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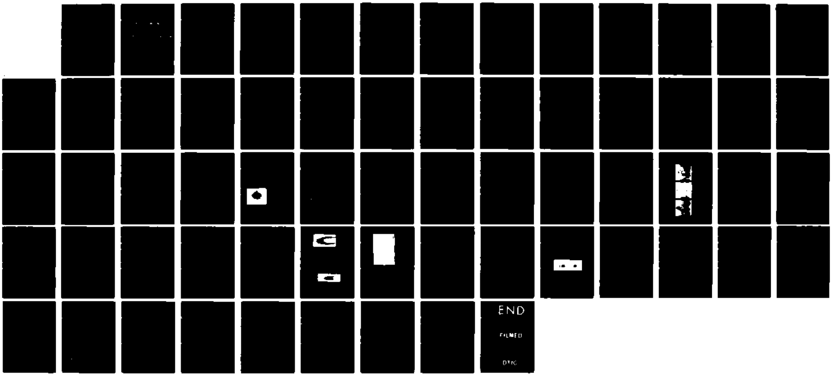

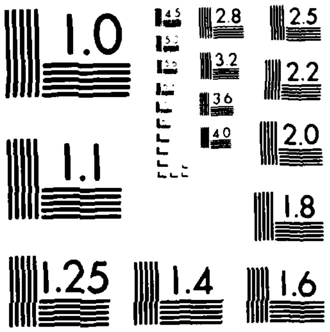
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1984

AFOSR

RESEARCH MEETING

ON

DIAGNOSTICS OF REACTING FLOW

21-22 March 1984

Yale University
New Haven, Connecticut

84 12 17 065

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Same as #7

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COMBUSTION	DIAGNOSTICS
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SPECTROSCOPY	MULTI-PHASE FLOWS

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

This document contains expanded abstracts from the 1984 meeting on the Air Force basic research program on diagnostics of reacting flow. The meeting (held at Yale University on 21-22 March 1984) presented research directed at measuring temperatures, velocities, and concentrations in high performance combustion and plasma environments.

18. SUBJECT TERMS (Cont)

PLASMA FLOWS	SPECIES MEASUREMENT
AIRBREATHING ENGINES	VELOCITY MEASUREMENT
TEMPERATURE MEASUREMENT	

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PREFACE

This meeting presents the AFOSR sponsored research on diagnostics of reacting flows plus representative research conducted at AFRPL and AFAPL. During the two days, the attendees will be able to gather a reasonably complete picture of the Air Force research program on diagnostics of reacting flow. The first meeting on this topic was held at Stanford University in February 1982; at that time most of the AFOSR sponsored research on advanced diagnostics had been underway for about one year.

The host for this meeting is Professor Richard Chang.

The abstracts follow a specific format. The text begins with a short statement of the scientific questions addressed by the research, followed by an explanation of the scientific approach. A statement of the uniqueness of each approach was solicited from the investigators. The major portion of the text describes the results obtained during the last twelve months. The abstracts describe two figures: Figure 1 illustrates the main (or a representative) feature of the scientific approach and Figure 2 presents a primary accomplishment.

Hard copies of the vugraph material and collateral information are in file folders (one for each presentation) on a table at outside the meeting room.

A primary objective of the meeting is to encourage the participants to interpret the technological barriers and to consider new research approaches. Since a 25 to 30 percent annual turn-over is built into the program, each year opportunities exist for new research approaches and for new principal investigators. Several of the presentations provide introductions to some of the technological challenges. Prospective principal investigators should not feel constrained by these presentations and are encouraged to look beyond the identified items. Several of the participants will be able to provide specific information on Air Force requirements. Also, questions concerning research opportunities can be directed to:

Leonard H Caveny
AFOSR/NA
Bolling AFB
Washington, DC 20332
Phn: (202) 767-4937
Autovon: 297-4937

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AFOSR RESEARCH MEETING ON DIAGNOSTICS OF REACTING FLOWS

Yale University, New Haven, CT

WEDNESDAY (AM)

21 March 1984

TIME	NUM.	
0830		Registration and coffee* - Mason Laboratory, Room 211
0855		Welcome and Announcements

Session Chairman: Leonard H Caveny, AFOSR

Topic: Gas Phase

TIME	NUM.	
0900	1	COHERENT OPTICAL TRANSIENT SPECTROSCOPY IN FLAMES. John W Daily, University of California, Berkeley, CA
0930	2	RESONANT CARS DETECTION OF OH RADICALS. James F Verdieck, Robert J Hall, and Alan C Eckbreth, United Technology Research Center, East Hartford, CT
1000	3	WAVELENGTH MODULATION SPECTROSCOPY FOR SPECIES AND TEMPERATURE MEASUREMENTS. Ronald K Hanson, Stanford University, Stanford, CA
1030		Break
1050	4	DIAGNOSTICS FOR HIGH PRESSURE COMBUSTION. David P Weaver, AFRPL/PAP and David Campbell, University of Dayton Research Institute
1120	5	PICOSECOND LIDAR. Robert Goulard, George Washington University, Washington, DC
1150		Lunch at Commons Dining Hall (Reconvene 1400)
1245		Guided Tour* of the Yale Center for British Art

---

*Cost included in registration fee.

WEDNESDAY (PM)

21 March 1984

Session Chairman: Julian M Tishkoff, AFOSR

Topic: Multiphase

TIME	NUM.	
1400	6	SPRAY CHARACTERIZATION WITH A NONINTRUSIVE OPTICAL SINGLE PARTICLE COUNTER. Cecil F Hess, Spectron Development Laboratory, Costa Mesa, CA
1430	7	EVAPORATING FLOW USING LASER-INDUCED FLUORESCENCE. Donald Baganoff and Brian Cantwell, Stanford University, Stanford, CA
1500	8	SPRAY CHARACTERIZATION USING PHASE ANGLE DETECTION. William Bachalo, Aerometrics, Inc, Mountain View, CA (New Start)
1515	9	SINGLE PARTICLE SIZING BY MEASUREMENT OF BROWNIAN MOTION. Alan Stanton and Wai Cheng, Aerodyne Research, Inc, Bilerlica, MA (New Start)
1530		Break*
1550	10	EXCIPLEX SYSTEMS FOR REAL-TIME VISUALIZATION OF FUEL SPRAYS. Lynn Melton, University of Texas at Dallas, Dallas, TX
1620	11	LASER EXCITED FLUORESCENCE ON REACTING SURFACES. Lawrence P Goss and Arthur A Smith, Systems Research Laboratories, Dayton, OH
1640	12	DETERMINATION OF LIQUID DROPLET EVAPORATION RATES IN A SPRAY BY INELASTIC LIGHT SCATTERING. Richard K Chang, Huey-Ming Tzeng, Marshall B Long, and Boa-Teh Chu, Yale University, New Haven, CT
1710		ADJOURN SESSION
1715		Executive Session for AFOSR Principal Investigators
1930		Social Hour at Presidents' Room in Woolsey Hall**
2015		Dinner in the Presidents' Room in Woolsey Hall**

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*Cost included in registration fee.

**Cost included in $40.00 registration fee (or $20.00 for graduate students).

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THURSDAY (AM)

22 March 1984

0800 Coffee*

Session Chairman: Howard Schlossberg, AFOSR

Topic: Quantitative Visualization

TIME	NUM.	
0830	13	QUANTITATIVE FLOW VISUALIZATION. Ronald K Hanson, Stanford University, Stanford, CA
0900	14	QUANTITATIVE THREE-DIMENSIONAL FLOW VISUALIZATION. Lambertus Hesselink, Stanford University, Stanford, CA
0930	15	TEMPORAL EVOLUTION OF INSTANTANEOUSLY DETECTED TWO-DIMENSIONAL IMAGE OF GAS CONCENTRATION IN A JET FLOW. Marshall B Long, Joseph Lam, and Boa-Teh Chu, Yale University, New Haven, CT
1000		Break
1020	16	COMBUSTION DIAGNOSTICS RESEARCH SPONSORED BY APL. Bish Ganguly, Sig Kizirniz, and W M Roquemore, AFAPL/POSF
1050	17	TIME AND SPACE RESOLVED LASER DOPPLER VELOCITY MEASUREMENTS. Holger T Sommer, Carnegie Mellon University, Pittsburg, PA
1120	18	AFOSR INTERESTS IN ADVANCED DIAGNOSTICS OF REACTING FLOWS. Leonard H Caveny, AFOSR
1150		Lunch* in the Becton Center Faculty Lounge

THURSDAY (PM)

1300 Demonstration of:

a) Localized photoacoustic forcing of gas flows

b) Evaporation of droplets in a spray

c) Quantitative two-dimensional gas concentration measurements

d) Nonlinear optical effects from micro-objects

1500 Meeting Adjourned

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*Cost included in registration fee.

COHERENT OPTICAL TRANSIENT SPECTROSCOPY IN FLAME

John W. Daily

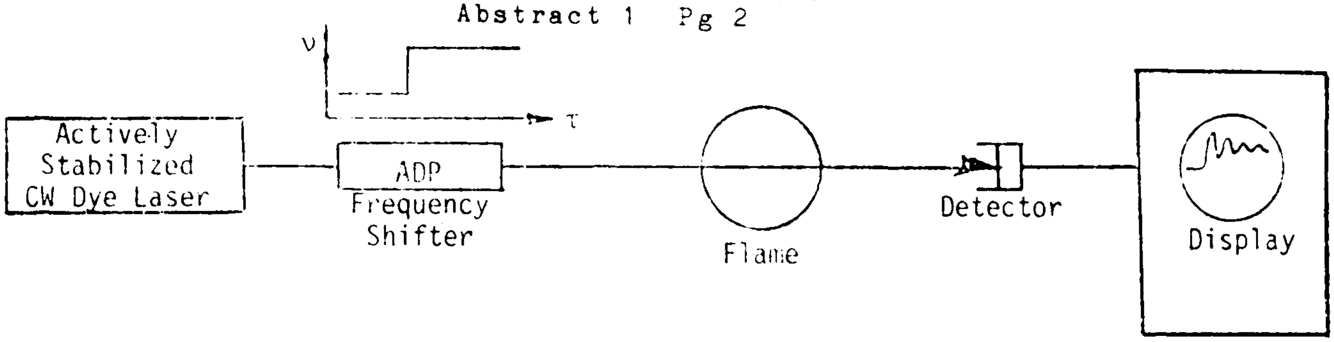
Department of Mechanical Engineering
University of California
Berkeley, CA 94720

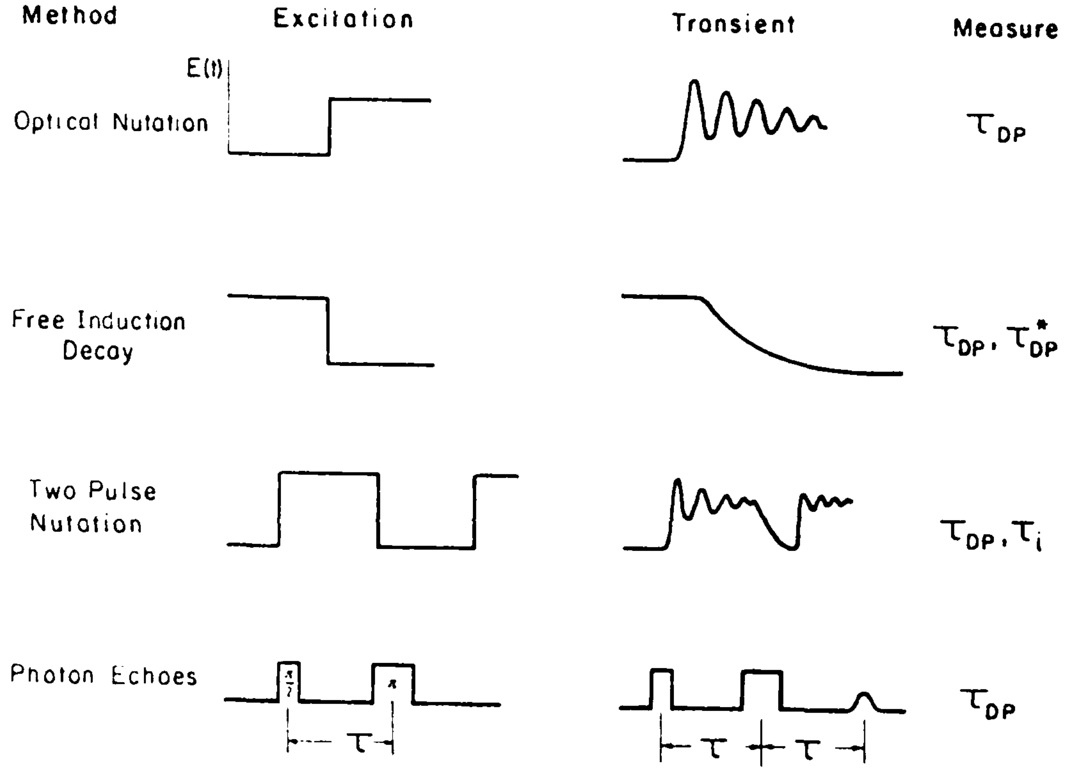
Coherent optical transient spectroscopy is a technique in which the transient response of a group of molecules to laser excitation is observed. The uniqueness of the method lies in the fact that when transient experiments are conducted on a time scale short compared to collisional relaxation times, coherent phenomena occur which enable one to directly observe the rates of a variety of collisional processes. Furthermore, the coherent phenomena can be quite strong, resulting in large signals and thus high data rates. Processes such as state-to-state energy transfer, optical dephasing and velocity redistribution can be studied.

