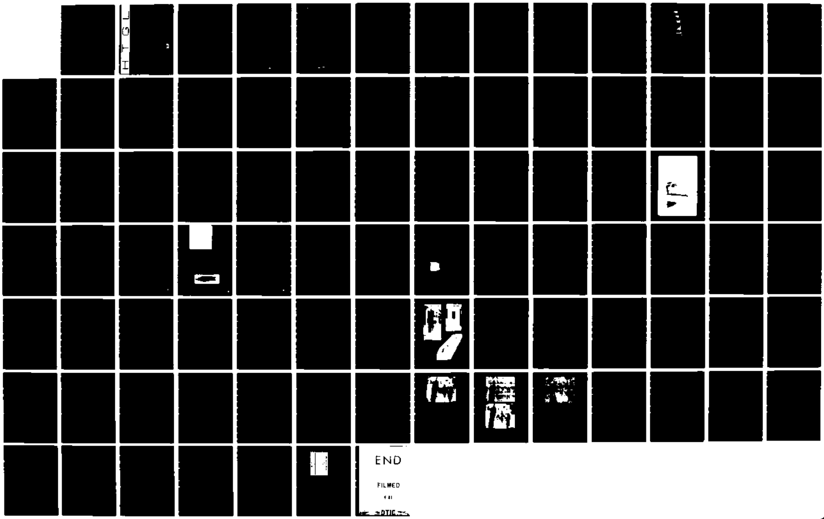
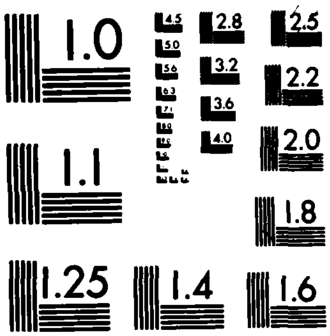
AD-A131 814 ADVANCED DIAGNOSTICS AND INSTRUMENTATION FOR CHEMICALLY REACTIVE FLOW SYS. (U) STANFORD UNIV CA HIGH TEMPERATURE GASDYNAMICS LAB R K HANSON ET AL. NOV 82 1/1

UNCLASSIFIED AFOSR-TR-83-0705 F49620-80-C-0091 F/G 20/5 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

AFOSR-TR- 83-0705

Final Scientific Report

on

ADVANCED DIAGNOSTICS AND INSTRUMENTATION

FOR CHEMICALLY REACTIVE FLOW SYSTEMS

Contract F49620-80-C-0091

AD A131814

Prepared for

Air Force Office of Scientific Research

For the Period

September 1, 1980 to September 30, 1982

"Original contains color plates: All DTIC reproductions will be in black and white."

Submitted by

R. K. Hanson, Project Director
D. Baganoff
C. T. Bowman
R. L. Byer
B. J. Cantwell
L. Hesselink
S. A. Self

Approved for public release; distribution unlimited.

HIGH TEMPERATURE GASDYNAMICS LABORATORY
Mechanical Engineering Department
Stanford University

83 08 19 086

Final Scientific Report

on

ADVANCED DIAGNOSTICS AND INSTRUMENTATION FOR CHEMICALLY REACTIVE FLOW SYSTEMS

Contract F49620-80-C-0091

Prepared for

Air Force Office of Scientific Research

For the Period

September 1, 1980 to September 30, 1982

Submitted by

R. K. Hanson, Project Director

D. Baganoff
C. T. Bowman
R. L. Byer
B. J. Cantwell
L. Hesselink
S. A. Self

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFOSR-TR- 83-0705	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Advanced Diagnostics and Instrumentation for Chemically Reactive Flow Systems	5. TYPE OF REPORT & PERIOD COVERED Final Scientific Report 9/1/80 to 9/30/82
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. K. Hanson	8. CONTRACT OR GRANT NUMBER(s) F49620-80-C-0091
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford University Department of Mechanical Engineering Stanford, California 94305	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2308/A1
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NA Building 410 Bolling AFB, D. C. 20332	12. REPORT DATE November 1982
	13. NUMBER OF PAGES 82
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Combustion	Temperature	Spectroscopy	Fiberoptic	Visible
Flame	Infrared	Turbulent	Probe	Ultraviolet
Diagnostics	Absorption	Fluorescence	Evaporation	Visualization
Laser	Raman	Reacting	Flow	Fast-Scanning

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Progress is reported at the completion of two years of an interdisciplinary program to investigate and establish modern diagnostic techniques for application to reacting flows. Project areas include: (1) optical probes for species measurements employing tunable ultraviolet, visible and infrared laser sources; (2) coherent anti-Stokes Raman spectroscopy (CARS) for temperature and velocity measurements in a supersonic jet; (3) computed absorption tomography for species measurements in a plane; (4) particle sizing

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) techniques, especially for rocket exhausts; (5) fast-response temperature monitor, based on line-reversal concepts; (6) quantitative flow visualization, including temporally and spatially resolved species measurements in a plane using laser-induced fluorescence; (7) multiple-point velocity visualization; (8) application of modern diagnostics to a two-dimensional reacting shear layer; (9) development of measurement techniques and a novel facility for investigations of droplet evaporation in turbulent flows; (10) holographic display techniques for 3-D visualization of flowfield data; (11) spatially resolved laser absorption spectroscopy using optical Stark shifting; and (12) fast-scanning dye laser for measurements of species, temperature and fundamental spectral parameters.

TABLE OF CONTENTS

1.0 INTRODUCTION

Progress is reported after two years of an interdisciplinary program to innovate modern diagnostic techniques for application to reacting flows. Project areas are: (1) optical probes for species measurements employing tunable ultraviolet, visible and infrared laser sources; (2) coherent anti-Stokes Raman spectroscopy (CARS) for temperature and velocity measurements in a supersonic jet; (3) computed absorption tomography system for species measurements in a plane; (4) particle sizing techniques, especially for rocket exhausts; (5)fast-response temperature monitor, based on line-reversal concepts; (6) quantitative flow visualization, including temporally and spatially resolved species measurements in a plane using laser-induced fluorescence; (7) multiple-point velocity visualization; (8) application of modern diagnostics to a two-dimensional reacting shear layer; (9) development of measurement techniques and a novel facility for investigations of droplet evaporation in turbulent flows; (10) holographic display techniques for 3-D visualization of flowfield data; (11) spatially resolved laser absorption spectroscopy using optical Stark shifting; and (12) fast-scanning dye laser for measurements of species, temperature and fundamental spectral parameters.

2.0 PROJECT SUMMARIES

Included in this section are summaries of progress in each of twelve project areas. Each project summary contains the following subsections: (a) Introduction; (b) Scientific Merit; (c) Status Report; (d) Publications and Presentations; (e) Personnel; (f) References. Additional descriptions of this work may be found in the cited publications and in our previous interim scientific report (November 1981).

2.1 Tunable Laser Optical Probes

Introduction

The establishment of techniques for the measurement of gaseous species concentrations with temporal and spatial resolution is widely recognized as critical to the development and validation of fundamental models of turbulent combustion and computational models of practical combustors. Techniques completely suitable for these purposes are not yet available, although research is actively underway in several laboratories to develop these measurement tools. The approach which we have pursued at Stanford emphasizes absorption or fluorescence spectroscopy as the physical sensing process with tunable lasers as radiation sources. This general approach shows considerable promise for use in a variety of diagnostic configurations, depending on measurement requirements, and for a wide range of species and concentrations.

Our early work in this area led to the first use of tunable infrared diode lasers to measure species concentrations and gas temperature in combustion gases. The techniques developed are both sensitive and simple. In most cases the laser wavelength is rapidly modulated and fully resolved absorption line profiles are recorded. An important advantage of this approach is its insensitivity to the presence of particles or droplets in the flow, which may be particularly important in the analysis of droplet or solid fuel combustion flows. Over the past few years, various experiments were conducted demonstrating the high accuracy and sensitivity possible with this technique for NO, CO and temperature in steady, fluctuating and sooting flames. This work also included the first known measurements of fundamental line strength and lineshape parameters of infrared absorption lines under combustion conditions.

Our success with tunable diode laser spectroscopy, which is suitable only for infrared-active species, then prompted us to initiate similar research utilizing recently developed tunable ring dye lasers. This laser, which provides tunable, cw single-frequency output at ultraviolet and visible wavelengths, is better suited for detection of free radical species. The diode and dye laser research were complementary in that both radical species and stable infrared-active species could then be monitored.

More recently, we have directed our work towards alleviating the major objection to absorption spectroscopy as a diagnostic technique, namely that the spatial resolution is often insufficient. Our approach has been to design "optical probes", devices based either on absorption or fluorescence which can be conveniently inserted into combustion flows (even when optical access is limited) to yield the required spatial resolution. Our objective, in simple terms, is to combine most of the advantages of tunable laser absorption spectroscopy — accuracy, simplicity, species specificity, discrimination against particulates, and temporal resolution — with the advantages of probe techniques, particularly spatial resolution and applicability to remote operation in devices with poor optical access.

Scientific Merit

This research seeks to provide sensitive, species specific techniques for monitoring gaseous concentrations in reacting flows with high spatial and temporal resolution. Satisfactory techniques have not previously been available, and hence the development of such devices has the potential for significant impact on various scientific and engineering aspects of combustion and propulsion. Our approach is unique in that it seeks to combine recently developed tunable laser sources with novel absorption or fluorescence probes. The resulting diagnostics are well suited to meet a variety of practical measurement requirements, especially including remote measurements in hostile environments and in systems with limited optical access.

An important side-benefit of our use of optical fibers to link specialized laser sources with remotely located combustors has been to demonstrate the feasibility of multiplexing these laser sources with experiments at several different locations. This approach has obvious advantages in situations where several measurements of the same type are needed and also where different researchers in separate laboratories wish to share a common facility, much as they would share a large common computer facility.

Status Report

For purposes of this discussion, the work can be divided into two topics: (1) tunable diode laser absorption spectroscopy; and (2) tunable dye laser absorption/fluorescence spectroscopy.

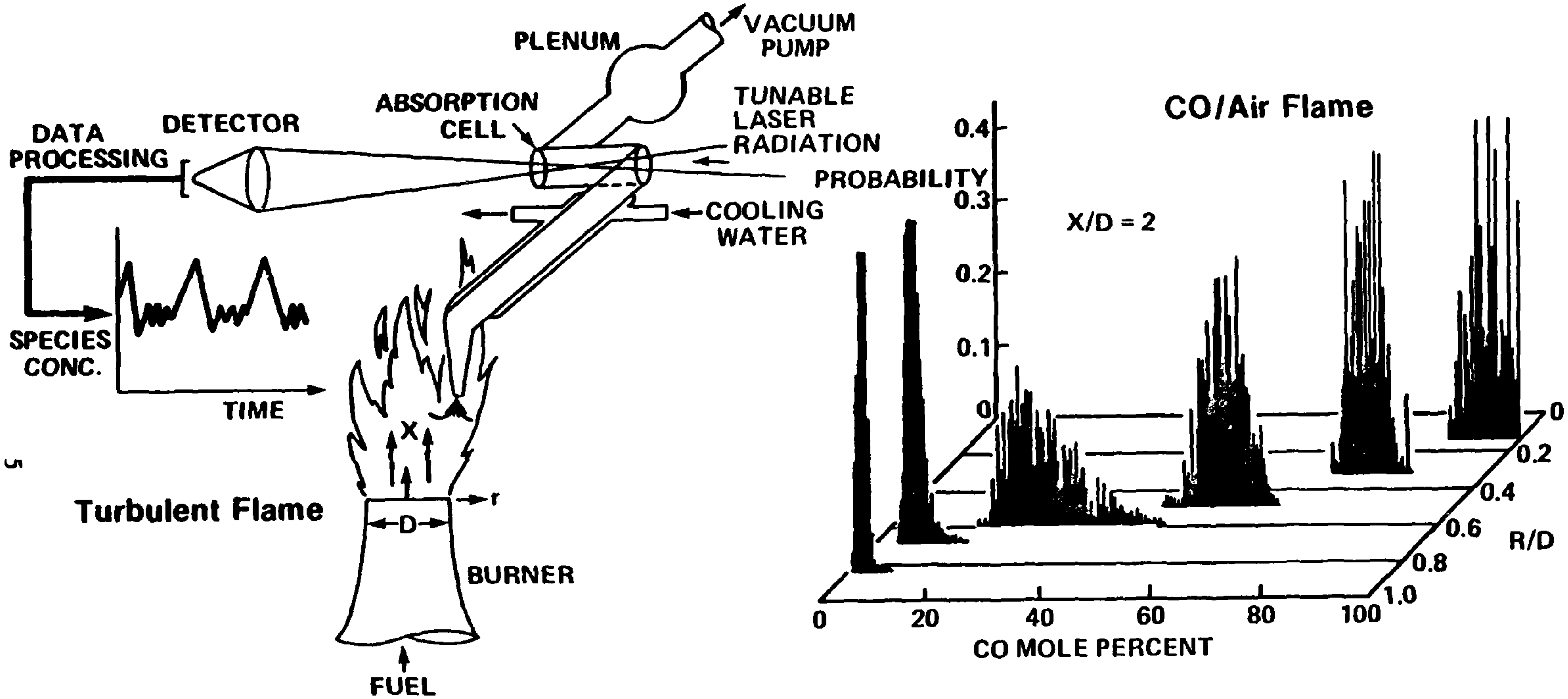
(1) Tunable Diode Laser Spectroscopy

During the past 24 months two absorption probes have been constructed and tested: a fast sampling probe with a miniature in-line absorption cell (see Fig. 1); and a variable path length, intrusive absorption probe with miniature optical elements (see Fig. 2). These probes are designed to be used in conjunction with tunable diode lasers and to yield continuous (real-time) spatially resolved species measurements. To our knowledge, these are the first such probes to have been developed, and they offer prospects for a variety of pioneering basic and applied measurements in combustion flows. We have also worked to develop an absorption probe with a fiber optic link between the probe and the tunable diode laser source, but have not yet found a suitable fiber material.

Detailed descriptions of the probes and their electro-optical arrangements have been published (see the papers cited below by Schoenung and Hanson). The probes were validated in a steady, flat flame

SPECIES DETERMINATION

TUNABLE-LASER ABSORPTION SAMPLING PROVIDES CONTINUOUS (REAL-TIME) SPATIALLY RESOLVED SPECIES MEASUREMENTS



- **First Continuous-Time Species Measurements in Flame Yield Critical Data for Turbulence Flames.**

Hanson/Stanford Univ

Figure 1. Laser absorption sampling probe for temporally and spatially resolved combustion measurements.

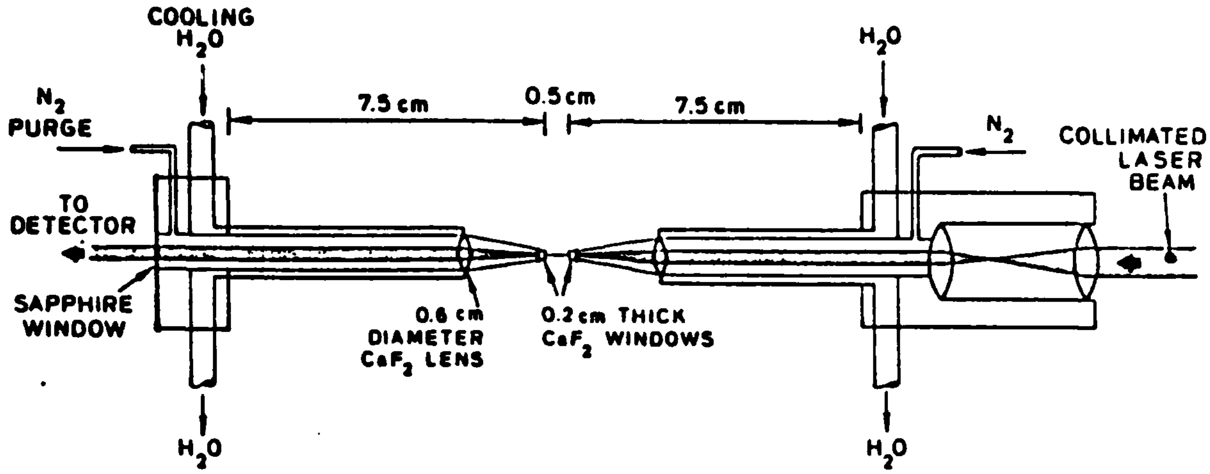


Figure 2. Schematic of infrared optical probe for spatially resolved <u>in situ</u> measurements.

burner and then applied to a turbulent CO/air diffusion flame. consisted of real-time recordings of transmitted laser intensity with the laser tuned to the center of a specific CO absorption line and with the probe fixed at a point in the flame zone. These data were fed to a computer which digitized the data and converted each point to a value for the CO mole fraction. Subsequently the data were manipulated to obtain probability distribution functions, as shown in Fig. 1, or to obtain a frequency power spectrum.

To our knowledge, these are the first continuous-time molecular species measurements obtained in a flame. The simplicity and accuracy of these techniques, and their applicability to a variety of infrared-active species and to a range of dirty and hostile combustion flows, suggests that this diagnostic will find use in future basic and applied studies of combustion.

(2) Tunable Dye Laser Spectroscopy

Three separate projects have been completed, the first two utilizing a tunable cw ring dye laser and the third utilizing a tunable pulsed dye laser source:

1. Optical absorption/fluorescence probe for flame measurements using a cw dye laser.

2. Laser absorption measurements in a shock type using a remotely located cw dye laser.

3. Optical fluorescence probe for measurements in an enclosed combustor using a pulsed dye laser.

A schematic of the first-generation cw absorption/fluorescence probe system is shown in Fig. 3; an improved probe configuration is shown in Fig. 4. A typical recording of the probe, applied to Na measurements in an open flame is shown in Fig. 5. Important accomplishments of this project on cw laser optical probes includes: (a) successful testing of an absorption/fluorescence probe employing 1 mm fused silica fibers to monitor Na; (b) development of hardware/software to modulate the laser wavelength, transmit data to a microcomputer and process data to recover fully resolved absorption line profiles, species concentration and temperature; (c) assembly and testing of an extra-cavity frequency doubling scheme to shift laser output into the UV. The use of a combined absorption/fluorescence probe is very attractive from the point of view

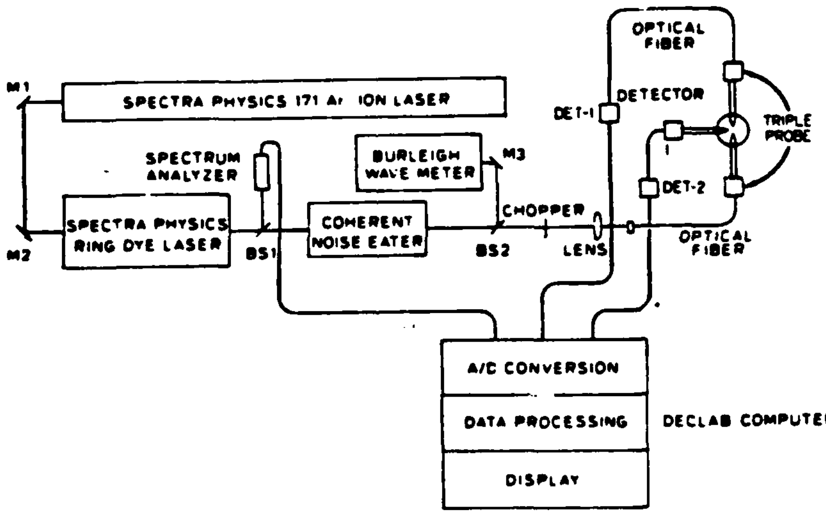


Figure 3. First-generation system for remote, spatially defined sensing of chemical species using cw tunable laser absorption/-fluorescence spectroscopy.

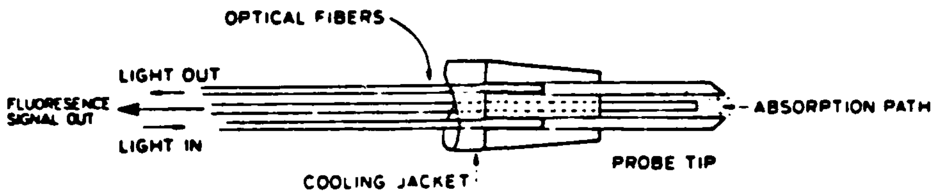


Figure 4. Alternative probe configuration.

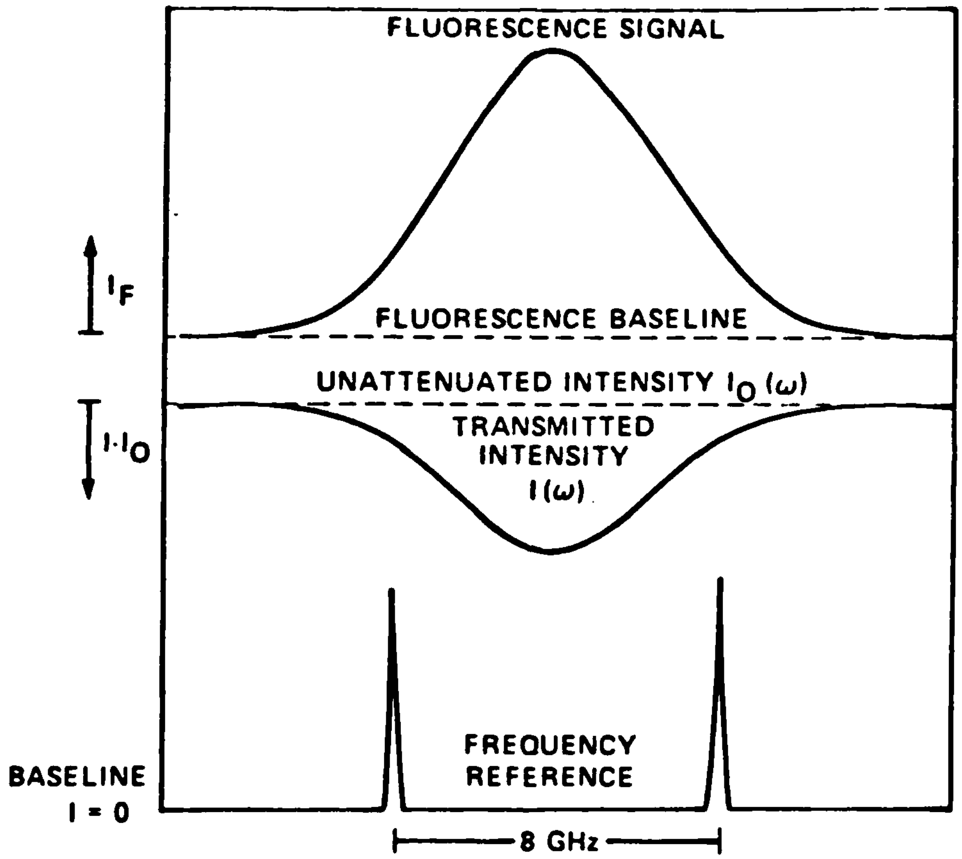


Figure 5. Typical trace with tunable cw laser and absorption/-fluorescence probe applied to measure Na above a flat flame burner.

