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Progress is reported for the past year of an interdisciplinary program aimed at establishing advanced optical diagnostic techniques applicable to combustion and plasma flows. The primary effort is on digital flowfield imaging techniques, which offer significant potential for a wide range of spatially resolved 2-d and 3-d measurements. The imaging is accomplished by recording light scattered from a planar laser-illuminated region using a modern solid-state camera. The scattering process is generally laser-induced fluorescence, though Mie, Rayleigh and Raman scattering may also be used. Activities reported herein include: (1) image processing of PLIF data; (2) PLIF imaging in nonequilibrium shock tube flows; (3) temperature and velocity imaging in supersonic flows; (4) concept for simultaneous measurement of multiple parameters; (5) digital camera for high-speed imaging; (6) plasma diagnostics; (7) laser photolysis shock tube; and (8) cw UV laser absorption diagnostics.

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Submitted by

R. K. Hanson, Principal Investigator

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1.0 INTRODUCTION

Progress is reported for the past year of an interdisciplinary program aimed at establishing advanced optical diagnostic techniques applicable to combustion and plasma flows. The primary effort is on digital flowfield imaging techniques, which offer significant potential for a wide range of spatially resolved 2-d and 3-d measurements. The imaging is accomplished by recording light scattered from a planar laser-illuminated region using a modern solid-state camera. The scattering process is generally laser-induced fluorescence, though Mie, Rayleigh and Raman scattering may also be used. Activities reported herein include: (1) image processing of PLIF data; (2) PLIF imaging in nonequilibrium shock tube flows; (3) temperature and velocity imaging in supersonic flows; (4) concept for simultaneous measurement of multiple parameters; (5) digital camera for high-speed imaging; (6) plasma diagnostics; (7) laser photolysis shock tube; and (8) cw UV laser absorption diagnostics.

2.0 PROJECT SUMMARIES

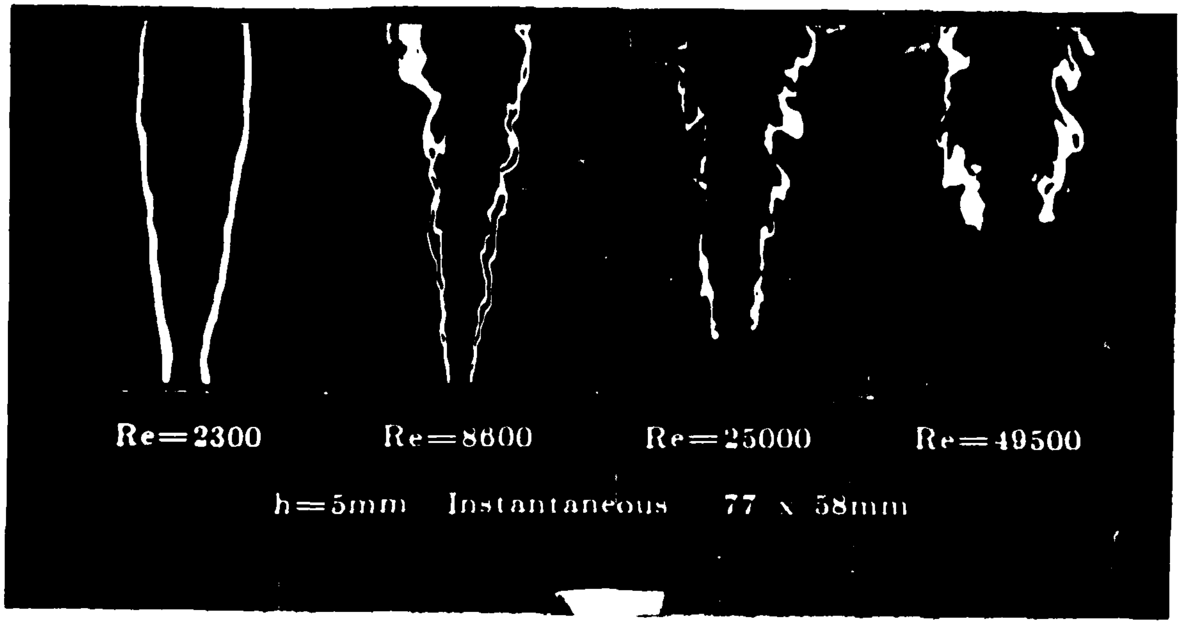
Included in this section are summaries of progress in each of eight project areas. Additional descriptions of this work may be found in the publications listed in Section 3.2. Reprints of these papers are available on request. Personnel involved in these projects are listed in Section 4.0.

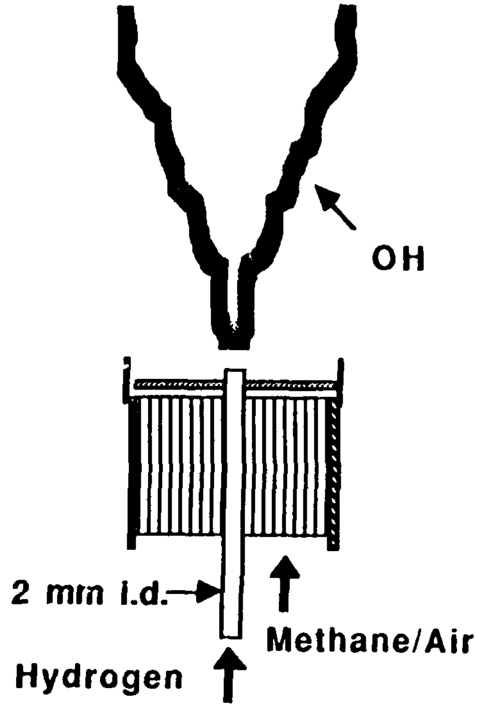
2.1 Image Processing of PLIF Data

One of the primary motivating issues for the development of planar laser-induced fluorescence (PLIF) is the need for improved understanding of turbulence, and in particular turbulent combustion. The hope is that multi-dimensional data, of the type generated by PLIF, will provide improved insights into turbulence owing to the increased experimental information available. Since the type of data obtained is quite different from that gathered with traditional single-point observations, there are new, important questions as to which quantities should be monitored and how the image data should be processed. In our attempts to answer these questions, we have begun to acquire image data sets for recognized fundamental turbulent flowfields and we have dedicated a portion of our effort to computer processing of such image data sets. We have found considerable interest in the fluid mechanics community in this work, and the resulting interaction with several leading fluid mechanists has been invaluable in clarifying our perspective on the proper quantities to be imaged and the optimum quantities to be extracted with image processing. Our philosophy, then, has been that an effort on image processing is a crucial adjunct to our overall program on laser-based diagnostics.

In the present section, three examples are given of our work on image processing. The first effort was carried out using OH image data acquired in a turbulent H_2-air jet flame. A schematic of the burner and representative single-shot OH data are shown in Fig. 1 for a range of Reynolds numbers. In these images, the OH serves to mark the instantaneous flame front. The important points to note are: (1) the image data are of extremely high quality and indicate considerable progress over the past few years in obtaining useful images of OH; and (2) the influence of increasing Reynolds number (turbulence level) is to introduce considerable structure into the flame and to cause lift-off of the flame from the burner surface. Examples of current work to process these image data sets are shown in Fig. 2. Details of this work will appear in the forthcoming paper by Seitzman et al. (see papers 26 and 30 in Section 3.1 of this report).