An example experiment is shown in Figure 1. An actively stabilized CW dye laser is used as a source. By passing the beam through a traveling wave modulator to which a high voltage pulse has been applied, the frequency may be shifted up to 15 GHz within 50 psec for periods of several nanoseconds. Thus, one may shift into or out of resonance with an absorption line of interest and observe the transient behavior that results. One type of transient is optical nutation in which the laser beam is suddenly shifted into resonance with an absorption line and the absorption signal observed. The decay rate of the transient signal is the collisional dephasing rate for that transition and thus a direct measure of the line width. Also illustrated in Figure 1 are several types of excitation, the transient they produce and the quantities one can obtain.

During the first year, our work focused on developing the theoretical capability for predicting various coherent phenomena that arise due to optical excitation of diatomic radical species of interest in flames. For example, shown in Figure 2 is the expected response to a two pulse nutation experiment in which the rotational relaxation rate for a molecule like OH or CH is determined by measuring the nutation signal strength as the function of pulse delay. Continuing the experiment to longer time delays one may also trace out chemical decay which gives a measure of state-to-state chemistry. By systematically varying flame composition and stoichiometry, one can study the kinetics of such processes over a wide range of in situ conditions.

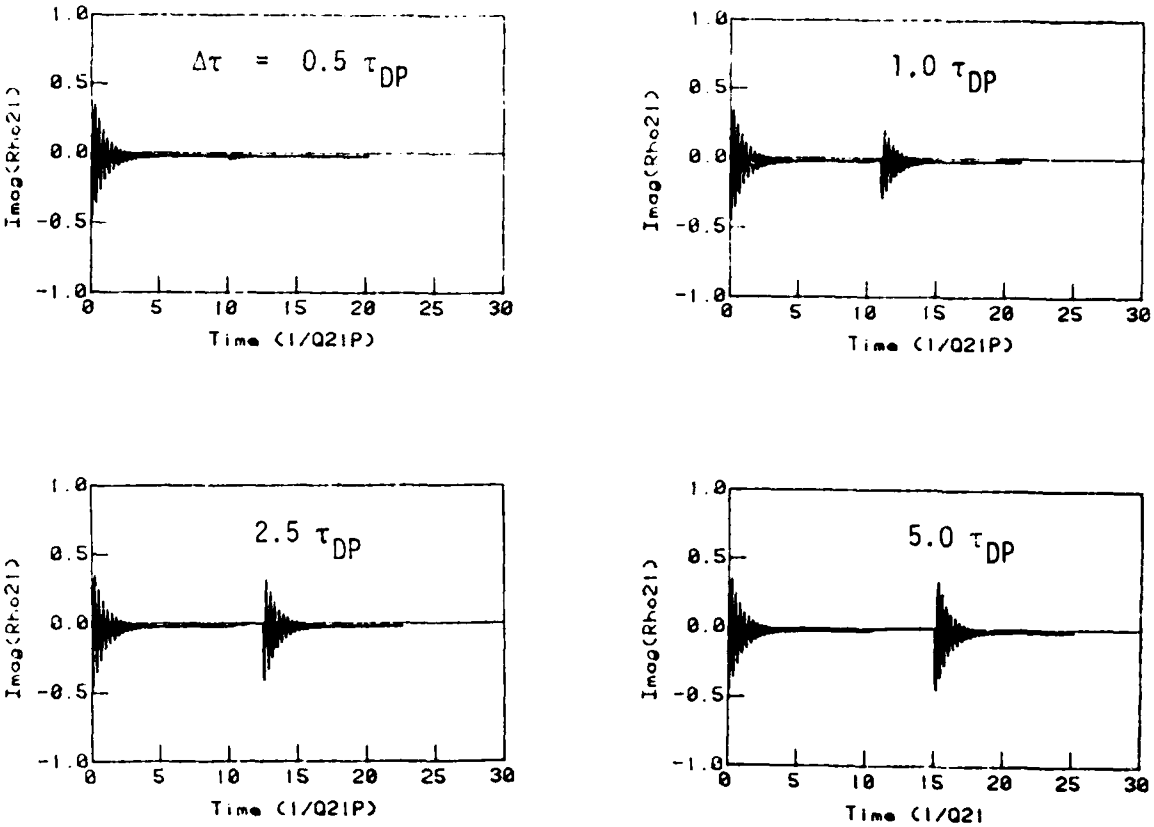
Over the past year we have been assembling and testing the apparatus required to perform coherent transient experiments. As of January 1 we have all components of the experiment in place and operating except the traveling wave modulator. We hope that the modulator will arrive and we can begin experiments before the meeting.



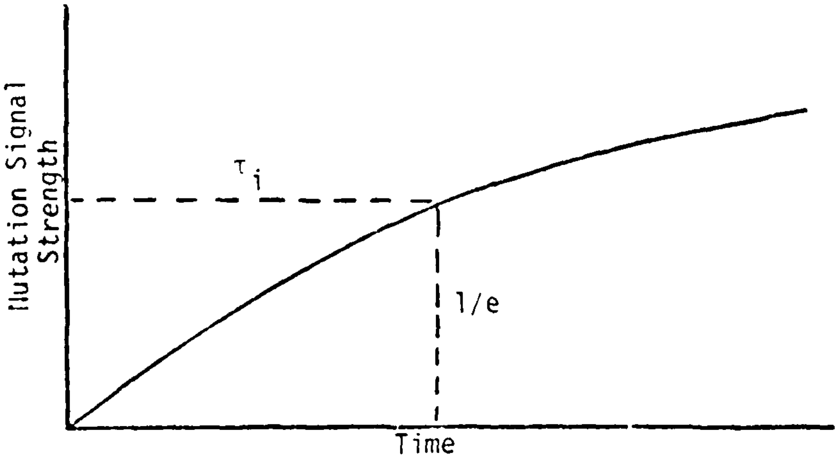


Measure	Learn	Why Important
τ_{DP} Optical Dephasing	Line Widths	Nonlinear Raman spectra require linewidth information for interpretation
τ_{DP} Doppler Dephasing	Velocity Redistribution Rates	Give handle on collision integral for use in evaluating transport properties
τ_i State Decay Rates	State to State Energy Transfer Rates	Required for accurate correction of quenching effects in fluorescence spectroscopy
	Chemical Relaxation Rates	Direct measure of state to state chemical rates give important insight into combustion kinetics

Figure 1



a) An example of the effect of delay time on the two pulse nutation signal. At small delays the population in the excited state is unchanged. As the delay increases, more ground state molecules are available for the transient response.



b) The integral of the transient response is proportional to the ground state population. Plotting the integral against time traces out the decay of population from the excited state and gives a direct measure of the energy decay rate.

Figure 2 Two Pulse Nutation

RESONANT CARS DETECTION OF OH RADICALS

James F. Verdieck, Robert J. Hall and Alan C. Eckbreth
United Technologies Research Center
East Hartford, CT 06108

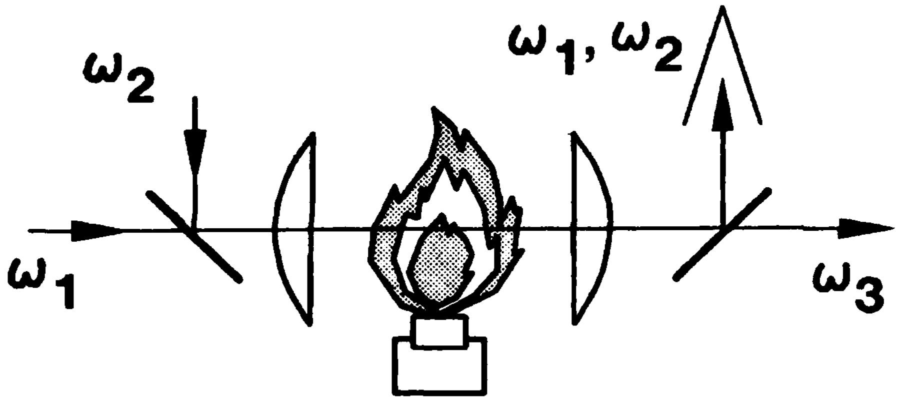
Coherent anti-Stokes Raman spectroscopy (CARS) is an important spectroscopic technique which fulfills several requirements (superior spatial and temporal resolution, remote, non-perturbing, good accuracy, and high-pressure high-temperature capability) for probing hostile combustion environments that are of primary interest to the Air Force. At atmospheric pressure, normal CARS methods are limited to species whose concentration is about 1 percent or greater. The scientific aim which this program addresses is, can CARS diagnostics be extended to minority species, particularly OH, through the technique of electronically resonant CARS?

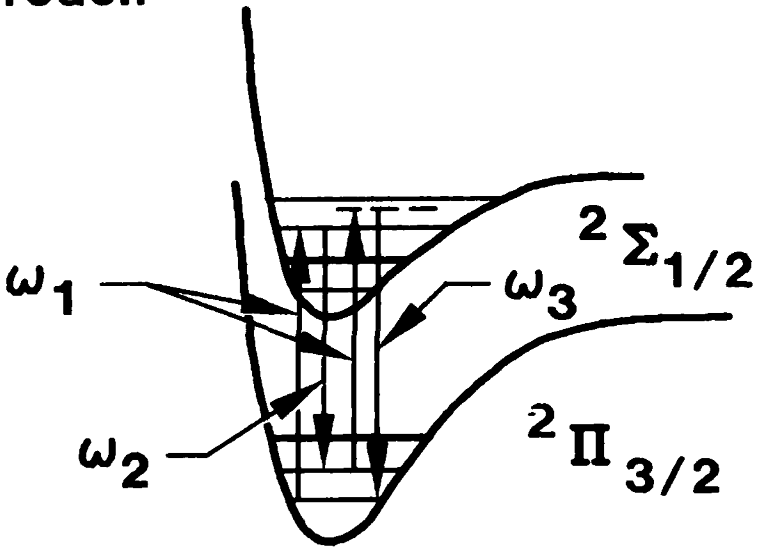
The hydroxy radical was chosen as a candidate molecule because of its seminal importance in both combustion and atmospheric chemistry. The approach taken is, after observing resonant CARS in OH, to explore the improvement in minor species detectivity attainable with electronic resonance enhancement. Achievement of these goals requires an understanding of the physics of electronic resonant CARS spectroscopy which includes the effect of tuning through the resonance, laser linewidth dependence, choice of electronic transition, and saturation considerations. Additionally, the subject of multiple electronic resonance, e.g., combinations of ω_1, ω_2, and ω_3 electronically resonant, must be investigated and compared with the singly electronically resonant case. Finally, a quantitative assessment of the CARS detectivity and analytical applicability to OH must be made.

At UTRC the first observation of resonant CARS in OH has been found for several different choices of the ω_1 resonant frequency. The amplitude and shape of the OH resonant CARS spectrum is very sensitive to the precise tuning of ω_1 to the electronic resonance. The most striking feature of the OH resonance CARS spectrum is its much greater amplitude than the adjacent water conventional CARS spectrum, even though the water concentration may be much higher than that of OH. In addition to the experiments, the theory of resonant CARS in OH has been treated. Agreement between theory and experiment is generally good except for the experimental observation of satellite structure about the central line, probably caused by collisional redistribution in rotational levels. Evidence of saturation was observed through dimunition of the incident ω_1 laser power. The variation of the resonant CARS spectrum as a function of laser beam height in the flame was observed and offers promise that resonant CARS will be applicable to quantitative measurements, even under saturation conditions.

