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STANFORD UNIV CALIF HIGH TEMPERATURE GASDYNAMICS LAB F/G 21/2
DEVELOPMENT OF COMBUSTION DIAGNOSTICS AND APPLICATION TO TURBUL--ETC(U)
NOV 80 R K HANSON, C T BOWMAN F49620-78-C-0026

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Final Scientific Report

on

DEVELOPMENT OF COMBUSTION DIAGNOSTICS
AND APPLICATION TO TURBULENT COMBUSTION

Contract F49620-78-0026

Prepared for

Air Force Office of Scientific Research

For the Period

February 16, 1978 to September 30, 1980

Submitted by

R. K. Hanson and C. T. Bowman

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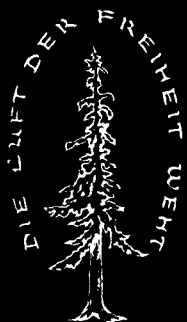
HIGH TEMPERATURE GASDYNAMICS LABORATORY
MECHANICAL ENGINEERING DEPARTMENT

STANFORD UNIVERSITY ■ STANFORD, CALIFORNIA

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⑨ Final rept. 16 Feb 78
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM												
1. REPORT NUMBER ⑧ AFOSR-TR-8-0113	2. GOVT ACCESSION NO. AD-A095719	3. RECIPIENT'S CATALOG NUMBER												
4. TITLE (and Subtitle) ⑥ Development of Combustion Diagnostics and Application to Turbulent Combustion		5. TYPE OF REPORT & PERIOD COVERED Final 2/16/78 to 9/30/80												
7. AUTHOR(s) ⑩ R. K. Hanson and C. T. Bowman		6. PERFORMING ORG. REPORT NUMBER												
9. PERFORMING ORGANIZATION NAME AND ADDRESS Stanford University Department of Mechanical Engineering Stanford, California 94305		8. CONTRACT OR GRANT NUMBER(s) ⑮ F49620-78-C-0026												
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research/NA Bldg. 410 Bolling AFB, D.C. 20332		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F ⑬ 2308 ⑭ A2												
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) ⑫ 17		12. REPORT DATE ⑪ November 1980												
		13. NUMBER OF PAGES 14												
		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) <table border="0"><tr><td>Combustion</td><td>Temperature</td><td>Spectroscopy</td></tr><tr><td>Flame</td><td>Infrared</td><td>Turbulent</td></tr><tr><td>Diagnostics</td><td>Absorption</td><td>Fiber Optics</td></tr><tr><td>Carbon Monoxide</td><td>Laser</td><td></td></tr></table>			Combustion	Temperature	Spectroscopy	Flame	Infrared	Turbulent	Diagnostics	Absorption	Fiber Optics	Carbon Monoxide	Laser	
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Measurements with a tunable diode laser absorption system have been conducted in steady, fluctuating and sooting atmospheric-pressure flames produced in either a flat flame or a slot burner. Parameters measured include temperature, CO species concentration and CO spectroscopic parameters (line strengths and collision half widths). The measurements were made with two optical/tuning arrangements: (1) by rapidly scanning the narrow-linewidth diode laser across individual vibration-rotation lines in the fundamental band of CO at 4.6 microns														

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to record fully-resolved absorption line profiles in times as short as 100 microseconds; and (2) by fixing the laser wavelength at the absorption line center and recording the absorption in real time. A conventional microprobe sampling system has been used to monitor CO and CO₂ concentrations to enable comparisons between laser-based and conventional probe-based measurements in steady flames; thermocouples have been used to allow comparisons with laser-based temperature measurements. Good agreement was found between the laser-based and probe-based measurements of CO when the sampling probe was operated at low pressures, $p < 8 \times 10^3$ Pa (60 torr), but a substantial error in probe measurements, due to conversion of CO to CO₂ interior to the probe, was observed at higher, more typical probe pressures.

A tunable dye laser system for high-resolution absorption spectroscopy of combustion gases at visible and near-ultraviolet wavelengths has been developed. The system has been assembled and feasibility experiments involving measurement of sodium in a flat flame burner have been completed.

Work was initiated to develop laser-based fiber optic absorption probes for spatially resolved, remote measurements of species concentrations and temperature. Separate probe systems have been assembled for use with tunable infrared diode lasers and tunable uv/visible dye lasers. These probes are water cooled and have variable path lengths (typically 1 cm). Associated electronics and data processing systems are still undergoing development.