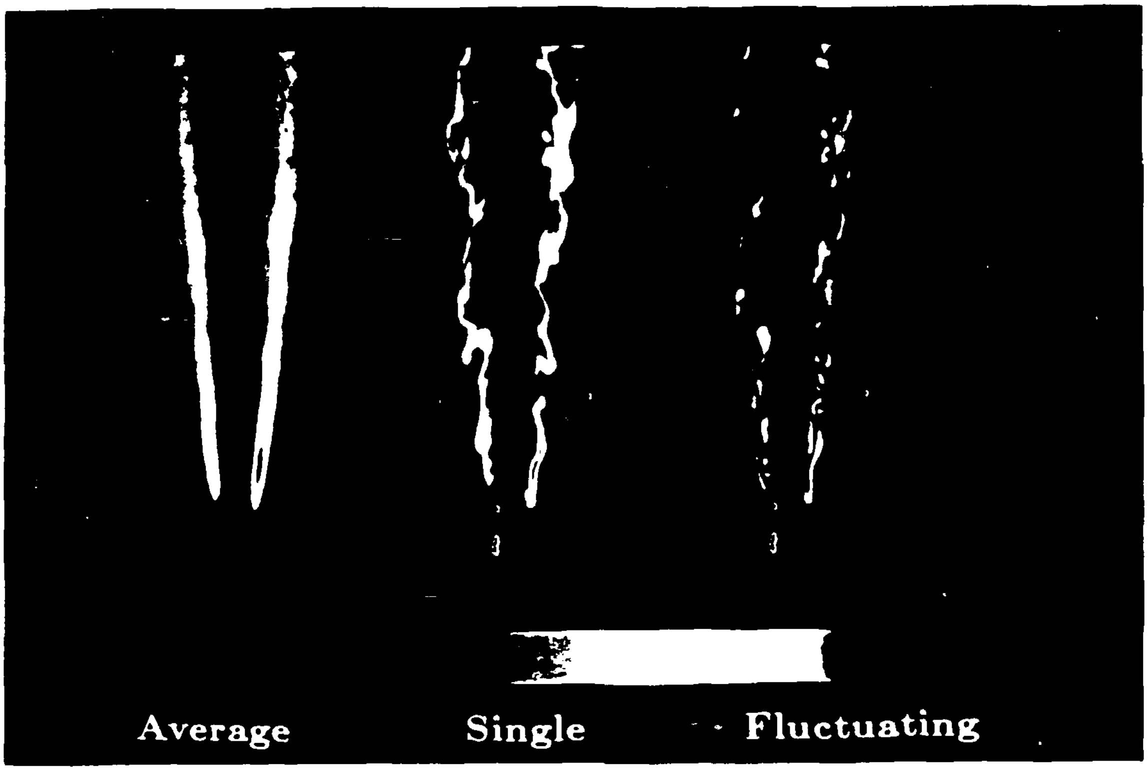
STRUCTURE OF H_2–AIR JET FLAMES REVEALED BY PLIF IMAGING



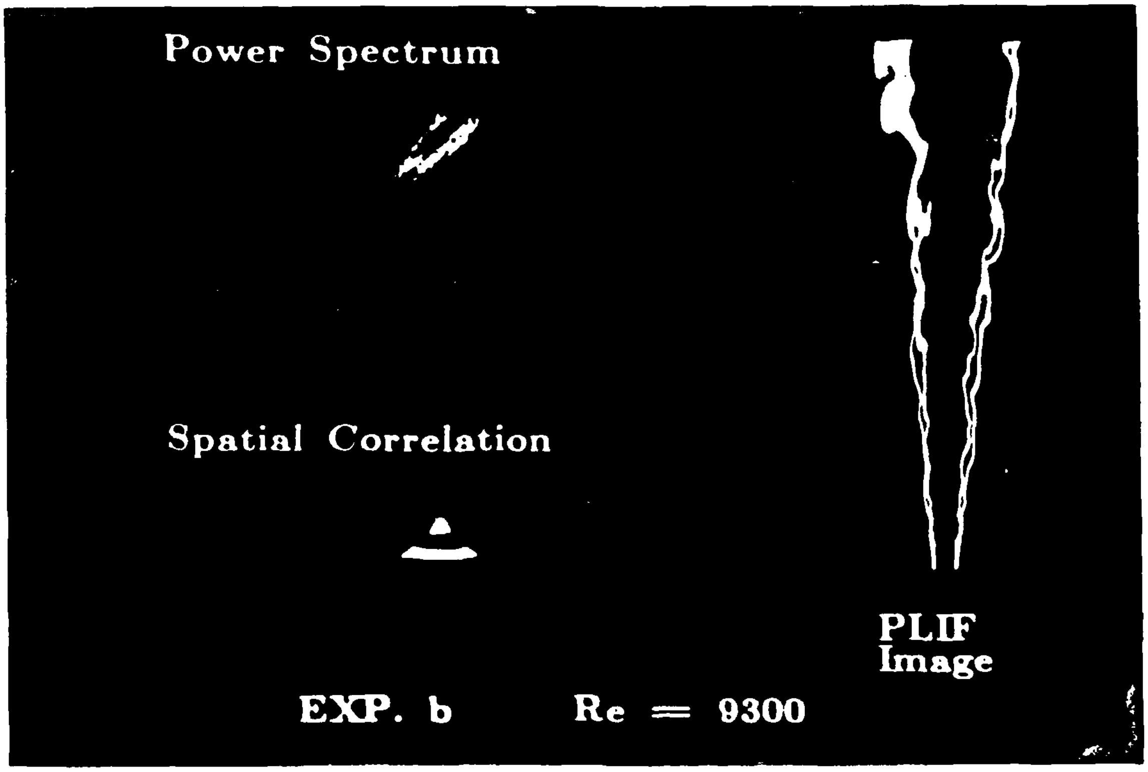


- Flame lift-off and turbulent structure studied as function of Reynolds number
- New camera system allows rapid acquisition of high-resolution images (80 images of 512 x 240 pixels = 10 Mpixels in 8 sec)
- Multiple image data sets allow statistical analysis for comparison to combustion models
- New image processing algorithms for PLIF data reveal details of flame structure

Figure 1. PLIF study of the structure of turbulent H_2-air jet flames.



a) Extraction of fluctuating OH field.



b) Power of spectrum and spatial correlation plots for Re = 9300 case.

Figure 2. **Examples of image processing of PLIF data for OH in turbulent H_2-air jet flames.**

Another example of image processing of PLIF data is shown in Fig. 3. Here the quantity being imaged is the instantaneous mole fraction of jet fluid on the central axis of a turbulent, nonreacting round jet. The species imaged is biacetyl, which has been seeded at low levels into nitrogen carrier gas. The ambient gas is also nitrogen, and a large number of single-shot images have been acquired so that various statistical quantities can be extracted from the image data. Figure 3 illustrates two useful quantities, both shown in false-color, namely the RMS fluctuation field and the dissipation field. The RMS fluctuation image is based on an average of 25 single-shot images, while the dissipation field shown is for a single laser shot. These results represent the first known data of this type, and both the magnitude and spatial variation of these quantities contain new information on turbulence. For example, the image of the instantaneous dissipation field clearly shows a strong maximum signal along lines oriented at 45 degrees to the flow axis, which corresponds to the expected lines of maximum strain in the flow.

As a final example of image processing, Fig. 4 illustrates a new method for compactly displaying a large number of sequential 2-d images in a perspective plot. In this case, "background lighting" and opaqueness were set to emphasize the external boundary of two different nonreacting jets. In the left-hand figure, a low Reynolds number, axially forced jet is imaged using PLIF of biacetyl in a seeded round jet. In the right-hand figure, a very high Reynolds number flow is imaged. The important point is that the visualization method allows the viewer to focus on the external boundary of such flows, and thereby to suppress the information contained in the internal regions of the flow. This approach allows important confirmation of the role of large-scale structures in such flows, even at extremely high Reynolds numbers where many fluid mechanists believe that the flows are fully randomized.

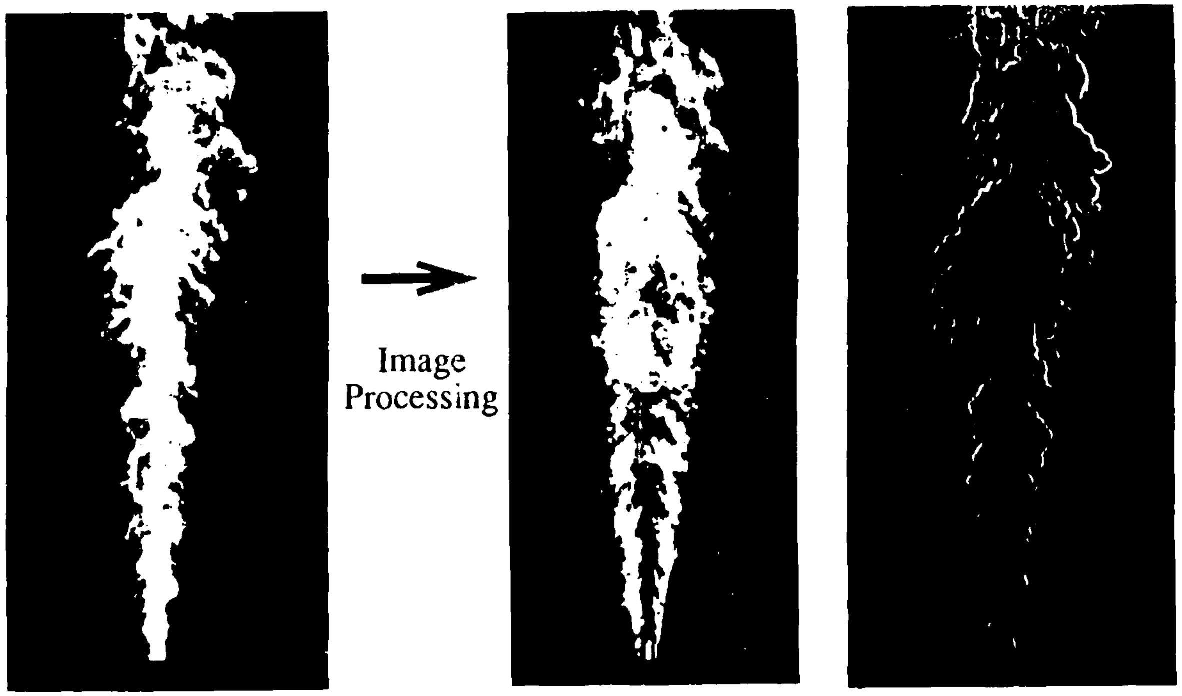
2.2 PLIF Imaging in Nonequilibrium Shock Tube Flows

Nonequilibrium hypersonic flows, relevant to current research on scramjets, pose new measurement problems for experimentalists. For example, experiments are often conducted in pulsed flow facilities in which the available measurement time is quite limited, thereby putting a premium on the ability to acquire complete data sets in very short times. In addition, many flows of interest exhibit a high degree of nonequilibrium, thereby requiring experimental methods sensitive to such nonequilibrium effects. PLIF has high potential for dealing with both of these critical problems, in that the data provide population densities in specific quantum states of the species probed at a very large number of flowfield locations. During the past two years we have initiated research which addresses some of the problems inherent in extending PLIF to transient hypersonic flows, and these experiments are now beginning to yield important results.

AIR FORCE BASIC RESEARCH

Aerospace Sciences

SEPARATION OF FLUCTUATING AND DISSIPATION FIELDS BY PLIF IMAGE PROCESSING ALLOWS VALIDATION OF TURBULENCE MODELS



Unprocessed PLIF Data for Turbulent Jet

RMS Fluctuation Field

Dissipation Field

APPROACH

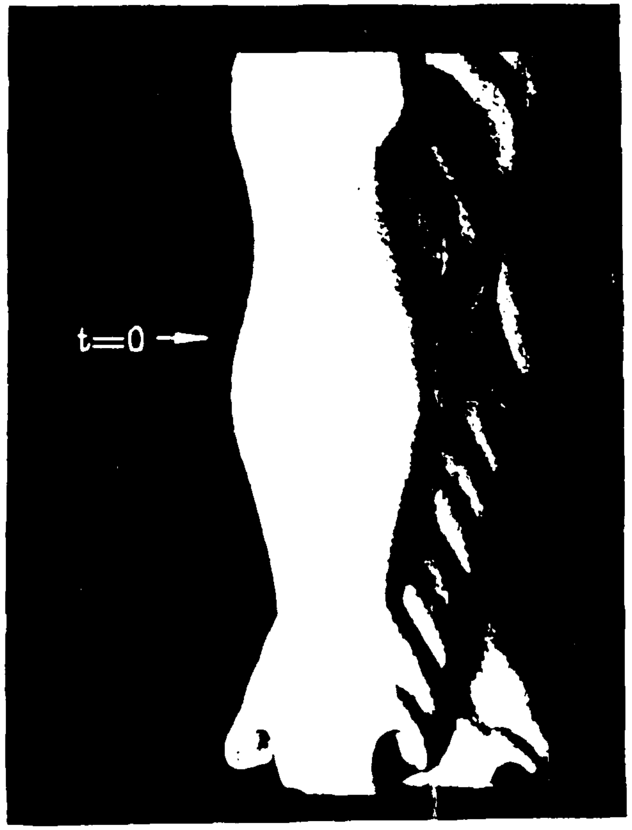
- Turbulence closure models assume that RMS fluctuations and scalar dissipation are correlated
- Processing of image data allows validation of this and other modelling assumptions

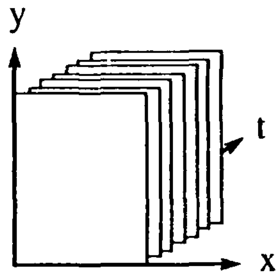
- First demonstration of correlation between lines of maximum dissipation and maximum strain
- Can also provide intermittency, spatial fourier transform, and spatial autocorrelation fields

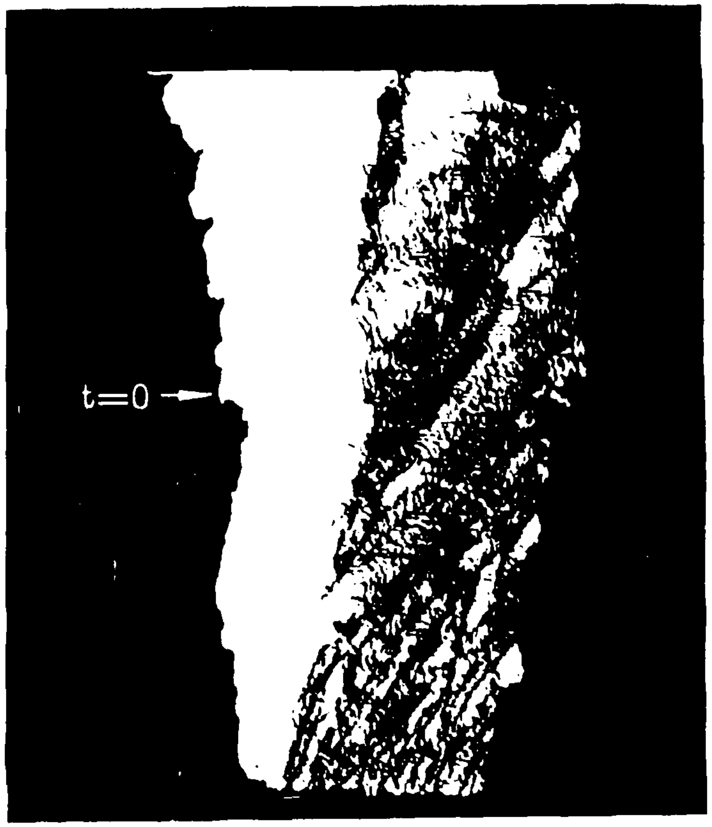
Hanson / Stanford

Figure 3. Processing of PLIF image data to extract turbulence ...