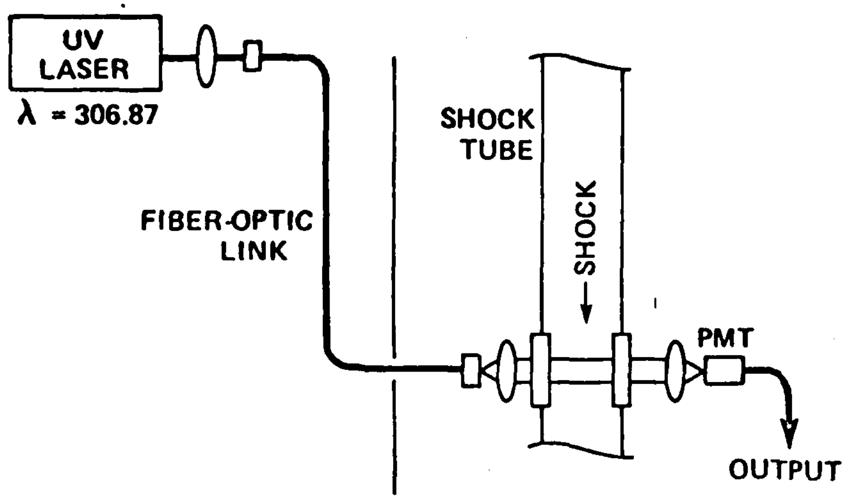
of accuracy, simplicity and dynamic range. At high species concentrations, absorption can be used directly, while also providing a convenient calibration for the fluorescence measurement. At low concentrations, fluorescence can be used to extend the range of the instrument well below the detection limit based on absorption.

Use of the cw dye laser and a fiber optic link (37 meters long) to measure OH by absorption in a shock tube is highlighted in Fig. 6. The laser is located in a separate building, and in this case is fixed at a specific wavelength at the center of an OH line at 306 nm. Because the oscillator strength and lineshape function are well known, the measured fractional absorption is directly related to the OH number density, thereby providing a very accurate and sensitive determination of OH. This first use of a tunable cw dye laser to measure species concentrations in a shock tube represents an important advance for the field of chemical kinetics. The fact that the measurement was made remotely proves the feasibility of running multiple experiments, in different locations, with the same laser source.

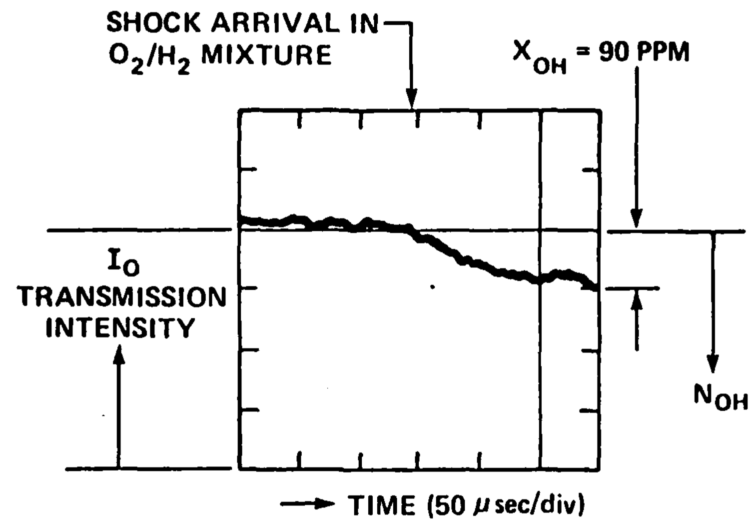
Finally, our third and most recent laser probe project is highlighted in Fig. 7. Our goal was to build a fiber optic probe suitable for fluorescence measurements in enclosed combustors with poor optical access. Use of pulsed laser illumination leads to a detection limit of about 20 ppm for OH with the present configuration. Fibers are 1 mm diameter of fused silica, polished at both ends. Smaller fibers could not tolerate the large energy flux (1 mJ/pulse) from the laser. Although probes of this type may perturb the flow, we believe they have important potential to provide radical species information in a wide range of flows where limited optical access prohibits the use of conventional laser-induced fluorescence.

REMOTE OPTICAL ACCESS/SPECIES DETERMINATION

SUCCESSFUL USE OF FIBER-OPTIC LINK TO REMOTELY MEASURE CONCENTRATIONS IN HOSTILE ENVIRONMENT



Fiber-Optic Link to Shock Tube Experiment



Rate of OH Increase used to Establish Kinetic Relationship

- Fiber Optics Established as a Solution to Optical-Window Degradation Problems.
- Capability Established to Accurately Determine Spectroscopic Parameters under Hostile Conditions.

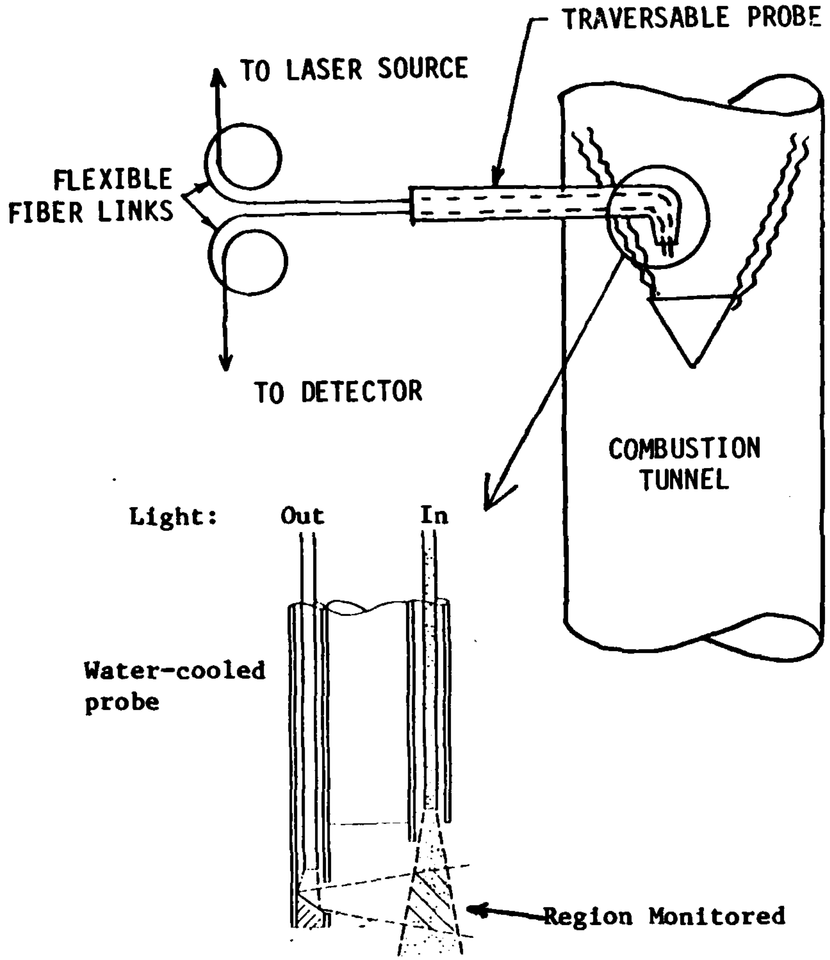
Hanson/Stanford Univ

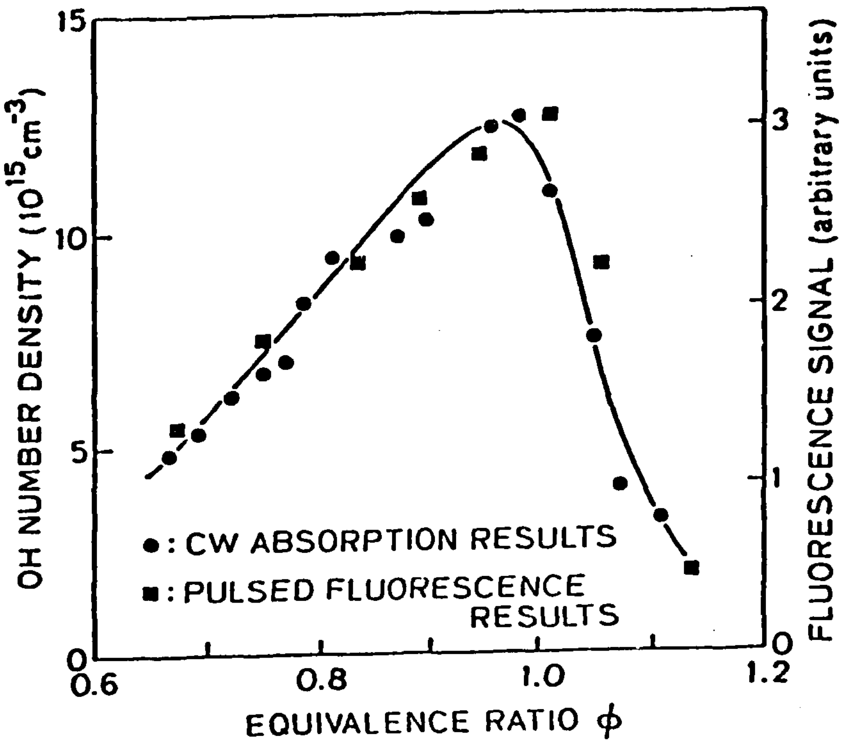
Figure 6. Schematic of system used to monitor OH in a shock tube using a remotely located, frequency-doubled cw ring dye laser.

REMOTE DETECTION OF SPECIES

USE OF FIBER-OPTIC PROBE WITH LASER-EXCITED FLUORESCENCE

ENABLES REMOTE MEASUREMENTS IN ENCLOSED COMBUSTOR SYSTEMS





RESULTS FOR CH_4/AIR FLAME

- FIBER OPTIC LINKS ALLOW REMOTE PLACEMENT OF LASER/DETECTION/ANALYSIS SYSTEMS
- TRAVERSABLE PROBE SUITED FOR USE IN SYSTEMS WITH LIMITED OPTICAL ACCESS
- LASER-EXCITED FLUORESCENCE GIVES SENSITIVE (PPM) DETECTION OF REACTIVE SPECIES (E.G., OH, CH, CN)
- TECHNIQUE SUCCESSFULLY DEMONSTRATED FOR OH
- FIRST SOLUTION TO PROBLEM OF RADICAL SPECIES MEASUREMENTS IN COMBUSTORS WITHOUT OPTICAL ACCESS

Figure 7. Fiberoptic fluorescence probe for use with tunable pulsed lasers and enclosed combustors.

Publications and Presentations

Presentations

1. G. Kychakoff and R. K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," presented at 1981 Los Alamos Conference on Optics, April 1981.

2. S. M. Schoenung and R. K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," presented at 1981 Conference on Lasers and Electro-Optics (CLEO), Washington, June 1981.

3. S. M. Schoenung and R. K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in Turbulent CO Diffusion Flame," paper WSS/CI 81-33 at Western States Section, Combustion Institute meeting, Phoenix, October 1981.

4. G. Kychakoff and R. K. Hanson, "Tunable Laser Absorption/-Fluorescence Fiberoptic Probe for Combustion Measurements," at Western States Section, Combustion Institute meeting, Phoenix, October 1981.

5. G. Kychakoff, R. D. Howe and R. K. Hanson, "Spatially Resolved Combustion Measurements Using Crossed-Beam Saturated Absorption Spectroscopy," paper THM2 at CLEO '82, Phoenix, Az., April 14-16, 1982.

6. M. A. Kimball-Linne, G. Kychakoff, R. K. Hanson and R. A. Booman, "A Fiber-Optic Fluorescence Probe for Species Measurements in Combustors," paper 82-50 at Western States Section, Combustion Institute meeting, Livermore, Ca., October 11-12, 1982.

Publications

1. S. M. Schoenung and R. K. Hanson, "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques," Combustion Science and Technology 24, 227-237 (1981).

2. S. M. Schoenung and R. K. Hanson, "Laser Absorption Sampling Probe for Spatially and Temporally Resolved Combustion Measurements," Applied Optics 21, 1767-1771 (1982).

3. S. M. Schoenung and R. K. Hanson, "Temporally and Spatially Resolved Measurements of Fuel Mole Fraction in a Turbulent CO Diffusion Flame," 19th Symposium (Internation) on Combustion, The Combustion Institute, in press (1982).

4. G. Kychakoff and R. K. Hanson, "Optical Fiber Probe Using Tunable Laser Absorption Spectroscopy for Combustion Measurements," The Los Alamos Conference on Optics, 81, D. L. Liebenbert, Ed., Proc. SPIE 288, 236 (1982).

5. R. K. Hanson, S. Salimian, G. Kychakoff and R. A. Booman, "Shock Tube Absorption Measurements of OH Using a Remotely Located Dye Laser," Applied Optics, submitted for publication (Nov. 1982).

6. G. Kychakoff, M. A. Kimball-Linne and R. K. Hanson, "Fiber-Optic Absorption/Fluorescence Probes for Combustion Measurements," to be published.

7. G. Kychakoff, M. A. Kimball-Linne and R. K. Hanson, "Laser-Based Fiber-Optic Probes for Combustion Measurements," to be published.

Personnel

Ronald K. Hanson	Professor (Research), Mechanical Engineering
George Kychakoff	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1982)
Susan Schoenung	Graduate Student, Mechanical Engineering (Ph.D. awarded in June 1982)
Mark A. Kimball-Linne	Graduate Student, Mechanical Engineering (Ph.D. expected in September 1983)
Richard A. Booman	Research Engineer, Mechanical Engineering

2.2 Coherent Anti-Stokes Raman Spectroscopy (CARS)

Introduction

The objective of this aspect of the program is to develop innovative laser spectroscopic techniques to supersonic and combustive turbulent flows. During the past two years we have successfully utilized the Coherent Anti-Stokes Raman Spectroscopic (CARS) technique to measure temperature and velocity in a supersonic jet flow. We have, in addition, used the same apparatus to measure density in the flow by an induced fluorescence technique. This latter measurement method led to a joing Applied Physics/Astronautics Ph.D. research program that culminated in the Ph.D. of Jim McDaniel.

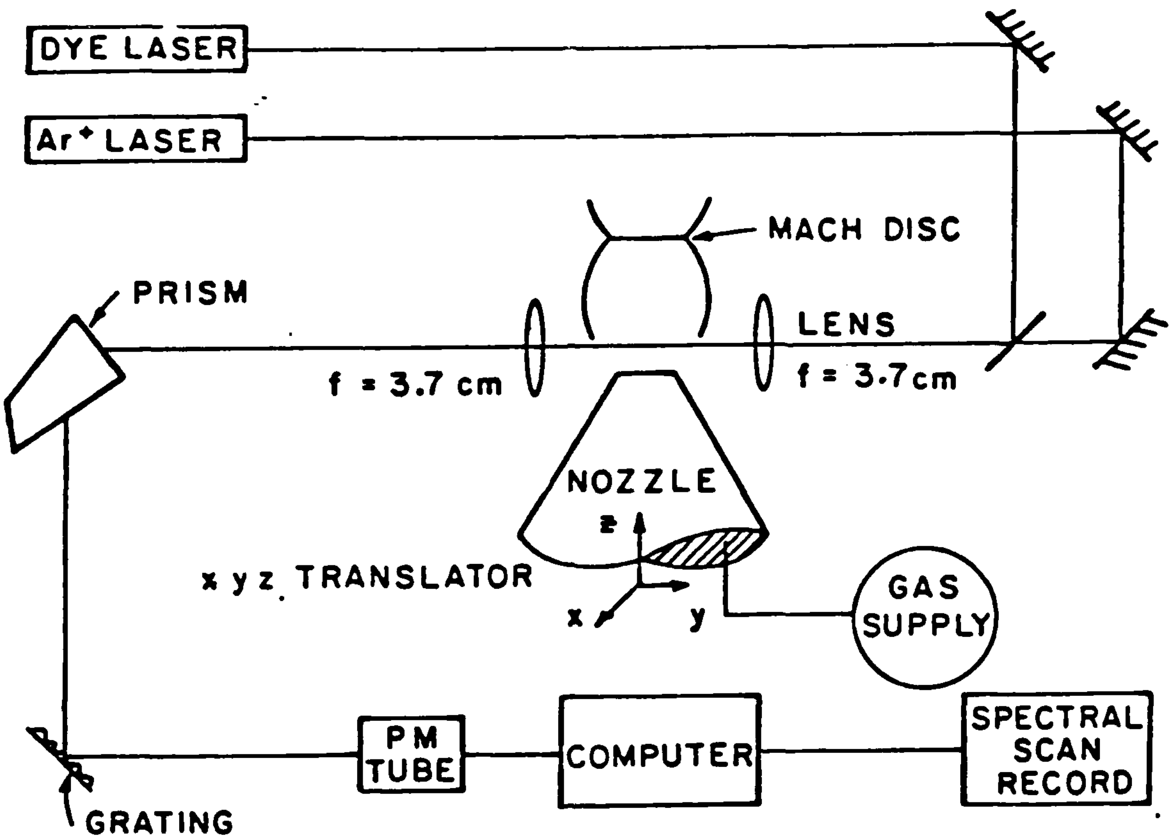
Scientific Merit

CARS spectroscopy has been increasingly used as a diagnostic probe for combustion and fluid flow studies. Our work on high resolution CARS in supersonic jets has led to a new understanding of the CARS process in cold expansion flows. We have demonstrated the highest resolution Raman spectra ever achieved. We have measured velocity and temperature to high accuracy in the flow, and we have completed a detailed theory for transit time broadened CARS in a supersonic flow. This latter work is the basis for the Ph.D. thesis of Eric Gustafson.

The combination of high resolution laser sources and supersonic expansion cooled molecular flows has now been recognized as an important advance in laser spectroscopy.

Status Report

We have completed measurements of temperature and velocity using cw CARS in a Mach 5 supersonic flow, (see Fig. 1). The results were presented at the C.L.E.O.S. Conference in June 1981. We have submitted for publication our velocity measurement work, and we are preparing a publication describing the theory of transit time broadening in CARS. Spectra are illustrated in Fig. 2.



OBJECTIVE: DEVELOP NON-INTRUSIVE DIAGNOSTIC FOR SPATIALLY RESOLVED TEMPERATURE, PRESSURE AND VELOCITY

DEVELOP GASDYNAMIC-OPTICAL TECHNIQUES FOR SUB-DOPPLER HIGH-RESOLUTION RAMAN SPECTROSCOPY

STATUS: FEASIBILITY DEMONSTRATED

Figure 1. Supersonic jet CARS spectroscopy.

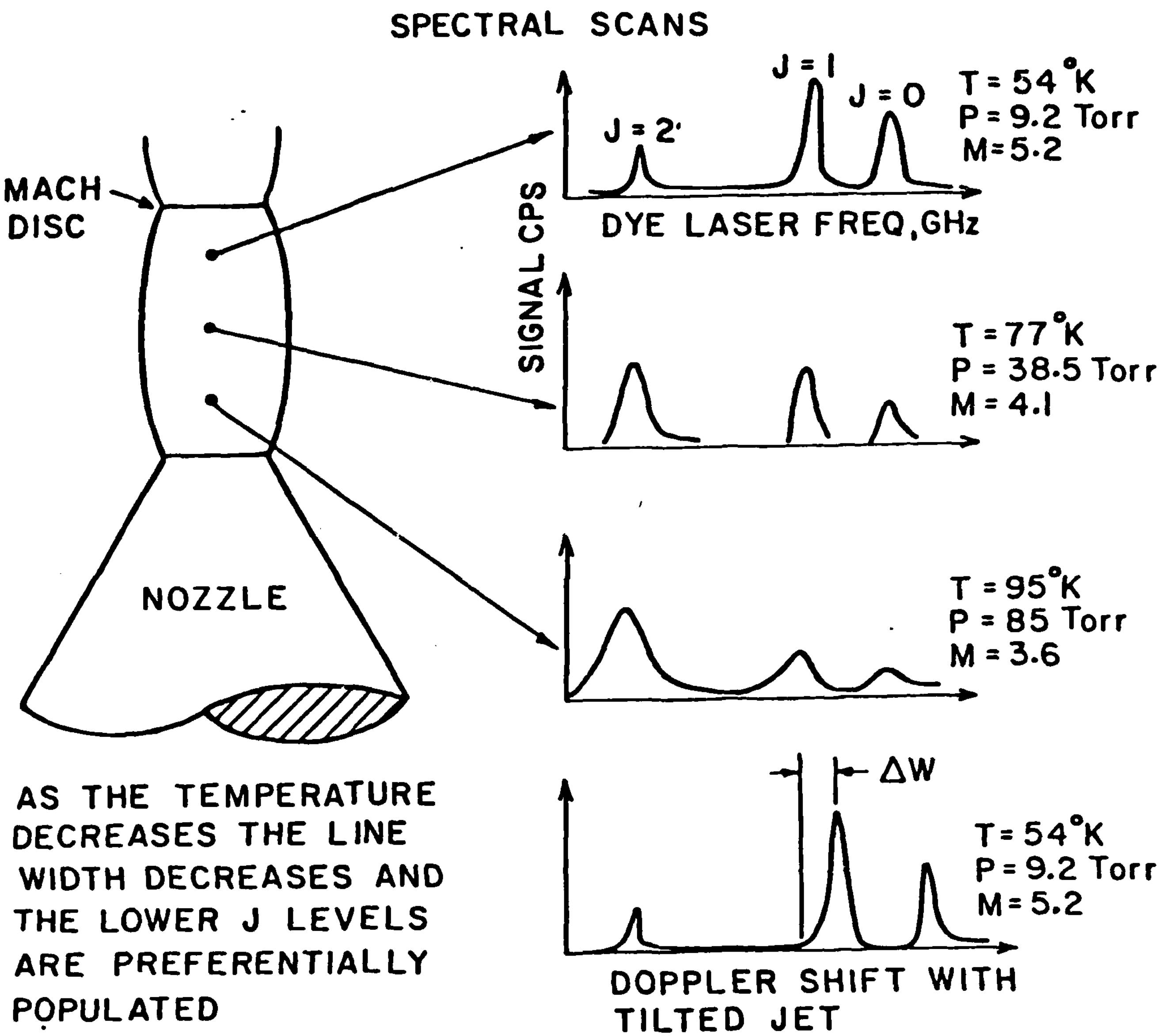


Figure 2. Schematic of the supersonic jet expansion showing the location of the CARS measurements along the jet axis. cw CARS spectra of CH_4 Q-branch at the temperature indicated.

We have described our CARS spectroscopic studies of CH_4 in the supersonic flow at the Laser Spectroscopy Conference and have prepared a manuscript for publication. Part of the work described in that paper was the cw CARS measurements in the supersonic flow.

In conjunction with the above work, we have completed density measurement studies in an I_2 seeded flow by a detuned fluorescence method. This work is described elsewhere in this report. However, it was performed on the apparatus used in the cw CARS studies and led to the Ph.D. thesis of Jim McDaniel.

During the past two years we have also worked on a single axial mode Nd:YAG source for use as a local oscillator for high resolution CARS spectroscopy studies, for high resolution I_2 fluorescence studies, and for flow velocity measurements by laser doppler velocimetry.

The source is now operating in both a cw mode and a pulsed mode. Linewidth measurements are in progress. The laser is expected to produce 1W of peak power in 1 μsec long pulses at less than 1 MHz linewidth. The 1W power is to be amplified in a Nd:YAG amplifier system to 3 MW of peak power or 300 mJ of energy at 10 pps.

When frequency doubled into the green, this laser source will pump a tunable dye laser and be used for very high resolution CARS spectroscopy studies. In addition, we plan to loan a second Nd:YAG oscillator to General Motors Research Laboratories for high resolution measurements of O_2 and atomic oxygen in a controlled flame. This work is in cooperation with Dr. Richard Teets of General Motors.

Publications and Presentations

Presentations

1. E. Gustafson, J. McDaniel and R. L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet," paper W01, CLEO Conference, June 1981, Washington, D.C.

2. R. L. Byer, M. Duncan, E. Gustafson, P. Oesterlin and F. Konig, "Pulsed and cw Molecular Beam CARS Spectroscopy," presented at the International Laser Spectroscopy Conference, July 1981, Jasper, Canada.

Publications

1. E. Gustafson, J. McDaniel and R. L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet," IEEE Journ. Quant. Electr., December 1981.

2. R. L. Byer, M. Duncan, E. Gustafson, P. Oesterlin and F. Konig, "Pulsed and cw Molecular Beam CARS Spectrocscopy," proceedings of the Laser Spectroscopy Conference.