RESONANT CARS DETECTION OF OH RADICALS

Scientific Approach



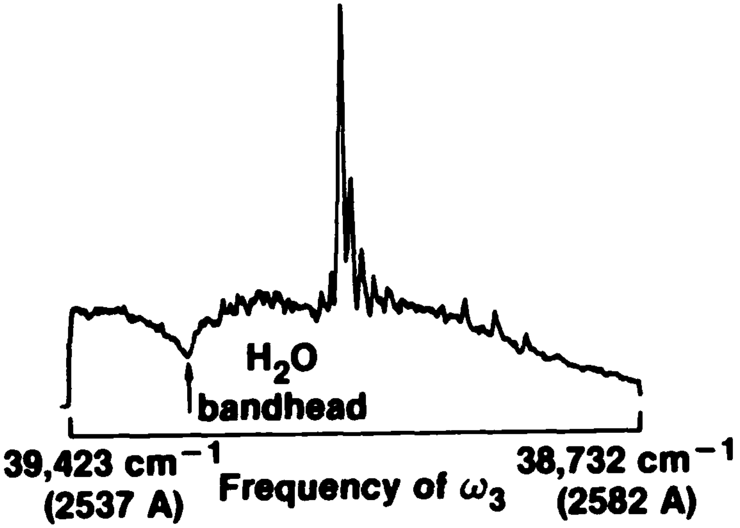


GOALS

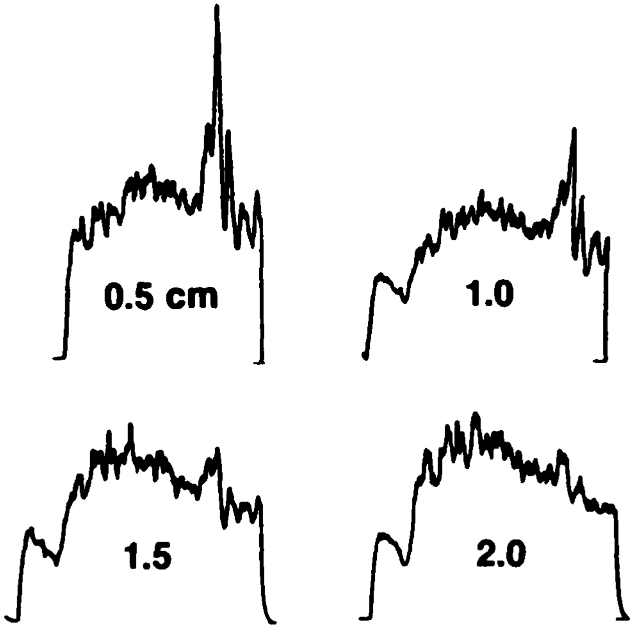
- Improve CARS species detectivity via electronic enhancement
- Study the physics of resonant CARS spectroscopy
- Investigate multiple electronic resonances
- Determine the CARS detectivity limit for OH

RESONANT CARS DETECTION OF OH RADICALS

Experimental results



Resonance CARS spectrum for ω_1 tuned to $Q_1(2)$.



Variation of the resonant CARS spectrum with change in laser beam height relative to burner surface.

Results:

- Resonant CARS of OH observed for several choices of ω_1
- OH resonant CARS spectrum stronger than H_2O CARS spectrum
- Intensity of OH CARS signal varies with concentration
- Evidence of saturation of resonant CARS signal observed

WAVELENGTH MODULATION SPECTROSCOPY FOR SPECIES AND TEMPERATURE MEASUREMENTS

Ronald K. Hanson

Mechanical Engineering Department
Stanford University
Stanford, California 94305

Species and temperature measurements play central roles in studies of reacting flows, and hence improved methods for such measurements have broad potential to impact fields relevant to energy conversion, including combustion and propulsion. In this research we are investigating a new approach which offers prospects for simultaneous measurements of species concentration and temperature, with spatial and temporal resolution, and at much higher repetition rates than achieved previously.

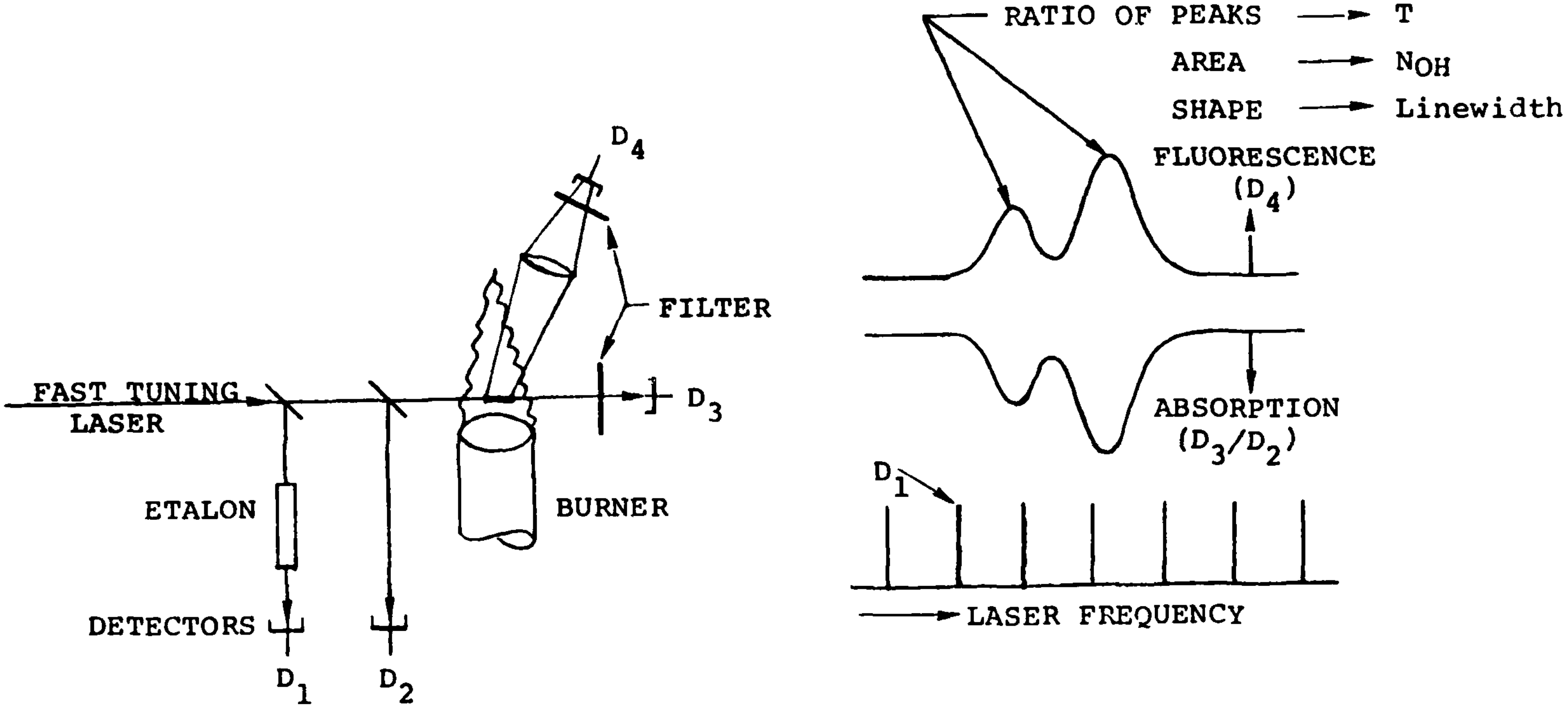
The technique, termed wavelength modulation spectroscopy, involves quickly scanning a narrow-linewidth cw laser across one or more isolated absorption transitions (of the species to be monitored) and recording the fully resolved (spectrally) absorption line profile using either absorption or fluorescence detection. The method is applicable to infrared transitions, using commercially available diode laser sources, and to UV/visible transitions by using a ring dye laser modified for fast-scanning operation. A primary advantage of wavelength modulation is that it provides a simple means of discriminating against continuum extinction effects which seriously hinder conventional absorption or fluorescence measurements in two-phase flows. Moreover, recording fully resolved profiles eliminates the need for uncertain linewidth assumptions, used in converting measured absorption (or fluorescence) to species concentration or temperature, and provides a means for determining previously unmeasured linewidths.

A schematic of the approach for combined absorption and fluorescence measurements of OH in a flat flame burner is shown in Fig. 1. A fast-scanning, intracavity-doubled ring dye laser (developed in our laboratory) serves as a source of tunable radiation near 306 nm. The single-mode laser is tuned about 75 GHz so as to encompass two transitions of OH, the $R_1(7)$ and $R_1(11)$ lines of the (0, 0) band, at a repetition rate of 4 KHz. Fully resolved absorption and fluorescence records are thus acquired every 250 microseconds. The detector outputs are, at present, stored and processed off-line. Line-of-sight-averaged (absorption) and point (fluorescence) values of temperature can be inferred from a simple ratio of the signal peaks, although a Voigt profile analysis is usually employed. The analysis to infer the species concentration differs for the absorption and fluorescence records, but follows, once the temperature is known, from the integrated area under the profile.

Examples of reduced data are shown in Fig. 2. The left-hand panel is for absorption in a stoichiometric CH_4-air flame with a known (thermocouple) temperature of 1925 ± 20K. The agreement with the best-fit absorption value, T = 1925K ± 25K, is excellent. The fluorescence data in the right-hand panel (lean flame, $\phi = 0.8$) yield a temperature of 1930K (± 100K) which is 100K higher than the thermocouple value. Further work to investigate and improve the wavelength modulation technique is in progress.

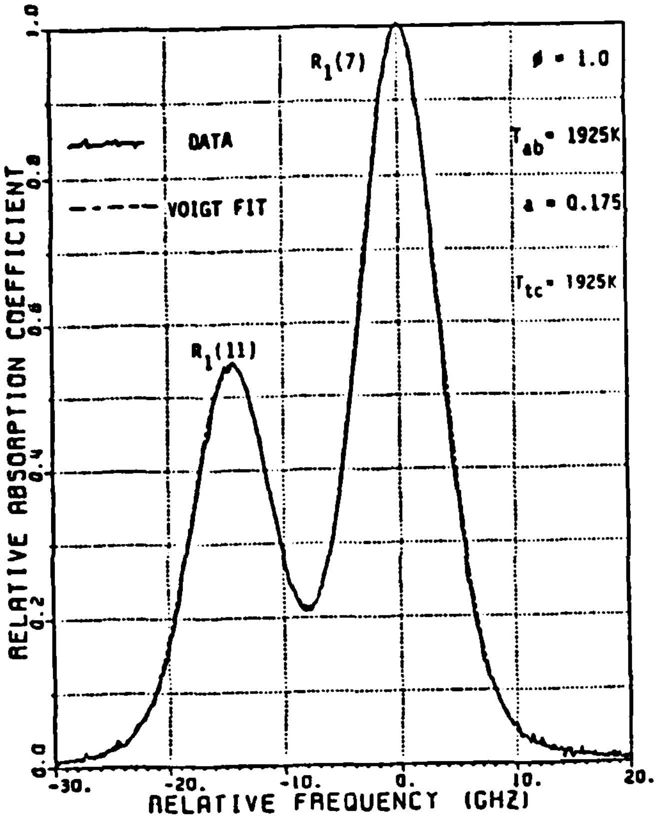
WAVELENGTH MODULATION SPECTROSCOPY

ENABLES SIMULTANEOUS TEMPERATURE, SPECIES MEASUREMENTS AT HIGH REPETITION RATE

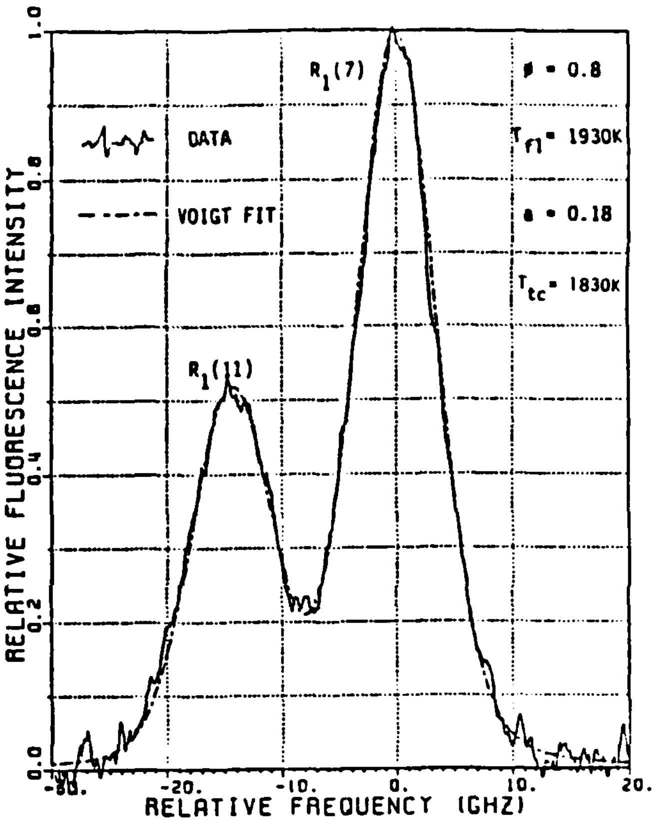


- First Simultaneous T, N_{OH} Measurements in a Flame
- Advance in Measurement Rate (10 Hz to 4 kHz) Important for Turbulence Studies
- Technique Suitable for Measurements in Two-Phase Flows
- Fully Resolved Profiles Yield Fundamental Collision Linewidths Directly
- Fully Resolved Profiles Eliminate Usual Need for Assumed Lineshape Function
- Combined Absorption and Fluorescence Measurements Enable Measurement of Quenching Rates

Fig. 1. Wavelength Modulation Spectroscopy: Approach and Key Features



Single sweep absorption trace and Voigt fit for wavelength modulation experiment in a flat flame burner; $\phi = 1.0$.



Single sweep fluorescence trace and Voigt fit for wavelength modulation experiment in a flat flame burner; $\phi = 0.8$.