VOLUME RENDERING OF X-Y-T DATA PROVIDES NEW TOOL FOR FLOW VISUALIZATION







PLIF Data for Pulsed Jet (Re = 2000)

Rocket Motor Exhaust (Re = $2x10^8$)

- New technique integrates a temporal sequence of planar data (x-y-t) into a single view
- Enhances observation of large scale flow evolution in rocket exhausts
- Reveals presence of reentrainment in jet mixing process

Figure 4. New method for 3-d display of 2-d, time-varying data.

Most of the experiments have been conducted in a standard pressure-driven shock tube and have emphasized measurements of nitric oxide (NO). This species is attractive owing to its presence in many combustion and high temperature air flows of interest. An initial problem, now resolved, concerned synchronization of the laser pulse and intensified camera gate with the shock wave location This now can be done with an uncertainty of less than one microsecond, or equivalently a few millimeters of shock location. In addition, a new square shock tube, designed to facilitate imaging experiments, has been assembled and put into routine operation. Research in the past few months is illustrated by Fig. 5 which shows PLIF images obtained at two instants of time following reflection of a strong shock wave from a stepped end wall in the shock tube. Such shocks are curved and exhibit significant vibrational equilibrium. Significant aspects of current research involve selection of optimum laser wavelengths for excitation of NO and development of a suitable model describing the finite spatial resolution of the imaging system. Details of this work are available in paper 16 by McMillin et al. listed in Section 3.2.

To our knowledge, this work represents the first application of PLIF to hypersonic flows, flows with vibrational nonequilibrium, and to pulsed flow facilities. The potential of PLIF for fundamental and applied studies of such flows is clear, and the results have already generated considerable interest in the hypersonic flow community.

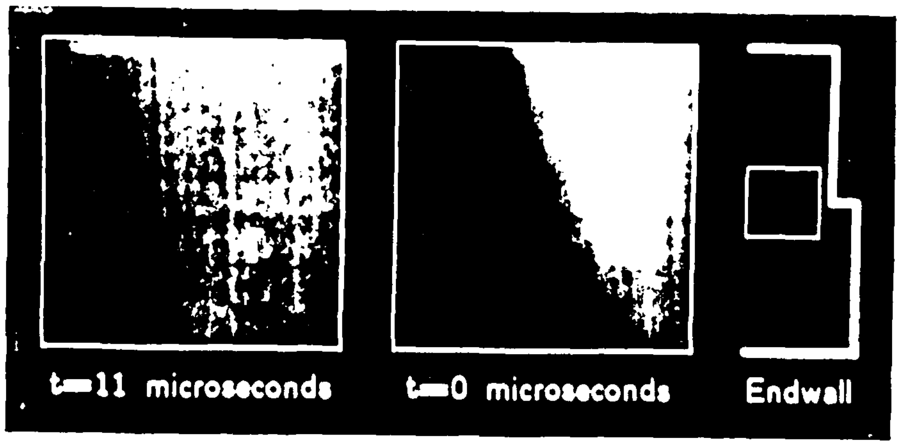
2.3 Temperature and Velocity Imaging in Supersonic Flows

In supersonic, compressible flows parameters of particular importance include temperature and velocity, and new methods of probing these quantities nonintrusively are urgently needed. PLIF schemes are especially attractive owing to the relatively high signal levels which can be achieved and the potential ability to acquire 2-d (and eventually 3-d) data sets in a single laser shot. Over about the past two years we have utilized a continuous flow, supersonic underexpanded jet facility to investigate PLIF concepts in supersonic flows. Recently, we have made particular progress on imaging temperature and velocity, and these results are summarized here.

With regard to temperature, good results have been obtained with two methods, referred to as the "single line" and "two-line" concepts. In both cases the measured signal (at each flowfield point or pixel) essentially reflects the population density in a specific quantum state of the species probed. With the single-line approach, the PLIF signal is generated by exciting only a single absorption line, using a single laser. In the two-line approach, two absorption lines are excited sequentially (with two lasers) and used to generate two separate PLIF images. In any case, the signal is proportional to both the mole fraction of the species and to the temperature-dependent Boltzmann fraction in the absorbing state. When the mole

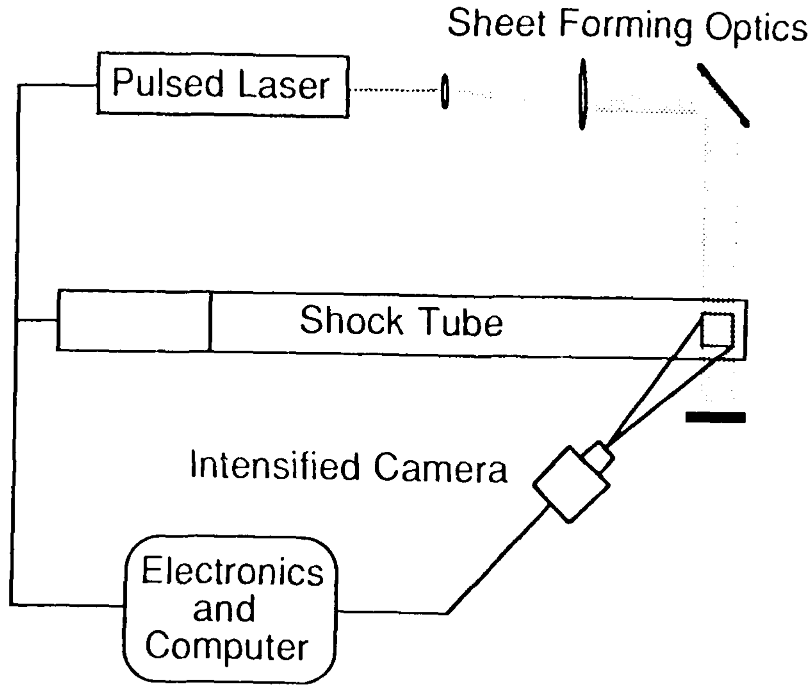
PLIF Imaging Used To Probe Nonequilibrium In Pulsed Supersonic Flows

Vibrational Nonequilibrium
Downstream of a Reflected Shock



0.5% Nitric Oxide in Nitrogen

T_2=1103 K, P_2=0.47 atm; T_5=1963 K, P_5=2.75 atm



- Images reveal shock wave structure and record nonequilibrium flowfield phenomena
- Technique permits species and quantum state-specific analysis
- Applicable to high enthalpy, hypersonic flow facilities (shock tunnels, arc jets)

Figure 5. First use of PLIF to probe nonequilibrium flows in a shock tube.

Hanson/Stanford

fraction is constant (i.e., a nonreacting flow), the PLIF signal variations across the flow essentially reflect temperature variations, and the single-line concept can be used (together with a simple calibration) to image temperature. For reacting flows (i.e., varying mole fractions), the two-line approach is necessary; in this case the ratio of the two signals is utilized, since that removes the dependence on mole fraction.

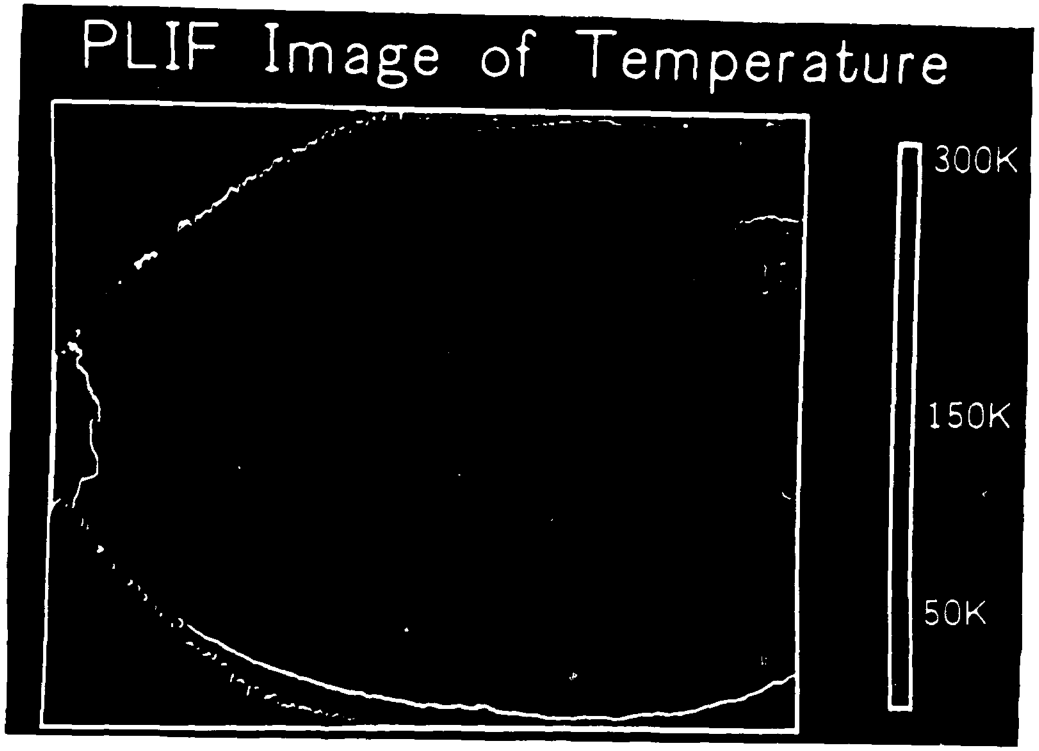
Our research has been concerned with exploring these ideas in flows containing NO, O_2 and OH. A sample result for NO in a strongly underexpanded jet (M = 7 at the Mach disk) is shown in Fig. 6. Although work remains to optimize the measurement strategy and to evaluate the absolute accuracy, the good signal levels obtained are a positive indication of the progress being made to develop this new measurement concept. To our knowledge, these are the first 2-d temperature images obtained by LIF in supersonic flows.

