densities as low as 1/6 of an atmosphere, and at temperatures ranging from room temperature down to 70 K or below. In the future we expect that the density range can be extended by optimizing the interrogation step, either using a very high temperature UV flashlamp or a laser system whose wavelength is in the 185 nm range.

2. Development of UV Rayleigh Scattering for Density Cross Sections

As first shown in the paper entitled, "Instantaneous Supersonic Velocity Profiles in an Underexpanded Sonic Air Jet by Oxygen Flow Tagging," (Phys. Rev. A1, February 1989) (Appendix 3), the ultraviolet Rayleigh scattering from the argon-fluoride laser is sufficiently strong to give a two-dimensional cross-sectional image of the air density. While the focus of this paper was the use of the RELIEF technique for marking lines, the images clearly show cross-sectional features of an underexpanded sonic jet. These include the Mach disk, barrel shocks, reflected shocks, slip lines, etc. Each cross-sectional image is recorded instantaneously during the 10 nsec argon-fluoride laser pulse. A quantitative analysis of images such as these gives a measure of the instantaneous density at various regions in the flow field. By analyzing numerous such images, the average density can be computed and fluctuations about that average can be determined. Detailed examples are shown in the papers, "Velocity, Vorticity, and Structure--The Present State of Laser Diagnostics in High-Speed (Unseeded) Air," presented at the 17th International Symposium on Shock Waves and Shock Tubes, July 17-21, 1989, and also "Density Cross Sections and Velocity Profiles in High-Speed Air by UV-Rayleigh Scattering and By Raman Excitation + Laser-Induced Electronic Fluorescence (RELIEF)," which will be presented at ICALEO '89, October 15-20, 1989. These papers are included as Appendix 6 and Appendix

7, respectively. Here, images of the underexpanded sonic jet are analyzed to give indications of coupled motion in the flow. For example, a two-dimensional spatial correlation can be used to indicate those regions of the flow which are correlated with the motion of the slip line. Similar two-dimensional correlations can be done with tagged lines to give images indicative of correlated velocity fluctuations.

A small vertical wind tunnel with a cross section of 13 mm x 26 mm, and a Reynolds number based on momentum thickness of about 14,000 was constructed and fitted with one section which had quartz walls, allowing unrestricted optical access to the boundary layer. UV-Rayleigh scattering was used to get instantaneous two-dimensional density cross sections in the boundary layer. This work is also reported in the above papers (Appendices 6 and 7) as well as the recent publication, "Compressible Boundary Layer Density Cross Sections by UV-Rayleigh Scattering," Optics Letters 14, 1989 (Appendix 8). These two-dimensional cross sections were taken both across the boundary layer and parallel to the wall, and used to compute the probability density distribution functions of the density as well as two-dimensional correlations to give the scale and structure of turbulent features. Much of this work is reported in a thesis prepared by Michael Smith entitled, "Flow Visualization in Supersonic Turbulent Boundary Layers," which was prepared with support from this grant as well as from AFOSR-88-0120. A copy of the abstract of that thesis is included as Appendix 9.

The UV-Rayleigh scattering results indicate that it will be a principle diagnostic tool in the future. This outcome was not anticipated at the initiation of this grant, and represents an exciting extension beyond the original bounds of the projected research. The very high Rayleigh scattering cross section plus low background scattering in the ultraviolet means that modest energy lasers (tens of millijoules) can be used to obtain these images. Of particular interest are images that were taken with a 16° angle wedge placed in the flow field to give instantaneous cross sections of shockwave/boundary layer interactions. While these images are only preliminary, they clearly indicate that UV-Rayleigh scattering can be used to observe complex fluid phenomena in regions of practical interest.