A new facility for studies of the dynamics of fluctuating or turbulent combustion flows has been designed, assembled and checked out. The facility generates a two-dimensional shear flow which will be used to study the coupling between fluid dynamic and chemical processes in a turbulent mixing layer. The selection of the two-dimensional geometry enables use of line-of-sight optical techniques including diode laser spectroscopy.

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1.0 RESEARCH OBJECTIVES

This program has provided fundamental research in the areas of: advanced non-interfering optical diagnostics, particularly for application to the measurement of species concentration and temperature in combustion flows; the investigation of combustion dynamic phenomena, particularly chemically reacting turbulent flows. Objectives of the work have been as follows:

- a. Develop and apply tunable diode lasers for the measurement of major and minor species concentrations and temperature under steady, fluctuating and sooting combustion conditions. Species have included CO and NO. Experiments were conducted in flat-flame and slot burners.
- b. Compare measurements obtained with diode laser absorption techniques with results obtained using existing methods, specifically point sampling probes for CO species concentration and thermocouples for temperature.
- c. Develop laser-based fiber optic absorption probes for spatially and temporally resolved remote sensing of species concentrations and temperature, particularly for applications to combustion flows.
- d. Investigate coupling effects between reaction kinetics and turbulence in a two-dimensional shear flow.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)

NOTICE OF TECHNICAL DATA

This technical data is approved for release under E.O. 12958-12 (7b).

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2.0 STATUS OF RESEARCH EFFORT

Research has been performed in two areas: (1) laboratory flame studies to develop tunable laser absorption spectroscopy; and (2) an investigation of turbulent reacting shear flows. A summary of progress in these program areas follows below.

2.1 Development of Tunable Laser Absorption Spectroscopy and Applications to Laboratory Flames

During this 30-month period, we have made good progress in the development and application of tunable laser absorption spectroscopy as a diagnostic for combustion flows. Significant accomplishments include: successful tunable infrared diode laser measurements of CO concentration and temperature in a variety of steady, fluctuating and sooting flames; initial dye laser measurements of Na lineshapes and concentration in a flat flame; and initial development of laser-based, fiber optic absorption probes for spatially and temporally resolved remote sensing of species concentration and temperature. Details of completed work have been given in recent publications (see Section 3 of this report). A summary of relevant activities follows below:

a) Species Measurements with a Tunable Diode Laser

Carbon monoxide concentrations have been measured in the postflame region of laminar, premixed methane/air flames using both tunable diode laser absorption spectroscopy and conventional probe sampling. The optical technique employed a diode laser tuned to specific vibration-rotation lines in the fundamental band of CO at 4.6 microns; a schematic of the system employed is shown in Fig. 1. The data for each fully-resolved absorption line were analyzed by computer to obtain a best-fit Voigt profile, thereby determining simultaneously both the CO partial pressure and the collision-broadened halfwidth for the line under flame conditions. The agreement between the laser-based value for CO and the chemical equilibrium value computed using the measured fuel and air flowrates was good, for rich flames, as shown in Fig. 2. For lean flames, the laser values for CO exceed equilibrium levels, as expected, due to finite rate chemistry. In the sampling experiments, combustion gases were extracted using both an uncooled, aerodynamically-quenched quartz microprobe and a water-cooled stainless steel microprobe. The sampled gases were analyzed for CO and CO₂ using NDIR instruments. The sampling probe measurements, which were made in both lean and rich flames, yielded total carbon consistent with the input stoichiometry, but indicated substantial conversion of CO to CO₂ in the probe, with the extent of conversion being dependent on the probe pressure. The probe results for CO obtained with a sampling pressure of 150 torr, shown in Fig. 2, are consistently below the laser values by 5-10%, for both probes. We conclude from this work that: (a) laser absorption measurements are accurate and reliable if proper consideration is given to temperature nonuniformities along the optical axis; and (b) sampling probes should be operated at low pressures to preserve sample integrity. A detailed description of this work has recently been published (see Section 3).