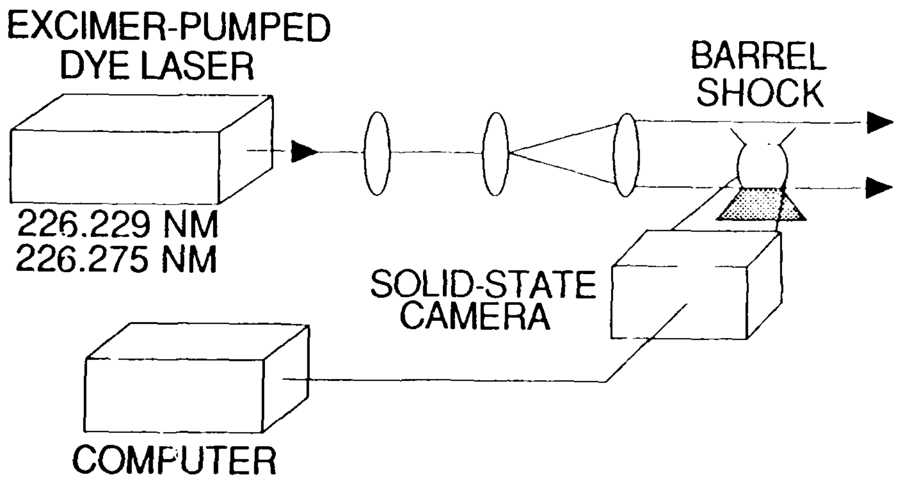
Efforts to image velocity have been based on the Doppler effect, which has the effect of shifting the relative frequencies of an illumination laser and a molecular absorption line when the gas is moving relative to the direction of laser illumination. When the laser is slightly nonresonant with the absorption line, changes in velocity (in the laser direction) result in a modulation of the light absorbed and, hence, in the quantity of fluorescence emitted. Of course other flowfield variations, such as density, can also affect the fluorescence signal, and so much of our research has been aimed at finding strategies which allow simple relationships between fluorescence signal and velocity. At present, our preferred strategy involves use of forward and counterpropagating laser beams, so that two PLIF images are generated with each laser pulse. This generates two PLIF signals at each flowfield point, and processing of these signals to find the relative change in the signal with laser direction, leads directly to the velocity component. An example of this work, using NO seeded at low levels in a supersonic underexpanded jet, is shown in Fig. 7. As shown in the right-hand panel, agreement between the measured and calculated velocities is quite good. Although this work is still in a preliminary stage, the results obtained are extremely promising in terms of developing a nonintrusive scheme for imaging velocity. Such a method will be especially important in future hypersonic flow research where traditional LDV methods are not feasible. For details, see the papers by Paul et al. listed in Section 3.2.

2.4 Concept for Simultaneous Imaging of Multiple Parameters

Eventually, it will be necessary to image multiple flowfield parameters simultaneously. This is particularly true for compressible flows where large variations in pressure, density, temperature, composition and velocity may occur. In addition, instantaneous correlations between fluctuating values of various flowfield parameters will be needed to validate computational models. Finally, the interpretation of fluorescence signals to infer species

2-D TEMPERATURE MEASUREMENTS IN SUPERSONIC FLOWS PLIF OF NO



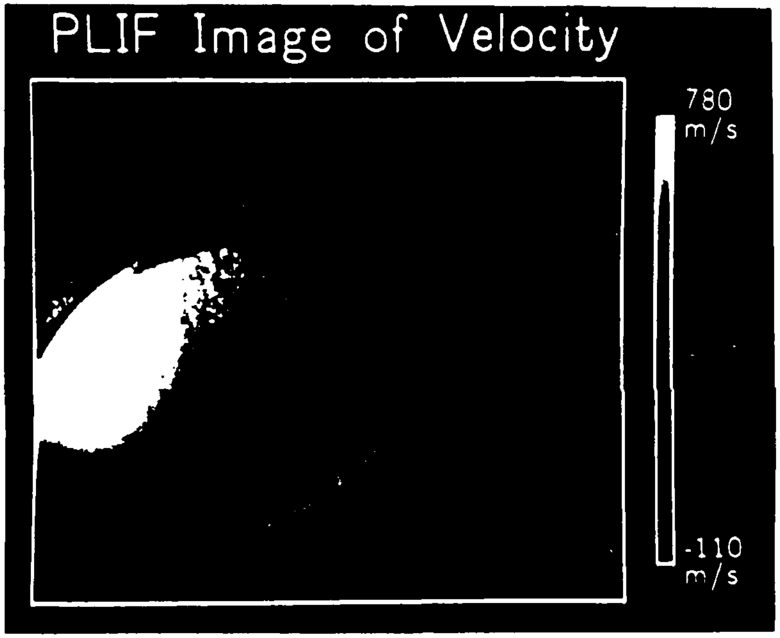


EXPERIMENTAL SCHEMATIC

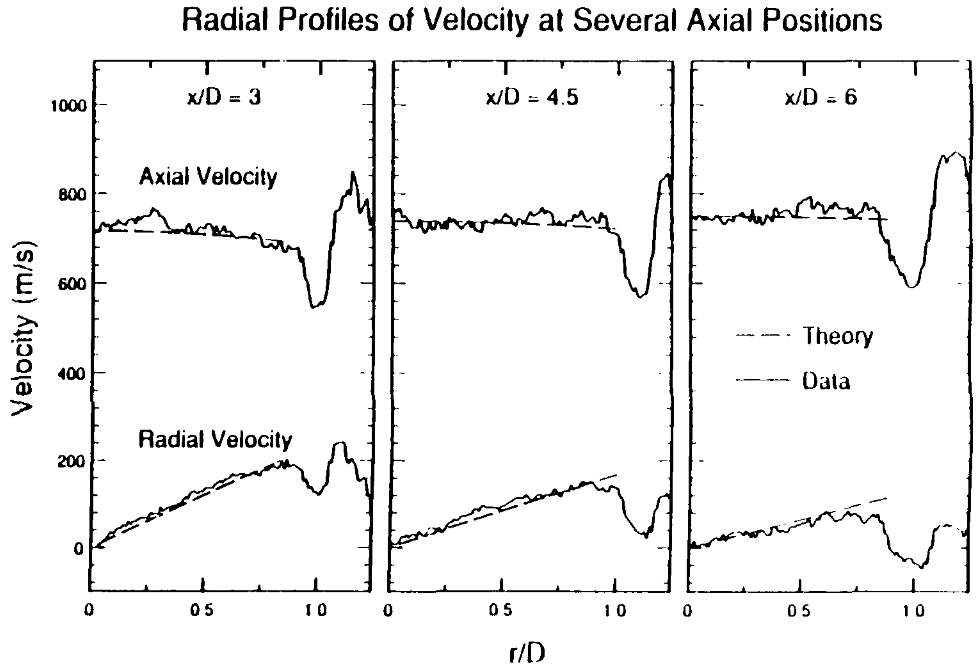
- 2-D imaging of temperature using PLIF of NO is a promising diagnostic for supersonic flows
- Both one-line and two-line techniques are being investigated
- Single-shot temperature measurements are possible
- Technique applicable to other species, including OH and O_2

Figure 6. PLIF imaging of NO temperature in a supersonic under expanded jet

NEW BROADBAND LASER CONCEPT ENABLES TIME-RESOLVED VELOCITY FIELD MEASUREMENTS



One-component velocity data for supersonic jet of N_2 with 0.5% NO



Comparison between measured and theoretical velocity components

- Eliminates need for particulate seeding
- Suitable for subsonic to hypersonic velocity measurements
- Potential for single-shot measurements of two velocity components
- Technique applicable to other molecular species, including OH, O_2, Na and Cu

composition may require knowledge of other parameters, such as temperature. Thus it is appropriate to begin consideration of PLIF schemes capable of yielding simultaneous results for multiple quantities.

During the past year, we have conceived one particularly promising scheme for combined imaging of velocity and temperature which merits mention. A schematic of the experimental arrangement required is shown in Fig. 8. A single pulse from an excimer laser is used to excite two separate tunable dye lasers, with an appropriate time delay between the two dye laser pulses. Each of the dye lasers is tuned to a separate absorption transition of the same species, e.g., NO, O_2 or OH. Furthermore, each of the dye lasers can be used to measure the gas velocity along a particular direction using the velocity scheme discussed in Section 2.3 above. The average of the forward and counterpropagating beam signals, for each laser, is essentially the signal for no Doppler shift; hence this is proportional to the fractional population of the species in the state monitored. The ratio of these average signals for the two wavelengths can be used to infer temperature from the ratio of Boltzmann fractions. Thus, by recording four separate PLIF images, all initiated with a single excimer laser pulse, information is available to infer two velocity components and temperature. The status of this work is that a second dye laser has recently been acquired and is undergoing installation to provide the laser portion of the schematic in Fig. 8. Assembly of a four-camera recording system awaits further funds, but two cameras will be made available to test the critical aspects of the measurement concept during the coming year.

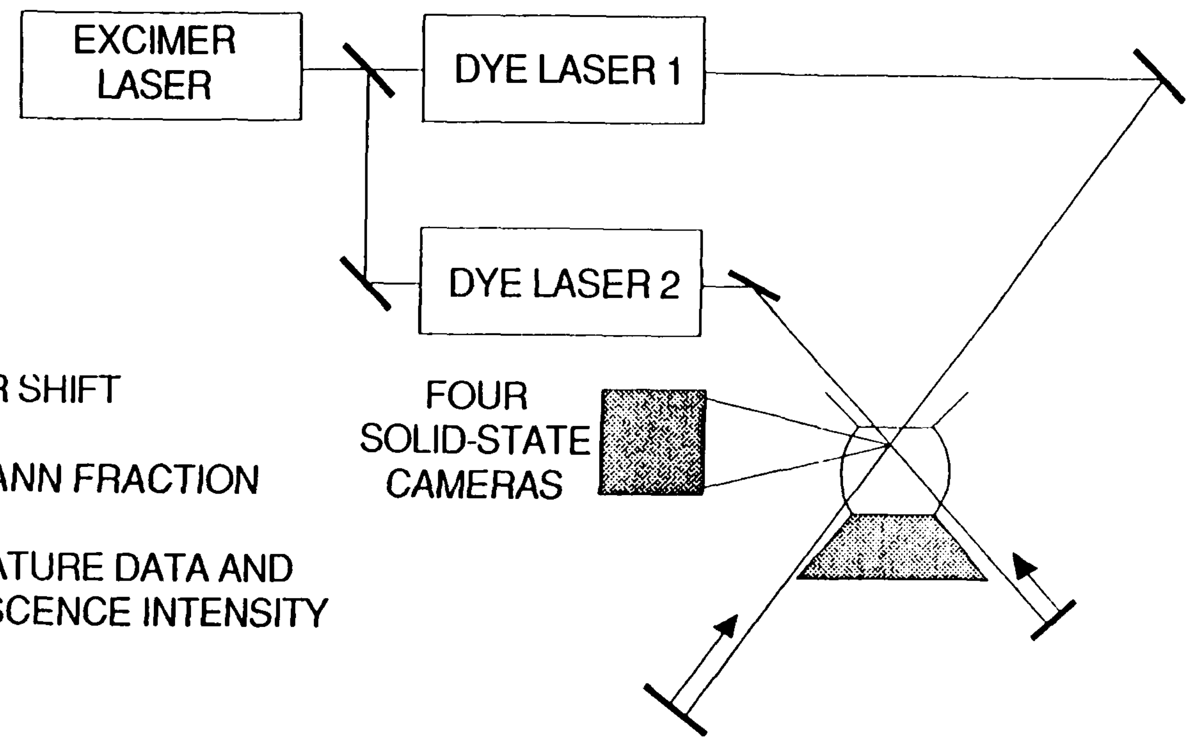
2.5 Digital Camera for High-Speed Imaging

The advancements made with PLIF as a diagnostic technique are tightly coupled to improvements in both laser sources and solid-state cameras, since the quality of the PLIF signal is often proportional to the spectral intensity of the laser source and the sensitivity of the camera. For this reason, a portion of our overall program is dedicated to advancing the state-of-the-art in lasers and solid-state cameras. A major part of this effort in the past two years has been aimed at building a new camera with the capability for light-efficient, high-speed recording of PLIF images. The basic system, shown schematically in Fig. 9, is comprised of three critical elements: (1) a commercial image converter camera (Imacon 790 from Hadland); (2) a large (4 inch dia) tapered fiber-optic bundle; and (3) a large, high-resolution CCD array (400x1200 pixels from Reticon).