Personnel

Robert L. Byer	Professor and Chairman Applied Physics Department
Eric Gustafson	Graduate Student, Applied Physics (Ph.D. expected in January 1982)
Jim McDaniel	Graduate Student, Aeronautical and Astronautics (Ph.D. awarded in December 1981)
Sun Yun Long Dr. Sun is working on the single frequency Nd:YAG source.	Visiting foreign scholar North China Institute of Electro-Optics

2.3 Computed Absorption Tomography

Introduction

The imaging and potential benefits of laser tomography to combustion diagnostics were summarized in the original proposal. Discussions with researchers in combustion diagnostics and fluid flow visualization research have confirmed our original assumption that tomographic images are indeed very useful.

We have learned that General Motors Research Laboratories is very interested in applying tomography to the study of internal combustion engine processes. Discussions are in progress to initiate a joint research effort between General Motors and Stanford University in this area. We feel that such joint research efforts are beneficial to both industry and to the university and that they provide a focus for the research effort on problems that are of current interest.

Scientific Merit

The goal of our tomography effort is to apply tunable laser sources and tomographic image technology to the study of combusting flows. The interest stems from the potential for inferring the distributions of temperature, density and species concentration in a plane. The visualization of these parameters is very important for the understanding of complex conditions that occur in real combustion systems. A better knowledge of turbulence and combustion on more complex combustors should lead to improvements in the design of combustors for both improved efficiency and longer operational life.

Status Report

During the past two years we have made substantial progress in implementing laser tomography measurements. Briefly, we have received and installed a PDP11/44 computer, the AED color display monitor, the high speed Versatec graphics printer and the CAMAC 4 MHz A/D system. We have installed the computer software system and have transferred our earlier tomography reconstruction programs to the PDP11/44.

We have written display driver progams and have generated color tomographic images from our model programs on the color display unit. We have written software for axial tomography image reconstruction that will be useful for pulsed tomography.

We are writing interface software for the A/D converters and the CAMAC dataway. We have identified, tested and purchased the detectors, amplifiers and multiplexers for the tomography image circle. Our goal is to demonstrate tomographic imaging in well known flow systems using cw laser sources. Our first measurement system will use I_2 seeded flows and the available argon ion laser source for absorption tomography studies.

We feel that we have made substantial progress in tomography during the short time since the installation of the computer system. We remain very positive about the use of laser tomography as a new combustion diagnostic tool.

We propose to set up and make cw laser tomography measurements using 100 silicon diode detectors in a fan beam geometry array. This work is proceeding as rapidly as programming, interfacing and electronics assembly allows. The goal is to complete initial measurements by the end of the first year and to complete detailed studies early in the second year.

Following the cw laser tomography measurements we propose to investigate pulsed laser tomography using axial beam geometry and reticon diode arrays. The pulsed laser sources allow generation of wavelengths from the ultraviolet to the infrared so that a wide range of atomic and molecular species can be probed. Pulsed laser tomography studies should provide very useful time-resolved, two-dimensional images of combusting flows.

Publications and Presentations

Publications

1. D. C. Wolfe and R. L. Byer, "Model Studies of Laser Absorption Computed Tomography for Remote Air Pollution Measurements," Applied Optics 21, 1165 (1982).

Presentation

2. R. L. Byer, "Laser Tomography for Combustion Diagnostics," General Motors Research Laboratory Colloquium, November 13, 1980.

Personnel

Robert L. Byer	Professor and Chairman Applied Physics Department
David C. Wolfe	Post Doctoral Fellow, Applied Physics
Keith Bennett	Graduate Student, Applied Physics
Greg Farris	Graduate Student, Applied Physics

2.4 Particle Sizing for Rocket Exhausts

Introduction

The mechanisms of generation and the evolution of the particle size distribution in solid fuel rockets are important to understand for two primary reasons. First, as they affect rocket motor performance, particularly the loss of specific impulse associated with large particles in the exhaust; second, as they affect the plume signature, both with regard to thermal emission from particles and with regard to plume visibility due to scattering.

While elaborate computer models have been developed to describe the evolution of the particle size distribution in the rocket chamber, including coalescence due to acoustic interaction and disruption due to strong acceleration in the nozzle, there is virtually no experimental data concerning particles inside the chamber.

With regard to the plume, a number of measurements of the size distribution have been made, as reviewed by Hermson[a], but the results are disparate and do not allow a conclusive *empirical model* to be established. There is need for more reliable and systematic measurements of particle size distribution in the plume. At Stanford we have experience of measuring the ash particle size distribution from coal-fired MHD combustors where the temperatures and velocities are similar to those of rocket exhausts. Two techniques have been developed. The first is a two-wavelength laser transmissometer[b] capable of measuring the Sauter mean diameter in the range 0.3-3 μm, together with the loading. The second is an in situ sampling wire filter[c] which appears to overcome many of the problems associated with conventional extractive sampling probes.

Scientific Merit

The determination of particle size distribution and loading in the hostile environment of high velocities and temperatures existing in rocket plumes is a severe challenge to the experimentalist and is the reason why so little information in available in this area. The scientific importance of obtaining such data is outlined above.

Status Report

In order to test the techniques developed previously for application to solid rocket exhausts it was judged best to carry out preliminary experiments using small (2 x 4) test motors. It proved impractical, for reasons of safety, to mount such experiments at Stanford. However, after consulting and visiting Drs. R. Hermson and R. Brown of United Technology, arrangements were made to use the UTC facilities in Sunnyvale for preliminary tests on 2 x 4 motors.

The two-wavelength transmissometer instrument shown schematically in Fig. 1 has been refurbished and ruggedized for installation in the UTC test cell. Arrangements were made to mount both the transmissometer and the sampling probe on the test pad at UTC. The transmissometer was used a short distance downstream of the exit plane, while the sampling probe was mounted further downstream in the plume. The first experimental test runs were made in September. A total of six test firings of 2x4 rocket motors containing 3% by mass of aluminum in the propellant were made. It would have been desirable to have used higher loadings of aluminum to obtain larger extinction of the laser beams, but the 3% loading was the only propellant available at the time. A preliminary assessment of these tests is given below; first for the transmissometer data and secondly for the filter data.

The transmissometer instrument basically measures the extinction due to particle scattering of two laser beams, one in the UV (0.325 μm) the second in the IR (3.39 μm). The Sauter mean diameter of the particles can then be obtained from the ratio of the extinctions (i.e. decrease of transmission) at the two wavelengths. In practice it is important to spectrally filter the detection channels so as to reduce the gas and particle emission signals to negligible proportions, compared with the reduction in laser signal due to scattering.

The signals from the UV and IR detectors, chopped at 500 Hz, were recorded before, during and after each test firing, on magnetic tape for subsequent analysis. It was found that the UV signal increased by an average of about 5% while the IR signal showed a very small decrease ($\lesssim$ 1%) during the firing.

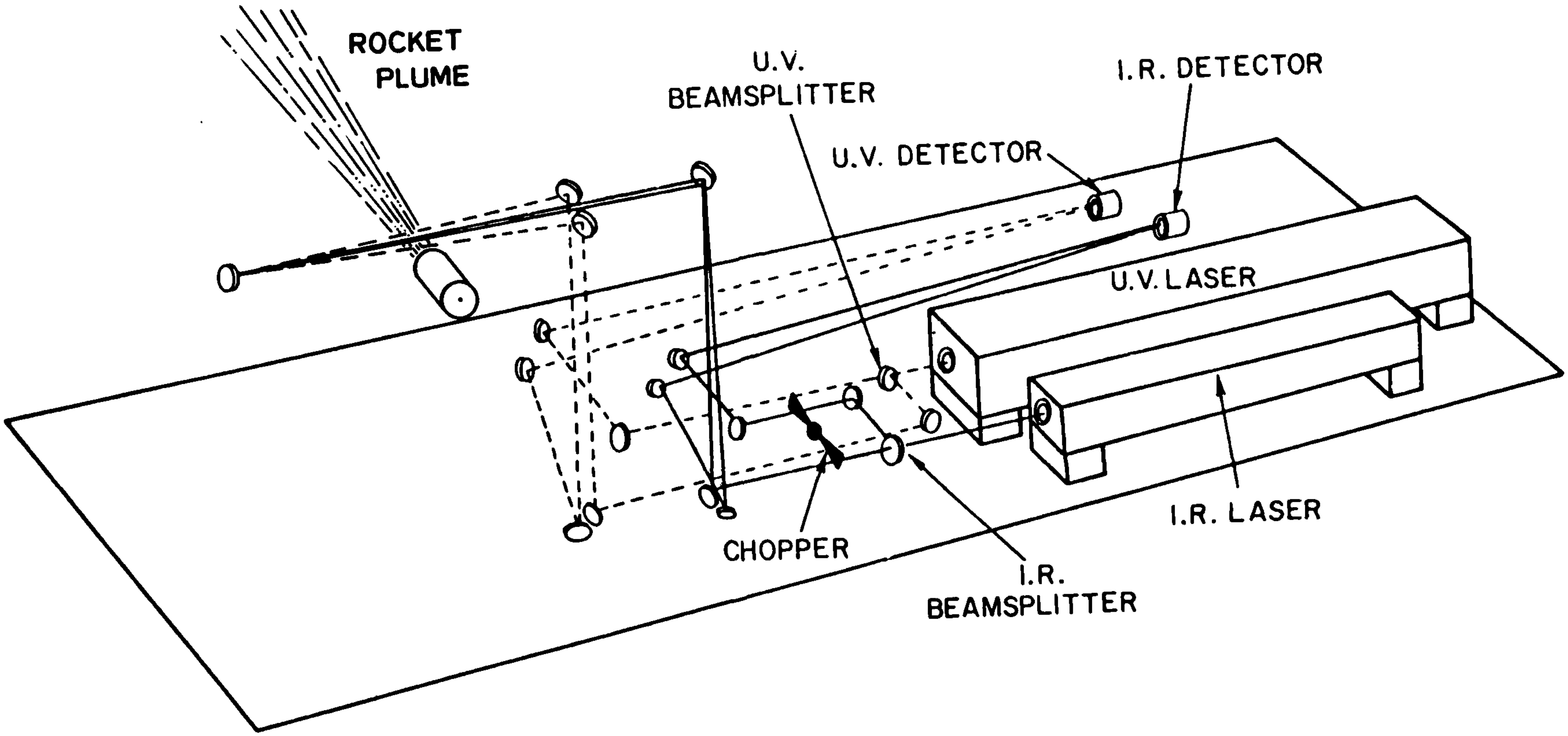


Figure 1. Schematic of two-wavelength laser transmissometer for measuring particle size in rocket plumes.

The increase in UV signal was unexpected and must be attributed to an insufficiently narrow spectral filter (3nm) which transmitted emission from the gas and/or particles, and which masked the extinction due to scattering.

The small decrease in the IR signal indicates that the particles are small - submicron - though in the absence of an extinction value from the UV channel it is not possible to deduce a value for the Sauter mean diameter.

Although these preliminary experiments did not result in useful size measurements, they indicated how the technique should be modified to obtain results for rocket exhaust applications. These indications are as follows:

(i) Narrower spectral filters are required, especially for the UV channel. If necessary, by using a Fabry-Perot etalon, the bandpass could be reduced by a factor of 100 or more.

(ii) A propellant with higher aluminum loading and/or a motor of larger cross-section is desirable to obtain larger extinctions, which would be more easily measured.

Besides the wire filter mentioned above, a total filter in the form of a porous stainless steel plate with nominal pore size of 0.5 μm was used to sample the plume. The wire and total filters were examined by scanning electron microscope and by x-ray microprobe to establish that the particles were indeed alumina.

On both filters, two types of alumina particle were seen. First, there were a few large irregular agglomerates of size up to 10 μm. These presumably result form coagulation of smaller particles either in the combustion chamber itself, or in the nozzle due to differential slip of particles of different size.

The bulk of the particles detected were well sub-micron, $\lesssim$ 0.3 μm. The limiting resolution of the SEM was about 0.1 μm. In the case of the porous metal total filter, it was difficult to detect these small particles which had penetrated into the rather large pores in the surface of the porous metal. This indicates that in future, total filters of the nucleopore type which have a smooth surface and are available with pore sizes down to 0.1 μm should be used. Some tests using such nucleopore filters are planned for the near future.

It should also be reported that Professor Self visited with Mr. D. Weaver at the AFRPL to discuss RPL's present equipment and needs for particle sizing on larger scale motors. Depending on the outcome of the small-scale tests at UTC, the possibility of using Stanford equipment at AFRPL will be explored.

Publications and Presentations

By invitation, Professor Self made a presentation and led the discussion on Particle Sizing at a Workshop on Advanced Diagnostic Techniques held at Carnegie-Mellon University, June 28-30, 1982.

Personnel

Sidney A. Self, Professor (Research) Mechanical Engineering

Richard Booman, Research Engineer, High Temperature Gasdynamics Laboratory

References

a. R.W. Hermson, "Aluminum Oxide Particle Size for Solid Rocket Motor Performance Predictions," 19th Aerospace Sciences Meeting, January 1981, AIAA Paper No. 81-0035.

b. P.C. Ariessohn, S.A. Self and R.H. Eustis, "Two-Wavelength Laser Transmissometer for Measurement of the Mean Size and Concentration of Coal Ash Droplets in Combustion Flows," Applied Optics 19, 3775-3781 (1980).

c. S.A. Self and R.L. Keating, "In-Situ Particle Sampling Filter for High Temperature, High Velocity Flows," HTGL Report #117, (May 1980).

2.5 Packaged, Fiber Optic Temperature Measuring Instrument

Introduction

The measurement of gas temperatures by the spectroscopic line-reversal method is an old established technique which has been widely used at Stanford on MHD and other combustion flows. However, hitherto, a suitable optical set up utilizing mirrors, lenses and a grating monochromator has been assembled on an optical bench for each individual application. Not only does this result in a bulky system, but the techniques employed have given only slow, time-averaged measurements. By using state-of-the-art components, including optical fibers, narrow-band filters and fast choppers, together with a microcomputer we are developing a compact, self-contained temperature measuring instrument with fast time response, to ~ 1 msec.

Schematics of the optical and electronic systems are shown in Figs. 1 and 2. All the components enclosed in the block outline (Fig. 1a) are assembled in a box or cabinet mounted remotely from the combustion system under study. Transmitting and receiving fibers lead to the system, and terminate in cooled, purged tubes or probe tips containing small collimating lenses which are designed specifically to suit the rig under study. Depending on the application, these transmitting/receiving optics assemblies may be located outside the flow to give line-of-sight average temperaure, or may be ganged together for use as a movable, immersible probe for local measurements.

By using a reference path identical to the measuring path, a beam splitter B, and two synchronized, miniature choppers C_1, C_2, each detector D_1, D_2, sees a repetitive sequence of three signals, namely S_L from the tungsten ribbon lamp, S_G from the gas and S_{L+G} from the gas trans-illuminated by the lamp.

It is possible to show that the gas temperature T_G is given in terms of the brightness temperature T_L of the lamp and these three signals by the formula

$$T_G = T_L \left[1 - \frac{T_L}{C_2} \ln \left(\frac{S_G}{S_G+S_L-S_{L+G}}\right)\right]^{-1} ,$$

where C_2 = 1.438 cm-K is the second radiation constant.

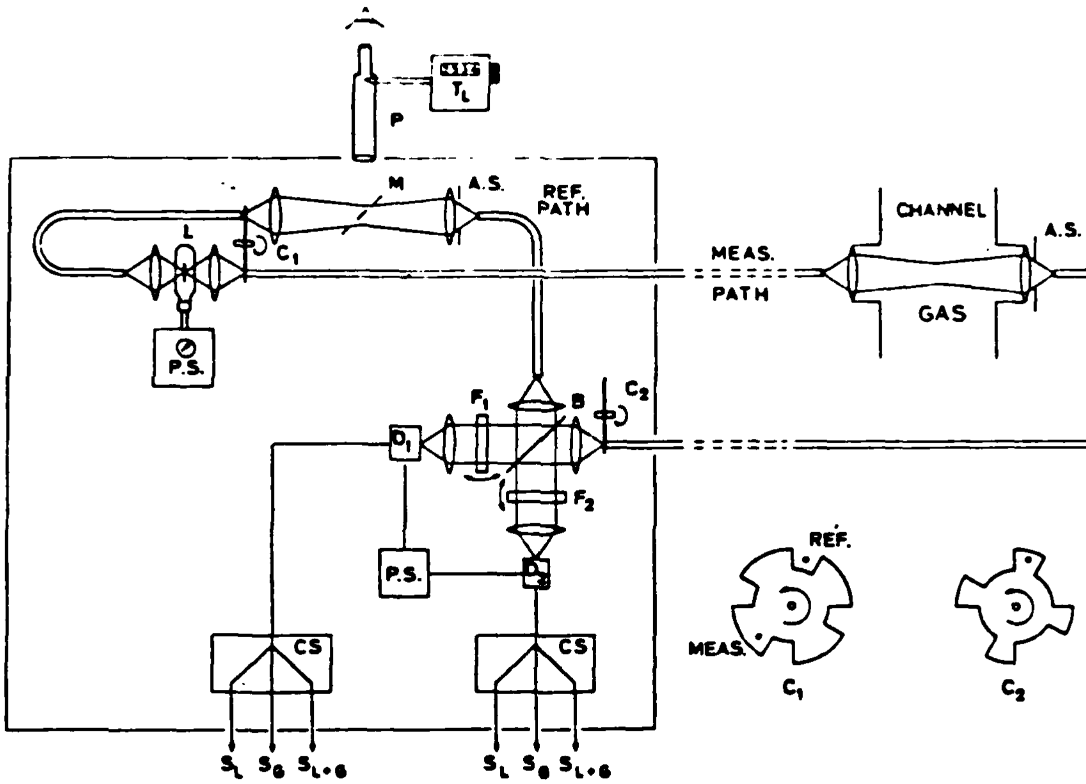


Figure 1. Schematic of optical system.

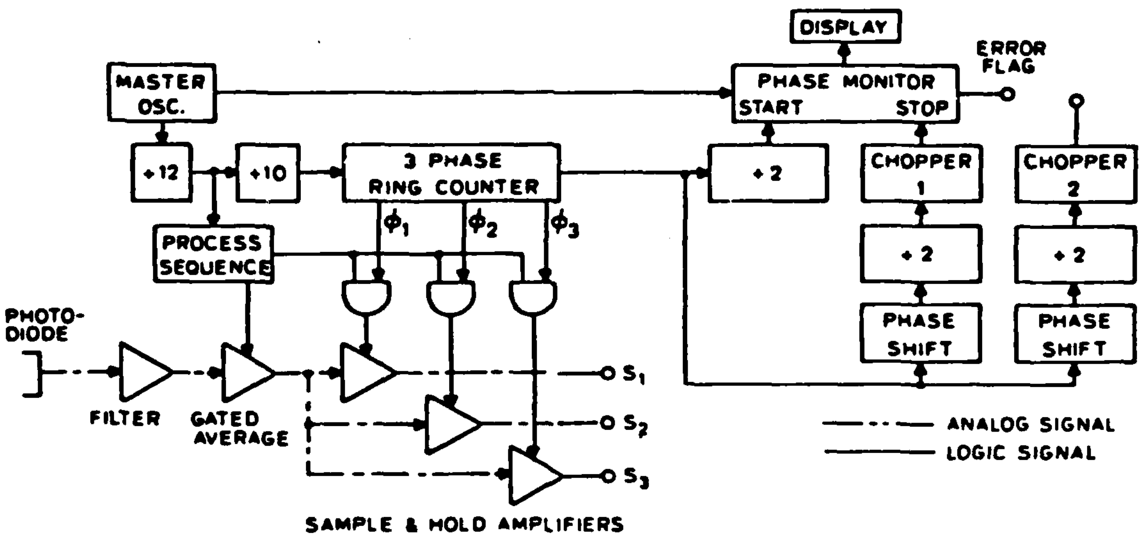


Figure 2. Schematic of electronic system,

The signal processing electronics and chopper control circuits are shown in Fig. 2. The output of each detector feeds into a channel separator unit, consisting of gated sample and hold circuits, and the three outputs are then fed to a minicomputer or microprocessor which calculates T_G from the above algorithm and outputs the temperature. Use is made of miniature choppers, commercially available, that give a measuring sequence time of 1 msec, thus providing temperaure measurements to 1 kHz for studying fluctuations.

The mirror M, shown in the reference path, is a high reflectivity front surface mirror which can be inserted when required to measure the brightness temperature of the lamp with a standard calibrated pyrometer.

Traditionally, in the line-reversal technique, a grating monochromator has been used for spectral selection, but this leads to a cumbersome setup. For applications involving heavy seed concentrations and large path lengths, where the spectral lines are very broad, we are using narrow band $\lesssim$ 3 Å dielectric filters shown as F_1, F_2 in Fig. 1, which can be tuned sufficiently by tilting. For applications involving low seed concentrations and shorter path lengths, where the spectral lines are narrow, higher resolution is necessary. For this purpose we are using a tunable Fabry-Perot etalon in combination with a broader band dielectric filer.

Certain conditions must be met to maximize the measurement accuracy in using this technique. First, the lamp temperature should be set as close to the average gas temperature as possible, so as to minimize the sensitivity to error or noise in the three signals when calculating from the above algorithm. The maximum temperature of tungsten ribbon lamps, consistent with adequate long-term stability of their calibration, is about 2500 K, so that only for gas temperatures higher than this is one obliged to extrapolate significantly.

The second condition involves the optical depth of the gases, which is a function of the alkali metal seed concentration, the optical path length, and the wavelength relative to line center of the resonance line. To obtain accurate measurements, the optical depth, $\alpha_\lambda \ell$ (where α_λ

is the absorption coefficient and ℓ is the path length), should be of order unity, so that the three signals in the denominator of the logarithm in the above formula, are of similar magnitude. With sodium or potassium seed, and gases or plasmas of laboratory scale (~ 10 cm), this condition can be met with conveniently low mole fractions of seed ~ 0.01 - 0.1%.

Another question related to the optical depth and seed concentration is the self-reversal of the emission line in flows where there is a significant temperature profile, e.g., where the thermal boundary layers have an appreciable thickness relative to that of the core. In such cases, a measurement through the whole body of the gas gives some line-of-sight average temperature which is difficult to interpret. One method for obtaining the core temperature in this case is to detune into the wing of the emission line, where the optical depth is ~ 0.5, and apply a correction to the apparent measured temperature obtained from calculations based on an estimated boundary layer temperature profile.

Traditionally, sodium seed has been used in the line-reversal technique, with measurements made close to the shorter of the two resonance lines at 589.0, 589.6 nm, using a photomultiplier as detector. We are exploring the use of potassium seed whose resonance lines lie at 766.5, 769.9 nm, where silicon photodiodes have their maximum quantum efficiency (~ 70%). Such diodes are smaller, cheaper and, importantly, have a more stable sensitivity than photomultipliers, and are now available with integral amplifiers.

To this point, the discussion has been directed at temperature measurements in clean combustion flows, and a single filter and detector channel suffices for this case. For particulate laden flows, e.g., sooty flames or solid-fuel rocket exhausts, the conventional line-reversal technique is invalidated by scattering, absorption and thermal emission from the particles, and there is need of a modified technique for such applications. It can be shown that by making measurements, as described above, simultaneously at two wavelengths, one can derive a formula which gives the gas temperature, as well as information about the particles, in terms of the three signals at the two wavelengths. One wavelength is chosen on, or close to a resonance line of the seed as discussed above; the other is made at a wavelength slightly detuned off the line, where the seed emission/absorption is smaller compared with that due to the particles. This is accomplished by the second filter and detector channel shown in Fig. 1.