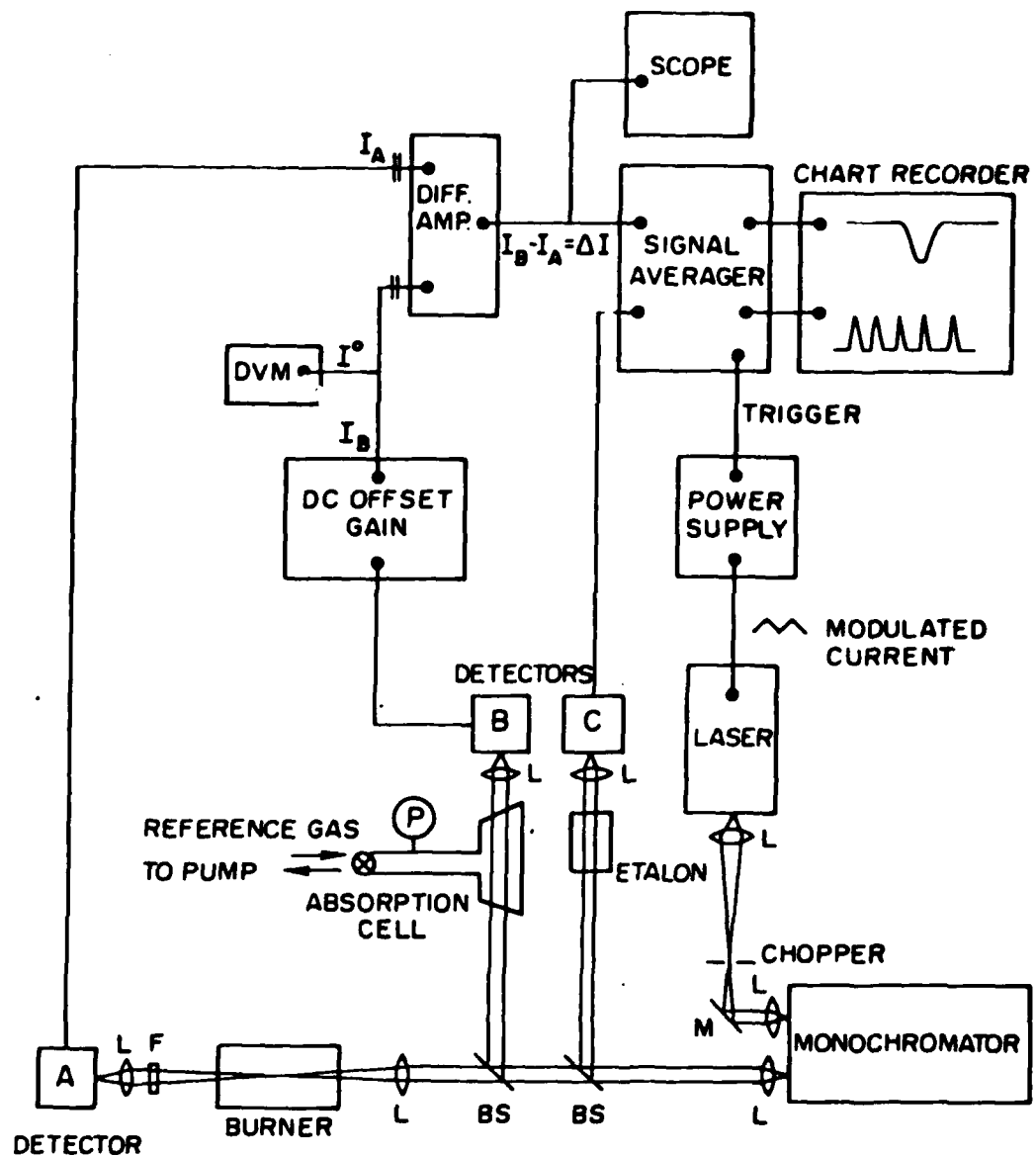


Figure 1. Optical arrangement for tunable diode laser spectroscopy in combustion gases. The detectors (A, B and C) are liquid nitrogen-cooled InSb; the Fabry-Perot etalon is Ge (2.54 cm thickness); BS denotes beam splitter, M mirror, F filter, L calcium fluoride lens, and P pressure gauge.