The image converter camera provides the basic fast-framing capability, allowing recording of up to 50 million frames per second (depending on the plug-in module) in a flexible output format containing a variable number of images (16 is a typical choice, though a larger number of lower-resolution images is possible). The output appears on a phosphor

CONCEPT FOR SIMULTANEOUS 2-D IMAGING OF SPECIES, TEMPERATURE AND VELOCITY

- Will enable acquisition of T, P and two components of V in a single laser shot



VELOCITY	FROM	DOPPLER SHIFT
TEMPERATURE	FROM	BOLTZMANN FRACTION
PRESSURE	FROM	TEMPERATURE DATA AND FLUORESCENCE INTENSITY

- Single pump laser concept essential for synchronous measurements
- Amenable to several species (O_2, NO, OH, etc.)
- Multiparameter data sets needed to confirm fluid mechanics models

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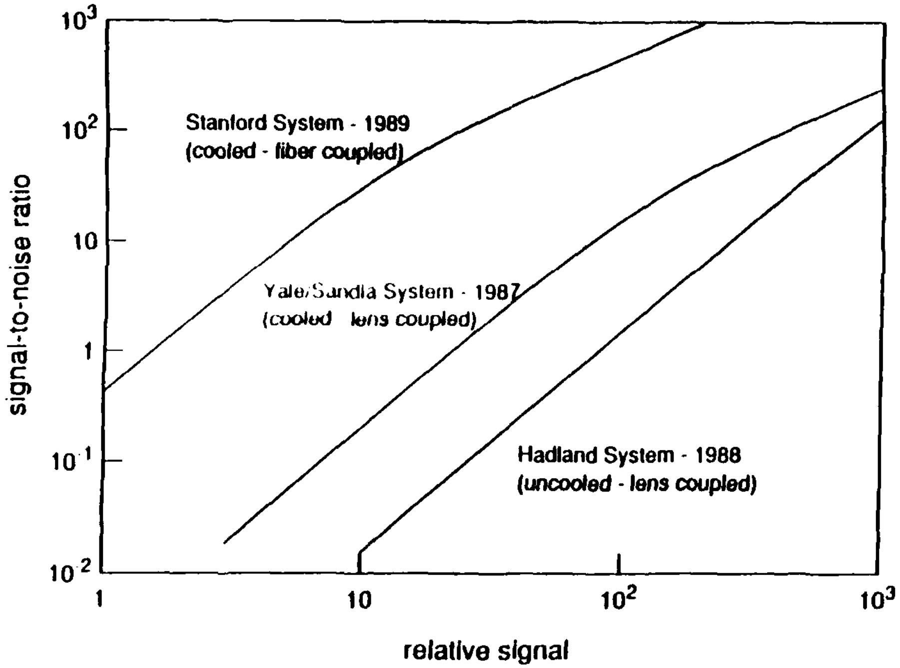
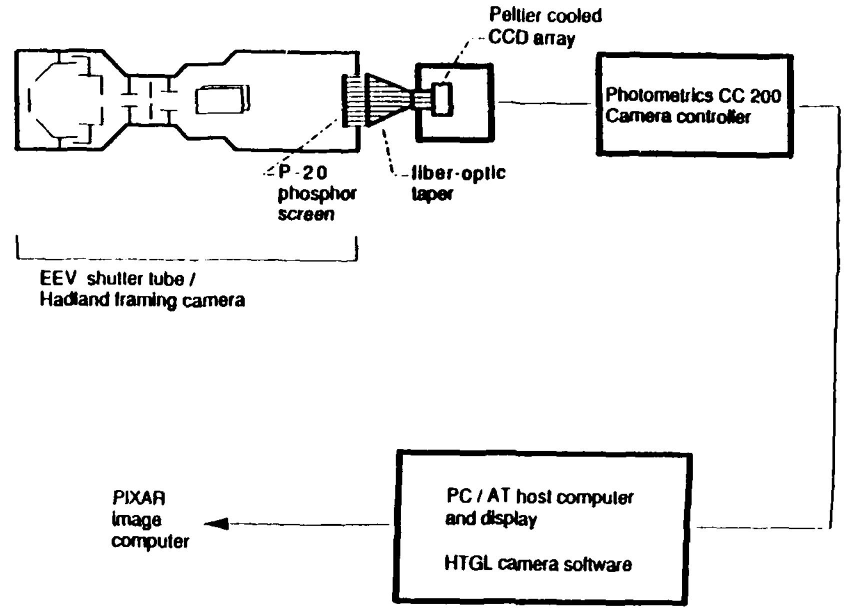
Figure 8. Concept for simultaneous PLIF imaging of multiple

NEW DIGITAL CAMERA FOR HIGH–SPEED PLIF IMAGING





- System operates at 2k - 20M frames/sec.
- 10^2x improvement in light throughput over commercial version.
- 10x improvement in spatial resolution.
- Use of CCD detection provides direct digitization of images.

Figure 9. New digital camera for high-speed PLIF imaging.

backplate and has traditionally been transferred to permanent storage with film. More recently, Hadland and others (e.g., a group from Yale and Sandia) have begun utilizing CCD arrays for recording the phosphor images. This has been done with lens coupling, however, which is much less efficient than transferring the images with a fiber bundle. Our approach to this problem has been to utilize a tapered fiber-optic bundle which matches (at one end) the output dimensions of the phosphor screen and (at the other end) the dimensions of the CCD array. This coupling scheme gives efficient transfer of light while maintaining high spatial resolution. The taper used is based on recently developed technology which allows production of bundles up to 4 inches in width. The last feature of the camera worth mention is the high-resolution CCD array, which contains 480,000 pixels. This large format is nearly ideal for transferring the Imacon output to a CCD array without degradation of spatial resolution. Of course, once the images are stored on the array, the experimenter is free of the problems inherent with film and has access to all the advantages of on-line data processing and display. The status of our new camera is that it is in the final stages of assembly. In particular, the direct coupling of a large fiber bundle to the large format CCD array has not previously been attempted and has required a special grinding procedure to give a surface shape to the bundle which matches that of the array.

Although the system has not yet been bench-tested, our calculations of expected system performance suggest significant improvements over existing systems, as shown in Fig. 9. For the light levels expected in a representative PLIF imaging experiment, we estimate an improvement of over two orders of magnitude in signal-to-noise ratio relative to the current commercial system.

We have defined two types of experiments which will utilize the new camera: (1) 3-d PLIF imaging; and (2) 2-d time histories of PLIF images. In the first case, the goal is to be able to record an "instantaneous" 3-d image of the quantity being monitored by PLIF. This will be accomplished using a relatively long-pulse tunable dye laser (2 microsecond pulse length) which is formed into a light sheet and swept rapidly across the flow of interest. The camera will record a sequence of snap-shot PLIF images during this brief period which taken together constitute a 3-d image with multiple 2-d planes. Such 3-d recording is important for several reasons, for example to allow examination of the directional dependence of properties such as dissipation. The second camera application, namely fast movies, is needed to allow study of very fast transients in a single 2-d plane. As an example, several plasma processes, such as laser ignition of combustion gases or electrical breakdown in electric propulsion devices, occur on very short time scales. These short times preclude use of current video cameras (which frame at up to a few hundred Hertz) and lasers (up to about 1 kilohertz) for time-resolving fast phenomena.

In summary, we expect this new camera to allow important extensions of PLIF into problems areas where, at present, laser diagnostics have not yet been developed. As excitation and recording times become shorter and shorter, we also expect new issues of laser-matter interactions to come into play and influence the direction of our research.

2.6 Plasma Diagnostics

During the past year we have increased our activity in the area of plasma diagnostics. Two diagnostic concepts are under study: laser wavelength modulation spectroscopy using cw ring dye lasers; and PLIF imaging employing either a tunable pulsed dye laser or a tunable narrow-bandwidth excimer laser. In this report we will summarize progress with PLIF imaging.

In order to investigate plasma diagnostics we have built two plasma facilities, a low-pressure plasma chamber and a high-pressure (atmospheric) plasma torch. Work during the past year has been conducted in the high-pressure RF-powered torch which offers continuous operation and good optical access to a wide range of plasma mixtures. A schematic of the experimental set-up used in given in Fig. 10. The arrangement is similar to that used with PLIF imaging in small-scale combustors, although the temperature and luminosity of the plasma gases are much higher. As an example of recent progress, Fig. 11 shows a single-shot PLIF image of NO. The experiment was carried out with an argon plasma, but high levels of NO are formed as the hot, ionized argon exits the torch and mixes with surrounding air. The formation of NO is induced by the dissociation of molecular oxygen into atomic oxygen and the subsequent reaction of O with molecular nitrogen in air. Thus the imaging of NO serves to mark the hot interface between the plasma and the surrounding air, much as a flame marks the interface between fuel and oxidizer in a diffusion flame. Aside from the important insight such images provide regarding the mixing of very hot and cool gases, these results represent a critical milestone in that they provide the first known PLIF images in a plasma environment. Now that we've learned to deal with problems such as electrical interference between the plasma and the recording camera and electronics, and the issue of very high background luminosity, the research will begin to emphasize measurements in the hot plasma core of the torch gases. This effort will involve new spectroscopy and physics beyond that encountered with combustion gases owing particularly to the presence of electrons and positive ions.