- Good Agreement Between Spectroscopic (T_{ab}, T_{fl}) and Thermocouple (T_{tc}) Temperatures
- Simple (Peak Ratio) Analysis Could Enable Real-Time Temperature Monitoring

Fig. 2. Best-fit Voigt profiles and inferred temperatures for absorption and fluorescence records of OH in a CH_4/air flame. The inferred temperatures (T_{ab} and T_{fl}) are seen to agree well with the thermocouple values (T_{tc}).

SPRAY CHARACTERIZATION WITH A NONINTRUSIVE OPTICAL SINGLE PARTICLE COUNTER

Cecil F. Hess
Spectron Development Laboratories, Inc.
3303 Harbor Boulevard, Suite G-3
Costa Mesa, CA 92626

The objective of this research program is to advance the understanding of droplet sizing technology in combustion environments using light scattering. In particular, to study two novel and unique concepts that offer the potential of significantly advancing spray characterization technology. Several basic questions are being asked in this reseach study: what information of the scattered light is better suited to provide the size and velocity of droplets?; how is this information affected by the disturbance present in real environments (large particle concentration, hot and turbulent environments)?; what size and velocity ranges and what accuracy can be obtained?

Two techniques have been identified which offer great potential in the measurement of sprays. The first is referred to as "IMAX", and it consists of a nonintrusive pulse height analyzer. The second is referred to as "visibility/intensity (V/I)" and it performs a size measurement by examining the visibility and the pedestal intensity of a Doppler burst. The research conducted over this past year indicates that the IMAX technique provides a larger dynamic range and higher accuracy than V/I. It also shows that the two-color IMAX concept provides a higher S/N primarily because of the high efficiency in spectrally separating the two signals.

The two-color IMAX concept is described in Figure 1a. Two small beams of a given wavelength (4880Å) are crossed in the middle of a larger beam of different wavelength (5145Å) thus identifying a region of almost uniform intensity within the large beam. The two small beams will interfere where they cross and a fringe pattern will be formed in the middle of the large beam. Droplets crossing the fringes also cross the middle of the large beam. Since the peak intensity of the large Guassian beam is known, a unique relationship between droplet size and scattered light is established. It is predicted that a dynamic size range in excess of 30:1 will be possible with this technique, thereby considerably advancing the state of the art. The velocity of the droplets is also measured using the classical Doppler approach. Figure 1b shows a schematic representation of the breadboard system used to acquire the reported data.

The size distribution of two kinds of sprays are reported here. The first is produced by a Berglund-Liu droplet generator with dispersion air. Monodisperse, bimodal, and trimodal sprays with an angle of about 10° were thus produced, and the results are shown on Figure 2a. The theoretically predicted sizes are 49 μm, 62 μm, and 70 μm, respectively. Good accuracy and resolution can, therefore, be observed. The second spray was produced by a pressure nozzle. The results are shown on Figure 2b. In order to test the resolution of the system, data were obtained using three different size ranges: 5 to 50 μm; 10 to 100 μm; and 20 to 200 μm. This is one of the most difficult self-consistency tests imposed on any technique, and most available techniques will show a shift in the predicted data. IMAX shows excellent matching of the data.

IMAX CONCEPT FOR SPRAY CHARACTERIZATION

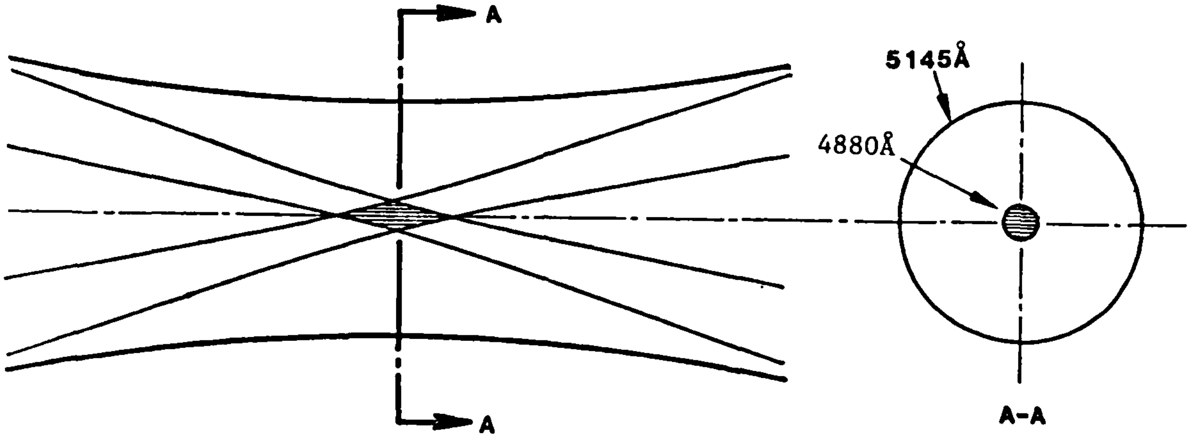


Figure 1a. Probe Volume of Two-Color IMAX Technique

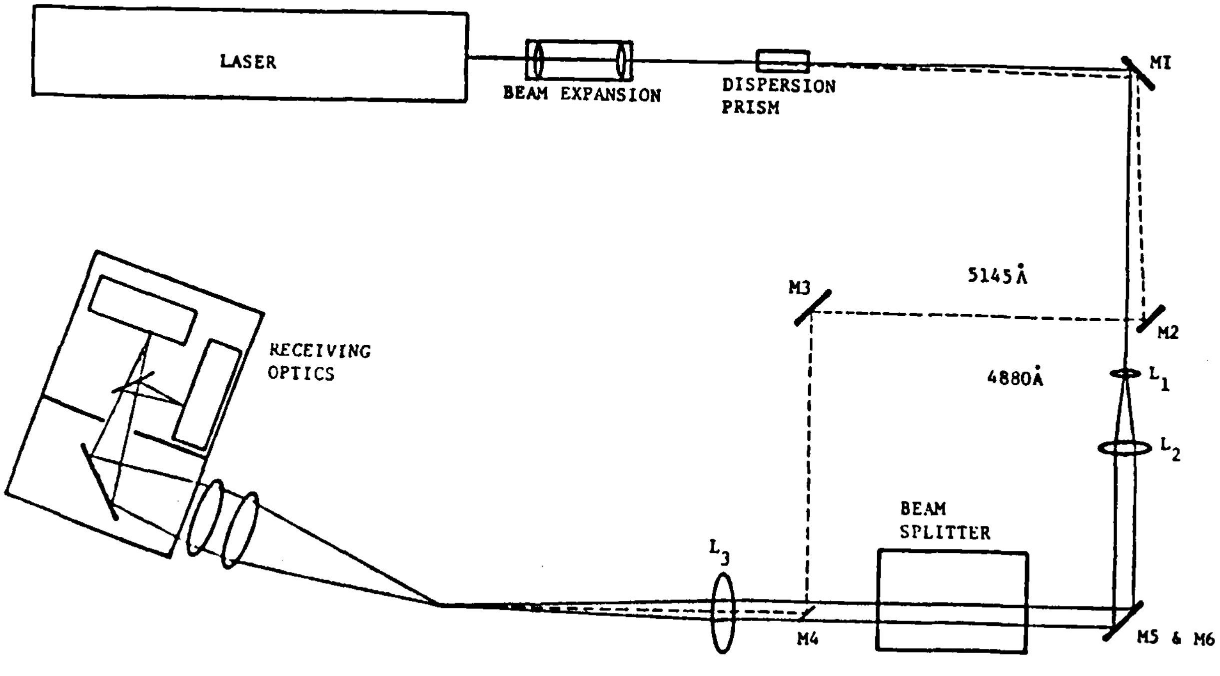


Figure 1b. Schematic IMAX Breadboard System

IMAX DROPLET SIZE MEASUREMENTS

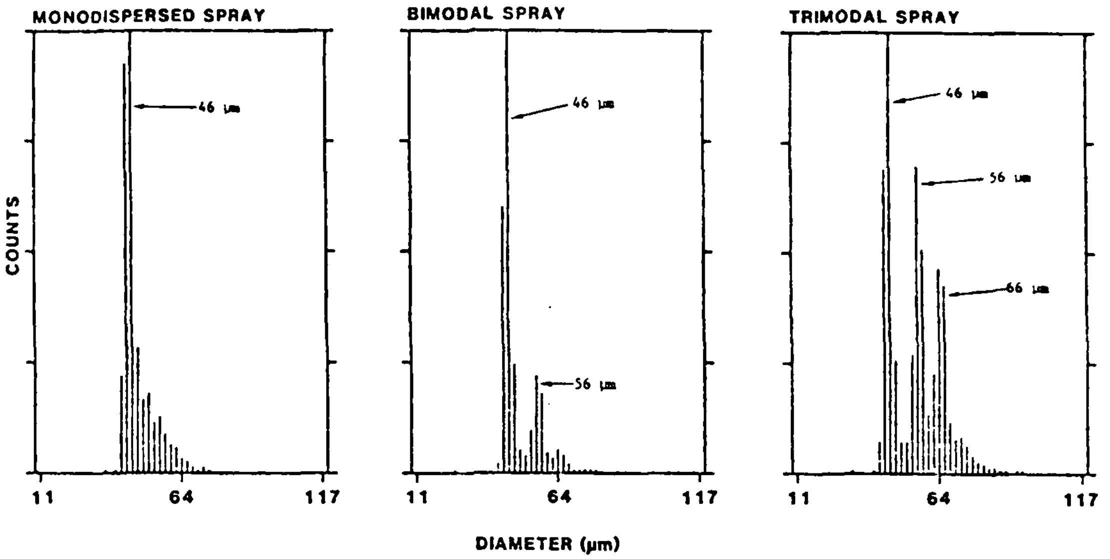


Figure 2a. Size Distribution of Spray Produced by a Berglund-Liu Generator with Dispersion Air

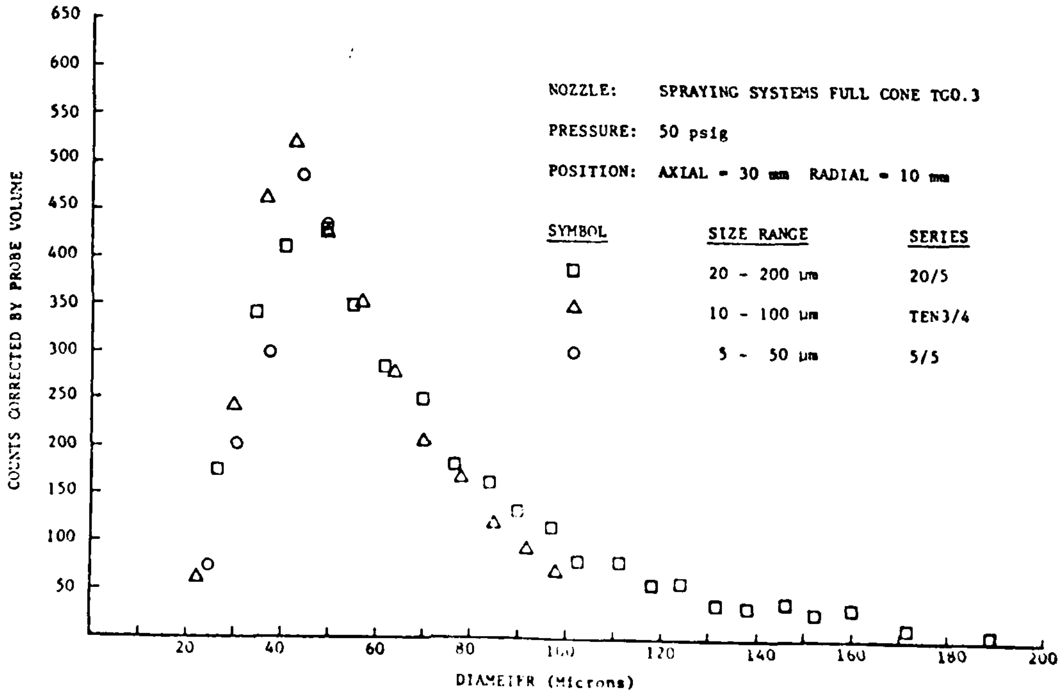


Figure 2b. Size Distribution of Spray Produced by a Pressure Nozzle

STUDY OF EVAPORATING FLOW USING LASER-INDUCED FLUORESCENCE

Donald Baganoff and Brian Cantwell
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Stanford, California 94305

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. A multipoint measurement of the vapor concentration field in the neighborhood of an evaporating droplet in an unsteady flow would shed important light on factors which control the evaporation, diffusion, and mixing of a droplet; and would provide the basic data needed for theoretical comparison. 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, a problem for which no method of measurement presently exists.

The approach being use is dipicted in Fig. 1. A small droplet consisting of octanol alcohol with iodine in solution is formed and then allowed to drop from the tip of a fine hypodermic needle (approximately 100 µm in diameter). Octanol is chosen for its compatibility with iodine, which is used as the fluorescing specie in the experiments. Iodine is present in the octanol vapor cloud in a sufficient concentration to allow detection of its fluorescent signal by photography, photomultipliers, and a Vidicon camera, once it is excited by the green output of an argon-ion laser. The laser beam is formed into a sheet of laser light and the sheet is then used to illuminate a transverse section of the vapor cloud, giving data on the vapor concentration in a particular cross section of the cloud. A slow flow of nitrogen in the vertical direction is used to purge the chamber so that iodine does not saturate the enclosing volume.