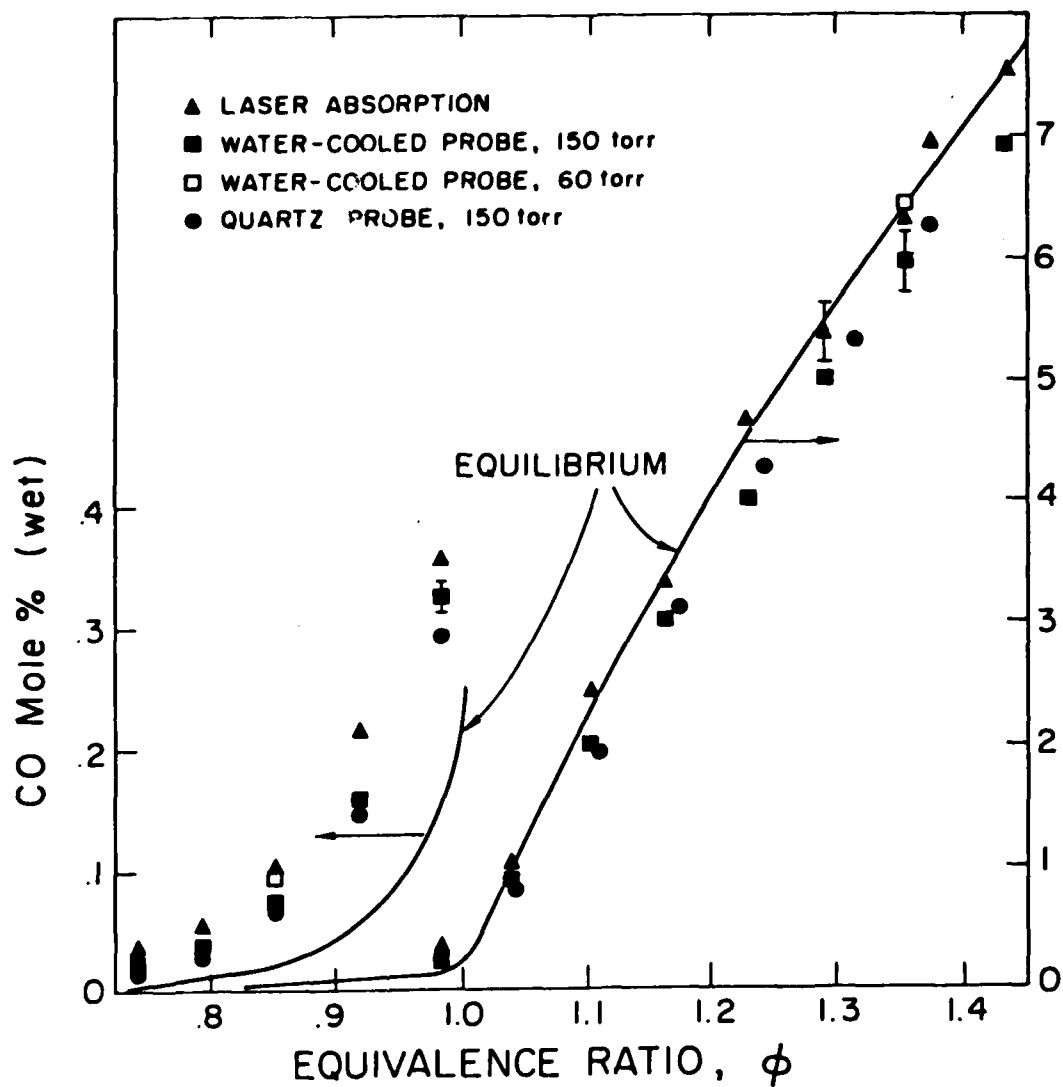


Figure 2. Measured and equilibrium CO mole % (wet basis). Probe-measured values corrected for water vapor assuming equilibrium products at flame conditions. Data points for 60 torr probe pressure were obtained using a modified sampling system.

b) Temperature Measurements with a Tunable Diode Laser

In this research, a new technique for in situ measurements of temperature has been developed and validated in the steady post-flame gases above a flat flame burner. The technique involves rapidly tuning a diode laser across a spectral interval encompassing two nearly coincident vibration-rotation lines originating from two different vibrational levels of the same infrared-active species. The relative absorption in these two lines can be a sensitive indicator of the average temperature along the line-of-sight. By fully resolving both lines, possible effects of different line-width are eliminated. Validation of this new technique was accomplished using fine-wire thermocouples (radiation-corrected) in atmospheric-pressure methane-air flames over a range of equivalence ratios. CO was the absorbing species. Other important aspects of this completed work include a survey of optimum absorption line pairs in CO and development of a scheme to enable modulation of the laser in times as short as 50 μ sec. A more extensive description of this work has been published (see Section 3).