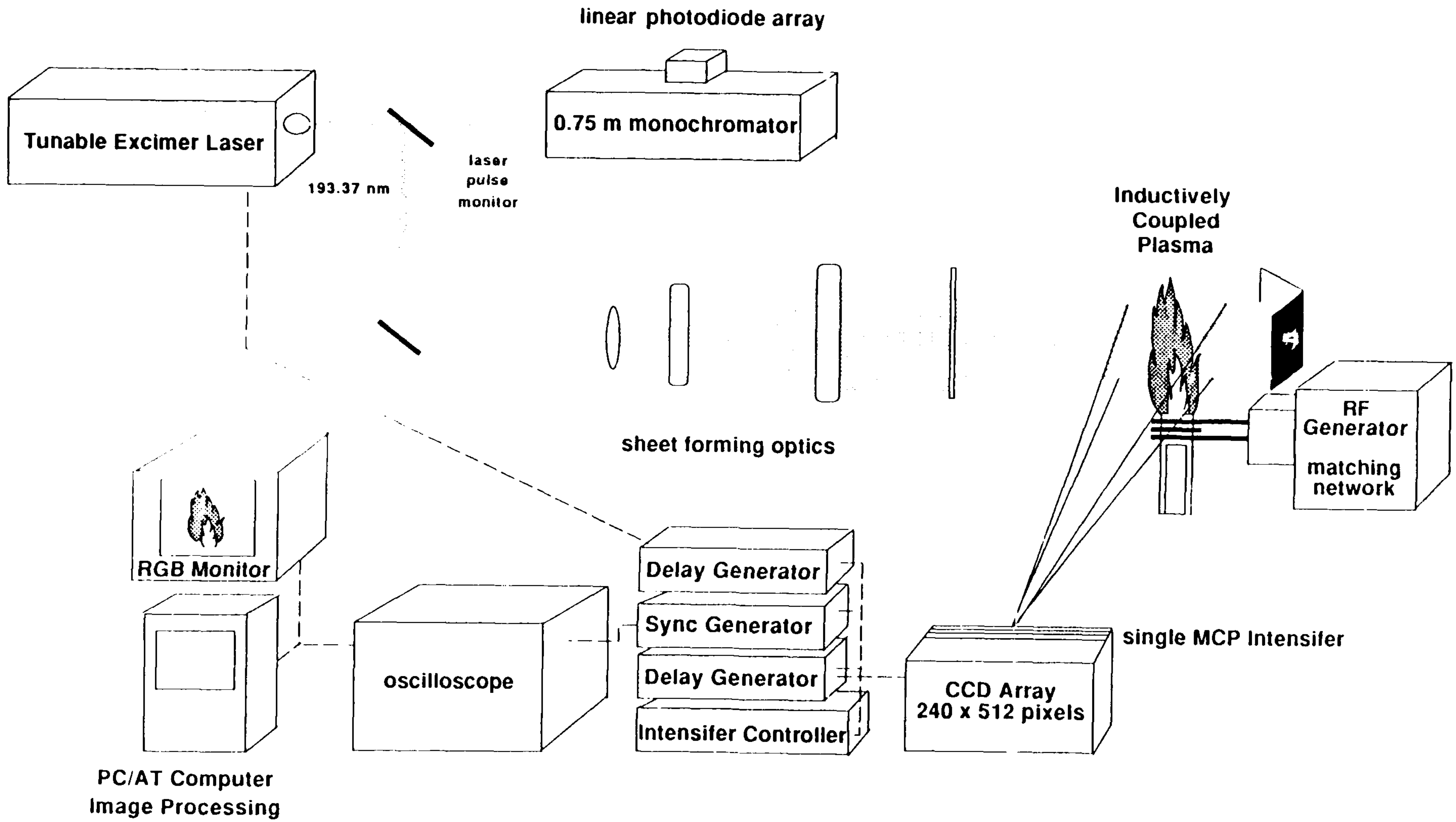


Figure 10: Experimental setup for PLIF Imaging of NO in an Inductively Coupled Plasma

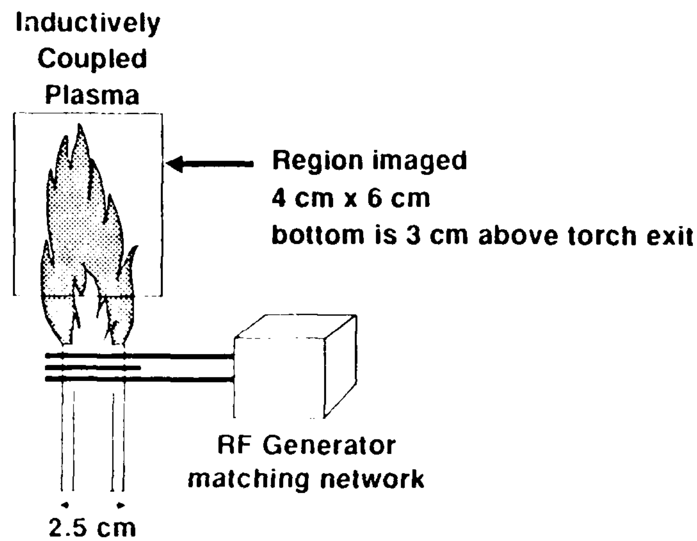


Figure 11: Single-shot PLIF image of NO in a RF powered Inductively Coupled Argon Plasma. Laser excitation wavelength is 193.37 nm. Broadband fluorescence detection is used.

2.7 Laser-Photolysis Shock Tube

The laser photolysis shock tube is a new concept for generating controlled levels of free radical species in a high temperature environment. In brief, a shock tube, operated in the reflected shock mode, is used to heat a gas sample to desired high temperature conditions and a pulsed excimer laser is used to illuminate portions of the gas with high intensity ultraviolet radiation. The UV photons act to photolylze a fraction of the initial molecules and thereby crease a controlled level of free radicals. Such a clean, instantaneous source of radicals is of scientific interest because it will enable more direct studies of spectroscopic and reaction kinetic parameters of these species than have been possible in the past. Fundamental studies of free radicals are relevant to combustion and propulsion science. The concept of a laser-photolysis shock originated in our laboratory, and the facility we've built is the first of its type. The facility is now operational and is being used in studies to develop absorption diagnostics for radical species and in kinetic studies of combustion reactions.

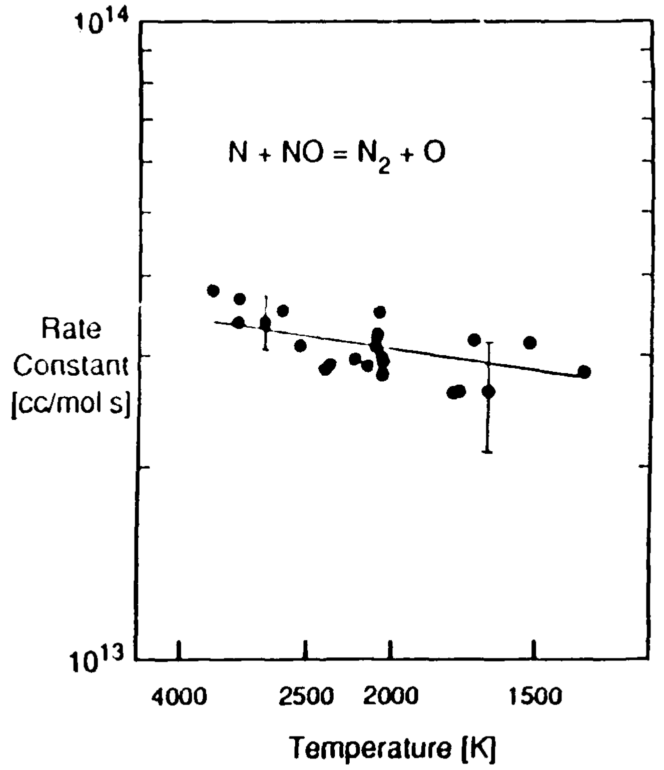
A schematic of the shock tube facility and a sample result from recent work are shown in Fig. 12. Note that the photolysis laser can produce bursts of photons at either 193 or 157 nm, the latter allowing photodissociation of bonds with dissociation energies of nearly 8 ev. Another unique element of this facility is the capability to detect low levels of several atomic and molecular species. Our sustained effort over the past 15 years to develop quantitative and sensitive detection schemes (and the associated spectroscopic codes) for combustion species now enables us to detect more than a dozen radicals. Although only two or three of these can be detected in a single experiment, since each measurement requires a separate source, the variety of species accessible now allows study of a large number of chemical reactions not previously investigated.

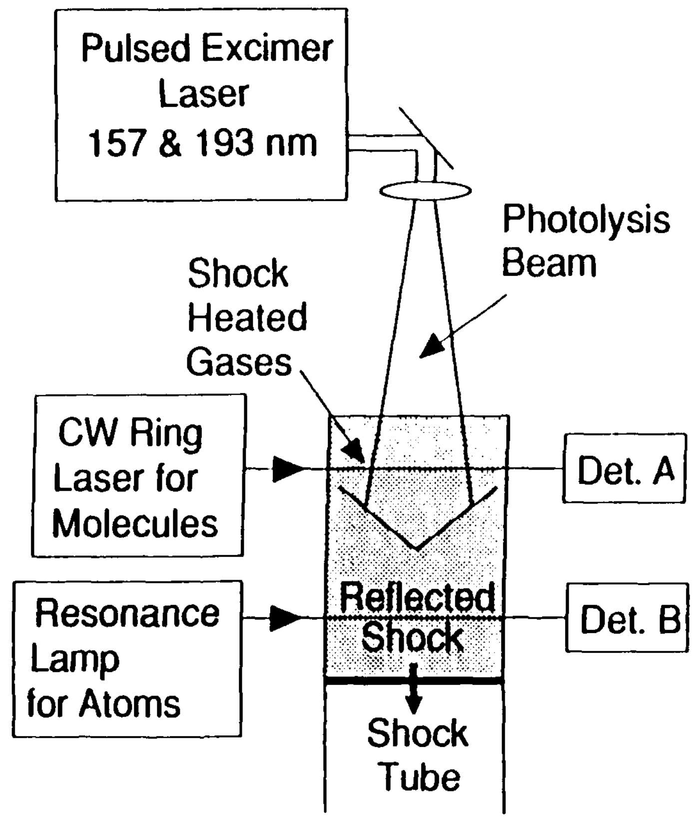
The sample result shown is for the reaction $N + NO \rightarrow N_2 + O$, one of the Zeldovich reactions which control the formation and removal of NO in combustion flows. The source of N was NO itself, partially photolyzed with 193 nm light. The subsequent decay of N was monitored using atomic resonance absorption spectroscopy (ARAS) at 120 nm. These results represent the first direct measurement of this rate coefficient in this temperature range.

2.8 CW UV Laser Absorption Diagnostics

Continuous-wave (cw) laser sources offer certain advantages for laser diagnostics. In our laboratory, for example, we've developed several diagnostics concepts based on cw single-mode ring dye lasers. Such lasers provide a continuous, low power source of nearly monochromatic light well suited for probing the details of spectral lineshapes and making

EXCIMER PHOTOLYSIS SHOCK TUBE ENABLES DIRECT MEASUREMENTS OF COMBUSTION REACTION RATES





<u>Approach</u>

- Shock tube generatures high temperature
- Laser photolyzes molecules
- Rate constant determined from absorption decay

- Ring laser for OH, CN, CH, NH, NH_2 , NO; resonance lamp for H, N, C, O
- Access to combustion reaction rates not previously obtainable

Figure 12. Schematic of laser photolysis shock tube and recent results for N + N_2 + O.

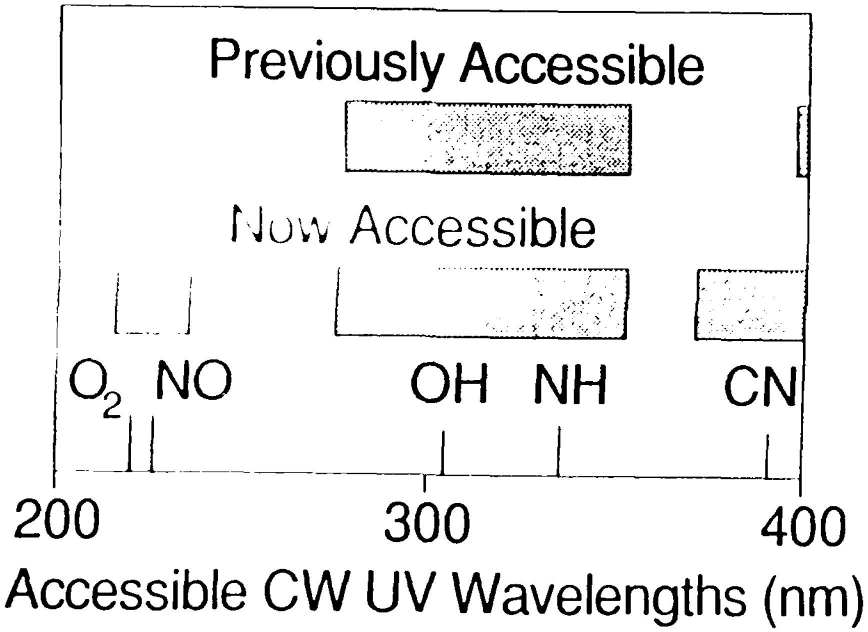
extremely quantitative species measurements based on absorption spectroscopy. These approaches are well suited to flows which are one-dimensional, so that conditions are uniform along a line-of-sight, such as the flow in a shock tube, shock tunnel or flat flame burner. During the past year there have been two aspects of our work in this area of note, described below.