Scientific Merit

The merits of this work are several-fold. First, as noted above, there is a need for a packaged, versatile instrument that can be used remotely to measure temperature in a variety of combustion flows, with a direct readout. Second, the instrument has a resolving time of 1 msec which will allow temperature fluctuations to be followed to a frequency of the order of 1 kHz. Third, the instrument can be extended to measure temperature in particulate-laden flows provided the optical depth due to the particles is not too great.

Status Report

The optical system has been designed and the components, including lamp, fibers, lenses, beam splitter, detector and choppers assembled and tested.

Two alternative spectral selective elements are available depending on the application. For heavily seeded flows or flows of large dimensions, when the resonance lines are broad, a narrow band interference filter of bandpass 3 Å is used. For lightly seeded flows of small dimensions when the lines are narrow, a tunable Fabry-Perot etalon of bandpass ~ 0.2 Å and free spectral range 18Å is used in conjunction with a dielectric filter of 12 Å width to ensure single mode operation of the Fabry-Perot.

A complete electronics system for controlling the choppers and demultiplexing the signals has been assembled and tested satisfactorily.

For preliminary tests a Perkin-Elmer acetylene-air slot burner, with facility for sodium aerosol seeding has been used, as reported in the last annual report. However, this proved to be less than satisfactory for a number of reasons. First, the flame temperature achievable is limited to 2200K. Second, the feedrate of the seed solution aerosol cannot be reliably controlled, so that the seed concentration is difficult to determine. Third, self-reversal of the lines occurs due to the thermal boundary layers. This can be overcome by using an unseeded shroud flame but the Perkin-Elmer burner does not have this facility.

For these reasons, we have designed, built and tested a special burner to act as a well controlled and versatile vehicle for testing the temperature measuring instrument. A photograph of the burner is shown in Fig. 3.

It is a flat flame diffusion burner designed to burn any gaseous fuel in air or oxygen. The adequacy of the thermal design is illustrated by the fact that it has been operated successfully on H_2 or CO with pure oxygen to yield flame temperatures over 3000K.

Controlled concentrations of up to 1% by mass of potassium can be introduced into the flame from a temperature-stabilized boiler. The outer row of fuel and oxidant holes in the burner surface are not fed with potassium, so that there is an unseeded sheath flame. Thus the main flame has uniform conditions which eliminates the problem of self-reversal due to seeded thermal boundary layers.

The burner also has provision for feeding refractory powder into the flame so that it can be used to study the problems associated with making temperature measurements in particle-laden flows.

The burner which operates at a maximum power of about 10 kW feeds into a ceramic lined chimney to reduce heat losses and give a good height over which flame conditions are reasonably uniform. The chimney is fitted with diagnostic ports to facilitate optical measurements or the introduction of thermocouples or probes. An Iridium Langmuir probe was used to establish that the flame temperature was adequately uniform over the cross-section at a height of $\sim$ 2 cm above the burner surface, where the inhomogeneities due to the individual flamelets had smoothed out.

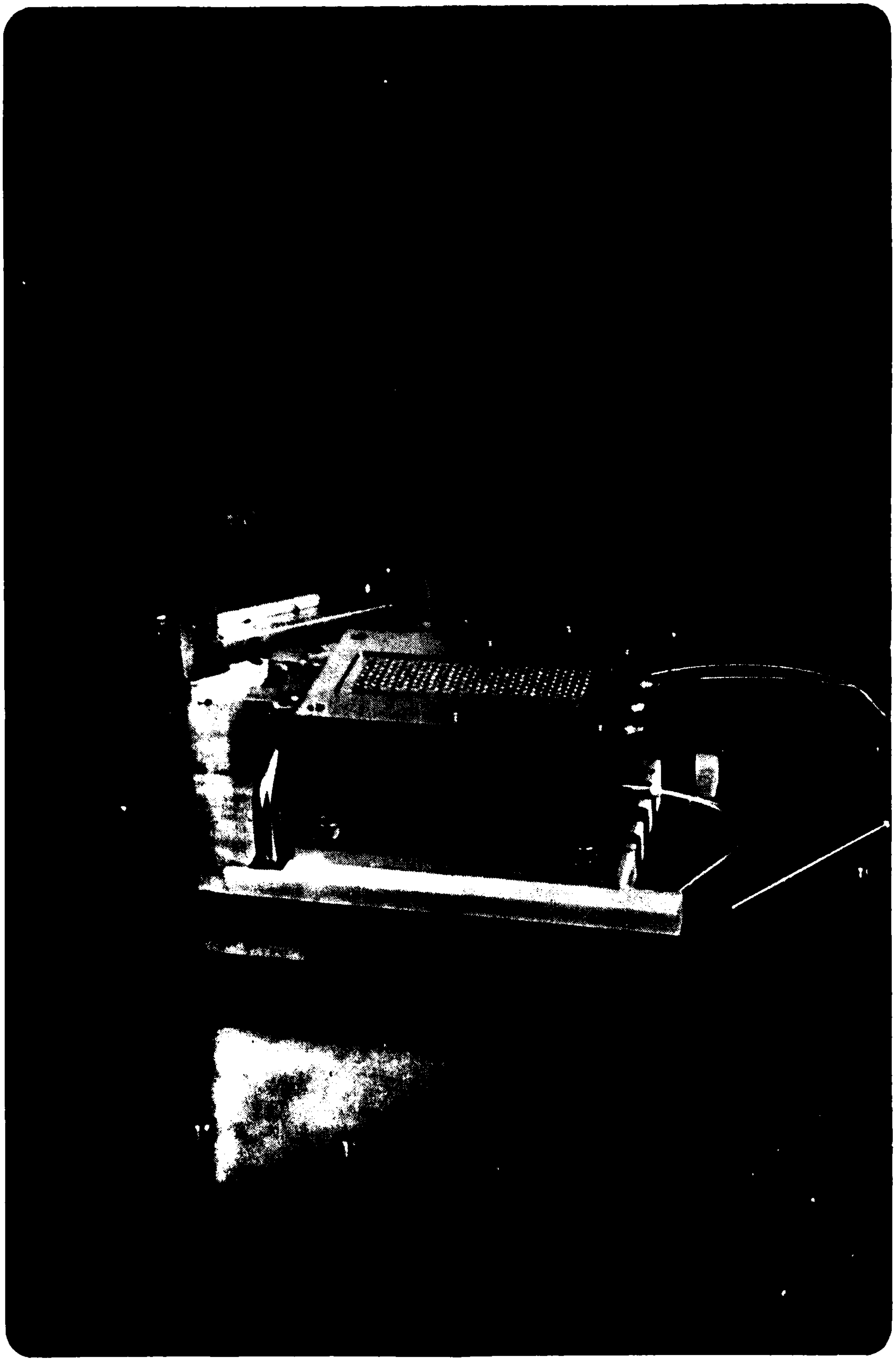


Figure 3. Photograph of bench scale burner of diagnostics testing.

To measure temperatures up to and exceeding 3000K, it would be desirable to have a calibrated source capable of achieving brightness temperatures of the same order of magnitude. As noted earlier, conventional tungsten ribbon lamps cannot be operated above about 2500K since their calibration drifts due to evaporation of the filament onto the glass envelope.

We have found that tungsten-quartz halogen lamps can be operated stably at brightness temperatures in excess of 3000K. Unfortunately they are not available with ribbon filaments, only with coiled-coil filaments, which would not be suitable for conventional emission-absorption measurements where the source is imaged through the system. However, when the coiled-coil filament is imaged onto the end of the input fiber, the image is scrambled on passage through the fiber. Thus the output end of the fiber appears as a uniform source with a brightness temperature we have measured at over 3000K. This appears to be a very useful technique for use as a reference source at temperatures up to at least 3000K, well above the limit of conventional standard lamps.

At the present time a systematic check of the burner over a wide range of operating conditions is nearly completed. When this is done, the burner will be used to test the operation of the temperature measuring instrument over a wide range of conditions.

This work will be discontinued as a component of the AFOSR program at the end of the current year but will be continued to completion with NSF support.

It should be mentioned that negotiations have been instituted between Stanford University and Spectron Development Laboratories with a view to commercialization of the instrument.

Publications and Presentations

A presentation entitled "A Packaged, Fiber-Optic Spectroradiometer for High Temperature Gases with Automatic Readout," by S.A. Self, P.H. Paul, and P. Young was made by Professor Self at the "Sixth Symposium on

Temperature; Its Measurement and Control in Science and Industry," organized by the National Bureau of Standards, March 1982. The paper has appeared in the Symposium Proceedings, Vol 5, pp. 465-470.

Personnel

S.A. Self	Professor (Research), Mechanical Engineering
P. Young	Graduate Assistant, (through January 1982) Mechanical Engineering
P. Paul	Graduate Research Assistant, Mechanical Engineering (Ph.D. expected in June 1983).

2.6 Quantitative Flow Visualization

Introduction

The utility of flow visualization as a diagnostic in studies of fluid mechanics and gas dynamics is well established. However, most visualization techniques are qualitative and are based on line-of-sight approaches which are poorly suited for flows with three-dimensional characteristics. With the recent development of laser-based light scattering techniques, it should be possible to obtain temporally resolved quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and a scattering technique such as Raman, fluorescence or Mie scattering. In fact, pioneering work along these lines using Mie scattering from seeded particles was initiated at Yale a few years ago, and during this past year significant progress has been made at Stanford, Yale and SRI using fluorescence-/and Raman-based scattering techniques to obtain simultaneous, multiple-point measurements of species concentration in planar regions. For example, instantaneous (5 nsec) measurements of OH at 10^4 flowfield points in a flame have recently been reported at Stanford, with sensitivity in the 10's of ppm range and spatial resolution of better than 1 mm. Of equal importance, we have recently demonstrated variations of this approach which yield temperature and velocity (see Section 2.7) at multiple points without particle seeding. These new techniques represent a significant advance in measurement capability with important applications which extend well beyond the field of combustion for which they were originally developed.

Scientific Merit

This is a fast-moving area of research with the potential to effect significant scientific advances, particularly in the fields of fluid mechanics and combustion. The methods under study may also lead to (as well as utilize) new advances in important areas such as lasers, laser spectroscopy and image processing. In a sense, the thrust of the work is, as is now the case in many areas of science, "information processing". We wish to acquire orders-of-magnitude more information (data) on flows than can be obtained with single-point measurements, and the development of the diagnostic methods simultaneously raises new, closely related questions regarding the processing, display and even the interpretation of such expanded data sets.

Status Report

The first year of this project (1 Oct. 1980-30 Sept. 1981) was spent on experimental design and selection of system components including a tunable pulsed dye laser source, illumination and detection optics, a detection system, digitizing and data storage systems and computer interfacing. A detailed schematic of the first-generation system, suitable for intermittent single-frame recording of PLIF (planar laser-induced fluorescence) images species in a plane is shown in Fig. 1. The pulsed dye laser is a Quanta-Ray system, tunable (with charges of dye and mixing crystals) from 220-900 nm. The detection system is an EG&G Reticon photodiode array (100 x 100) which has been intensified (ITT) with a dual microchannel plate intensifier. The output of the Reticon array is fed via a camera controller unit to a fast A/D unit in our DEC 11/23 computer. Hard copies of processed data are output on a plotter.

During this past year, the system has been put into operation and initial PLIF results have been obtained for Na (590 nm), OH (306 nm) and NO (225 nm) in several combustor flowfields. Typical results for OH and NO in a turbulent, premixed flame seeded with 2000 ppm of NO are shown in Fig. 2. Although the data are digitized to 8 bits, they are displayed here in only 6 levels; i.e. each color corresponds to a range equal to 1/6 of the maximum signal, which is about 1500 ppm for OH and 2000 ppm for NO. The highest levels of OH are found in the regions of maximum temperature, while the highest level of NO appears early in the flow on the burner axis, before mixing with surrounding air acts to dilute the NO level.

At present we have the capability to record intermittent single-frame PLIF images of species which absorb at wavelengths accessible with

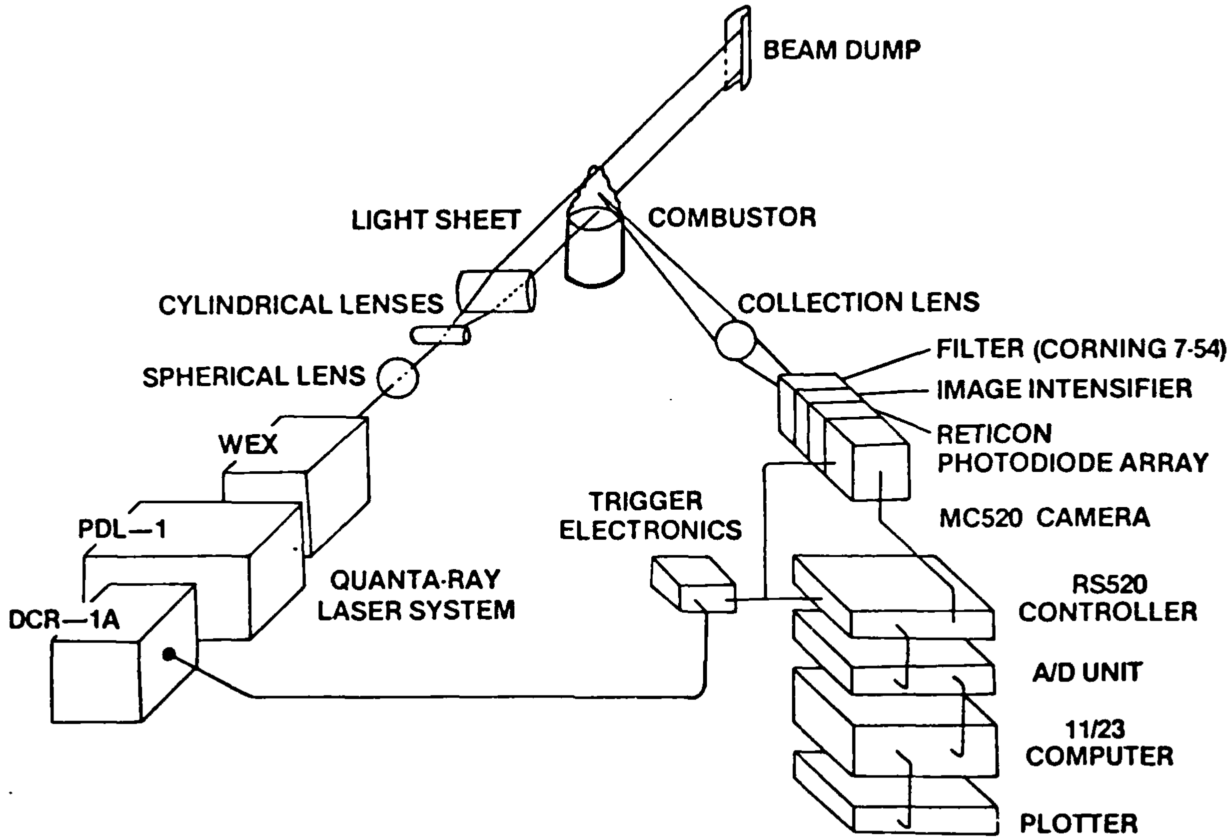
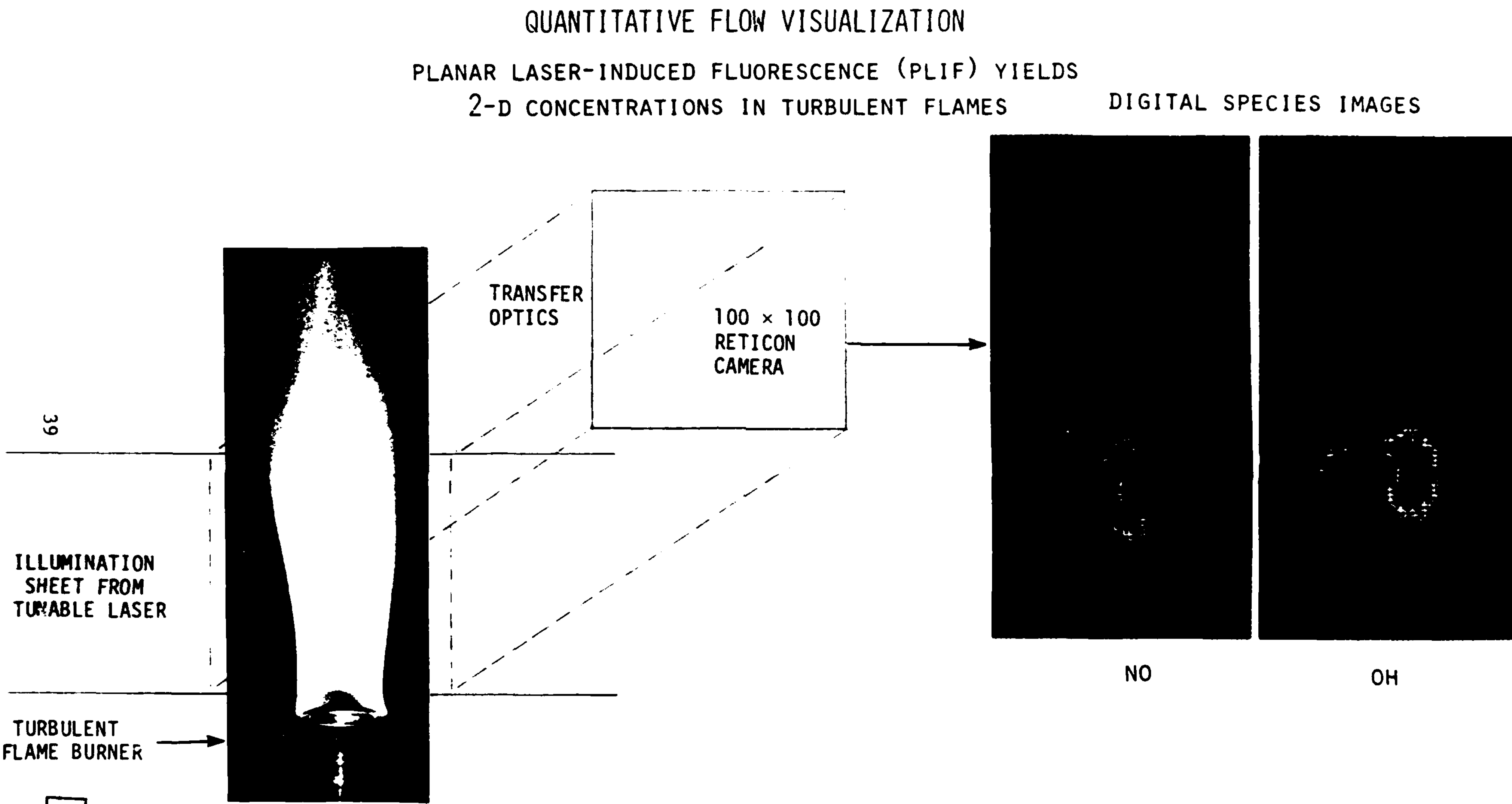


Figure 1. Detailed schematic of first-generation electro-optic system for PLIF species measurements in flames.

our pulsed dye laser, and we have successfuly made measurements in several combustion flows including premixed laminar and turbulent flames and turbulent diffusion flames. The detector limit is species dependent, but is typically 10's of ppm for diatomic radicals such as OH. We are currently working to develop a variation of the technique visualizing temperature and are also planning to upgrade the system to allow multiple frame recording at high repetition rates. The capability to record (as well as process and display) multiple frames at high rates is important because it will allow monitoring the real-time evolution of fluid structures. Such data are not presently available and are of fundamental importance for the development of improved combustion and fluid mechanics models.



- FIRST INSTANTANEOUS MULTIPLE-POINT SPECIES MEASUREMENTS IN A FLAME (10^4 POINTS)
- HIGH SPATIAL (0.4 × 0.4 × 0.2 MM) AND TEMPORAL (5 NSEC) RESOLUTION
- POTENTIAL MAJOR IMPACT ON COMBUSTION MODELLING

FIG. 2. HIGHLIGHTS OF QUANTITATIVE FLOW VISUALIZATION PROJECT.

Publications and Presentations

Presentations

1. G. Kychakoff, K. Knapp, R.D. Howe and R.K. Hanson, "Quantitative Flow Visualization in Combustion Gases", paper No. 82-60, presented at Fall 1982 meeting, Western States Section/The Combusiton Institute, Livermore, CA., (October 1982).

2. G. Kychakoff, R.D. Howe, R. K. Hanson and K. Knapp, "Flow Visualization in Combustion Gases," paper 83-0405, to be presented at 21st Aerospace Sciences Meeting of AIAA, Reno, (January 1983).

Publications

1. G. Kychakoff, R. D. Howe, R. K. Hanson and J. C. McDaniel, "Quantitative Visualization of Combustion Species in a Plane," Applied Optics 21, 3225 (1982).

2. K. Knapp, G. Kychakoff, R. D. Howe and R. K. Hanson, "Flow Visualization in Combustion Gases Using Nitric Oxide Fluorescence," submitted to AIAA J. (1982).

3. G. Kychakoff, R. D. Howe, R. K. Hanson, M. Drake, R. Pitz and M. Lapp, "Quantitative Visualization of Combustion in a H_2-Air Diffusion Flame," in preparation for submission to Science (1982).

Personnel

Ronald K. Hanson	Professor, Mechanical Engineering
George Kychakoff	(Ph.D. Expected in June 1983)
Mark Allen	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1985)
Klaus Knapp	Visiting Postdoctoral Scholar
Robert Howe	Research Physicist, Mechanical Engineering

2.7 Velocity Visualization

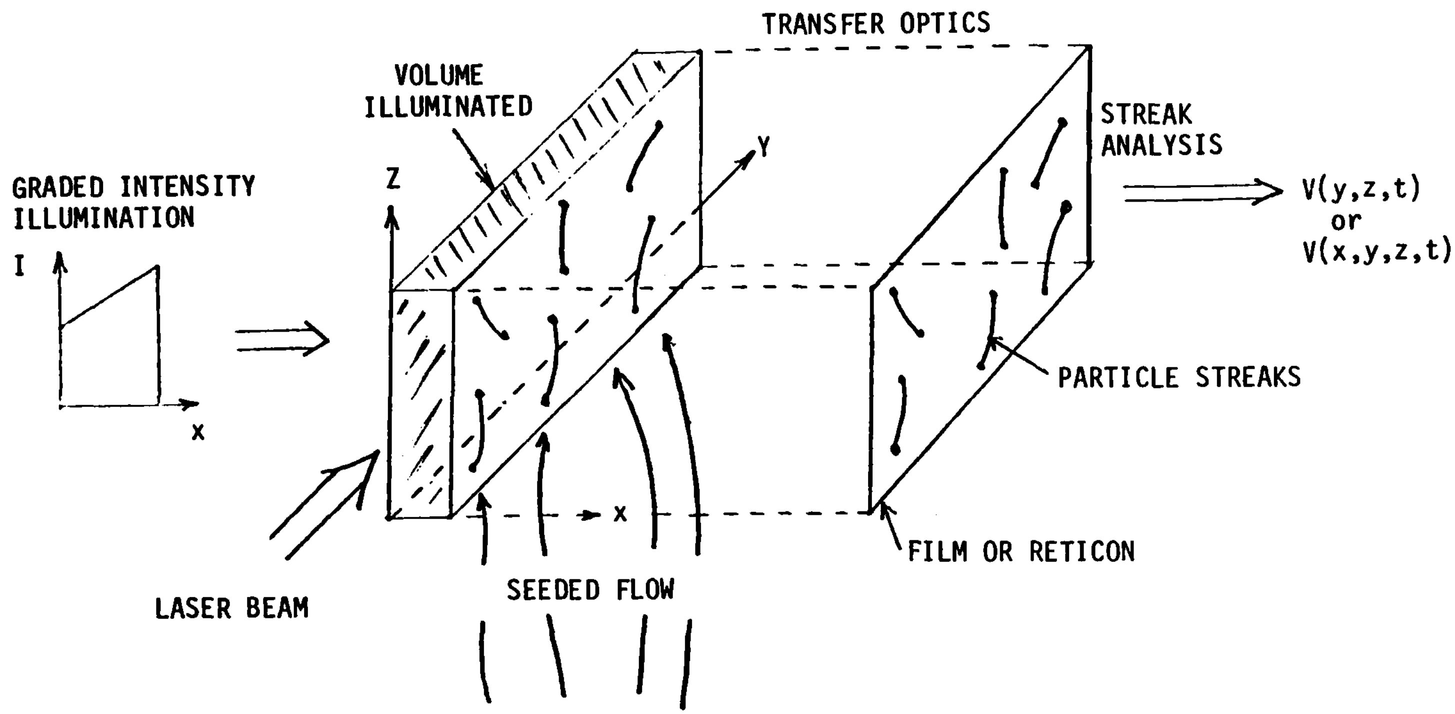
Introduction

Velocity measurements provide essential input for many basic and applied fluid mechanics studies. At present, hot wire anemometry and laser Doppler anemometry are the most commonly used techniques. Both methods have advantages and disadvantages, but in particular they are single-point diagnostics. Clearly, a technique yielding simultaneous multiple-point velocity data would represent a significant diagnostics contribution and could stimulate important advances in many areas involving fluid flow.