In our experiments we have obtained photographs of the iodine fluorescence intensity, for different transverse sections of the vapor cloud, for a suspended drop and have collected similar data on video tape by using a Vidicon tube to record the intensity distribution for a falling drop. In either case, we are able to display the distribution of fluorescence intensity, or iodine concentration, in graphical form as shown in Fig. 2. The video camera proves to be more sensitive than photographic film, and in addtion, it offers a greater convenience in reducing the data. For example, individual raster lines can be selected from the tape for detailed study, and one can display the concentration distribution along a single line in the plane of observation in this way. Also, data can be collected which corresponds to cuts perpendicular to the raster lines by processing the data from the tape in an appropriate way. Of course, the tape also provides the added advantage of allowing one to study the experiment in detail a large number of times by use of the tape recorder and monitor alone. Most of our experiments have been conducted at room temperature and at a pressure of 100 Torr where quenching is less severe. More recently, we have raised the temperature to study higher evaporation rates, and have also raised the pressure which is allowed by the higher iodine concentration.

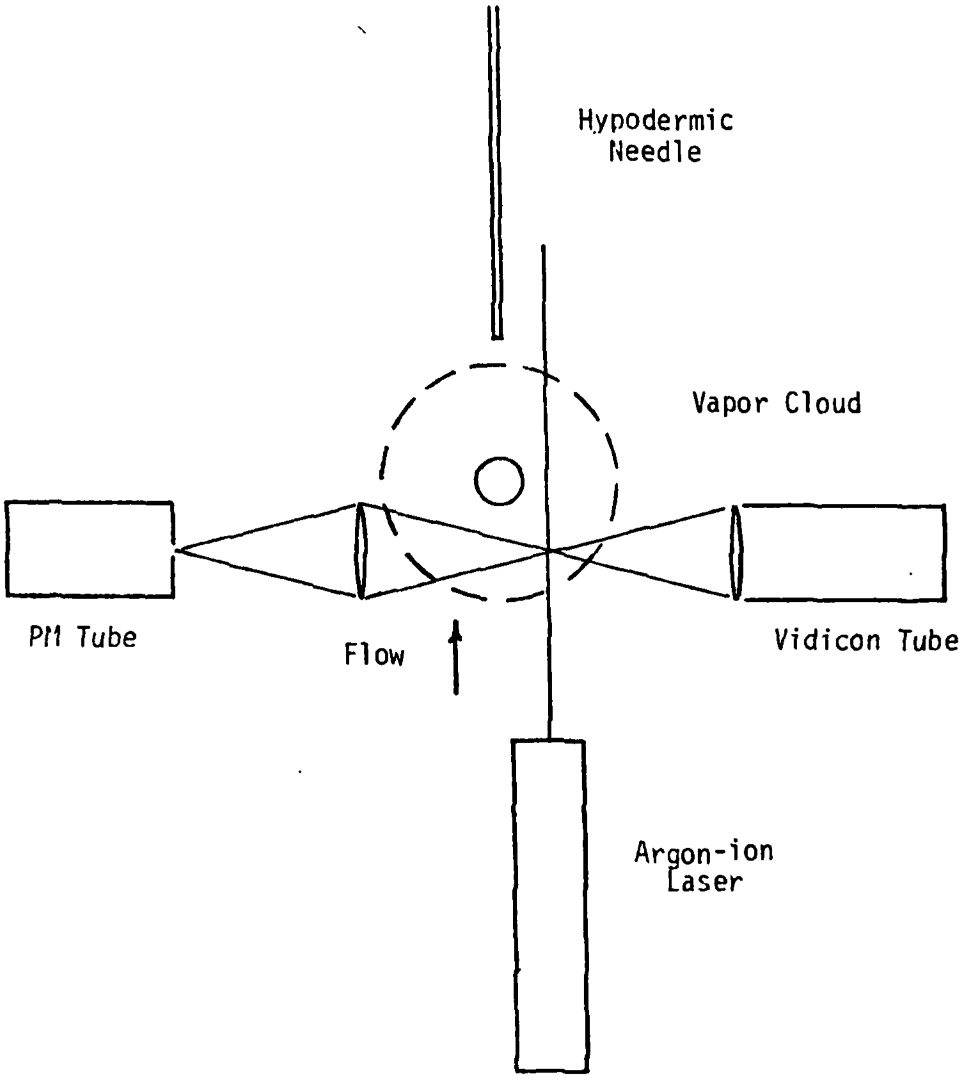

Fig. 1. Schematic diagram of the arrangement employed for studying droplet evaporation by use of laser-induced fluorescence in iodine. The Vidicon tube provides a view of an entire cross section, while the PM tube gives the time-dependent variation at a single spatial point.

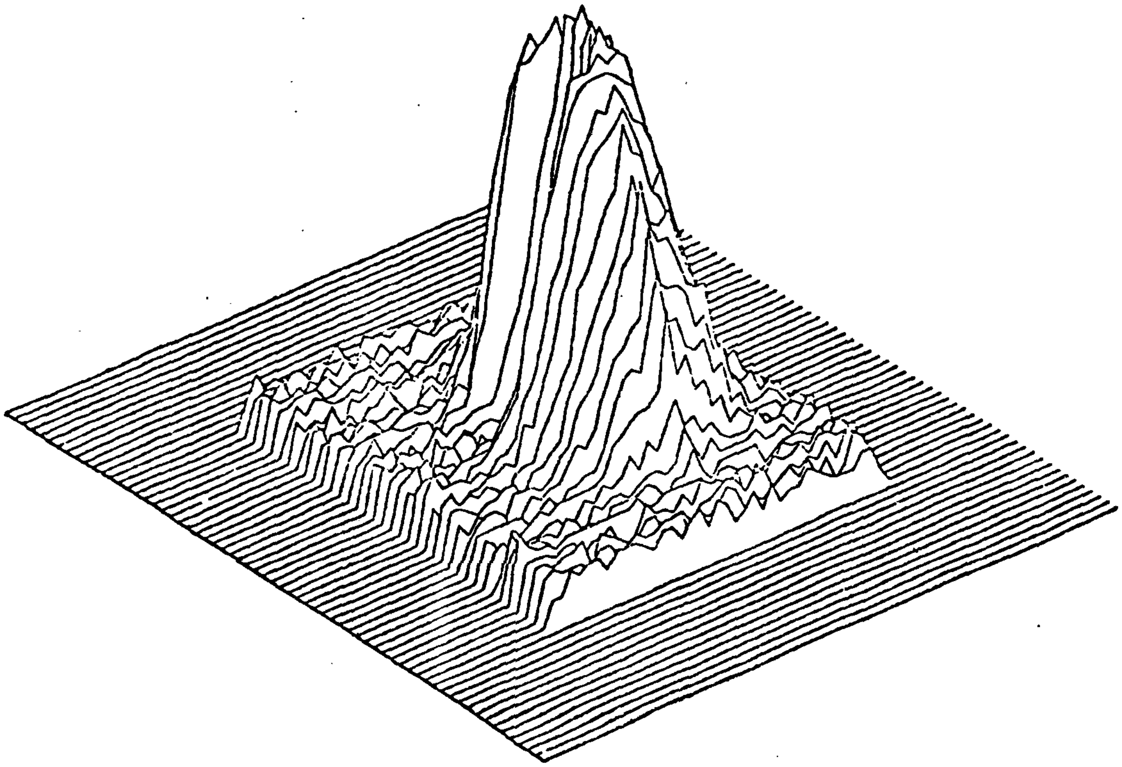

Fig. 2. Vapor concentration in a cross-section plane near an evaporating droplet. The hole appearing in the diagram is a result of the shadow cast by the droplet, which is clearly seen in the photograph.

SPRAY CHARACTERIZATION USING PHASE ANGLE DETECTION

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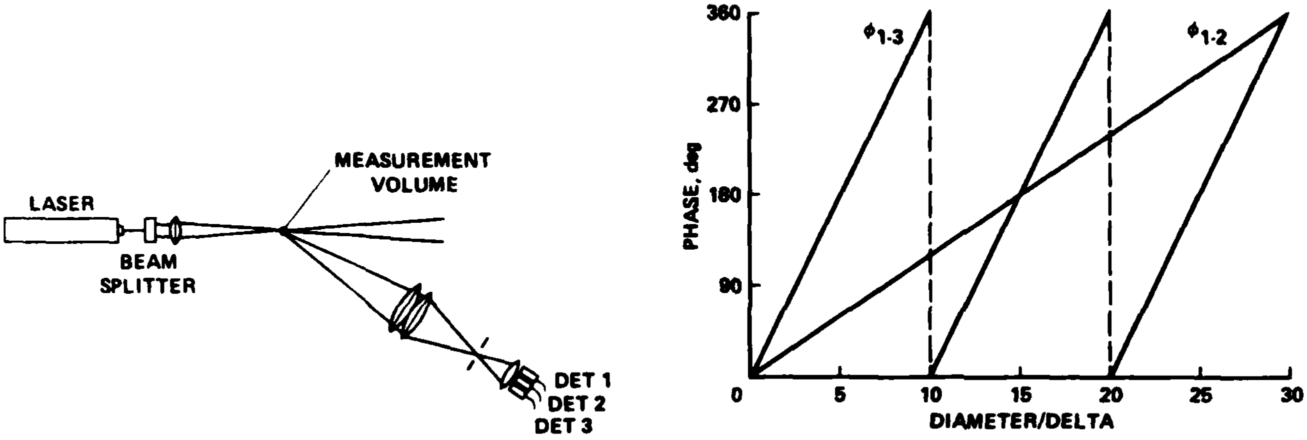
Accurate spray characterizations are required for a broad range of research and development activities related to spray combustion. These applications include the investigations of spray formation, droplet dynamics, two-phase turbulent flows, and the droplet evaporation and burnout in heterogeneous combustion. The planned research program will consist of a theoretical and experimental investigation to determine the potential of the Phase/Doppler technique for providing these data. Because the proposed method is analogous to the laser Doppler velocimeter, the probability of acquiring accurate drop size and velocity distributions in realistic spray environments and ultimately, in combusting sprays warrants further investigation.

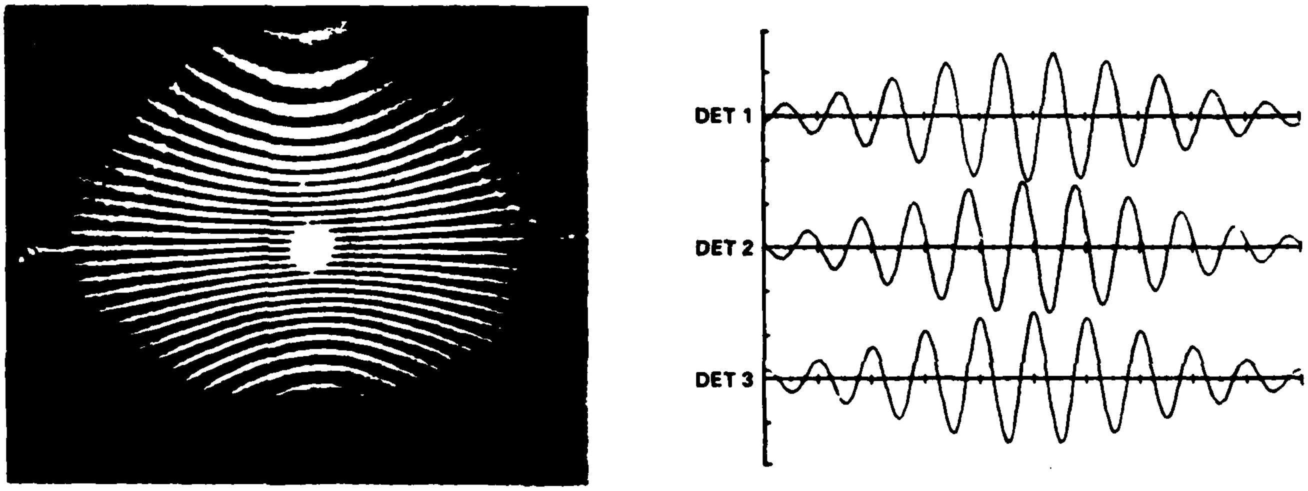
The method, as illustrated in figure 1, consists of an optical system which is the same as a LDV except that three detectors are located at selected spacings behind the receiver aperture. Droplets passing through the intersection of the two beams scatter light which produces an interference fringe pattern. The spacing of the fringes is directly proportional to the droplet diameter but also depends on the light wavelength, beam intersection angle, droplet refractive index (unless reflected light is measured), and the location of the receiver. Measurement of the spacing of the fringe pattern produced by the scattered light may be achieved by placing pairs of detectors at selected spacings in the fringe pattern or its image. As the fringes move past the detector at the Doppler difference frequency, the detectors produce identical signals but with a phase shift proportional to the fringe spacing. The utilization of three detectors ensures that phase ambiguity does not occur, provides redundant measurements for signal validation and allows an expanded operating range while maintaining good sensitivity.