c) Diode Laser Measurements in Fluctuating or Sooting Flames

In addition to the experiments in steady, clean flames already described, laser absorption measurements of CO have also been carried out in fluctuating flame environments and in a heavily soot-laden flame. The objective in these experiments was to show the versatility of tunable laser absorption as a combustion diagnostic technique under conditions where most other techniques (conventional and laser-based) would fail. In each case the experiments were highly successful and entirely consistent with available theory.

The principal advantage of tunable laser absorption for measurements in sooting flames, and indeed in any two-phase flow, is that modulation of the laser wavelength on and off an absorption line enables simple discrimination against continuum extinction effects. In the case of diode laser measurements in fluctuating flows, the laser was either operated in a fast wavelength modulation mode (100 μ sec/modulation cycle) or at a fixed, line-center wavelength, so that variations in CO concentration at frequencies of 10^4 Hz and higher could be monitored. The critical requirement, of course, in this and other applications of tunable laser absorption as a flowfield diagnostic, is that conditions along the optical axis are sufficiently uniform to allow simple interpretation of the measured fractional absorption. Details of measurements in fluctuating and sooting flames have been published (see Section 3).

d) Development of a Tunable UV/Visible Laser Absorption System

The success of work with tunable diode laser absorption stimulated our interest in developing a laser absorption system for the ultraviolet and visible regions of the spectrum. Such a device has considerable potential for measuring low concentrations of radical species and thus complements the infrared diode laser system which is best suited for species present in higher concentrations. During this contract period we have assembled such a system and completed initial experiments to checkout the system components.

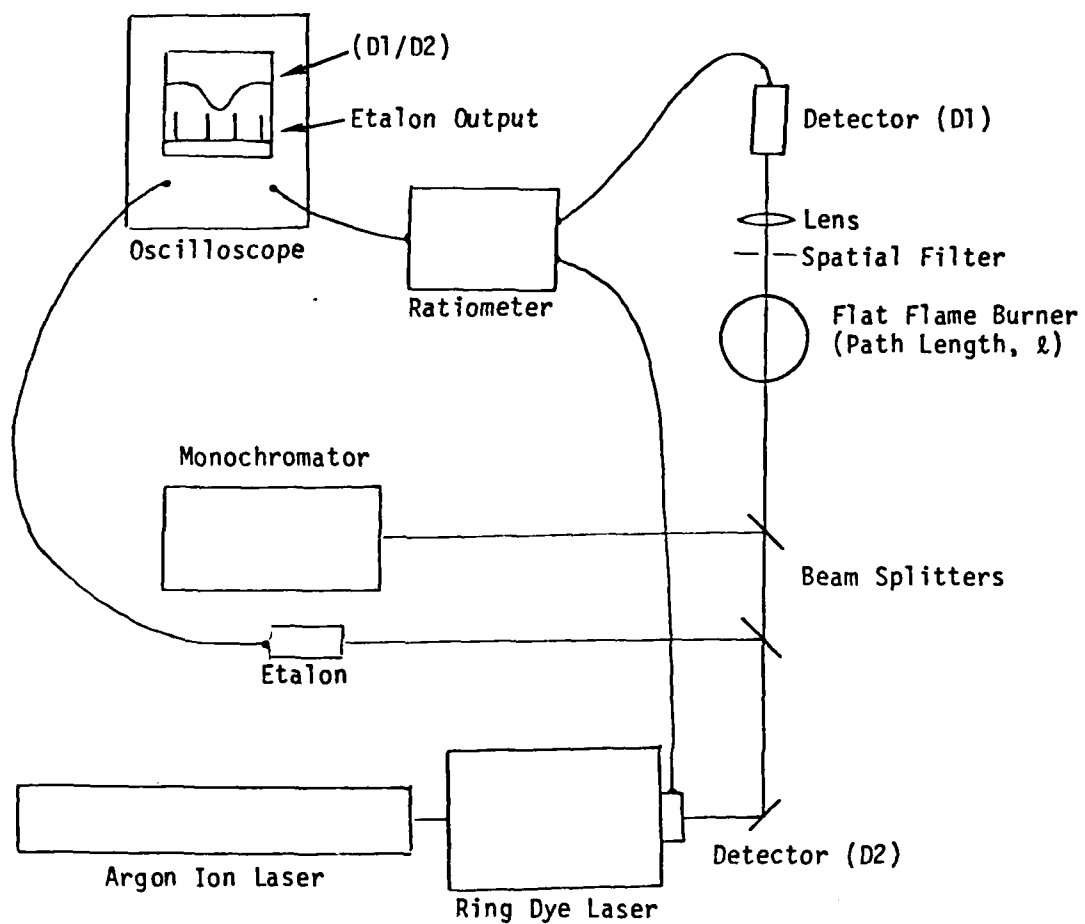
A schematic of the overall system is shown in Figure 3. An argon ion laser (4W, multi-line) is used to pump a ring dye laser (Spectra Physics Model 380A). The narrow-linewidth (single axial cavity mode) dye laser output is repetitively modulated in wavelength over a single absorption line using a standard scanning electronics package available with the dye laser. For UV absorption studies, an external frequency doubling element is used. The laser wavelength is set using a monochromator and scanning interferometer in conjunction with the observed absorption record. Variations in laser power during each modulation cycle are minimized with a commercial dye laser light regulator which is connected to the pump laser power supply through a feedback control circuit. A ratioing technique (see Fig. 3) is used to minimize the effect of any residual power variations. A direct measurement of the change in wavelength during each scan, needed to infer the absorption line halfwidth, is made with a conventional spectrum analyzer or Fabry-Perot etalon. The outputs of the spectrum analyzer and the detectors are recorded and temporarily stored on a digital oscilloscope or signal averager prior to subsequent transfer to a dedicated laboratory minicomputer. Preliminary results for absorption by Na in a flat flame burner have been obtained in a study aimed at validating the system performance. Typical results for a fully-resolved absorption profile in Na are shown in Fig. 4. To our knowledge, this is the first application of a tunable ring dye to high-resolution flame spectroscopy.