3. Preliminary Measurements for Two-Dimensional Temperature and Density Imaging

An argon-fluoride or similar ultraviolet laser may also be used to generate laser-induced fluorescence from oxygen for temperature measurements. The possibility of combining laser-induced fluorescence and Rayleigh scattering to give instantaneous temperature and density measurements is explored in a paper entitled, "Proposed Single-Pulse Two-Dimensional Temperature and Density Measurements of Oxygen and Air," Optics Letters 13, p. 195, 1988. This paper is included as Appendix 10. In this work the argon-fluoride laser was injection-locked and tuned across a small portion of the oxygen Schumann-Runge band while fluorescence was collected. This was done at a variety of temperatures to generate the spectral signature of oxygen as a function of temperature. Simultaneously, a computational model was generated and compared to the experiment. This model was then extended to higher temperatures to predict fluorescence and Rayleigh scattering as a function of temperature. By looking at Rayleigh scattering only, as was previously mentioned, a two-dimensional density cross section can be obtained. If the laser is tuned to the peak of absorption line, then the fluorescence may be simultaneously monitored and the ratio of the fluorescence to density taken to generate a two-dimensional image of the temperature. This work was jointly sponsored by Lockheed California Company, and shows the versatility of using a narrow linewidth UV laser for diagnostics.

D. OTHER PUBLICATIONS

Other papers prepared under this grant include the following:

1. "Three-dimensional Quantitative Flow Diagnostics," Lecture Notes in Engineering 45, "Advances in Fluid Mechanics Measurements," Springer-Verlag, Berlin, Heidelberg, 1989. This paper is a review of three-dimensional flow diagnostic methods prepared for the Springer-Verlag Lecture Notes series. In addition to the RELIEF and Rayleigh scattering methods described above, this review also covered particle scattering, Raman scattering, fluorescence, hydrogen bubble marking, photochromism, flow marking by photodissociation, acoustic and magnetic resonance imaging. Various methods of acquiring volumetric data are discussed and new algorithms for volumetric data projection are presented. (Introduction included as Appendix 11.)

2. "Instantaneous Velocity Profiles and Density Cross Sections in Supersonic Shear Layers," Proceedings of the Conference on the Physics of Compressible Turbulent Mixing, Princeton University, 1989. This paper reports RELIEF measurements across the free shear layer of an underexpanded

sonic jet and gives the turbulence intensity and lateral velocity correlation as a function of distance downstream from the orifice. This paper also reports the use of UV-Rayleigh scattering to observe instantaneous density cross sections in a turbulent boundary layer and shockwave/boundary layer interactions. Two-dimensional density correlations are used to give an image of the shape and size of turbulent structure in the boundary layer and two-dimensional probability density distribution functions are used to indicate that this boundary layer is largely bimodal in the outer region. (Included as Appendix 12.)

3. "The Structure of Supersonic Turbulent Boundary Layers as Revealed by Density Cross Sections," presented at the 7th Symposium on Turbulent Shear Flows, Stanford University, 1989. This paper reports the use of UV-Rayleigh scattering together with hot-wire probes to examine the intermittency of the outer region of the boundary layer and to generate two-dimensional spatial correlations, both in the plane of the boundary and perpendicular to the boundary, in order to give a quantitative measure of the size and scale of turbulent structure. (Included as Appendix 13.)

4. "The Structure of the Instantaneous Density Field in Supersonic Turbulent Boundary Layers," Australian Fluid Mechanics Conference, 1989. This paper, once again, reports the Rayleigh scattering results in a turbulent boundary layer. Here, more details of the shockwave/boundary layer interaction are presented along with the two-dimensional spatial correlations and probability density distribution functions. (Included as Appendix 14.)

5. "Stimulated Raman Scattering and CARS in High-Pressure Oxygen," (in preparation). In an effort to simplify the RELIEF technique, we have developed a high-pressure oxygen cell which, by stimulated Raman scattering, produces the 0.58μ beam, thereby replacing the tunable dye laser. Research on the development of this cell has been underway for the last year and has included detailed measurements of oxygen pressure-broadening, pressure-shifting, and pressure-narrowing, which occur at the high pressures which are required to achieve stimulated Raman scattering. In this paper, the threshold conversion energy and conversion efficiency for the cell are reported, and high-resolution measurements of oxygen spectra as a function of pressure are made. Comparisons with new theories on the pressure-broadening of spectral line profiles are included, and Dr. J.P. Looney from the National Institute of Standards and Technology (formally the National Bureau of Standards) is a co-author. This paper will be submitted to the Journal of the Optical Society of America B, and the final draft is included as Appendix 15.

Papers Presented at Technical Meetings

1. R. Miles, "Multi-Point Oxygen Flow Tagging by Raman Excitation + Laser Induced Electronic Fluorescence," November 24-26, 1985, Thirty-Eighth Meeting of the Division of Fluid Dynamics, American Physical Society, Bulletin of the American Physical Society 30, Paper CH-3, page 1720, New York: American Physical Society, 1985.