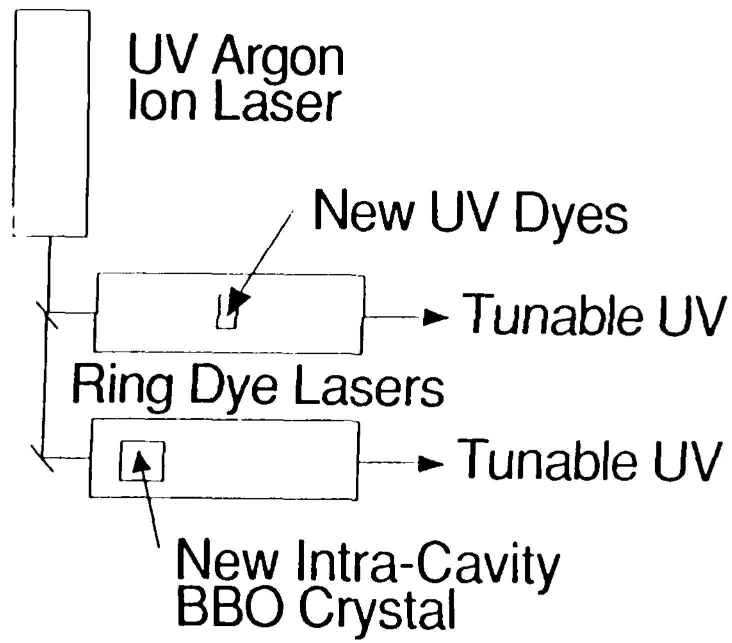
One of our accomplishments was to extend the wavelength operating range of our ring dye lasers into the UV, as indicated schematically in Fig. 13. Two approaches have been used, one involving recently developed dyes compatible with UV excitation and the other involving recently developed materials with improved frequency-doubling capability in the UV. Thus far we've been able to extend the spectral range of our laser into the important regions 220-230 nm and 380-405 nm, both of which are relevant owing to the presence of strong absorption bands of molecules of interest. For example, the use of BBO doubling in our ring (the first application of this technology to our knowledge) should allow the first high-resolution laser absorption studies of NO and O_2, two species of interest in scramjet combustor research. We hope to demonstrate this new measurement capability in the quantitative, sensitive detection of these species in shock tube experiments during this next year.

A second project of interest during this past year has involved a collaboration with nearby Ames Research Center to apply our cw laser absorption capabilities for OH in their hypersonic shock tunnel. The general approach is shown in Fig. 14. In brief, a cw ring dye laser, operating near 305 nm on an absorption line of OH, allows continuous recording of the level of OH throughout the duration of a shock tunnel test. The beam is split to allow observation at several stations simultaneously. Thus far, we've been able to demonstrate detection down to a few ppm of OH and thereby to guide current Ames research aimed at characterizing the performance of their shock tunnel. To our knowledge, this is the first application of laser absorption diagnostics in a hypersonic flow facility. Such measurements are likely to play an increasing and even essential role in the next generation of hypersonics research involving nonequilibrium flowfields.

NEW UV LASER EXTENDS CW DIAGNOSTIC CAPABILITIES FOR COMBUSTION SPECIES

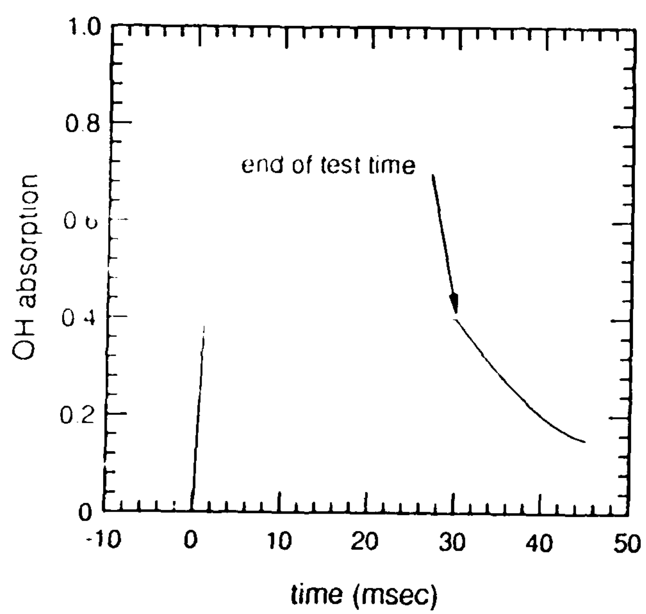
- Enables spectral studies of combustion species at elevated temperatures

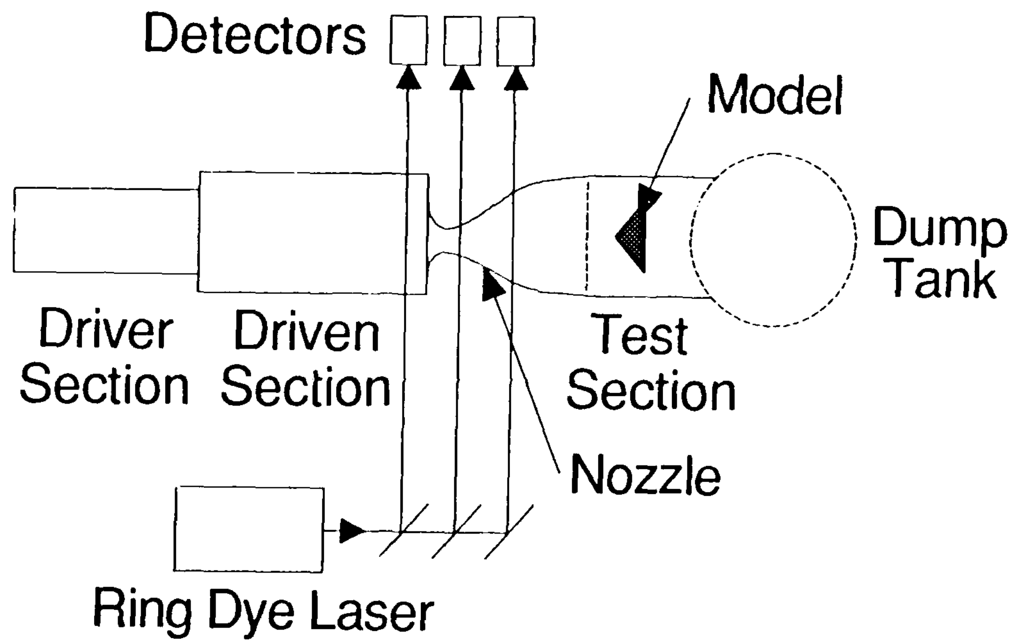




- Exalite UV dyes extend fundamental dye laser output below 400 nm
- First use of BBO extends doubled dye laser output to 215-235 nm
- Extends ability to study kinetics of combustion intermediates
- Important for both gas turbine and rocket fuel combustion

CW LASER ENABLES MEASUREMENTS OF SPECIES CONCENTRATION IN HYPERSONIC SHOCK TUNNEL





- Initial experiments performed in NASA Ames M=10 shock tunnel
- Enables quantitative measurements in non-equilibrium flowfields
- Enables improved characterization of facility performance

Figure 14. Schematic of set-up for cw laser absorption diagnostic in NASA Ames hypersonic shock tunnel.

3.0 PRESENTATIONS AND PUBLICATIONS

3.1 Presentations (10/88 -- 10/89)

1. R. K. Hanson, "Laser-Based Spectroscopic Measurements in High Temperature Gases," invited paper presented at 1988 Annual Meeting of the Optical Society of America, Santa Clara, CA, Oct. 31-Nov. 4, 1988.

2. R. K. Hanson, "Laser-Based Fluorescence Imaging of Gaseous Flows," invited paper presented at ICALEO '88, Santa Clara, Oct. 31-Nov. 4, 1988.

3. I. van Cruyningen, A. Lozano and R. K. Hanson, "Planar Laser-Based Fluorescence Imaging of Flowfield Scalars," presented at ICALEO '88, Santa Clara, CA, Oct. 31-Nov. 4, 1988.

4. J. D. Mertens, A. Y. Chang, R. K. Hanson and C. T. Bowman, "Decomposition Kinetics of HNCO at High Temperatures," paper 88-64 at Western States Section/The Combustion Institute, Laguna Beach, CA, October 1988.

5. A. J. Dean, D. F. Davidson and R. K. Hanson, "Development and Application of CH Laser Absorption Diagnostic for Shock Tube Kinetic Studies," paper 88-91 at Western States Section/The Combustion Institute, Laguna Beach, CA, October 1988.

6. P. H. Paul, J. M. Seitzman, M. P Lee, B. McMillin and R. K. Hanson, "PLIF Imaging in Supersonic Flows Using Planar Laser-Induced Fluorescence," paper WC-8 at ILS-IV, Atlanta, GA, October 2-6, 1988.

7. D. S. Baer, A. Y. Chang, P. H. Paul and R. K. Hanson, "Plasma Diagnostics Using PLIF and Wavelength Modulation Spectroscopy," paper E-14 presented at 42st Gaseous Electronics Conference, Minneapolis, October 17-21, 1988.

8. R. K. Hanson, "Applications of PLIF Imaging to Supersonic Flows," invited paper presented at 54th National Aero-Space Plane Symposium, NASA Langley Res. Ctr., Hampton, VA, October 18-21, 1988.

9. P. H. Paul, J. M. Seitzman, M. P. Lee, B. K. McMillin, and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging in Supersonic Flows," paper AIAA-89-0059 at AIAA 27th Aerospace Sciences Meeting, Reno, January 9-12, 1989.

10. A. J. Dean, D. F. Davidson and R. K. Hanson, "C-Atom ARAS Diagnostic for Shock Tube Studies of C + $N_2 \rightarrow CN + N$," presented at 17th International Symposium on Shock Tubes and Waves, Lehigh, PA, July 1989; to appear in Shock Tubes and Waves, ed. Y. Kim (Am Inst. Phys.).

11. D. F. Davidson, D. C. Snell and R. K. Hanson, "Shock Tube Excimer Photolysis and the Measurement of N Atom Kinetic Rates," presented at 17th International Symposium on Shock Tubes and Waves, Lehigh, PA, July 1989; to appear in Shock Tubes and Waves, ed. Y. Kim (Am Inst. Phys.).

12. B. K. McMillin, M. P. Lee, P. H. Paul and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging in a Shock Tube," paper AIAA-89-2566 at 25th AIAA/ASME/ASCE/SAE Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.

13. P. H. Paul, J. Seitzman and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging in Supersonic Flows," paper AIAA-89-2912 at 25th AIAA/ASME/ASCE/SAE Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.

14. I. van Cruyningen, A. Lozano and R. K. Hanson, "Quantitative Laser-Induced Fluorescence Imaging of Flowfields," presented at Electronic Imaging West '89, Pasadena, CA, April 10-13, 1989; published in conference proceedings.

15. D. F. Davidson, A. J. Dean, A. Y. Chang and R. K. Hanson, "Shock Tube Combustion Studies Using Optical Dilagnostics and Excimer Photolysis," to be presented at 1989 AIChI Annual Meeting, San Francisco, CA, Nov. 5-10, 1989.