Under the present effort, our basic theoretical description will be expanded to describe both the phase and amplitude of the fringe pattern produced by the scattered light. The possible effects of secondary interference produced by the mixed scattering components of refraction and reflection will also be evaluated. Zones wherein these combined scattering mechanisms may produce ambiguous signals will be defined. Experiments will be conducted to verify the theoretical description. The procedure of measuring monodisperse droplet streams through sprays and flames (figure 2) will be used to evaluate the effects of the measurement environment. These evaluations will also treat the conditions associated with the application of the method in turbulent two-phase flow research. Measurements of sprays with a range of size distributions and number densities and the comparison of these results with other measurements will be used as an evaluation procedure.



OPTICAL SYSTEM

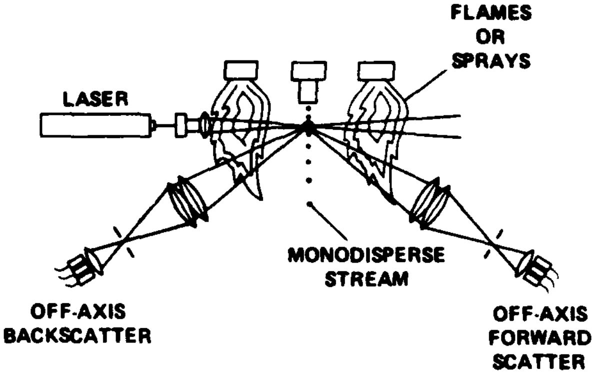
INSTRUMENT RESPONSE CURVES



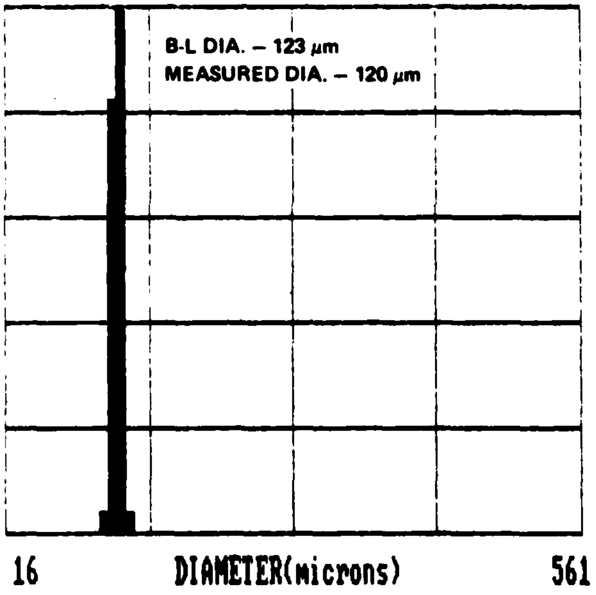
SCATTERED LIGHT INTERFERENCE PATTERN

FILTERED DOPPLER BURST SIGNALS

Figure 1. Schematic of the Phase/Doppler Spray Analyzer Technique.