Our effort in this area was prompted in part by our recent success in visualizing species at multiple points in a flow (see Section 2.6) and the growing recognition that combinations of flowfield quantities (e.g., species, temperature and velocity) may eventually be needed to test advanced flow models. Accordingly we have, in the past year, initiated a new effort to "visualize velocity", i.e. to measure velocity at a large number of spatially resolved flowfield points leading to a computer display of velocity. This particular element of our diagnostics program has been co-sponsored by AFOSR and NASA-Lewis Research Center.

Several schemes are under consideration, two of which are indicated schematically in Figs. 1 and 2. The first method (see Fig. 1) is essentially an improved variation of streak photography and involves recording (on a Reticon array or film) streaks from particles seeded into the flow. Rather than sheet illumination, however, we envision using volume illumination with an intentional (and known) intensity gradient in the transverse direction. If the particles are spherical (so the scattering signal is independent of rotation) and the streaks are recorded with a photodiode array (with a response linearly proportional to intensity), then the transverse velocity can be determined from the change in signal level along the streak. The in-plane velocity is obtained directly from the streak length and the known exposure time. Problems of verifying that the particle continuously resides in the illumination region can be handled by modulating the illumination

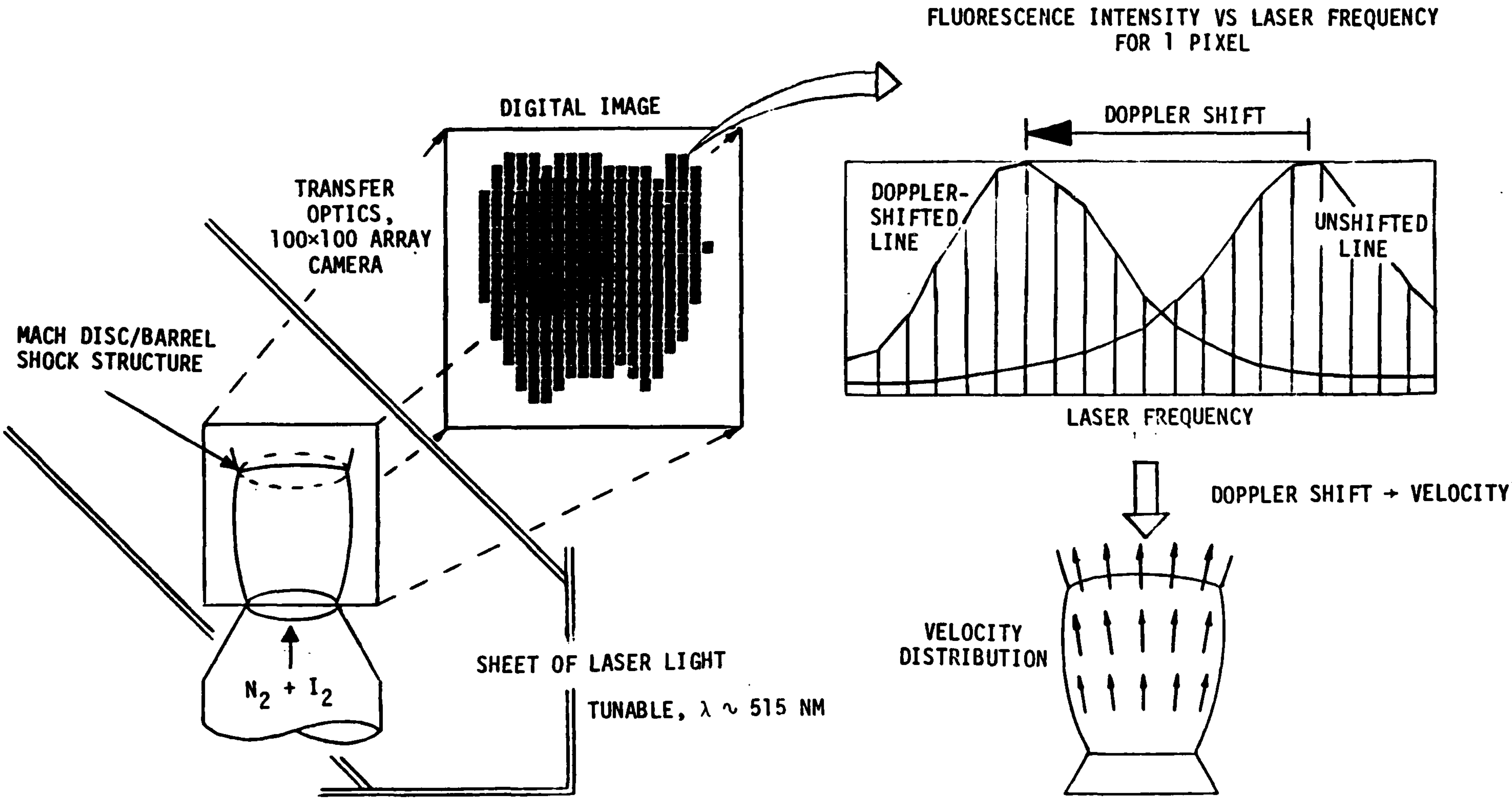
3-D VELOCITY VISUALIZATION
SIMULTANEOUS MULTIPLE-POINT MEASUREMENTS OF 3-D VELOCITY VECTORS MADE POSSIBLE WITH QUANTITATIVE STREAK RECORDING



- FLOW IS SEEDED WITH SPHERICAL PARTICLES
- FLOW IS ILLUMINATED BY BEAM WITH INTENSITY GRADIENT
- SCATTERED LIGHT IS RECORDED ON A 2-D DETECTOR ARRAY
- VARYING INTENSITY OF PARTICLE TRACK GIVES TRANSVERSE VELOCITY (V_X)
- LENGTH OF TRACK GIVES VELOCITY IN PLANNE (V_Y,V_Z)
- SUITABLE FOR WIDE RANGE OF FLOW SPEEDS BY VARYING EXPOSURE TIME
- USE OF DETECTOR ARRAY ELIMINATES NEED FOR FILM DEVELOPMENT AND CALIBRATION
- DIGITAL OUTPUT ENABLES FAST, CONVENIENT COMPUTER ANALYSIS IN NEAR REAL TIME

Figure 1. Overview of advanced streak recording for multiple-point 3-D velocity measurement.

VELOCITY VISUALIZATION
SIMULTANEOUS MULTIPLE-POINT VELOCITY MEASUREMENTS BY
SENSING DOPPLER-MODULATED LASER ABSORPTION WITH A DETECTOR ARRAY



- FIRST QUANTITATIVE MULTIPLE-POINT VELOCITY MEASUREMENTS IN A GAS FLOW
- NO PARTICLE SEEDING REQUIRED
- NO TEMPERATURE PERTURBATION (AS WITH SODIUM SEEDING)
- VERY GOOD AGREEMENT WITH THEORY
- GOOD PROSPECTS FOR EXTENSION TO SUBSONIC FLOWS WITH TEMPORAL RESOLUTION

Figure 2. Multiple-point velocity measurements using Dopple-shifted absorption with fluorescence detection.

(laser) intensity or the Reticon responsivity (e.g., via the intensifier control voltage) at the beginning and end of the exposure. Although the Reticon has important advantageous as a recording element (linear to intensity level, and directly interfaced with computer leading to near real-time displays), particularly with regard to data processing time, it may suffer from poor resolution. (Although we are using a 100 x 100 array at present, 256 x 256 arrays are now available and even larger arrays are expected in the future.) If high velocity resolution is more important than processing time, then film recording becomes attractive. Tentatively, we plan to test both film and Reticon recording; the latter will at least be attractive during set-up of experiments and for monitoring major features of the velocity field.

The second scheme under study (see Fig. 2) is based on the Doppler effect and involves monitoring the broadband fluorescence from a sheet-illuminated flow using a Reticon array. The flow is seeded with I_2 vapor (at about 1000 ppm), and a laser source is used to excite a specific I_2 transition. The fluorescence from a given flowfield point mirrors the absorption occurring there, which for a uniformly seeded flow depends only on the position of the laser wavelength within the absorption lineshape. Since the absorption line shifts with fluid velocity due to the Doppler effect, the amount of absorption (and hence fluorescence) is a measure of velocity. As this approach actually provides only the velocity component along the laser beam, it is necessary to use multiple beams to obtain the 2-D or 3-D velocity vector.

Scientific Merit

The importance of velocity as a fluid flow parameter is obvious, and so the discovery/establishment of an improved velocity diagnostic offers broad potential for improved scientific understanding of fluid flows. A successful multiple-point diagnostic, in particular, would represent a sufficiently large advance in measurement capability as to enable first-time observations of various flow phenomena and possible discovery of unexpected features.

One of the techniques proposed, based on the Doppler shaft of molecular absorption lines, offers prospects for a significant improvement over conventional laser Doppler (particle seeding) anemometry for supersonic flows or flows with high acceleration where particle lag is a serious problem.

Status Report

This research is still in its early stages. We have conceived and investigated several promising approaches for multiple-point velocity measurements, and we have selected two of these approaches described above for laboratory study. With regard to the streak recording concept, we have researched candidate seed materials and seeding procedures, as well as the electro-optical arrangement to be used (illumination system, optics and detection system), and we are now ready to order components and seed material (glass microballoons, of about 40 microns diameter).

Our work on Doppler shifted molecular absorption is further along, and in fact our initial experiments were sufficiently successful that they have been submitted (and recently accepted) for publication (see below). A detailed schematic of the experiments is shown in Fig. 3. A small quantity of I_2 vapor was seeded into a stream of N_2 prior to its expansion to form a steady supersonic jet. The flow was illuminated ($\lambda = 514.5$ nm) with a tunable single-mode argon ion laser, which happens to be coincident with a transition in I_2. The laser was scanned across about 20 axial modes of the laser and the camera recorded the fluorescence intensity at each laser frequency. Computer analysis of the voltage versus frequency for each pixel (photodetector) was used to find the frequency of peak absorption which in turn specifies the Doppler shift and velocity component. The result of this process using laser sheets at two angles is a record of the flow velocity at 10^4 points which agrees well with theoretical prediction.

In the next series of experiments, aimed at extending this technique to lower velocities, we plan to fix the laser wavelength in the wings of the absorption line and to infer the instantaneous velocity component

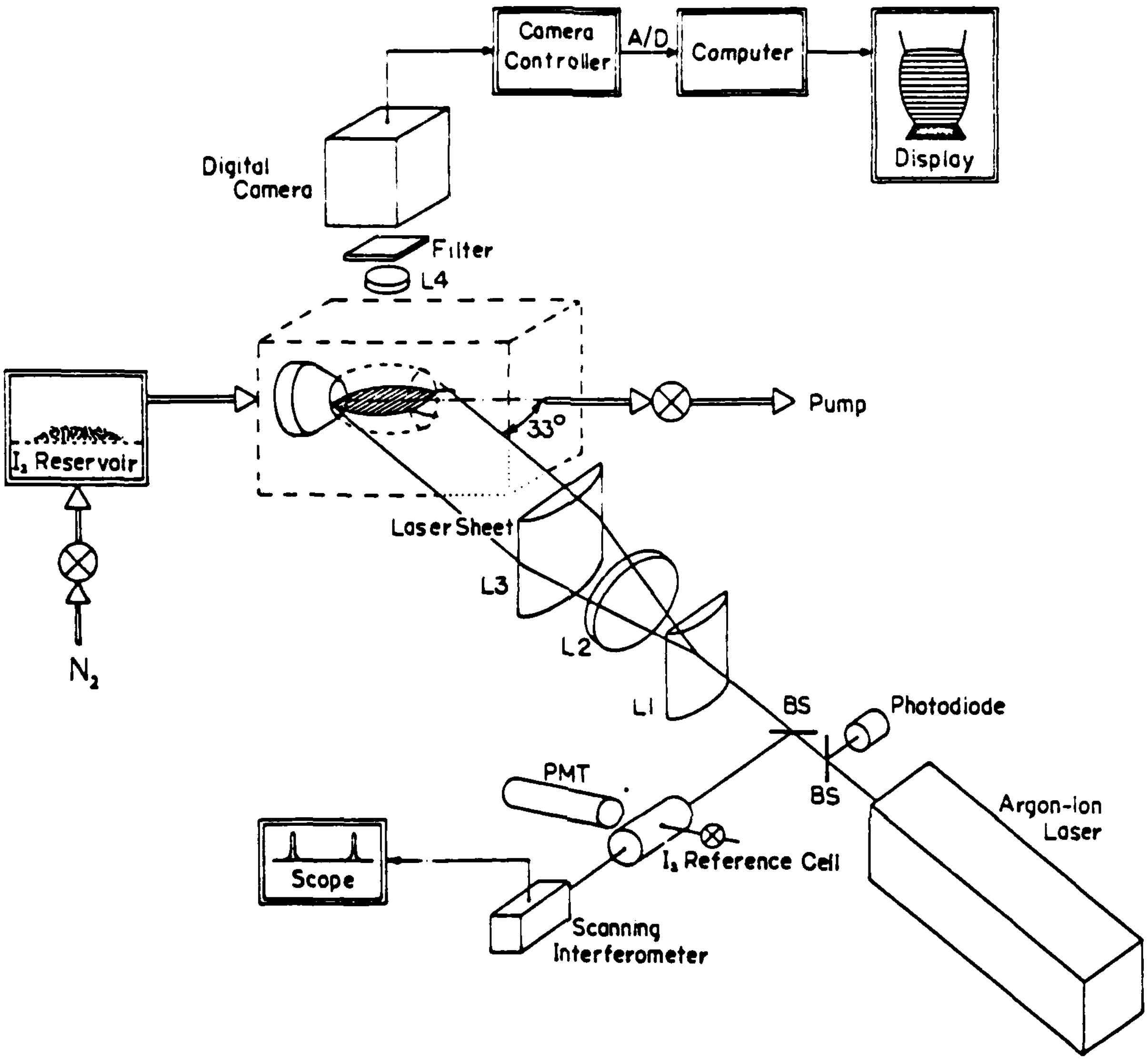


Figure 3. Sketch of experimental setup showing iodine-seeded underexpanded jet flowfield, probed by a thin sheet of argon-ion laser radiation, and imaging of the fluorescence distribution on a photodiode array camera.

associated with small Doppler shifts simply by subtracting a frame of data acquired with a static gas sample from that recorded with a moving gas. Some calibration will be needed, but this approach should yield essentially instantaneous velocity measurements.

Publications and Presentations

Presentations

1. J. C. McDaniel, "Velocity Measurement in a Flame Using Doppler-Shifted Laser-Induced Iodine Fluorescence," presented at Thirty-Fifth Meeting of the American Physical Society, Div. of Fluid Dynamics, Rutgers U., Nov. (1982).

Publication

1. J. C. McDaniel, B. Hiller and R. K. Hanson, "Simultaneous Multiple-Point Velocity Measurements Using Laser-Induced Fluorescence," Optics Letters, in press (1982).

Personnel

Ronald K. Hanson	Professor (Research), Mechanical Engineering
James C. McDaniel	Postdoctoral Research Fellow, Mechanical Engineering
Bernhard Hiller	Graduate Student, Mechanical Engineering

Publications and Presentations

Presentations

1. J. C. McDaniel, "Velocity Measurement in a Flame Using Doppler-Shifted Laser-Induced Iodine Fluorescence," presented at Thirty-Fifth Meeting of the American Physical Society, Div. of Fluid Dynamics, Rutgers U., Nov. (1982).

Publication

1. J. C. McDaniel, B. Hiller and R. K. Hanson, "Simultaneous Multiple-Point Velocity Measurements Using Laser-Induced Fluorescence," Optics Letters, in press (1982).

Personnel

Ronald K. Hanson	Professor (Research), Mechanical Engineering
James C. McDaniel	Postdoctoral Research Fellow, Mechanical Engineering
Bernhard Hiller	Graduate Student, Mechanical Engineering

2.8 Application of Diagnostic Techniques to Turbulent Reacting FLows

Introduction

A principal motivation for the development of advanced diagnostic techniques for reactive flows is the need to characterize flow fields in practical combustion devices. One component of the present overall program is the development of a laboratory-scale facility which simulates essential features of practical combustion devices and therefore provides a useful test facility for the evaluation of various diagnostic techniques. This facility is now available and is being used to evaluate several optical diagnostic techniques as well as to obtain flowfield data on flows of fundamental interest.

The flow configuration currently available is an atmospheric-pressure, two-dimensional shear flow, Fig. 1. This facility provides a means of simulating fuel-air mixing regions in air-breathing engines. The non-reacting flow field in this facility has been characterized by conventional diagnostic methods, such as hot wire anemometry, and work is underway to incorporate some of the diagnostics being developed in other parts of this program. Two different diagnostic techniques are being explored at the present time: a fiber optic probe for time-resolved point measurements of species concentration, and the planar laser-induced fluorescence flowfield visualization technique described in Section 2.6. An essential element of this study is the development of computer-based methods for quantitative reduction of the flow field data obtained from the two methods.

Scientific Merit

The evaluation and validation of advanced diagnostic techniques in well-characterized turbulent reacting flows is an important final step prior to transfer of technology to outside users. Furthermore, computer-based methods for reduction of flow field data are required to provide quantitative information on the reacting flow field structure.

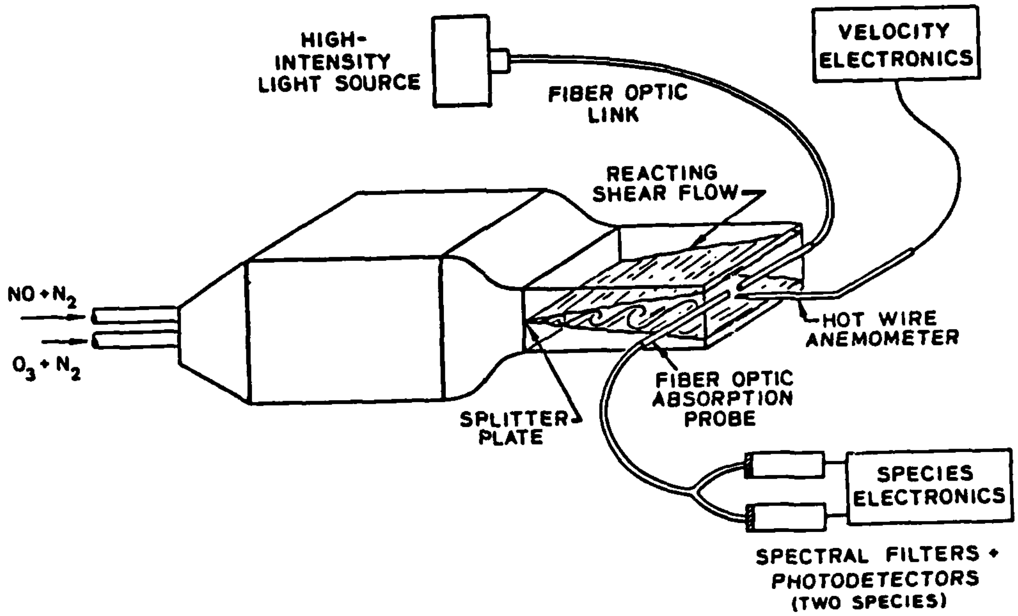


Figure 1. Two-dimensional reacting shear flow facility with fiber optic absorption probe.

Status Report

During the past year measurements on reacting flows with a fiber optic probe have been initiated. The initial measurements were conducted in the two-stream plane mixing layer, with one stream containing NO and the other stream containing O_3. In the mixing layer NO and O_3 react to form NO_2 principally by the irreversible reaction,

$$NO + O_3 \rightarrow NO_2 + O_2.$$

Simultaneous measurement of any two of these species provides a complete description of the concentration field in the mixing layer.

The fiber optic probe simultaneously measures absorption by O_3 and NO_2. The two absorption measurements provide real-time data on the concentrations of these two species at a particular location in the flowfield. Computer technique for the real-time acquisition and processing of the data have been developed. The computer output provides a variety of reacting flowfield properties of interest, including the frequency spectrum, probability density functions of concentration variables and correlations.

Publications and Presentations

1. S. M. Masutani and C. T. Bowman, "A Fiberoptic Absorption Probe for Measurement of a Conserved Scalar in a Non-Premixed Turbulent Reacting Flow," paper 82-62 at Western States Section/Combustion Institute Meeting, Livermore, CA, October (1982).

Personnel

C. T. Bowman	Professor, Mechanical Engineering
Stephen M. Masutani	Graduate Student, Mechanical Engineering (Ph.D. expected June 1984)

2.9 Concentration Measurements in Evaporating Flows

Introduction

A wide variety of combustion devices rely for their operation on the evaporation and mixing of liquid droplets in the presence of turbulent flow. For example it has been observed that ignition delay times in gas turbine combustors may often be correlated with droplet evaporation times. Results of this sort have motivated many investigators to incorporate the evaporation process into models of turbulent combustion. However, the behavior of droplets in a turbulent combusting flow is extremely complex involving simultaneous heat, mass and momentum transfer. The evaporation process is influenced by fuel type and chemistry, ambient gas composition, gas temperature and pressure, the droplet size distribution, droplet spacing, and the relative velocity between the droplet and surrounding gas. Consequently, models of spray combustion are often required to compute very detailed results for combusting flow fields without benefit of experimental data for comparison.