e) Development of a Tunable Laser-Fiber Optic Absorption Probe

Tunable laser absorption spectroscopy has several advantages for combustion measurements, including species specificity, simplicity and the ability to discriminate against the effects of particulates. Unfortunately, absorption spectroscopy also has one major disadvantage, for some applications, namely that it is a line-of-sight technique and hence does not provide high spatial resolution. As a means of alleviating this shortcoming, and at the same time providing a convenient packaged absorption spectroscopy instrument, we have designed and built a first-generation tunable laser - fiber optic absorption probe for use with tunable diode lasers and tunable uv/visible dye lasers.

Our approach has been to construct a water-cooled, intrusive probe with a variable length absorption path, typically less than 1 cm. Fiber optics are employed to transmit the tunable radiation from the laser source to the movable probe and also through the interior of the probe to the absorbing path. Several optical designs have been considered, featuring either single-pass or double-pass absorption, single or double fiber connections to the source and detector, and other options. The optimum design will depend on the specific application. Our immediate objective, which has recently been realized, has been to show feasibility in a laboratory flame environment. Specifically, a cooled probe with a 1 mm quartz macrofiber and a 5 mm absorption path was used to measure low-level, spatially varying Na concentrations in a flat flame burner. The ring dye laser was employed as the tunable laser source operating at 589 nm.

The proposed fiber optic absorption probes retain most of the advantages of non-intrusive tunable laser absorption spectroscopy, but



EXPERIMENTAL LAYOUT

Figure 3. Schematic diagram of tunable dye laser system for flame measurements.