MEASUREMENT ENVIRONMENT STUDIES



```
XMIT LENS = 220 mm          RCVR LENS = 495 mm
BEAM  SEP = 3.1 mm          COLL.ANGLE= 30 deg
FRNG SPAC = 44.9 microns    SLIT SEPR.= 50.8 mm
WAIST DIA = 213 microns     SLOPE     = .758
MIN.CYCLE = 6               SAMPLES   = 1000
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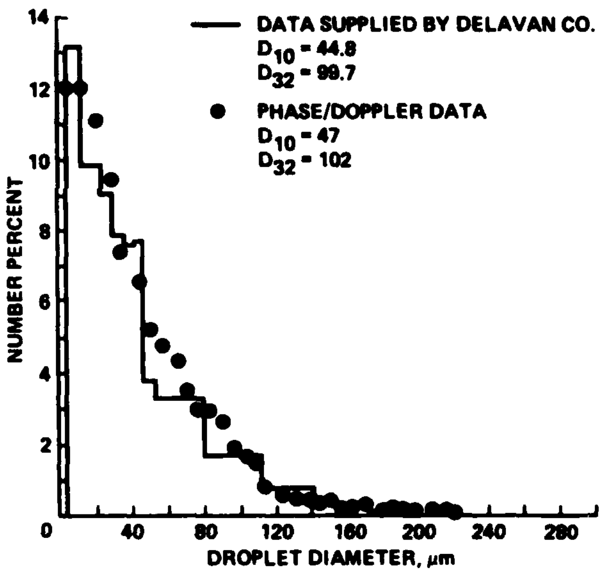
MONODISPERSE STREAM



PRESSURE ATOMIZER

Figure 2. Experimental Verification including the effects of the measurement environment.

SINGLE PARTICLE SIZING BY MEASUREMENT OF BROWNIAN MOTION

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The measurement of submicron particles is basic to achieving an understanding of important combustion processes. For example, soot formation and oxidation rates and mechanisms can be studied by measurement of the soot particle size evolution. Few nonintrusive techniques are available for measurement of particles in the size range smaller than 0.1 μm. Laser techniques based on the measurement of scattered light intensity or extinction require a knowledge of the optical properties of the particles. The goal of this research is to investigate a new optical technique for the measurement of submicron particles, using a laser Doppler system to measure the Brownian motion of individual particles in a gas stream. By measurement of the motion of many particles, the particle size distribution may be obtained. This technique is unique in that it requires no *a priori* assumption on the form of the particle size distribution, nor does it require a knowledge of the particle optical properties.

Two research stages are planned in the present program. In the first stage, presently in progress, the optical instrumentation, data acquisition, and data analysis techniques will be developed and applied to the measurement of particles of well characterized size. Our understanding of the experimental observations will be enhanced by computer simulation of the Doppler measurement of Brownian motion, using Monte Carlo techniques. The second stage of the program will be a study of applications of the technique. Such applications include direct measurements of soot in flames, where comparisons with other particle measurement techniques can be made. Also, the measurement of particle optical properties by correlation of the Brownian motion size measurements with scattering and extinction measurements will be studied.

The important time scales which characterize the Brownian motion of an individual particle are illustrated in Figure 1, which shows the instantaneous velocity as a function of time for a submicron particle in thermal equilibrium with an atmospheric pressure gas at room temperature. Collisions of the particle with gas molecules induce changes in particle velocity of $\delta v \sim 10^{-5}$ m s^{-1} with a time between collisions of $t_{collision} \sim 10^{-14}$ s. Over a relaxation time $t_{relax} \sim 10^{-7}$ s, the mean particle velocity approaches the mean Brownian velocity, $\bar{v} \sim 0.1$ m s^{-1}. In order to obtain adequate statistics on the velocity distribution so that $\bar{v}$ may be determined, the particle motion must be measured for a period $t \gg t_{relax}$ and sampled at intervals $t_{sample} \ll t_{relax}$. The research challenge is to develop the data acquisition and analysis techniques for determination of single particle velocity distributions from an LDV signal.

The type of result anticipated is shown in Figure 2. The velocity distribution function, shown here as a histogram, is obtained for a single particle by frequency analysis of the LDV signal as the particle traverses the measurement volume. The particle mass, m, is obtained from the width of the velocity distribution. The particle mass distribution (size distribution) is obtained by velocity analysis of a large number of individual particles.

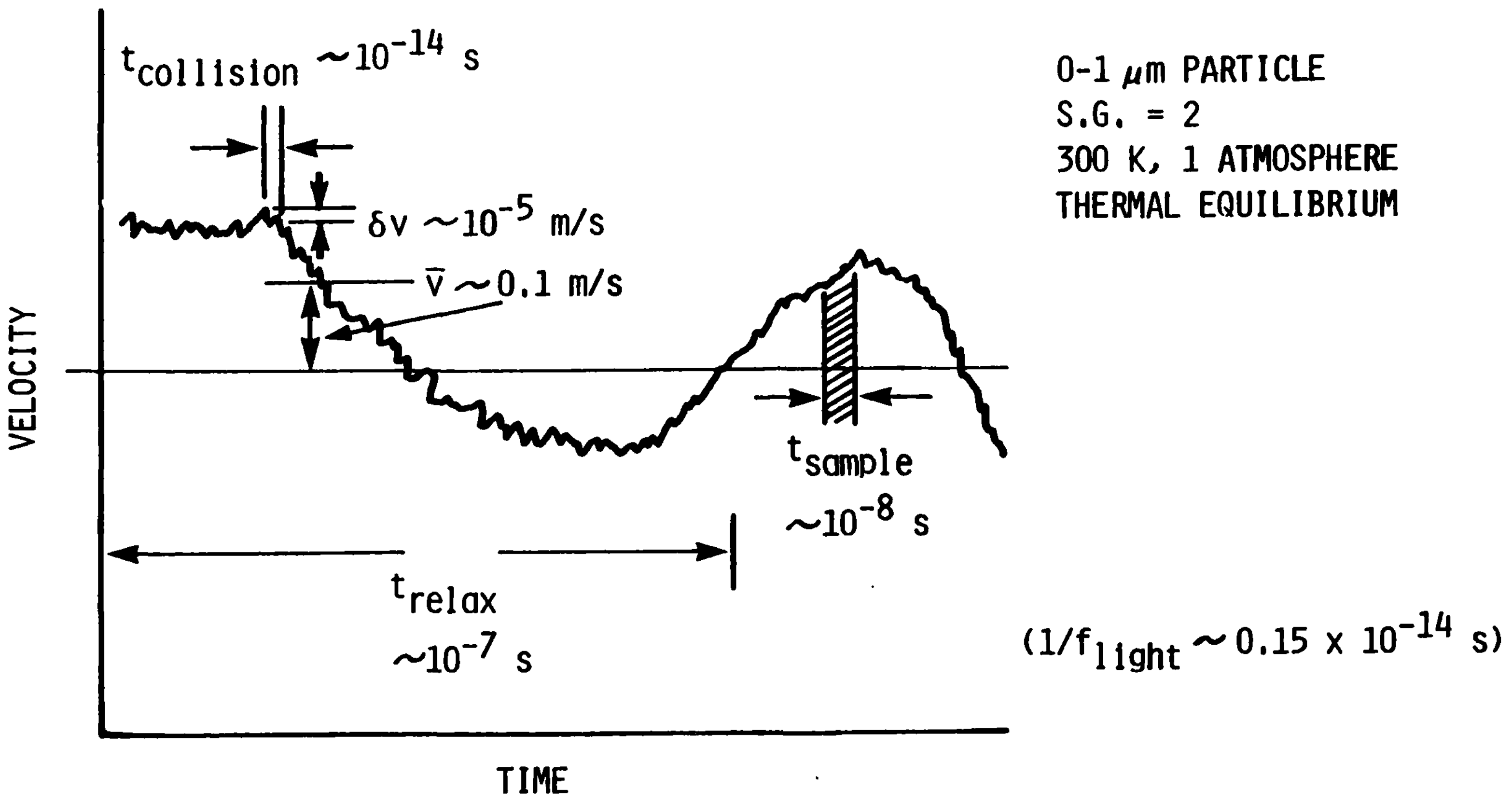

Figure 1. Relevant time scales for analysis of the Brownian motion of individual particles.

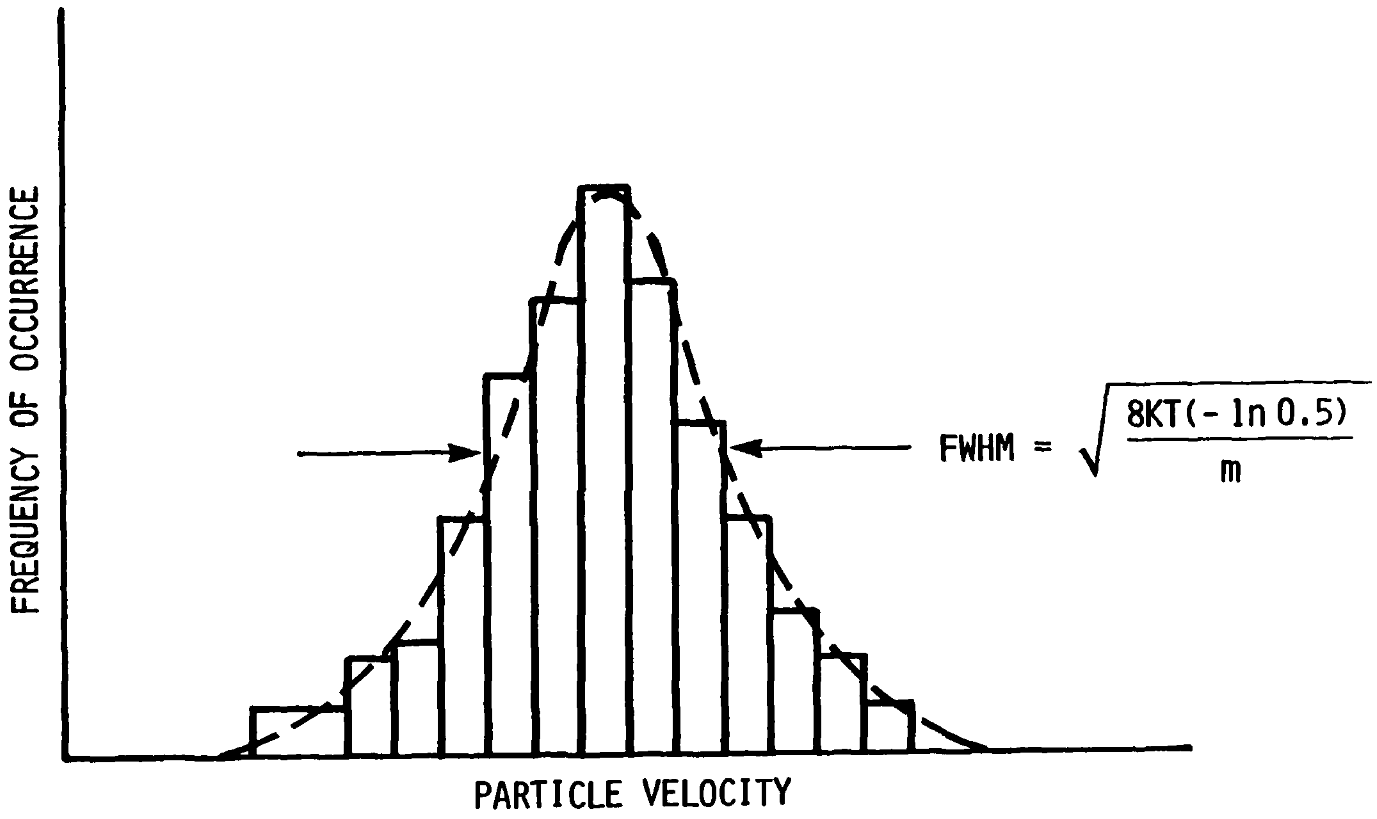

Figure 2. Anticipated result for the velocity distribution for a single particle. The width of the velocity distribution is related to the mean Brownian velocity and the particle mass, m.

EXCIPLEX SYSTEMS FOR REAL TIME VISUALIZATION OF FUEL SPRAYS

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Richardson, TX 75080

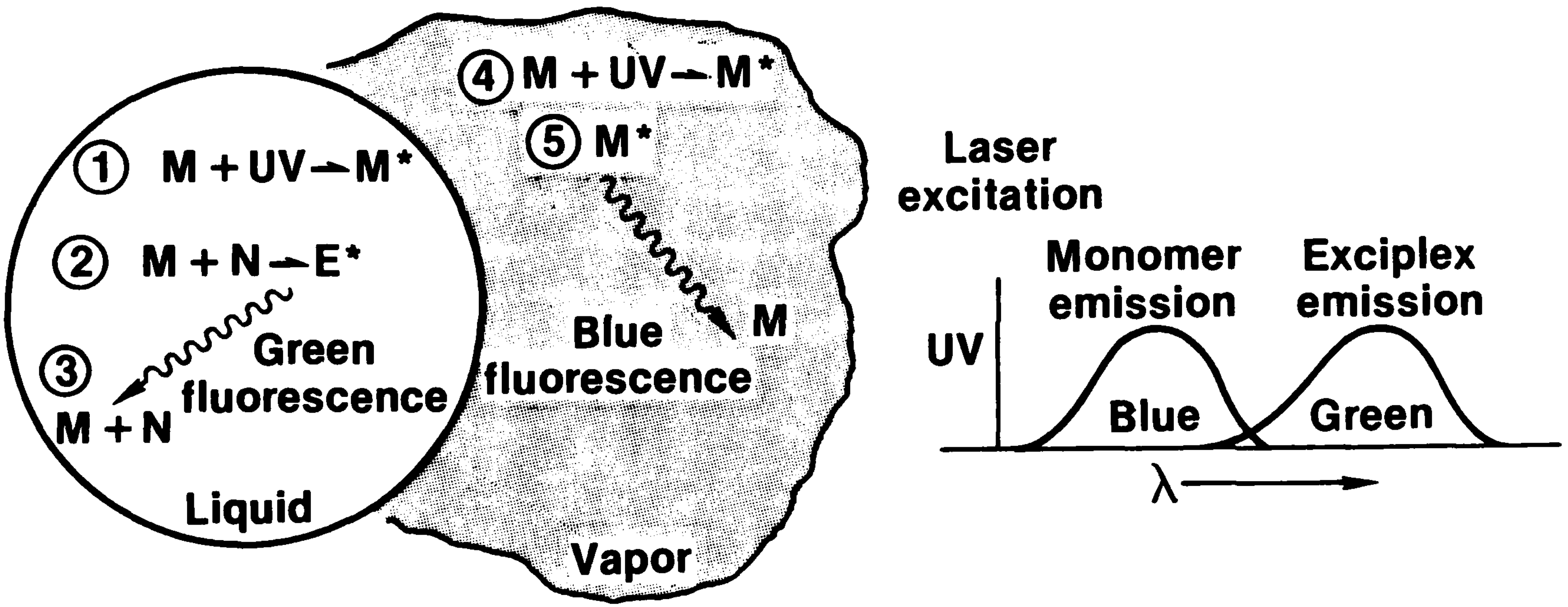
The analysis of the processes by which a fuel spray in a diesel or gas turbine engine atomizes, evaporates, mixes with the ambient air, and burns is made more difficult by the heterogenous nature of the droplet/fuel vapor/air mixture. One particularly desirable type of information is the spatial distribution of the fuel, as liquid droplets initially and as vapor later in the preignition phase of the combustion process. The exciplex visualization techniques we are developing will result in fluorescence emissions from the liquid and vapor portions of the fuel which are separated by 100-180 nm. With appropriate pulsed laser excitation, filters, and fast detection, we foresee the possibility of two dimensional, real-time, *in situ* measurements of the separated liquid and vapor portions of the fuel.

Previous analyses of evaporating fuel sprays have relied on photographs of droplets, laser light scattering, and/or laser absorption to deduce the liquid and vapor fractions. The present work is unique in that it exploits the photochemistry of organic exciplexes (excited state complexes) to shift the fluorescence from the liquid relative to that of the vapor. Because the time scales of excitation and fluorescence can be very short -- less than 100 nanoseconds -- "frozen flow" photographs showing the separate vapor and liquid portions of the evaporating fuel spray can be obtained.

Figure 1 illustrates the concepts involved in using organic exciplexes for fuel spray visualization. The fuel itself may or may not be fluorescent; it may be doped with a fluorescent organic molecule M which evaporates along with the fuel. In the vapor phase M may be excited and M^* may then fluoresce. The mixture of fuel and M is also doped with an exciplex forming molecule N, typically at concentrations of less than 1% by weight. Because exciplex formation is a bimolecular process, it is favored in the liquid, where the densities are high. Hence, the liquid emission is dominated by emission from the exciplex E^*, which emission is red-shifted relative to emission from the monomer M; the vapor emission is dominated by emission from the excited monomer M^*.

Figure 2 demonstrates a specific application of the exciplex visualization concept. A sheet of laser light (fourth harmonic of Nd:YAG, $\lambda = 266$ nm) passes through a hollow cone fuel spray composed of 96.5% hexadecane, 2.5% naphthalene (N), and 1.0% tetramethyl-p-phenylene diamine (M) injected into heated nitrogen. The photographs were taken with a single laser shot. With no filters between the emitting fuel spray and the camera, one photographs both the liquid and vapor portions. With a filter which suppresses the monomer emission (peaked at $\lambda = 380$ nm), one photographs the hollow cone of the liquid only; and with a filter which suppresses the exciplex emission (peaked at $\lambda = 470$ nm), one photographs the vapor only. The photographs in figure 2 were taken at the United Technologies Research Center, with the assistance of J. F. Verdieck.

REAL TIME, 2-D SPRAY/VAPOR MONITORING VIA EXCIPLEX FLUORESCENCE

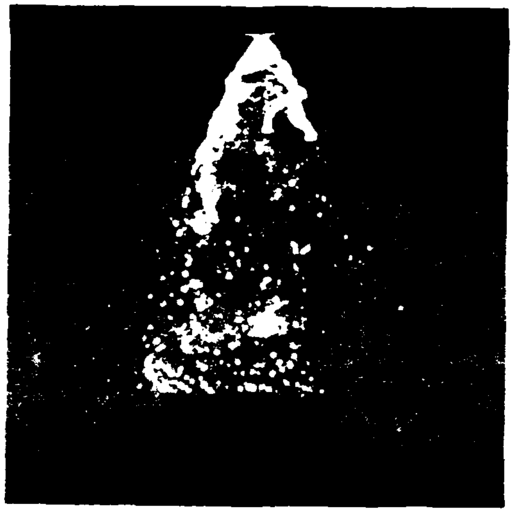


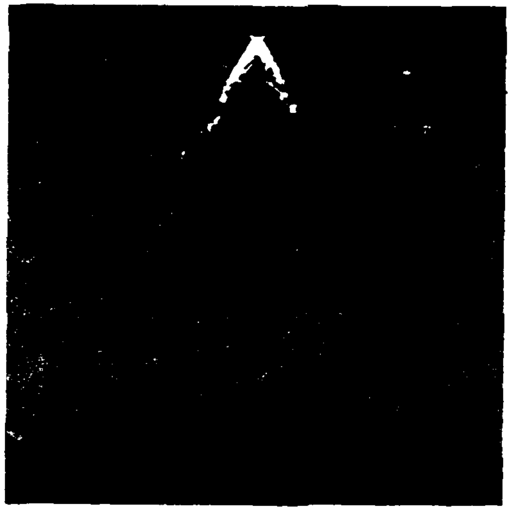
Concept

①, ④ Laser excitation of monomer in liquid or vapor