The research described here involves development of new diagnostic techniques and their initial application to measurements of droplet evaporation rates under controlled laboratory conditions. The aim is to develop a spatially and temporally resolved technique for measuring the concentration field around evaporating drops in an unsteady flow (fig. 1). The technique requires high spatial resolution as well as a wide dynamic range to accommodate flows in which the full range of concentration fluctuations is encountered. At the present time laser induced fluorescence using iodine as a fluorescent seed material appears to be the best choice for the concentration measurements. Fluorescence has significant advantages over other techniques for measuring concentration. Absorption techniques usually involve integration of the concentration along an optical path. Aspirating probes disturb the

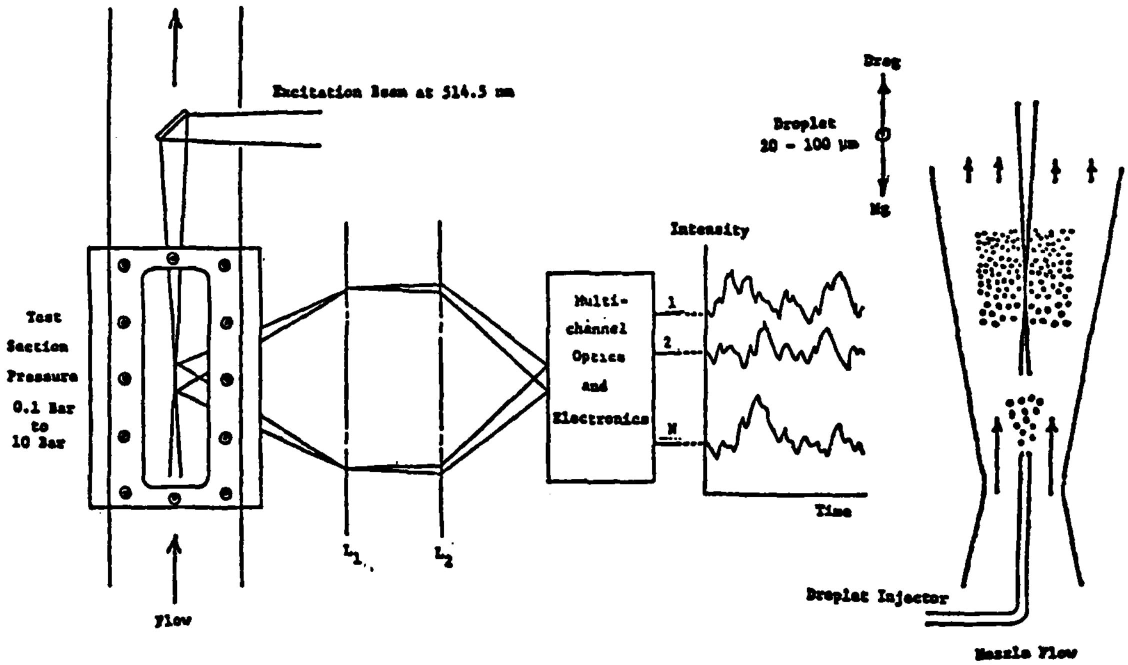


Figure 1. Multipoint concentration measurements abaout evaporating droplets.

flow and cannot achieve either the temporal or spatial resolution of the fluorescence technique.

In our current approach, an organic liquid with iodine in solution is introduced in a gas flow in droplet form and as the solution evaporates laser induced fluorescence from the iodine molecules is used to study the evaporation process. Fluorescence allows point measurements to be made in a general non-steady three-dimensional flow by using a focused laser beam to excite the fluorescing molecules and collection optics to select a particular segment of the beam path. Because evaporation can be studied as a constant pressure process, quenching of the fluorescence signal does not complicate data analysis. Iodine has an absorption band that is in near coincidence with the 514.5 nm argon-ion laser wavelength and it fluoresces in the orange-red part of the spectrum. Iodine fluorescence is not fully quenched at ambient pressure and its vapor pressure is high enough at room temperature (0.3 torr) to give a significant fluorescent signal at ambient conditions. There are a number of liquids whose vapor pressure curve is rather close to that of iodine and thus by matching the two vapor pressure curves and adjusting the carrier gas temperature one is able to control the ratio and rate of introduction of iodine molecules into the gas phase from the droplets.

Verification of the techniques developed for these studies will be carried out in a unique flow facility designed to operate over a wide range of pressure, particularly subatmospheric pressure appropriate to diagnostic techniques based on laser induced fluorescence. This feature of the facility will play a central role in the verification studies of laser based diagnostics in which the ambient pressure is a major limiting factor.

Scientific Merit

Improved knowledge of the physical process by which molecules leave the liquid state of a fuel droplet and diffuse or mix with the gas environment is needed in order to better understand the physical processes of spray combustion. In particular, one needs multipoint measurements of the vapor concentration field in the neighborhood of a droplet evaporating in an unsteady flow. At present, no technique has been developed to give this information. The aim of the present research is to develop a spatially and temporally resolved technique based on laser induced fluorescence for measuring the concentration field around evaporating drops in an unsteady flow.

Status Report

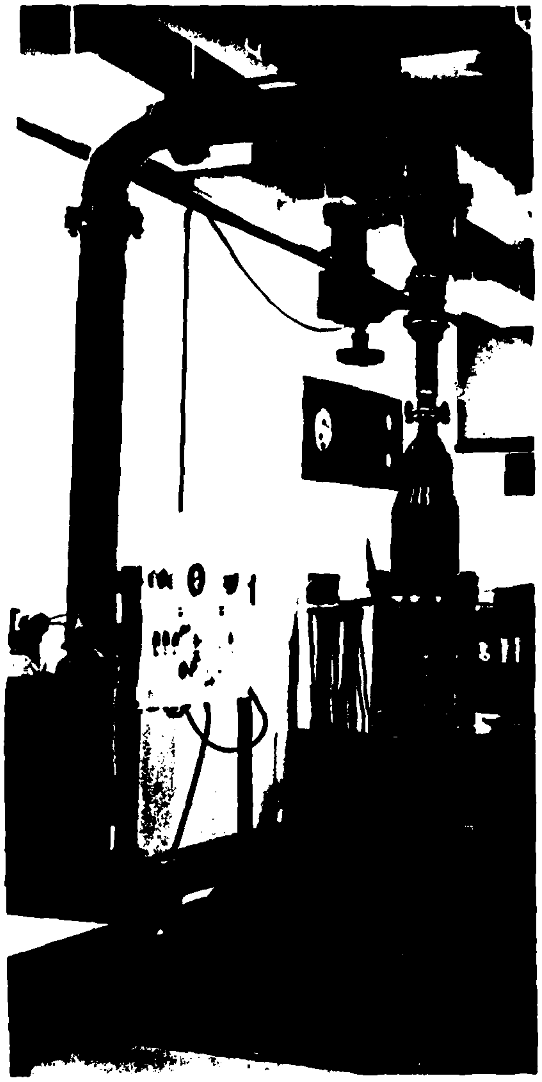
During the second year of funding, construction has been essentially completed on a new, variable pressure, flow facility for the study of droplet evaporation (figs. 2a and 2b). The facility is designed to permit studies of droplet behavior under pressure conditions ranging from hard vacuum to ten atmospheres. With the present vacuum system the minimum test section pressure under zero flow conditions is 10^{-2} torr. Under flowing conditions the minimum pressure at which reasonably uniform velocities can be achieved is in the range of 30–50 torr. The test section is mounted vertically to permit experiments in which droplets are suspended by the flow such as in the case of the diffuser flow shown schematically in figure 1. Flow velocities can be varied from a few millimeters per per second to a maximum of 10^3cm/sec.

The low velocity, low pressure end of the specified range of running conditions is determined by non–uniformity in the free stream velocity associated with the tendency for the flow to be fully developed at low Reynolds numbers. The high velocity, high pressure end of the range is determined by the maximum mass flow capabilities of the main regulator and upstream and downstream control valves used to set the test section velocity and pressure. Control of the free stream turbulence level is accomplished by a turbulence suppression system upstream of the test section. This is comprised of a six foot long section of 12 inch diameter stainless steel tubing (fig. 2a) containing a series of inserts (fig. 2c) including perforated plates, honeycomb, small mesh screens and an axisymmetric contraction with an area ratio of 3:1. This is followed by a circular to rectangular transition section with an area ratio of 1.6:1 giving an overall contraction ratio of 4.8:1. The turbulence suppression section and test section are both of modular construction and can be easily and quickly modified to accommodate a wide range of flow geometries and running conditions.

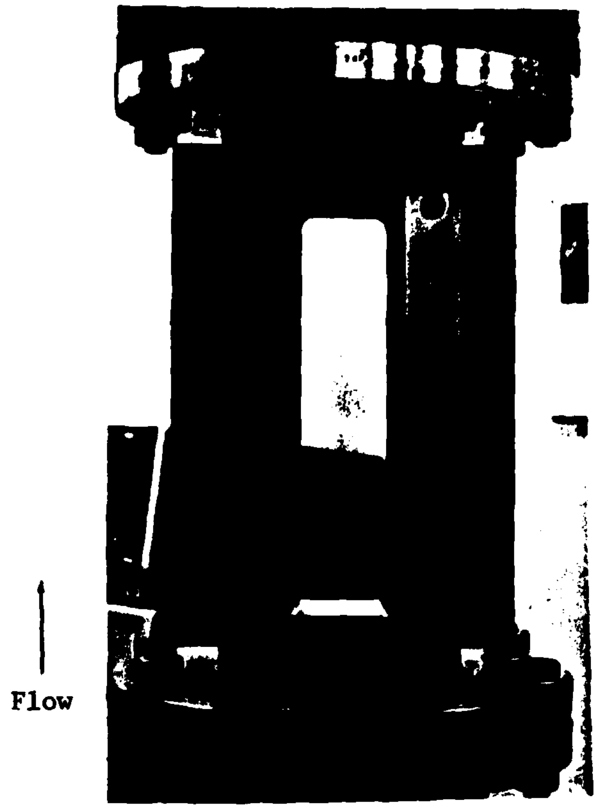
Running times of the facility vary from several seconds to continuous operation depending on test section velocity and pressure. For experiments involving subatmospheric pressures or noxious gases the flow exhausts into a $40ft^3$ volume which is at vacuum pressure when the run is initiated.

Full optical access to the flow is provided by glass windows mounted on all four sides of the test section. The windows are constructed of Hoya LE–30 glass $1\frac{1}{8}$ inches thick ground parallel to within 2 minutes of arc and to a flatness of 4 fringes over their 12 inch length. LE–30 is an aluminosilicate glass with hardness properties similar to fused silica. The thermal expansion coefficient is one–third that of common optical crown glasses and the transformation temperature is 686°C making it well suited to high pressure, high temperature operation.

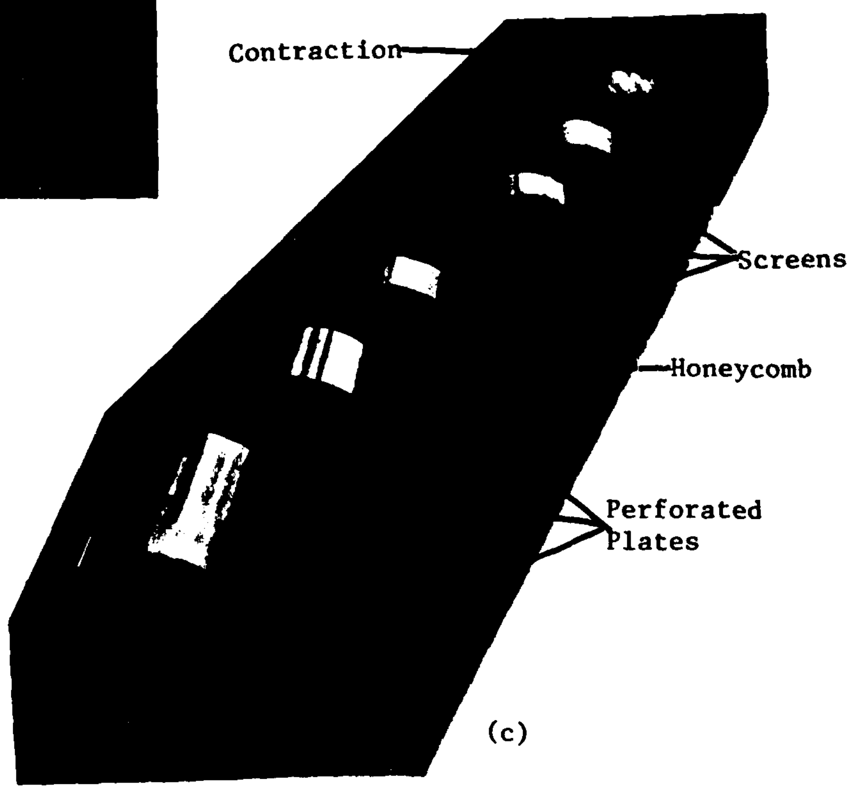
The use of iodine as a trace substance in studying droplet evaporation depends on the availability of a carrier liquid which has nearly the same vapor pressure and mass diffusion coefficient as iodine. The reason the match is desired is that, during evaporation, the iodine molecules would behave in exactly the same way as the carrier liquid, and its concentration would be expected to be in a fixed proportion to the concentration of the carrier liquid. Thus, by measuring the number density of iodine in the vapor phase, through its fluorescence intensity under laser excitation,



(a)



(b)



(c)

Figure 2. a) Variable pressure facility; b) Test section close-up
c) Inserts for the turbulence suppression system (exploded view).

one would be able to deduce the corresponding number density of the carrier liquid, which is the desired quantity to measure.

Several substances have been investigated and the ones that most nearly match iodine are shown in figure 3. We plan to run experiments over a range of temperatures. However, in the initial stages a temperature of 50°C, where the vapor pressure of iodine is approximately 3 torr., seems to be ideal. The figure shows that both kerosene and light fuel oil lie very close to iodine on the vapor pressure curve. In terms of the eventual simulation desired, namely droplet evaporation in a combustor, this is a very fortunate coincidence. However, both kerosene and fuel oils consist of mixtures of several substances having a wide range of properties; and in a basic study one would be interested in investigating a pure substance, in order to reduce the number of variables appearing in the problem. The alcohols represent pure substances which are quite suitable for our purposes. The one we have found that lies most closely to iodine's vapor pressure curve in the region of interest is Octanol ($C_8H_{18}O$), which is shown plotted in the figure for the range of temperature reported in the literature. Because of its relatively high molecular weight, it also has a diffusion coefficient at 25°C that is closer to iodine's than many of the other substances we reviewed.

Because our laboratory work has run in parallel with the literature search, which only recently uncovered the desirable properties of Octanol, most of our work to date has been with Benzyl Alcohol. In addition to the match discussed above, one must find that iodine molecules readily enter the vapor state as the carrier liquid evaporates rather than be left behind in the droplet in an ionic form. We have conducted tests to compare substances by passing a flow of nitrogen gas over a candidate solution and studying the resulting vapor in a small underexpanded low-pressure nozzle. When the iodine molecules readily follow the evaporating liquid, the flow in the nozzle can be made to fluoresce brightly by exciting it with an

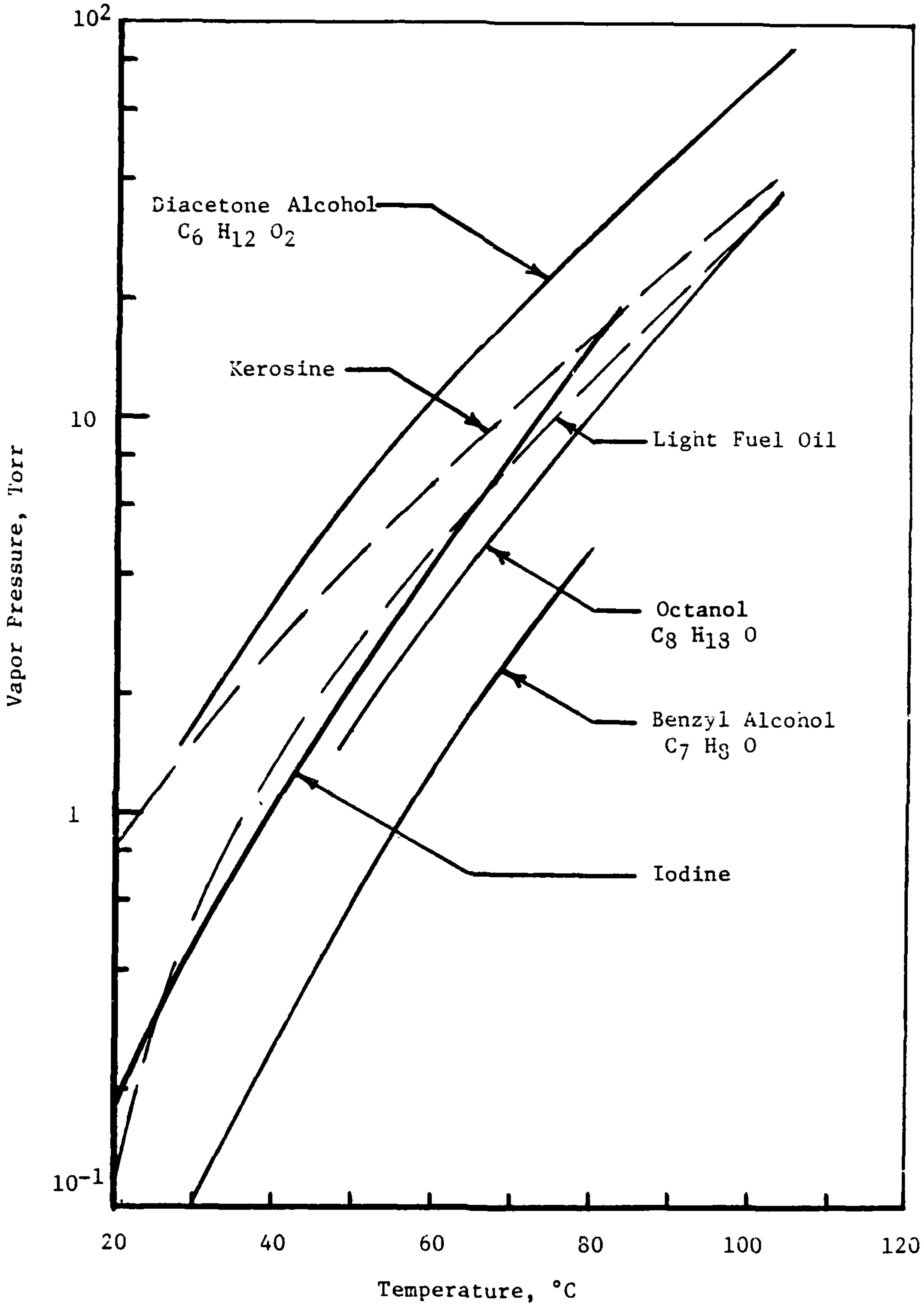


Figure 3. Comparison of the vapor pressure curves for several fuels and alcohols with iodine.

argon ion laser. On the other hand, when the iodine molecules do not enter the gas phase along with the evaporating carrier liquid, the iodine concentration in the jet becomes lower and the fluorescence intensity correspondingly decreases. We have found that the test with Benzyl Alcohol produces a fluorescence intensity nearly equal to the intensity for our standard test, one in which nitrogen gas is passed over iodine crystals alone before being analyzed in the nozzle.

Other experiments were conducted to develop quantitative information on iodine fluorescence for use in the flow facility once it is completed. A test cell was constructed to measure the iodine fluorescence intensity as a function of the partial pressures of iodine and nitrogen in the cell. The iodine partial pressure was varied by changing the temperature of the cell (up to 60°C) and making use of the known vapor pressure curve for iodine. The cell was fitted with Brewster angle windows for passing the laser beam through it with minimal attenuation. Figure 4 presents the results of these tests with iodine. The reason the tests were conducted, which can be quickly inferred from the figure, was to determine whether the iodine fluorescence intensity is proportional to iodine concentration, or equivalently iodine temperature, for our desired range of conditions. As seen in the figure, proportionality is observed if the nitrogen background pressure is above 200 torr. Proportionality is not observed if the nitrogen background pressure is low, because iodine–iodine collisions then become important and they are much more effective than iodine–nitrogen collisions in quenching iodine fluorescence. However, the high pressure region is precisely where we plan to conduct the experiments in the flow facility, so the experimental results confirm that this aspect of our approach is viable.

Detailed information on the attenuation of laser beam intensity as a result of absorption in iodine is also needed in planning the flow facility experiments. Figure 5 presents the results of a study where the path length for absorption was set at 5 cm. In this case the effect of changing nitrogen background pressure is fairly

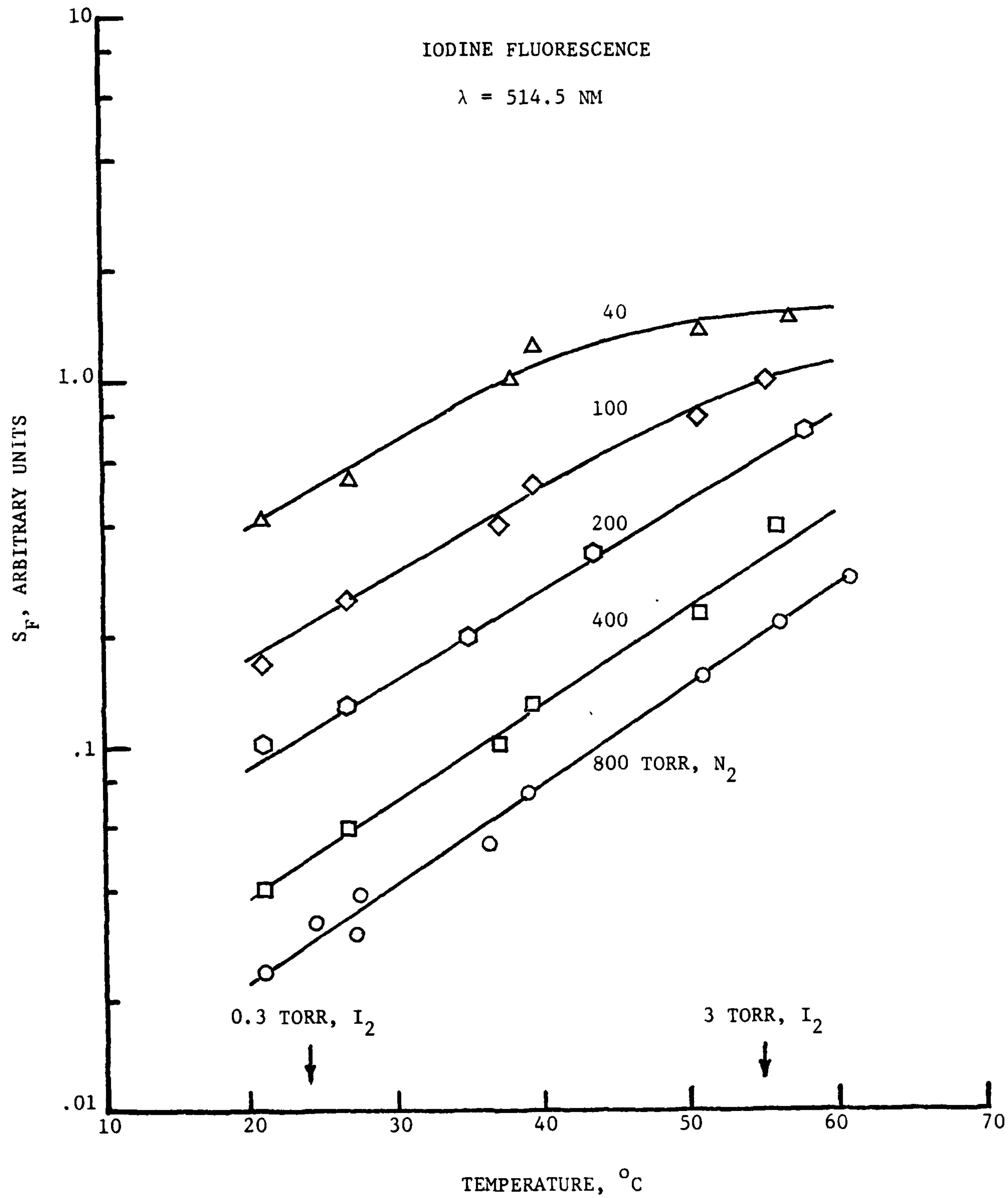


Figure 4. Iodine fluorescence intensity as a function of iodine partial pressure (temperature) and nitrogen background pressure.