$$\lambda = 589.0 \text{ nm}$$

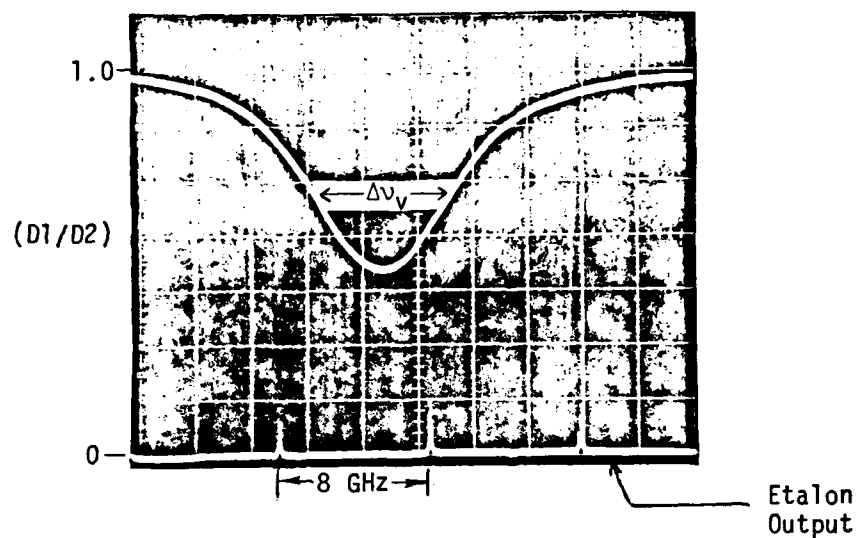


Figure 4. Fully-resolved absorption line record of Na in a flame. The Na concentration was approximately $10^{12}/\text{cc}$, the optical pathlength was 8 cm, and the infrared line halfwidth was $\Delta\nu_v = 7.5 \text{ GHz}$.

additionally offer important potential advantages for remote sensing of hostile systems where optical access is limited or the experimental environment is not compatible with local placement of expensive and sensitive laser systems. In principle, the laser and detector systems can be located a considerable distance from the probe locations and the probe position can be varied rapidly with simple electro-mechanical controls. Although the probes are intrusive, and are not likely to yield spatial resolution of less than a few millimeters, the ability to provide time-resolved species concentrations, for reactive radicals as well as stable species, suggests that these probes may still provide an important measurement capability for combustion research.

At the present time we are continuing this work with new support from AFOSR, and we are also investigating related, alternative tunable laser - fiber optic instrumentation concepts which should further improve detection sensitivity and spatial resolution.

2.2 Investigation of Turbulent Reacting Shear Flows

Coupling of fluid dynamic and chemical processes is a major factor in governing performance and pollutant emissions from combustion devices. At the present time, our understanding of the nature of this coupling is insufficient to permit extrapolation of results obtained from one combustion device to other devices or to allow quantitative prediction of the effects of changes in operating conditions on performance.

In the present program, we initiated an investigation of the coupling between fluid dynamic and chemical processes in turbulent reacting flows. Several flow configurations were considered for the experiments, including axisymmetric jets and two-dimensional shear layers. The qualitative similarities of turbulence structures in two-dimensional non-reacting shear layers and those found in the shear layers of turbulent flame burners suggest that measurements on two-dimensional reacting shear layers should provide considerable insight into the effects of turbulence structure on reaction rates in turbulent flames. From an experimental standpoint, the two-dimensional geometry offers several distinct advantages. There is extensive documentation of the turbulence structure of geometrically similar non-reacting flows. In addition, the geometry is amenable to advanced optical diagnostic techniques available in our laboratory for simultaneous, non-perturbing, in situ measurements of species concentration, temperature and velocity.

During the contract effort, a two-dimensional shear flow facility was designed and constructed. The experimental configuration, Figure 5, consists of two atmospheric-pressure gas streams separated by a splitter plate in a rectangular duct. Gas is supplied to the shear flow facility from a flow control system, which accurately meters up to four separate gas flows.

Tests were conducted on non-reacting flows to characterize the approach flow and the flow field structure downstream from the splitter plate using conventional hot-wire anemometry, using flowing N_2 in both gas streams. We are continuing this work with new support from AFOSR.