16. E. C. Rea, Jr., A. Y. Chang and R. K. Hanson, "Motional Narrowing in Spectral Lines of OH," paper 89-45 at Fall WSS/CI Meeting, Livermore, CA, October 23-24, 1989.

17. D. F. Davidson, K. Kohse-Hoinghaus, A. Y. Chang and R. K. Hanson, "A Pyrolysis Mechanism for Ammonia," paper 89-95 at Fall WSS/CI Meeting, Livermore, CA, October 23-24, 1989; submitted to Int. J. of Chem. Kinetics, July 1989.

18. J. D. Mertens, A. Y. Chang, D. A. Masten, R. K. Hanson and C. T. Bowman, "A Shock Tube Study of the Reactions of NH with NO, O and O_2," paper 89-96 at Fall WSS/CI Meeting, Livermore, CA, October 23-24, 1989.

19. D. A. Masten, R. K. Hanson and C. T. Bowman, "Shock Tube Study of $H + O_2 \rightarrow OH + O$ Using OH Laser Absorption," paper 89-97 at Fall WSS/CI Meeting, Livermore, CA, October 23-24, 1989.

20. P. H. Paul, M. A. Cappelli and R. K. Hanson, "Imaging of Laser Produced Plasmas Using Planar Laser-Induced Fluorescence," presented at Int. Laser Science Conference, ILS 4, Stanford, CA, Aug. 28-31, 1989

21. A. Gicquel, M. Cappelli, A. Y. Chang and R. K. Hanson, "Study of NH_3 Plasma/Titanium Surface Interaction: Measurement of NH Radical Production and Dissociation Kinetics by Laser Absorption Spectroscopy," presented and published in Conference Proceedings of Int. Plasma Chemistry Conference (ILPC), Beri, Italy, Sept. 1989.

22. M. P. Lee, P. H. Paul and R. K. Hanson, "2-D Velocity Measurements in Supersonic Flow Using Pulsed Planar Laser-Induced Fluorescence," to be presented at 1989 ASME Winter Meeting, Symp. of Flow Visualization, San Francisco, CA, December 10-15, 1989.

23. I. van Cruyningen, A. Lozano and R. K. Hanson, "Interpretation of Planar Laser-Induced Fluorescence Flowfield Images," to be presented at 1989 ASME Winter Meeting, Symp. of Flow Visualization, San Francisco, CA, December 10-15, 1989.

24. B. K. McMillin, M. P. Lee, J. L. Palmer, P. H. Paul and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging of Shock-Heated Flows in Vibrational Nonequilibrium," to be presented at 1989 ASME Winter Meeting, Symp. of Flow Visualization, San Francisco, CA, December 10-15, 1989.

25. R. K. Hanson, "Development of Planar Laser-Induced Fluorescence Imaging for Supersonic Flows," invited paper to be presented at AIAA 28th Aerospace Sciences Meeting, Reno, NV, Jan. 1990.

26. J. M. Seitzman, A. Ungut, P. H. Paul and R. K. Hanson, "PLIF Imaging and Analysis of OH Structure in a Turbulent Nonpremixed H_2–Air Flame," to be presented at AIAA 28th Aerospace Sciences Meeting, Reno, NV, Jan. 1990.

27. I. J. van Cruyningen, A. Lozano and R. K. Hanson, "Computer Rendering of Planar Fluorescence Flowfield Images," to be presented at AIAA 28th Aerospace Sciences Meeting, Reno, NV, Jan. 1990.

28. I. J. van Cruyningen, A. Lozano and R. K. Hanson, "Interpretation of Planar Laser-Induced Fluorescence Flowfield Images," paper W-6/TSF-7 at International Turbulent Shear Flow Conference, Stanford, CA, Aug. 21-23, 1989.

29. I. van Cruyningen, A. Lozano and R. K. Hanson, "Quantitative Planar Laser-Induced Fluorescence Imaging of Turbulent Jets," to be presented at 42nd annual meeting of the Fluid Dynamics Section of APS, NASA Ames Res. Center, CA, Nov. 19-21, 1989.

30. P. H. Paul, J. M. Seitzman, A. Ungut and R. K. Hanson, "Structural OH Imaging in a Turbulent H_2–Air Diffusion Flame," to be presented at 42nd annual meeting of the Fluid Dynamics Section of APS, NASA Ames Res. Center, CA, Nov. 19-21, 1989.

3.2 Publications (10/88 – 10/89)

1. U. Vandsburger, J. M. Seitzman and R. K. Hanson, "Visualization Methods for the Study of Unsteady Non-Premixed Flame Structure," Comb. Sci. and Technology **56**, 455-461 (1988).

2. E. C. Rea, Jr., A. Y. Chang and R. K. Hanson, "Rapid Laser Wavelength Modulation Spectroscopy Applied as a Fast Temperature Measurement Technique in Hydrocarbon Combustion," Applied Optics **27**, 4454-4464 (1988).

3. B. Hiller, P. H. Paul and R. K. Hanson, "Image-Intensified Photodiode Array as a Fluorescence Detector in CW-Laser Experiments," Review of Scientific Inst., in press.

4. R. K. Hanson and J. M. Seitzman, "Planar Fluorescence Imaging in Gases," Chap. 15, pp. 219-132, in *Handbook of Flow Visualization*, ed. W.-J. Yang, Hemisphere Pub. Corp., 1989.

5. E. C. Rea, Jr., A. Y. Chang, and R. K. Hanson, "Collisional Broadening of the $A^2\Sigma^+ \leftarrow X^2\Pi(0,0)$ Band of OH by H_2O and CO_2 in Atmospheric-Pressure Flames," J. Quant. Spectrosc. and Radiat. Trans. **41**, 29-42 (1989).

6. D. F. Davidson, A. Y. Chang and R. K. Hanson, "Laser Photolysis Shock Tube for Combustion Kinetics Studies," *Twenty-Second Combustion Symposium (International) on Combustion*, The Combustion Institute, 1877-1885 (1988).

7. B. Hiller and R. K. Hanson, "Properties of the Iodine Molecule Relevant to Absorption/Fluorescence Experiments in Gas Flows" Experiments in Fluids, in press.

8. K. Kohse-Höinghaus, D. F. Davidson and R. K. Hanson, "Quantitative NH2 Laser-Absorption Diagnostic for Shock Tube Kinetics Studies," J. Quant. Spectrosc. and Radiat. Trans. **42**, 1-17 (1989); also poster paper presented at 22nd Symposium (International) on Combustion, Seattle, Aug. 15-19, 1988.

9. A. Y. Chang and R. K. Hanson, "Measurements of Absorption Lineshapes in the $A^3\Pi_i \leftarrow X^3\Sigma$ (0,0) Band of NH in the Presence of Ar Broadening," J. Quant. Spectrosc. and Radiat. Trans. **42**, 207-217 (1989).

10. P. H. Paul, M. P. Lee and R. K. Hanson, "Molecular Velocity Imaging Using a Pulsed Laser Source," Optics Letters **14**, 417-419 (1989).

11. P. H. Paul, J. M. Seitzman, M. P. Lee, B. K. McMillin, and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging in Supersonic Flows," reprint AIAA-89-0059 at AIAA 27th Aerospace Sciences Meeting, Reno, January 9-12, 1989.

12. A. J. Dean and R. K. Hanson, "Development of a Laser Absorption Diagnostic for Shock Tube Studies of CH," J. Quant. Spectrosc. and Radiat. Trans., in press.

13. A. J. Dean, D. F. Davidson and R. K. Hanson, "C-Atom ARAS Diagnostic for Shock Tube Studies of $C + N_2 \rightarrow CN + N$," presented at 17th International Symposium on Shock Tubes and Waves, Lehigh, PA, July 1989; to appear in Shock Tubes and Waves, ed. Y. Kim (Am Inst. Phys.).

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15. D. F. Davidson, A. Y. Chang, K. Kohse-Höinghaus and R. K. Hanson, "High Temperature Absorption Coefficients of O_2, NH_3 and H_2O for Broadband ArF Excimer Laser Radiation," J. Quant. Spectrosc. and Radiat. Trans.**42**, 267-278 (1989).

16. B. K. McMillin, M. P. Lee, P. H. Paul and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging in a Shock Tube," reprint AIAA-89-2566 at 25th AIAA/ASME/ASCE/SAE Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.

17. P. H. Paul, J. Seitzman and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging in Supersonic Flows," reprint AIAA-89-2912 at 25th AIAA/ASME/ASCE/SAE Joint Propulsion Conference, Monterey, CA, July 10-12, 1989.

18. I. van Cruyningen, A. Lozano and R. K. Hanson, "Quantitative Laser-Induced Fluorescence Imaging of Flowfields," presented at Electronic Imaging West '89, Pasadena, CA, April 10-13, 1989; published in conference proceedings.

19. J. D. Mertens, A. Y. Chang, R. K. Hanson and C. T. Bowman, "Reaction Kinetics of NH in the Shock Tube Pyrolysis of HNCO," Int. J. of Chem. Kinetics, in press.

20. P. H. Paul, I. van Cruyningen, R. K. Hanson and G. Kychakoff, "High Resolution Digital Flowfield Imaging of Jets," submitted to Experiments in Fluids, April 1989.

21. J. Haumann, J. M. Seitzman and R. K. Hanson, "Quantitative Two-Dimensional Imaging of CO in Combustion Gases Using LIF," in *Instrumentation for Combustion and Flow in Engines*, D. F. G. Durao, J. H. Whitelaw and P. O. Witze, eds., proceedings of meeting held in Vimeira, Portugal, September 1987, *NATO Adv. Study Inst. Ser.* **154E**, 141-150 (1989).

4.0 PERSONNEL

Individual researchers supported by the program are listed below. All the work has been carried out in the High Temperature Gasdynamic Laboratory, in the Department of Mechanical Engineering, under the supervision of Professor R. K. Hanson.

Research Associates

Dr. P. H. Paul

Dr. D. F. Davidson

Dr. K. Kohse-Höinghaus (visiting scientist sponsored by DFVLR)

Graduate Research Assistants

Jerry Seitzman

Mike Lee

Larry Cohen

Ike van Cruyningen

Doug Baer

Brian McMillin

Albert Chang

Dave Hofeldt

5.0 SIGNIFICANT INTERACTIONS

In addition to the interactions associated with the presentations and publications listed in Section 3, we have had numerous visitors to our laboratory during this past year. Foreign visitors have come from Germany, France, Holland, Great Britain, South Africa, Canada, Spain and Japan; industrial and national laboratory visitors have included representatives from Rocketdyne, Physical Sciences, Lockheed, Boeing, Metrolaser, AEDC, NASA Ames, NASA Lewis, NIST, Sandia, Lawrence Livermore, General Motors and Ford. We have also had visits from technical monitors from AFOSR and ONR. Professor Hanson has given several invited presentations on our AFOSR-sponsored diagnostics research to industrial laboratories and government groups.

Interest in the potential application of advanced laser diagnostics to various practical problems, especially associated with hypersonic flow and the NASP program, is clearly growing, and the AFOSR-sponsored program at Stanford has achieved a high level of recognition for its contributions to this field. I believe that the increased interest we are witnessing is the leading edge of technology transfer of laser diagnostics to industrial and government labs. A sustained research effort, at Stanford and other university labs active in diagnostics research, will be required, however, to ensure that this technology transfer is successful. In particular, I believe that collaborative programs involving exchange visits between Stanford and industrial/government lab personnel, should be promoted.