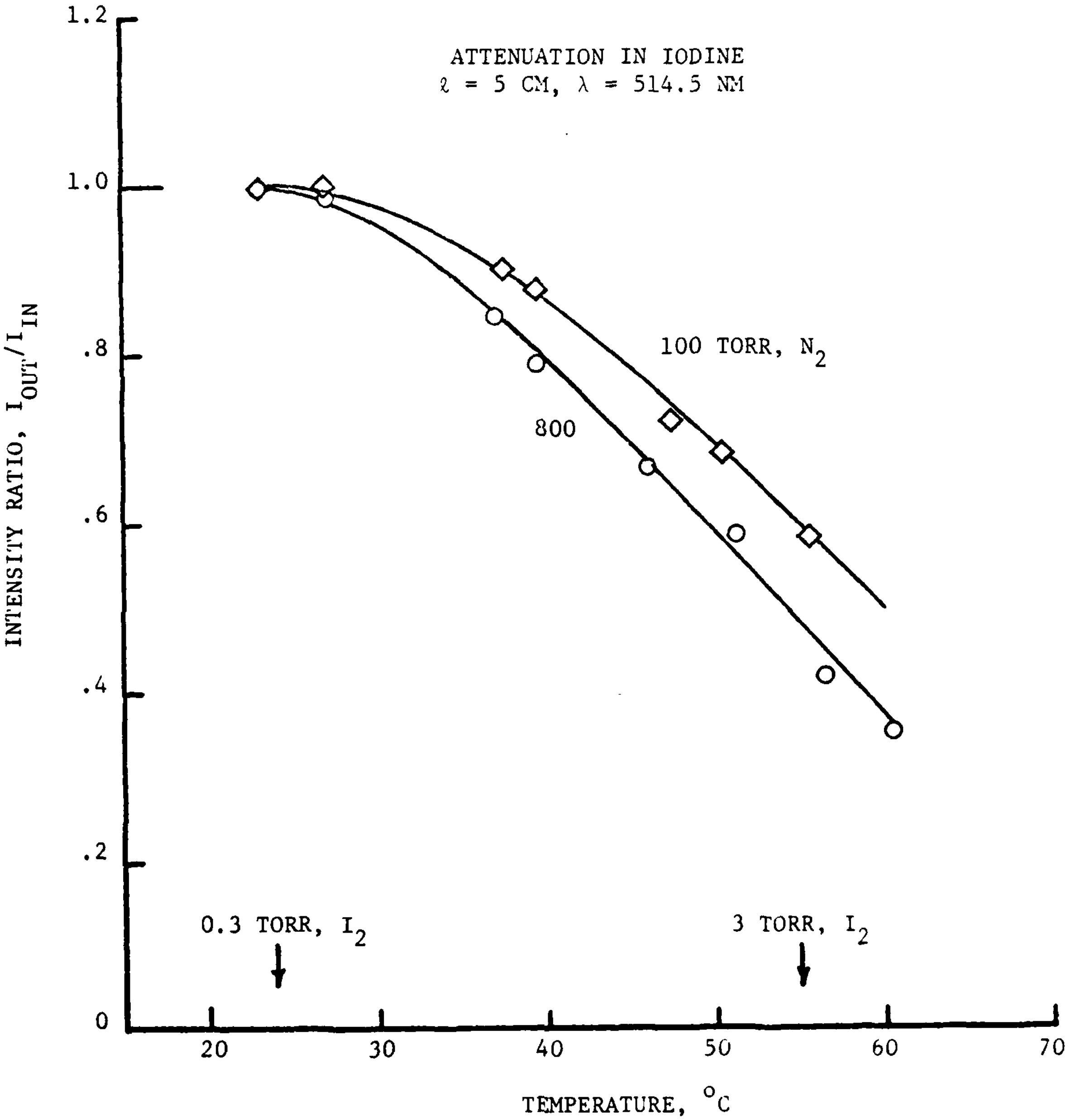


Figure 5. Absorption in iodine as a function of iodine partial pressure (temperature) and nitrogen background pressure.

small. The figure shows that the e-folding distance is roughly 5 cm when the iodine partial pressure is about 3 torr. Because we are expecting typical absorption path lengths near droplets in the flow facility to be at least an order of magnitude below 5 cm, and likewise the partial pressure of iodine will not be as high as 3 torr everywhere, the corrections for absorption in the flow facility are expected to be quite small. Consequently, both the exciting laser beam and the intensity of the iodine fluorescence in the droplet cloud would propagate nearly undisturbed.

With regard to the diagnostic technique we will be using in the flow facility, we have become extremely interested in a technique called four wave mixing. The technique is of interest to use because it promises to lead to an arrangement where concentration measurements could be made at a point in space with a detected signal much stronger than that expected for simple fluorescence. Also, the technique would have application to a wide variety of measurements in the field of combustion once it were fully developed.

In iodine the method would work as follows. The saturation intensity of iodine at 10 torr pressure is of the order of 10^4 watts/cm^2 and increase with pressure nearly linearly. Thus, saturation intensity is attainable in iodine with a 5 watt cw laser for pressures up to one atmosphere. Because the absorption coefficient varies with the degree of saturation, a standing wave pattern produced by the crossing of two coherent laser beams would present a spatial variation of absorption to a third probe beam and cause it to refract under suitable conditions (spatial variation must form a grating for the probe beam). The refracted beam is the fourth beam and it is the one that is detected in an experimental arrangement. The interest in the approach lies in the theoretical prediction that the power present in the detected beam can be made to vary, and most importantly, its energy is obtained from the two pump beams which are quite strong. Thus, in principle, a fairly strong detected signal could be obtained from a rather weak interaction.

An extensive literature presently exists on the subject because of its importance to a number of widely differing fields. Our application is sufficiently different from the ones that have been pursued that we are not able to simply incorporate directly what has been learned and must explore the matter further ourselves. The effect has been found experimentally for conditions other than the one we are interested in and we are presently seeking evidence for its existence in iodine as well as studying further the literature on the subject.

Publications and presentation

Presentation

1. J. C. McDaniel and D. Baganoff, "Density Measurements Using Laser-Induced Fluorescence," 34th Annual Meeting of the Division of Fluid Dynamics, Monterey, CA, Nov. 1981.

Publications

1. J. C. McDaniel, "Investigation of Laser-Induced Iodine Fluorescence for the Measurement of Density in Compressible Flows," Ph.D. Thesis, Stanford University, Stanford, CA, Jan. 1982 (also published as SUDAAR No. 532).

2. J. C. McDaniel, D. Baganoff and R. L. Byer, "Density Measurement in Compressible Flows Using Off-Resonant laser-Induced Fluorescence," The Physics of Flauids, Vol. 25, No. 7, p. 1105, July 1982.

Personnel

D. Baganoff	Prefessor, Aeronautics and Astronautics
B. J. Cantwell	Professor, Aeronautics and Astronautics
A. W. Strawa	Graduate Student, Aeronautics and Astronautics
D. R. Neal	Graduate Student, Aeronautics and Astronautics
U. Ackermann	Visiting Foreign Scholar, DFVLR, Berlin

2.10 Three-Dimensional Flow Visualization

Introduction

Non-reacting and reacting turbulent flows are inherently three-dimensional in nature. That is to say, flow parameters such as velocity, temperature, density or species concentration are all functions of three space coordinates and also time. The temporal character is often eliminated by averaging the appropriate equations over time, either by using a Reynolds averaging technique or by introducing similarity variables in order to make the flow as steady as is possible. Recent developments in the field of turbulence research indicate that large-scale coherent motions play an important role in turbulent flows. These structures are inherently three-dimensional in extent, and many investigators now believe that a Lagrangian description of the motion of these structures may provide very valuable information that hitherto has been hidden by the more traditional Eulerian approach. The Eulerian approach is simpler and more easily accessible by experimental techniques and it has in the past provided valuable engineering data. However at present no satisfactory physical model exists that can explain or predict many of the experimental observations. For instance, it is not possible to compute the spreading rate for a turbulent jet or the entrainment rate from first principles. Numerical solutions to the Navier Stokes equations cannot be obtained for many practical problems of interest, because of machine limitations. Recently it has been suggested that perhaps our understanding of turbulent flows may be improved by modeling on a computer the behavior of these large-scale vortical motions and their interactions. These new models will have to rely heavily on experimental data either for their input or for comparison with results. Therefore it has been the aim of many researchers in the field to develop diagnostic techniques for obtaining quantitative, instantaneous flow measurements in a plane or in a volume.

In the proposed research a cross section of the object is illuminated by a coherent sheet of light and scattered radiation is collected on film or a two-dimensional detector array as shown in Fig. 1. Three-

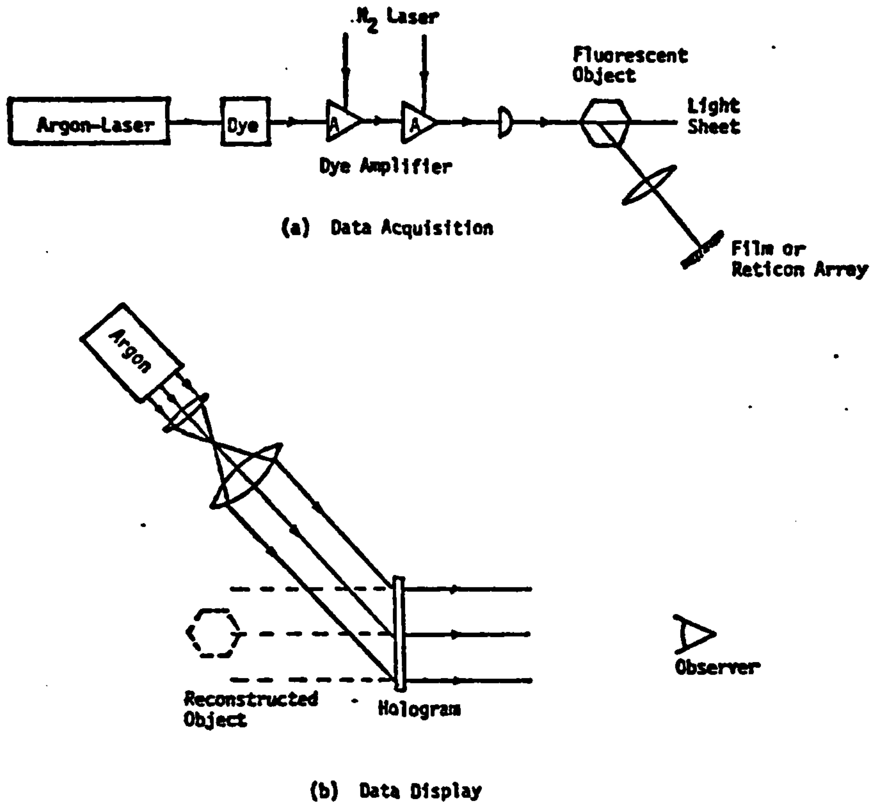


Figure 1. Experimental configuration for three-dimensional flow visualization project.

dimensional data are obtained by translating the sheet of light perpendicular to its surface. Ultimately four-dimensional Lagrangian data can be obtained by collecting volumetric data as a function of time. The acquired data, which can represent information about flow parameters such as velocity, density, temperature or species concentration, are then manipulated in a digital computer or a coherent optical processor for display and data reduction purposes. The display technique is based on a holographic method to give true depth perception. (See Fig. 1.)

Holography certainly is a competitive method for obtaining three-dimensional flow information, but is restricted to objects that diffusely scatter the incoming coherent radiation. The proposed method is superior to holography for the data acquisition phase of the method, because it is more generally applicable and has greater promise to provide quantitative information about density, species concentration or temperature fields. At present several efforts are underway at different universities and government laboratories to develop optical probes for measuring density [b,c], temperature [d], and velocity [e] either at a point or in a plane. This list is by no means complete, but it does give an indication of the work currently in progress. The main thrust in these projects is related to developing a suitable detection method using either fluorescence, Mie scattering, Rayleigh and Raman scattering or other scattering processes.

In the proposed research, the scattered radiation is recorded either on film or on a two-dimensional reticon photo detector array. The film has to be digitized before any processing of the data can be performed, and the film recording processes are inherently nonlinear, but proper processing can account for these non-linearities. A more direct method involves the use of a two-dimensional array of photo detectors. Presently an array is commercially available that has 10,000 elements and produces a video signal that can be interrogated at a rate of 10 MHz. The dynamic range and sensitivity of the detectors compare favorably with the parameters for film. The reticon array will be used in this project for both data acquisition and digitization of the film.

The data display technique involves the use of holography to obtain three-dimensional perception. The development of three-dimensional display techniques is a very active area of current research, due to the almost universal need to display three-dimensional objects. At least three distinct methods have been suggested, namely the vibrating mirror concept, the display of computer calculated views and the holographic method presented here. Of these methods only the first and the last one are capable of providing truly three-dimensional information. The first mentioned method involves the use of a video display and has no hard copy equivalent and requires an unusually high information bandwidth. The data handling problem will become prohibitive, at least for now, when time resolved volumetric data are considered. Holography certainly has the promise of being superior to either of the above mentioned alternatives, in terms of both information content and three dimensionality. The emphasis of the proposed project will be to manipulate the data obtained in fluid mechanics experiments into such a form that it can be displayed in three dimensions. Several holographic techniques will be investigated including multiplex, wide viewing angle and phase holograms. This effect will require substantial software development as well as optical processing. For this purpose a VAX 11/780 computer, an image processing facility and some input and output devices are available as well as general purpose image processing programs that were developed by the principal investigator during previous image processing work.

Scientific Merit

A novel diagnostic technique is proposed for measuring fluid properties in three dimensions. The feasibility of the measurement technique is tested using a stationary object. The new method, once developed, should make it possible, for the first time, to determine the instantaneous topology of the large-scale coherent motions known to dominate turbulent flows. The display technique uses holography and is of a general purpose nature. It has the ability to display three-dimensional objects as a function of time at a rate that can be optimized to suit the human observer. In particular it is possible to view and enhance interesting aspects of the object by properly processing the digital data.

Status Report

During the initial contract period, when no student support was available, emphasis was placed on investigating the properties of the holographic display technique, and to write general purpose image processing software for data reduction of combustion data. Progress made during the present grant period include the following:

- A test object was computer generated and a multiplex hologram was made to display the object. The displayed result is distorted due to the hologram formation process, and the sources of error have been evaluated. Subsequently a hologram was created using preprocessed data to eliminate the distortions. This hologram displayed the object with no discernible distortions, indicating that the corrention procedure functions properly.
- A considerable interest has been expressed in this technique for display of three-dimensional data, which

became evident during the 26th International SPIE meeting in San Diego. During this meeting a two day session on Processing and Display of Three-Dimensional Data was organized by L. Hesselink from Stanford and J. Pearson from Lockheed in Palo Alto. Many attendees, with interests in a wide spectrum of applications expressed a great enthusiasm for holographic display techniques. It became apparent that data obtained in fluid mechanics, meteorology, oceanography, combustion and geology research, to mention just a few areas, can be displayed with out holographic technique.

- During the summer student support became available and the development of image processing software for manipulating combustion data was begun. Two edge detection algorithms have been written, one based on the Sobol operator and the other on a Gaussian convolution technique. The Gaussian convolution method consists of convolving the image with two Gaussians of different standard deviation. The two resulting images are subtracted and the zero crossings form the edges in the original image. The algorithms are of a general purpose nature, but have been tailored for our specific application, a small scale laboratory flame. Examples of the capabilities of the system are included in this report. Figure 2 shows the test input image called Pepper, which was chosen because it has been widely studied by researchers in the Image Processing community and Fig. 3 represents the edge enhanced image using the Sobol operator. Figure 4 displays the results after a Gaussian convolution was performed on the data. Notice that the two methods produce different results. Figure 3 shows an abundant detail inside the central pepper, whereas Fig. 4 shows no detail there at all, but substantial high frequency detail is observed outside the pepper in the lower left quadrangle of the image. A substantial effort was made to investigate the effect of varying the variance of the Gaussian convolution mask and the ratio of the two Gaussians used for the edge enhancement technique. This experience will be of crucial importance for analyzing and processing the combustion data. We will perform filtering operations on the data either before or after the edge detection algorithm is applied. For this purpose a general image restoration and improbement software package has also been coded.

  Examples of the capabilities of the image restoration and improvement software are shown in Figs. 5 and 6. Again Fig. 2 was used as the test image and Fig. 5 shows a low

Figure 2. Pepper test image.

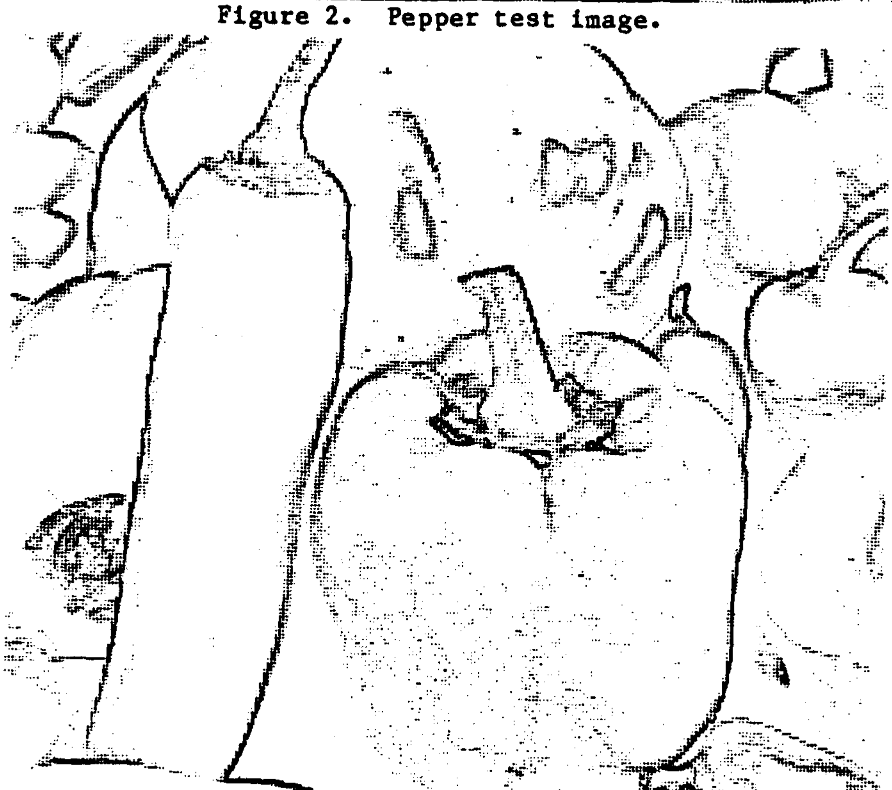


Figure 3. Edge enhanced image using Sobol operator.

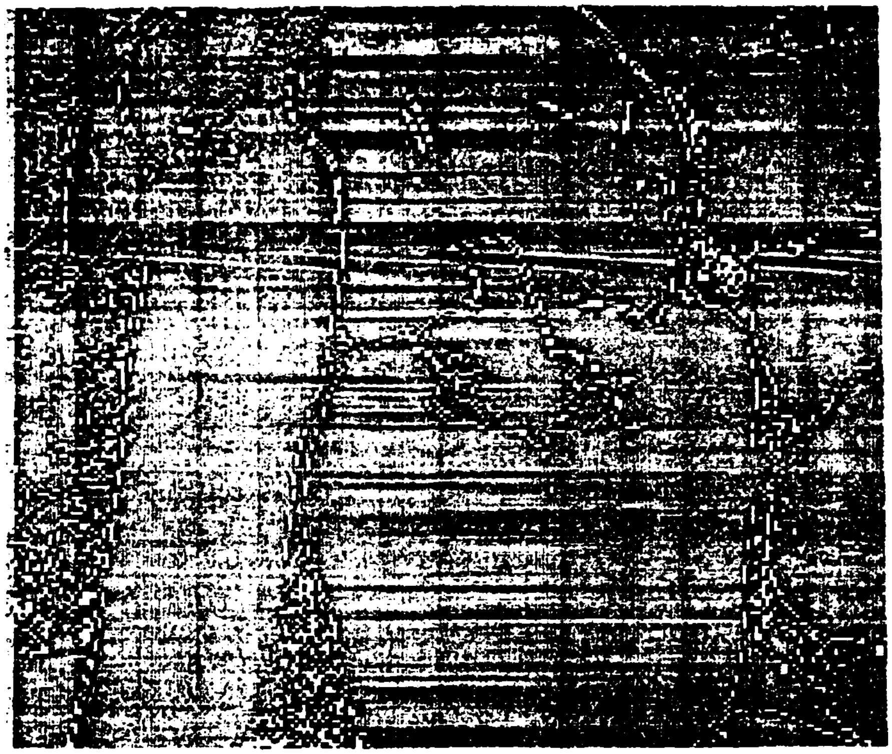


Figure 4. Edge enhanced image using Gaussian convolution

Figure 5. Low pass filtered image.

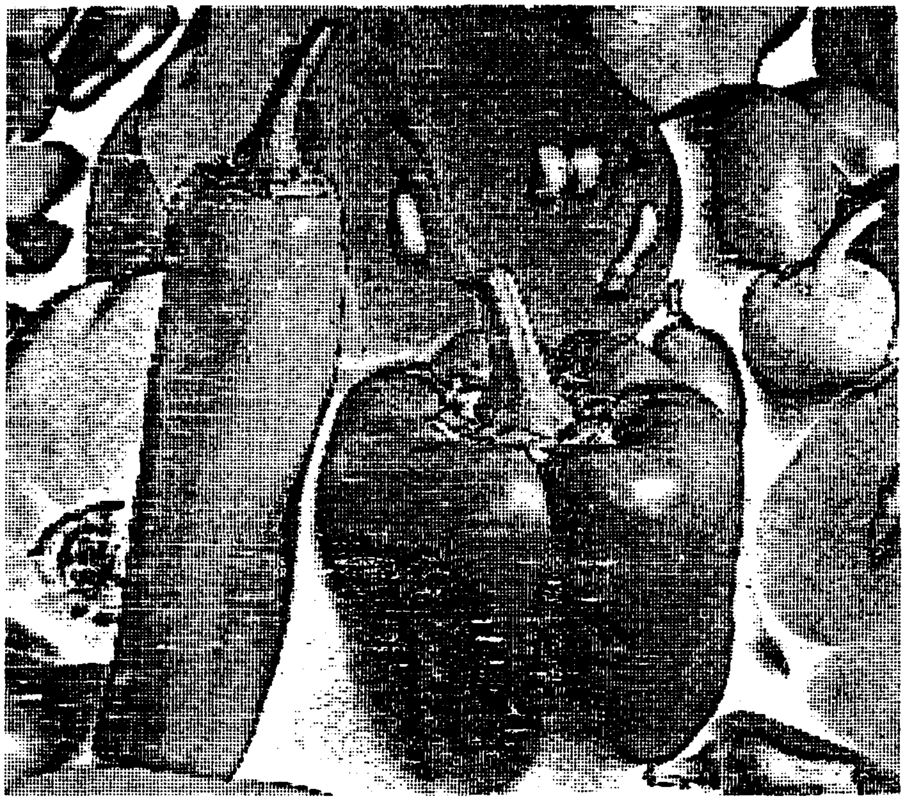


Figure 6. Edge enhanced image by removing dc component.

pass filtered version with blurred edges and the high spatial frequency components removed. Figure 6 shows the result of a high-pass filtering operation, with the dc-component removed from the image. Notice that this procedure enhances the edges and clearly reveals the high frequency detail to the south-south west of the central pepper, which was before processing not directly visible to the naked eye, but was picked up by the edge detection algorithm.

- Simultaneously we have performed software development to interface our image processing facility to our VAX 11-780. We now have the capability to record images using a vidicon camera and store the data directly in RAM at a rate of 30 frames per second. The images can be manipulated locally in the processor or can be processed in the host computer.

Presently we are engaged in collecting two-dimensional cross sectional data in a flame and are applying our software programs to these data. A multiplex hologram will be generated using the processed data.

Publications and Presentations

Publications

None

Presentation

1. L. Hesselink/J. Pearson were Session organizers and chairman of a two day meeting on: Processing and Display of Three-Dimensional Data, held in San Diego during the 26th International SPIE meeting, August 23-27, 1982.