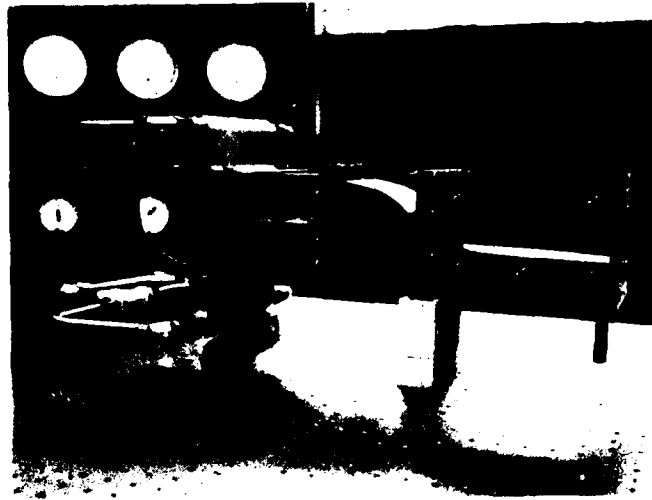


Figure 5. Two-dimensional shear flow facility.

3.0 PUBLICATIONS

1. R. K. Hanson and P. K. Falcone, "Temperature Measurement Technique for High-Temperature Gases Using a Tunable Diode Laser", *Applied Optics* 17, 2477 (1978).
2. S. M. Schoenung, R. K. Hanson and P. K. Falcone, "CO Measurements in Combustion Gases by Laser Absorption Spectroscopy and Probe Sampling," Western States Section/Combustion Institute Paper 78-46, October 1978, Laguna Beach, CA. Also AFOSR-TR-79-0326.
3. R. K. Hanson, "Combustion Gas Measurements Using Tunable Laser Absorption Spectroscopy," AIAA Reprint 79-0086; presented at 17th Aerospace Sciences Meeting, New Orleans, January 1979.
4. R. K. Hanson, P. L. Varghese, S. M. Schoenung and P. K. Falcone, "Absorption Spectroscopy of Combustion Gases Using a Tunable Infrared Diode Laser," American Chemical Society Symposium Series, "Laser Probes in Chemistry," Vol. 134, pp. 413-426 (1980).
5. R. K. Hanson, "Absorption Spectroscopy in Sooting Flames Using a Tunable Diode Laser", *Applied Optics* 19, 482 (1980).
6. 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*, in press (1980).

4.0 PROFESSIONAL PERSONNEL

The faculty involved in this research were professors R. K. Hanson and C. T. Bowman; participating graduate students were Ms. Susan Schoenung, Mr. Steve Masutani and Mr. George Kychakoff.

5.0 PROFESSIONAL INTERACTIONS

a) Talks given:

R. K. Hanson, "Absorption Spectroscopy of Combustion Gases Using a Tunable Infrared Diode Laser," invited talk presented at meeting of the American Chemical Society, Wash. D. C., Sept. 1979.

R. K. Hanson, "High-Resolution Absorption Spectroscopy in Combustion Gases," invited talk at FACCS meeting, Philadelphia, Sept. 1979.

R. K. Hanson, "Tunable Laser Absorption Spectroscopy and Chemical Kinetics Research at Stanford," invited presentation at University of California, Berkeley, Energy Seminar Series, April, 1979.

R. K. Hanson, "Combustion Gas Measurements Using Tunable Laser Absorption Spectroscopy," invited presentation at 17th Aerospace Sciences Meeting, New Orleans, January, 1979.

b) Visitors:

During the course of this 30-month program, we have entertained visitors from a number of outside laboratories, some of which are listed below:

Sandia Laboratories (Drs. Hartley, Gusinow, Hardesty, Cattolica)

AFRPL (Dr. Mann)

United Technologies Research Center (Drs. Eckbreth, Shirley, Seery)

General Electric Research Lab (Drs. Lapp, Penney, Vedder)

General Motors Research Lab (Drs. Chenea, Tracy, Teets)

AFAPL (Drs. Schrieber, Roh, Garscadden)

University of California, Berkeley (Profs. Sawyer, Daily, Oppenheim)

Lawrence Livermore Lab (Dr. Westbrook)

Lawrence Berkeley Lab (Drs. Brown, Scheffer, Robben)

Princeton University (Profs. Glassman, Dryer)

Massachusetts Institute of Technology (Prof. Sarofim, Dr. Haynes)

Arnold Air Force Station (Dr. Charles Fisher)

6.0 APPLICATION OF NEW KNOWLEDGE

This AFOSR-supported research has yielded new techniques for species and temperature measurement in high-temperature flows of general utility in aerospace technology. One new technique, the tunable laser - fiber optic absorption probe, is under consideration for a patent application.

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