2. R. Miles, "Oxygen Flow Tagging by Raman Excitation + Laser Induced Electronic Fluorescence," June 1986, CLEO'86-IQEC'86, Conference on Lasers and Electro-Optics, San Francisco, CA (Invited Paper).

3. R. Miles, J. Connors, S. Huang, E. Markovitz and G. Russell, "Time-Resolved Velocity Profiles by Vibrational Tagging of Oxygen," CLEO'87/IQEC'87, Conference on Lasers and Electro-Optics, Baltimore, MD, April 27-May 1, 1987.

4. R. Miles, G. Russell, J. Connors, E. Markovitz, "Acquisition and Visualization of Three-Dimensional Fluid Dynamic Data," Prepared for NSF Workshop on Image Processing and Analysis, Columbus, OH, October 16-18, 1987.

5. R. Miles, J. Connors, E. Markovitz, G. Roth and P. Howard, "Instantaneous 2D Temperature and Density Measurements in Oxygen and Air," 40th Anniversary Meeting of the Division of Fluid Dynamics of the American Physical Society, Eugene, OR, November 22-24, 1987.

6. R. Miles, "Instantaneous Supersonic Velocity Profiles by Oxygen Tagging," 1988 AFOSR Contractors Meeting on Turbulence, University of Southern California, Los Angeles, CA June 18-30, 1988.

7. E. Markovitz, J. Connors, G. Roth, P. Howard, and R. Miles, "Instantaneous and Time-Averaged Turbulent Structure in the Free Shear Layer of an Underexpanded Supersonic Air Jet," 41st Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Buffalo, New York, November 20-22, 1988.

8. J. Connors, E. Markovitz, G. Roth, P. Howard, and R. Miles, "Instantaneous Velocity Profiles and Density Cross Sections in High-Speed Air by RELIEF," 41st Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, Buffalo, New York, November 20-22, 1988.

9. R. Miles, J. Connors, V. Kumar, E. Markovitz, G. Roth, M. Smith, and A. Smits, "Velocity Profiles and Density Cross Sections in Supersonic Shear Layers by Simultaneous Flow Tagging and Rayleigh Scattering," submitted to the Conference on Lasers and Electro-Optics 1989, Baltimore, MD, April 24-28, 1989.

10. J. Poggie, W. Konrad, D.R. Smith, M.W. Smith, W. Lempert, R.B. Miles, and A.J. Smits, "The Effects of Reynolds Number on the Large-Scale Density Structures in High-Speed Turbulent Boundary Layers," APS Meeting, NASA Ames Research Center, November 19-21, 1989.

C. PERSONNEL

1. <u>Graduate Students</u>:

Edward Markovitz: Completed Masters' Degree, Fall 1988, "Measurement of Turbulent Quantities in the Near Field of an Underexpanded Sonic Jet by Raman Excitation and Laser-Induced Electronic Fluorescence"

John Connors: Currently writing Masters' Degree

Gregory Russell: Completed Ph.D., February 1989, "Volumetric Visualization of Scientific Data"

Michael W. Smith: Completed Ph.D., October 1989, "Flow Visualization in Supersonic Turbulent Boundary Layers"

Glenn Diskin: Third year graduate student working in conjunction with NASA/Langley on UV flashlamp development

Barry Zhang: Entered Fall 1988

Vinod Kumar: Entered Fall 1988

2. Undergraduate Students:

Gregory Roth: Completed senior thesis, Spring 1989, "Lifetime Measurements of Vibrationally Excited O_2 in the Presence of Water Vapor"

William Loinaz: Completed senior thesis, Spring 1989, "An Investigation into the Use of Stimulated Raman Scattering from Oxygen for Purposes of Supersonic Air Flow Visualization"

Chris Moore: Completed senior thesis, Spring 1987, "Design of a Wind Tunnel with a Supersonic Free Jet"

Clark Cohen: Completed senior thesis, Spring 1986, "Oxygen Flow Tagging"

3. Technician: Philip Howard

4. Research Scientist: Walter Lempert

5. Faculty: Richard B. Miles