Personnel

Lambertus Hesselink	Professor Aeronautics/Astronautics
Arturo Gamboa	Graduate student, Electrical Engineering
Ron Majewski	Graduate student, Electrical Engineering

References

a. P. G. Saffman and G. R. Baker, Ann. Rev. Fluid Mech. 11, 95-122 (1979).

b. M. B. Long, B. F. Weber and R. K. Chang, Appl. Phys. Lett. 34, 22 (1979).

c. R. L. McKenzie, D. J. Mason and R. J. Exberger, AIAA Paper 79-1088.

d. R. M. Kowalik and C. H. Kruger, Combustion and Flame 34, 135-140, (1979).

e. S. A. Self and J. D. Whitelaw, Int. J. Comb. Sci. and Tech. 13, 171-197 (1976).

2.11 Spatially Resolved Absorption by Optical Stark Shifting

Introduction

The objective of this work is to extend absorption spectroscopy, which is typically a line-of-sight method, to provide spatial resolution. This is accomplished through use of two laser beams which cross in the small measurement volume of interest. One beam (the probe beam) is from a low-power, cw laser tuned to a suitable absorption line of the species to be measured, while the second (pump) beam is from a non-resonant, high-power pulsed laser. The strong electric field from the pump beam causes a shift in the energy levels of the absorber and hence the absorption wavelength, thereby modulating the transmitted intensity of the probe beam. This intermittent modulation can be related to the change in absorption in the overlapping volume and hence the absorber concentration.

This approach, known as optical (or AC) Stark shifting was first suggested by Farrow and Rahn at Sandia (see Refs. a, b) who have used both a fixed-frequency CO_2 laser and a tunable F-center laser as probe beams. The probe beam in our work is a tunable infrared diode laser which has a much larger tuning range and hence can access a much greater number of IR-active species.

Scientific Merit

This work represents the first study of optical Stark shifting with tunable diode lasers. Measurements were made over a range of conditions including a laboratory flame, thereby providing unique data for testing Stark-shift theories as well as enabling evaluation of the approach as a combustion diagnostic. The significant virtue of employing a tunable diode laser probe beam is its wide tunability, from about 3-30 microns, thereby providing access to the large class of molecules with absorption bands in this range.

Status Report

This work was initiated and completed during the past 12 months by a visiting postdoctoral scholar, Dr. Klaus Knapp of West Germany. Dr. Knapp's previous experience with high-power Nd:YAG lasers and our own expertise with tunable diode lasers allowed fast progress on this difficult project.

A schematic of the concept is shown in Fig. 1, and a detailed schematic of the system is shown in Fig. 2. Experiments were conducted with a range of pump beam power levels (different Stark shifts) and probe beam wavelengths (all for the P(20) transition of CO at 2059.91 cm^{-1}) so that detailed comparisons could be made between calculated and measured Stark-shifted spectra. A comparison made with CO in a premixed flame and for a specific pump energy/pulse is given in Fig. 3. As may be seen, agreement is good, although it was necessary to normalize the theory and signals by their peak values due to a smaller-than-predicted measured change in peak modulation. Further details of this work are provided in the publication listed below.

Publications and Presentations

1. K. Knapp and R. K. Hanson, "Spatially Resolved Tunable Diode Laser Absorption of CO Using Optical Stark Shifting," submitted to Applied Optics, November 1982.

Personnel

Ronald K. Hanson	Professor (Research), Mechanical Engineering
Klaus Knapp	Visiting Postdoctoral Scholar, Mechanical Engineering

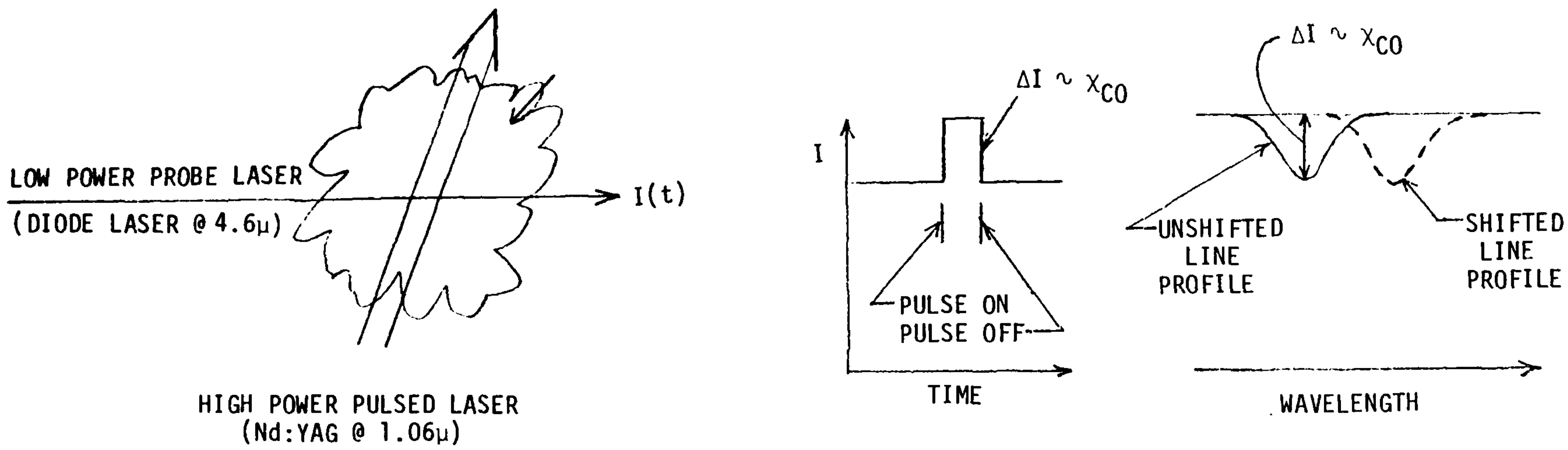
References

a. R. L. Farrow and L. A. Rahn, Opt. Lett. 6, 108 (1981).

b. R. L. Farrow, Applied Optics, in press (1982).

SPECIES DETERMINATION

OPTICAL STARK SHIFTING ENABLES SPATIALLY RESOLVED ABSORPTION MEASUREMENTS



- FIRST APPLICATION OF OPTICAL STARK SHIFTING WITH DIODE LASERS
- RESEARCH PROVIDES UNIQUE DATA FOR TESTING BASIC STARK SHIFT THEORY AND EVALUATING POTENTIAL OF APPROACH
- APPLICABLE TO MANY SPECIES (REQUIRES OPTICALLY ALLOWED TRANSITION)
- SPATIAL RESOLUTION BETTER THAN 5 MM DEMONSTRATED

Figure 1. Overview of optical Stark-modulation experiment.

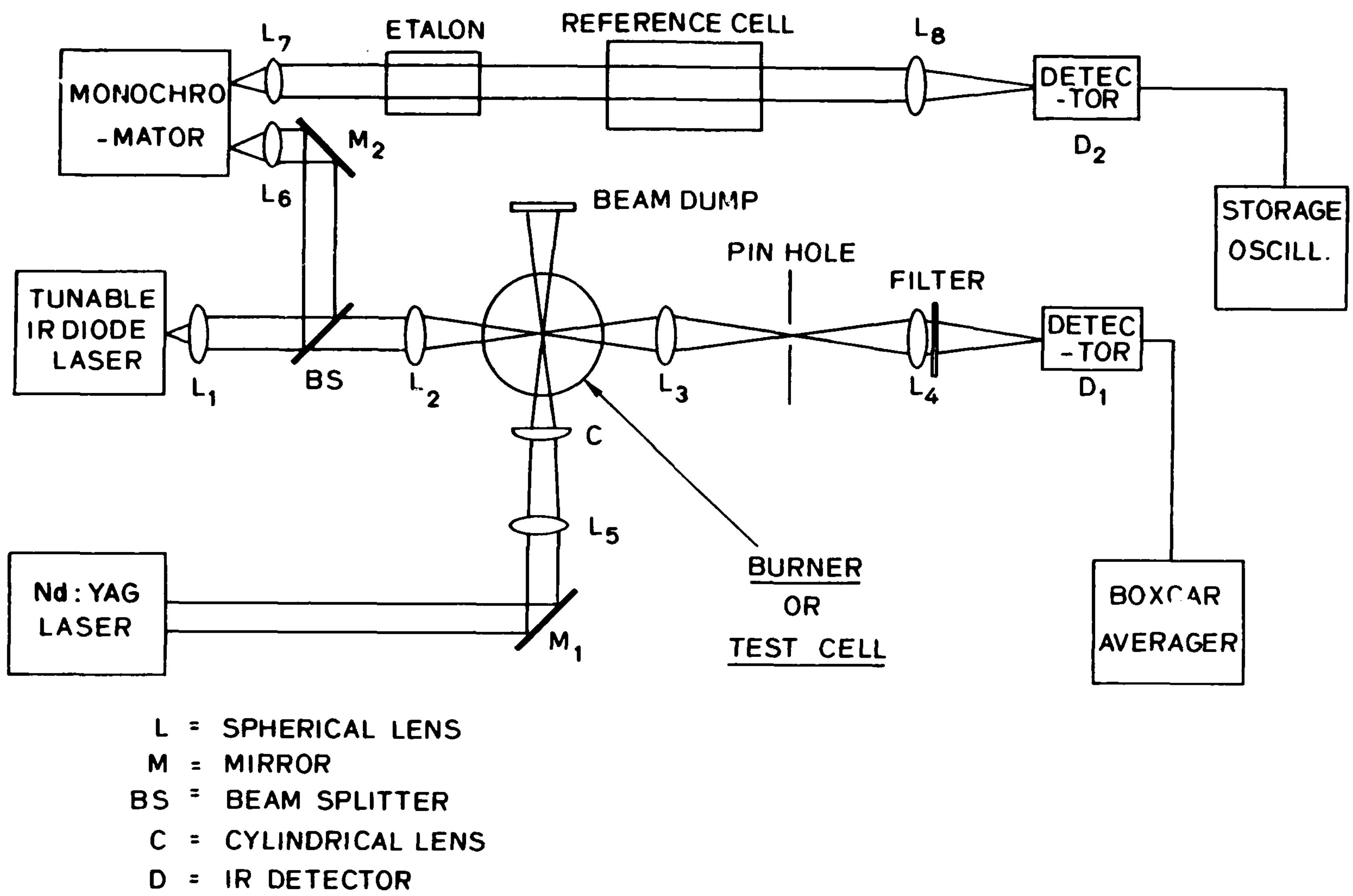


Figure 2. Schematic of electro-optical arrangement for optical Stark modulation experiment.

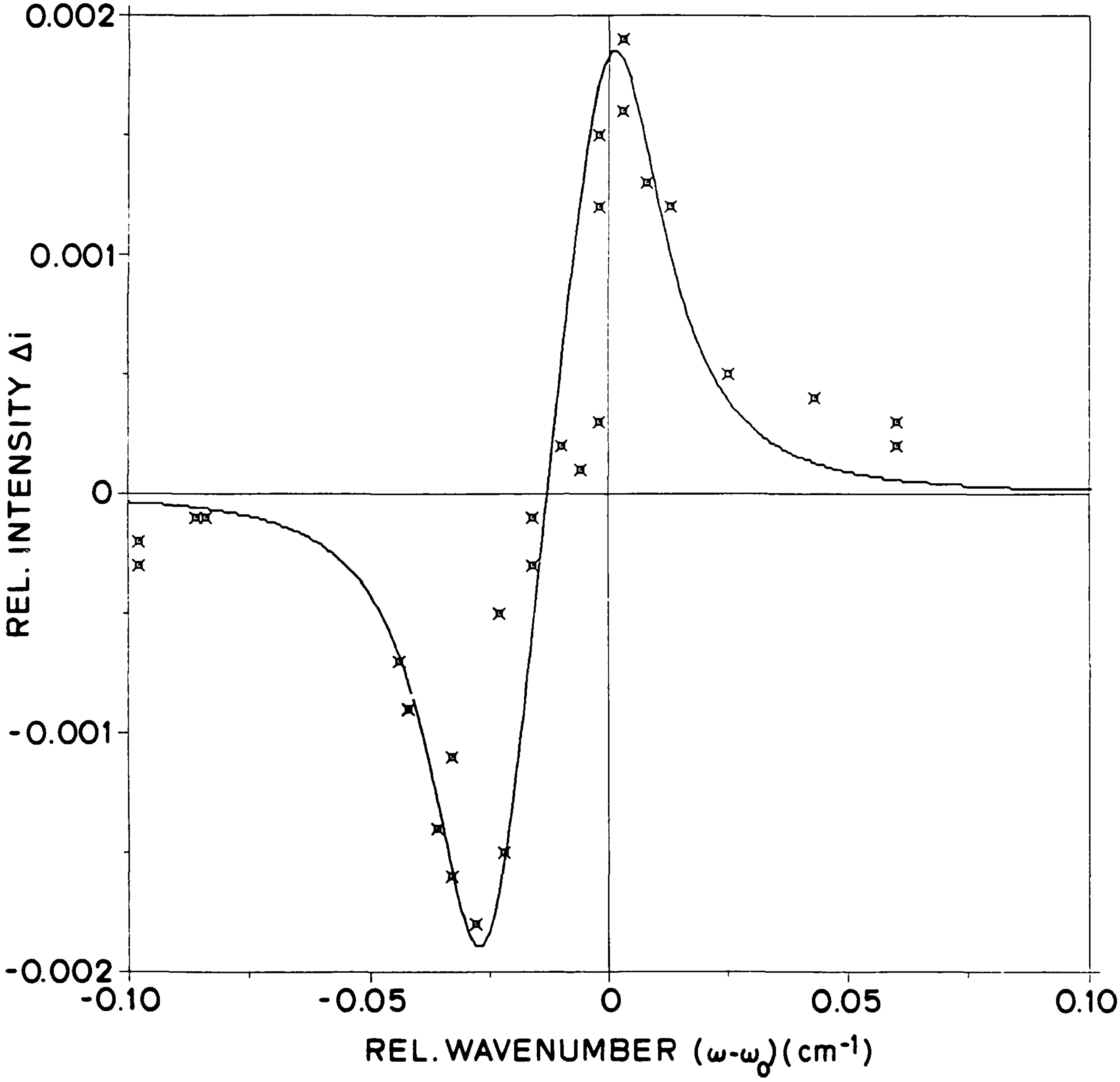


Figure 3. Measured and calculated optical Stark spectrum of the P(20)-CO line using a premixed CH_4/air flame; temperature: 1400K; total pressure: 1 atm; CO partial pressure: 0.05 atm; total absorption length: 1.6 cm; interaction length: 0.5 cm; Nd:Yag laser energy: 430 mj; Stark shift: - 0.035 cm^{-1}; FWHM = .046 cm^{-1}.

2.12 Fast-Scanning Ring Dye Laser

Introduction

Improvements in tuning rates of narrow-linewidth laser sources offers significant potential for advancements in diagnostic techniques and combustion-related measurements. In particular, wavelength modulation provides a simple means of discriminating against continuum extinction effects present in absorption- or fluorescence-based species measurements in two-phase flows. Additionally, the capability to record fully resolved absorption (or fluorescence) lines eliminates the need for uncertain linewidth assumptions in converting measured absorption (or fluorescence) signals to species concentration. Early work in our laboratory has clearly demonstrated the utility of these concepts using tunable infrared diode lasers.

Unfortunately, rapid-tuning dye lasers, needed for accessing a variety of important radical species which absorb in the near UV and visible, are not commercially available. Recognizing the importance of such a capability, we have developed a novel (and simple) modification to a commercial ring dye laser which increases the scan repetition rate by three orders of magnitude (from about 4 Hz to 4 kHz) for short scans ($1-2\ cm^{-1} = 30-60$ Ghz).

Scientific Merit

This is the first dye laser system, that we are aware of, which enables fast single-mode scans over spectral regions encompassing complete absorption lines (~ 30 GHz at combustion conditions). This capability provides several new opportunities for combustion research. In connection with practical combustors or laboratory devices where particulates or droplets are present, wavelength-modulation techniques can now be applied to discriminate between the gaseous absorption of interest and the interfering continuum extinction. Also, measurements of fully-resolved absorption lines (leading to determinations of species or temperature) can now be made in unsteady flows or in devices where transient phenomena are of interest. Finally, the significance of fast-scanning capability for basic spectroscopic measurements should be noted. For example, it should now be possible to record fully resolved absorption lines in a shock tube. Such experiments would yield unique data on linewidths at elevated temperatures, and offer prospects of determining oscillator strengths and heats of formation of radical species important in various combustion flows.

Status

A schematic of the dye laser modification and an example of the system capability are shown in Fig. 1. In brief, a rotating dual-element device, which changes the effective laser pathlength as it rotates, is installed in one corner of the ring laser adjacent to the output mirror. Use of two elements guarantees that the alignment of the beam (inside and outside of the cavity) does not change while the wavelength is changing. The tuning elements are mounted on the shaft of a commercial galvanometer which mounts conveniently in the standard ring cavity of our Spectra-Physics ring dye laser.

The tuner has been demonstrated successfully in the visible, providing continuous, single-mode scans up to 3 cm^{-1} (90 GHz) at 4 kHz. Recent efforts have been directed toward extending this capability into the UV by installing a doubling crystal into the same cavity. Preliminary experiments with an ADA doubling crystal, oven and mount provided by Spectra-Physics (recently announced and soon to be released as model 398A) show excellent performance, with outputs in excess of 5 mW at 300 nm (with a pump power of only 3.0 W all lines) and single mode scans of more than 100 GHz at 4 kHz repetition rate. We have been contacted by several researchers in other laboratories who are anxious to obtain this extended capability.

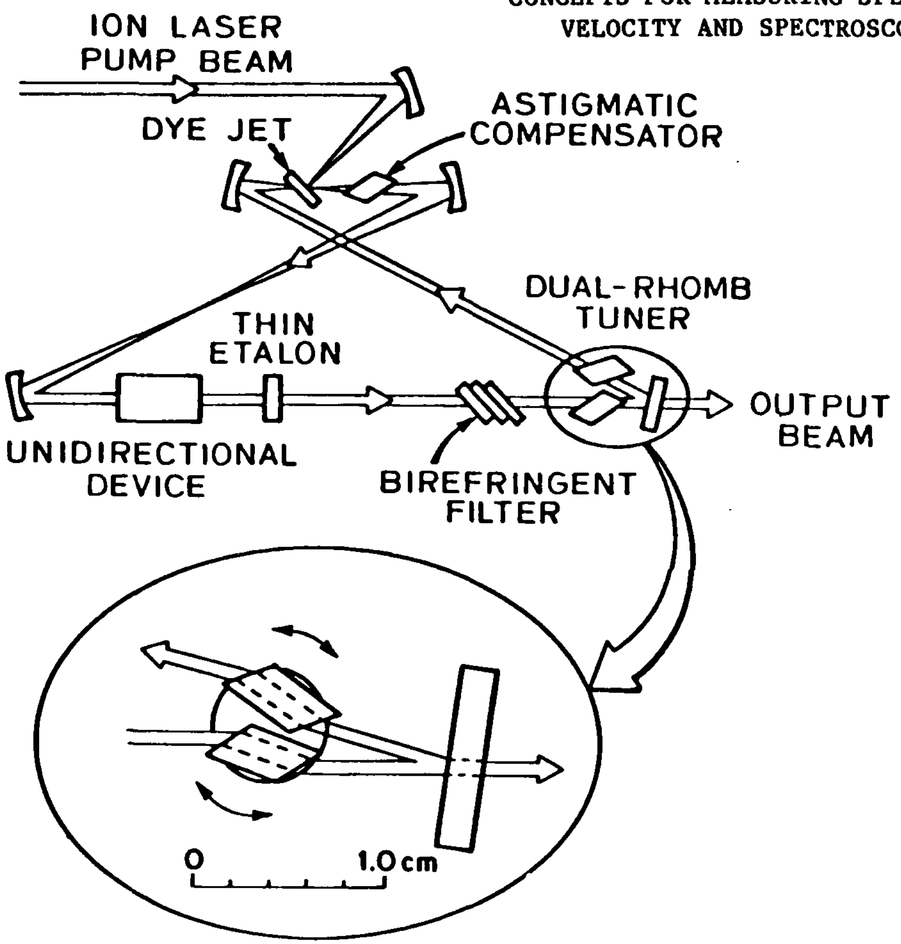
Presentations and Publications

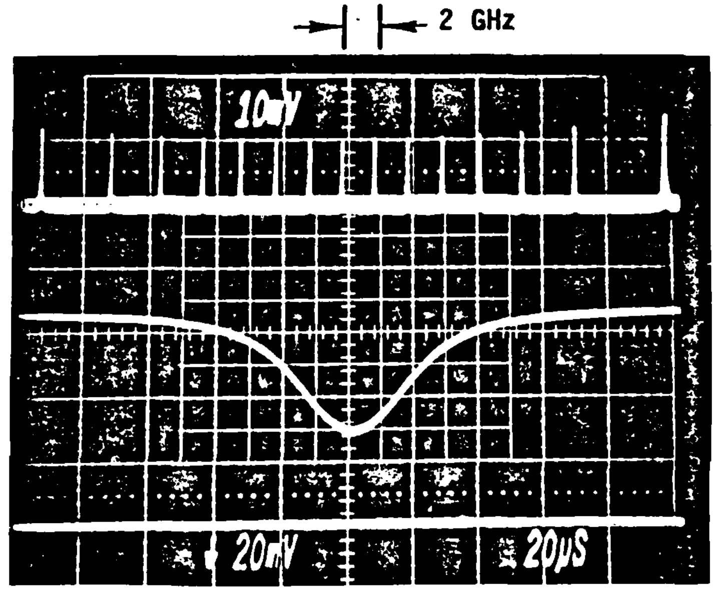
1. E. C. Rea, Jr. and R. K. Hanson, "Rapid, Extended Range Tuning of Single-Mode Ring Dye Lasers," Applied Optics, in press (1982).

Personnel

Ronald K. Hanson	Professor (Research), Mechanical Engineering
Edward C. Rea, Jr.	Graduate Student, Mechanical Engineering (Ph.D. expected in June 1985)

RAPID SCANNING RING DYE LASER ENABLES NEW WAVELENGTH-MODULATION CONCEPTS FOR MEASURING SPECIES, TEMPERATURE, VELOCITY AND SPECTROSCOPIC PARAMETERS





SINGLE SWEEP RECORD OF FULLY RESOLVED Na ABSORPTION LINE OBTRAINED BY PASSING TUNABLE LASER BEAM THROUGH FLAME.

- MODIFICATION IMPROVES SCANNING RATE OF LASER FROM 4 Hz → 4 kHz (60 GHz SCAN)
- SYSTEM PROVIDES FIRST HIGH-SPEED, HIGH SPECTRAL RESOLUTION CAPABILITY FOR STUDIES OF TRANSIENT PHENOMENA
- WAVELENGTH MODULATION CONCEPT ENABLES QUANTITATIVE ABSORPTION AND FLUORESCENCE MEASUREMENTS IN 2-PHASE FLOWS
- APPLICATIONS INCLUDE STUDIES IN FLAMES, SHOCK TUBES, SUPERSONIC FLOWS, COMBUSTION TUNNELS
- SYSTEM ENABLES UNIQUE MEASUREMENT OF BASIC PARAMETERS IN HIGH TEMPERATURE GASES (F-NUMBERS, LINESHAPES, ΔH_f)
- CONCEPT APPLICABLE FOR UV, VISIBLE AND NEAR IR WAVELENGTHS

Figure 1. Schematic of fast-scanning ring dye laser and typical data obtained in a flame.

END

FILMED

9-83

DTIC