② Exciplex (excited complex) formation, liquid phase only
③ Exciplex fluorescence occurs in green
⑤ Monomer fluorescence occurs in blue

LASER-INDUCED EXCIPLEX FLUORESCENCE FROM CONICAL FUEL SPRAY

Experimental results


Liquid and vapor


Liquid only


Vapor only

- Commercial nozzle operating with cetane doped with naphthalene/tetramethyl phenylene diamine (TMPD)
- Single, 10 nanosecond, fourth harmonic (266 nm) Nd:YAG laser excitation
- Two-color fluorescence separated with absorbing glass filters

APPLICATION OF ATOMIC FLUORESCENCE TO MEASUREMENT OF COMBUSTION TEMPERATURE IN SOLID PROPELLANTS

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The overall aim of this program is to develop a diagnostic technique for determining the surface temperatures of solid-fuel propellants. The approach is to utilize the laser-induced fluorescence of a doped material whose fluorescence spectrum or lifetime varies in a known manner with temperature, as demonstrated in Figure 1.

The goals of the program are:

a) to select a proper dopant which can be incorporated into the reacting material and possesses sufficient fluorescence and temperature sensitivity to permit an accurate measure of surface temperature,

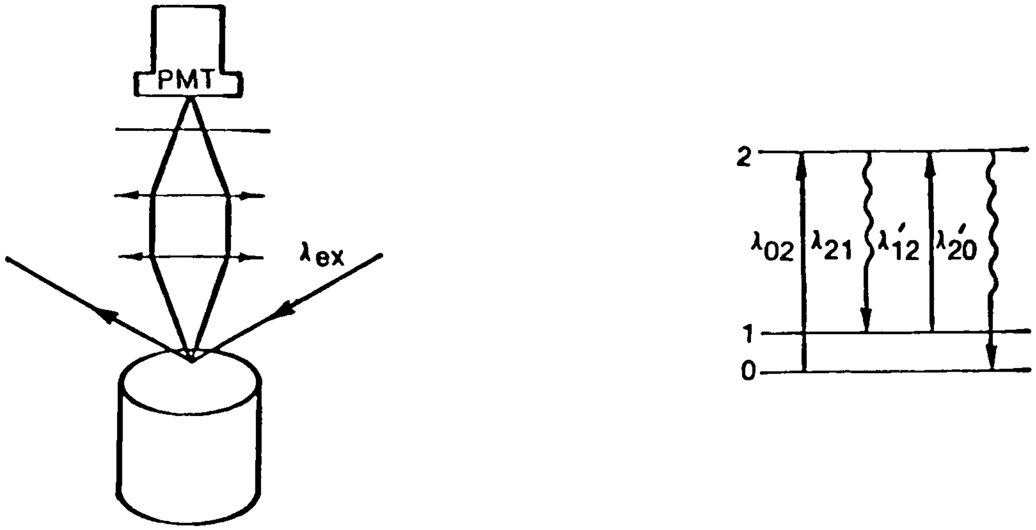
b) to select a model material which will simulate the surface of a propellant,

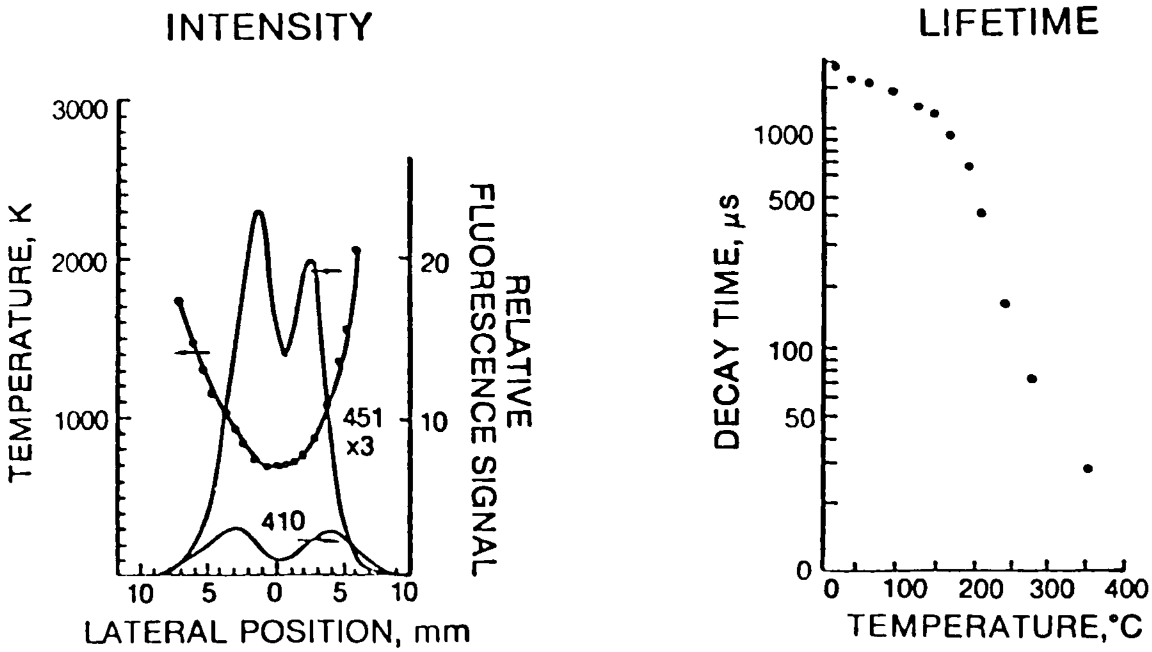
c) to verify the accuracy of the temperature measured by a comparison with data obtained from thermocouples and a fast pyrometer, and

d) to show the applicability of this technique by measuring surface temperatures under rapid heating conditions.

The critical phases of this program are outlined in Figure 2. The program is presently in Phase I - Fluorescent Material Selection. Materials which are being tested in the heated-cell experiments include, but are not limited to, $Sm^{+3}(CaF_2)$, $Pr^{+3}(CaF_2)$, $Tb^{+3}(CaF_2)$, $Er^{+3}(CaF_2)$, $Pr^{+3}(LaF_3)$, and $Dy^{+3}(LaF_3)$. Both fluorescent spectra and lifetimes of these compounds are being monitored as a function of the temperature variation from 20°C to 900°C.

Phases II and III will commence during the second and third year of this program, respectively.





ATOMIC FLUORESCENCE INTENSITY PROFILES OF INDIUM

$^5D_0$-$^7F_0$ TRANSITION OF BaClF:Sm^{+2}

Figure 1. Surface Temperature Measurement Approaches

PHASE I. FLUORESCENT-MATERIAL SELECTION
(HEATED-CELL EXPERIMENTS)

(A) SPECTRA

(B) LIFETIMES

PHASE II. CALIBRATION
(VERIFICATION OF TEMPERATURES)

(A) COMPARISON TO THERMOCOUPLE DATA

(B) COMPARISON TO FAST PYROMETER DATA

PHASE III. RAPID HEATING MEASUREMENTS
(CO_2 HEATING EXPERIMENTS)

(A) INERT ATMOSPHERE

(B) REACTIVE ATMOSPHERE

(C) VERIFICATION BY PYROMETRY

Figure 2. Surface Temperature Program Phases

DETERMINATION OF LIQUID DROPLET EVAPORATION RATES IN A SPRAY BY INELASTIC LIGHT SCATTERING

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Combustors and their chemical by-products are sensitive to the size distribution of the fuel droplets. The evaporation rate of a single droplet within a spray depends on the heat flux directed toward it and on its vapor environment. Both of these quantities depend on the proximity of neighboring particles and also on the collective evaporation and combustion properties of all the droplets.

We report on a new technique for determining the evaporation and condensation rate of droplets which are flowing. It is based on the principle that transparent spheres can support surface electromagnetic waves whenever the size parameter ($2\pi a/\lambda$, where a = particle radius and λ = vacuum wavelength) satisfies very stringent resonance conditions. Such morphology-dependent resonances can be calculated with the Lorenz/Mie formalism for the internal field and far-field elastic scattering. By adding efficient fluorescent dye molecules in the droplets (hereafter referred to as tagged droplets) and by irradiating these tagged droplets with a laser pulse, the structure dependent resonance peaks in the fluorescence spectra ($\lambda_{n,\ell}^{flu}$) from each spatially resolved tagged droplet can be detected. For a series of ethanol droplets, each generated with precisely the same radius, the evaporation or condensation rate of the droplets can be deduced by measuring the relative wavelength shifts of the structure resonances ($\Delta\lambda_{n,\ell}^{flu}$) among different individual spheres which form the series of droplets. This fluorescence structure resonance technique can be extended to the measurement of evaporation rates of tagged droplets within a spray of untagged droplets (containing no dye but the same liquid).

The experimental configuration is shown schematically in Figure 1. The droplets have a diameter in the 50 μm range and the spacing between the droplets is in the 100 μm range. The droplet velocity is 4 m/s, corresponding to a Reynolds number of 15, based upon the droplet diameter.

Figure 2 displays typical fluorescence spectra detected after a single N_2 laser pulse irradiating the series of droplets emerging into the ambient, at higher temperature, and in an environment containing higher ethanol vapor pressure. The fluorescence spectra from 8-9 individual droplets are displayed along the x-axis while different droplets which are progressively further away from the generator are displayed along the y-axis. The fluorescence intensity of the various structure resonances is plotted along the z-axis. Note that for evaporation the resonance peaks exhibit a blue shift, while for condensation the resonance peaks exhibit a red shift.

The determination of the evaporation or condensation rates for a series of droplets from such blue or red shifts will be discussed along with recent data of evaporation rates of tagged droplets in a spray of untagged droplets.

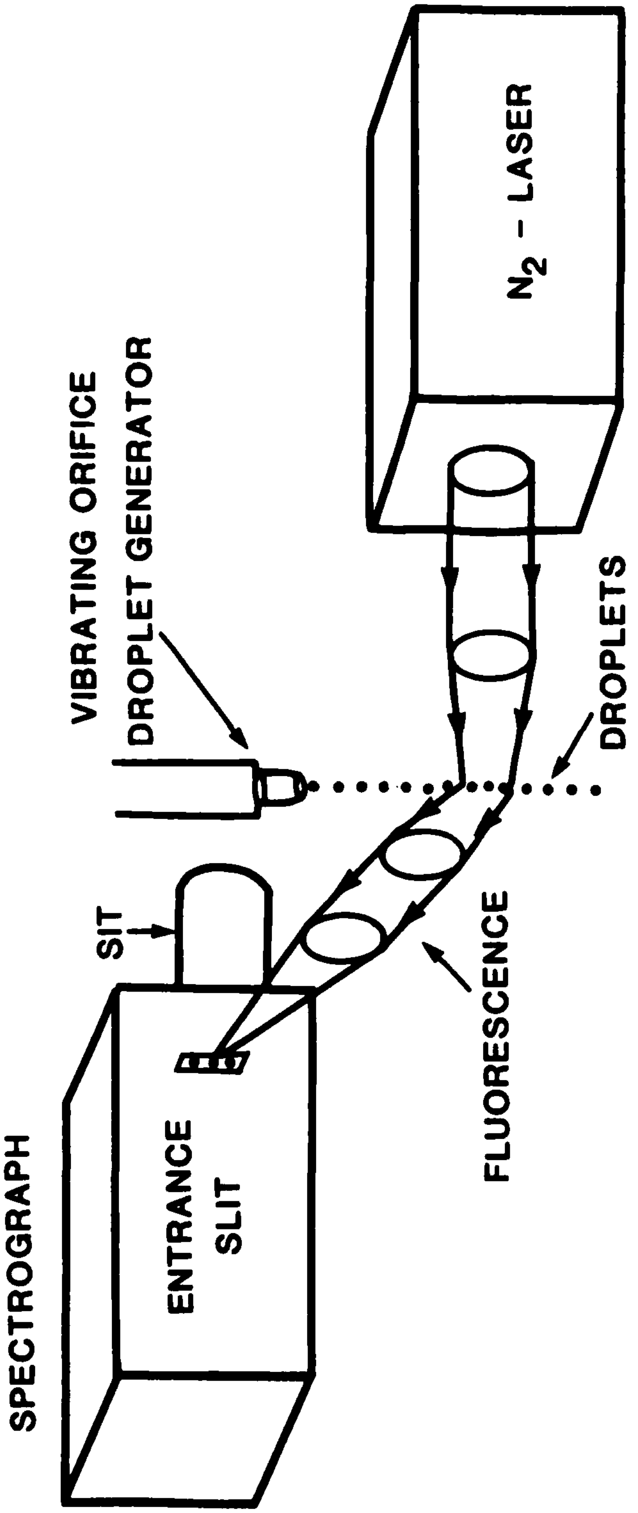

Figure 1. Experimental schematic diagram of the new technique to measure evaporation/condensation rates of tagged droplets (containing fluorescent dye molecules) from structure resonances in the fluorescence emission. The images from several droplets are focused onto the entrance slit of the spectrograph which disperses the fluorescence spectrum while maintaining the spatial integrity of the entrance slit.

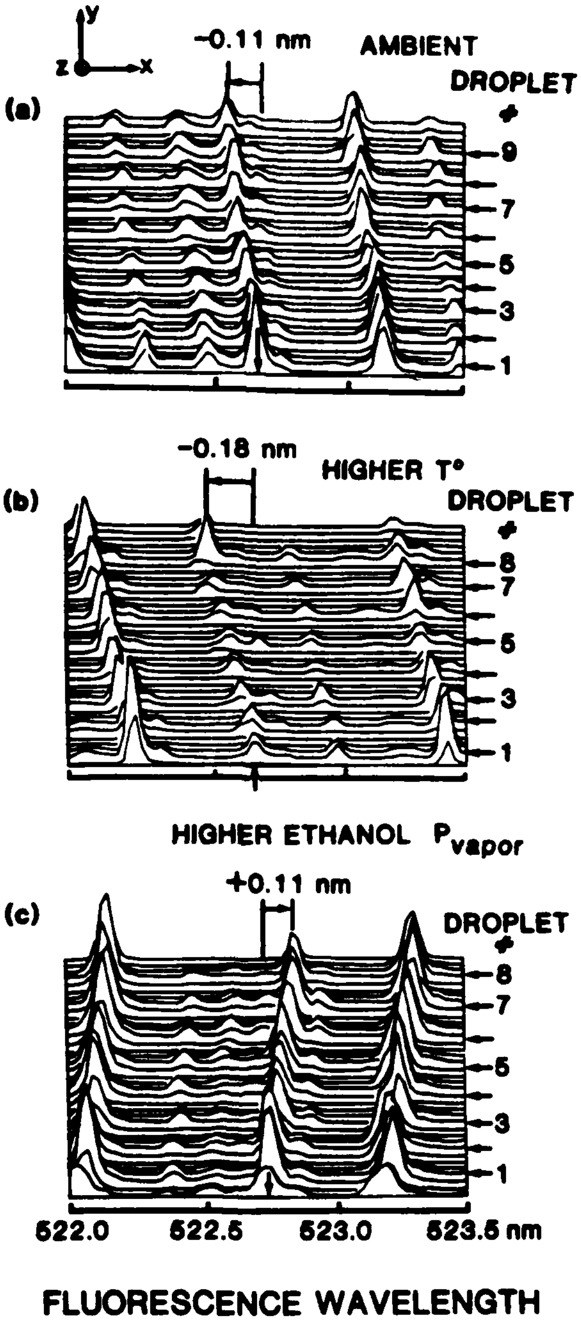

Figure 2. Single laser pulse data of the structure resonance of the fluorescence emission from 8-9 tagged droplets emerging into the ambient, at higher temperature, and in an environment containing high vapor pressure of ethanol. Evaporation causes the structure resonances from the preceding droplets to shift to the blue while condensation causes a shift to the red.

QUANTITATIVE FLOW VISUALIZATION

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Stanford University
Stanford, California 94305

The utility of flow visualization in fluid mechanics is well established. Until recently, however, most visualization techniques have been qualitative and based on line-of-sight approaches poorly suited for flows with three-dimensional characteristics and varying composition. With the development of laser-based light scattering techniques, it has become possible to obtain temporally resolved, quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and techniques such as Raman, fluorescence or Mie scattering. Pioneering work in this direction using Mie scattering from seeded particles was initiated at Yale a few years ago, and significant progress has been made recently by groups at Stanford, Yale, SRI and Sandia using fluorescence- and Raman-based methods. The quantitative 2D and 3D techniques which are forthcoming are likely to have a major impact on energy conversion research.

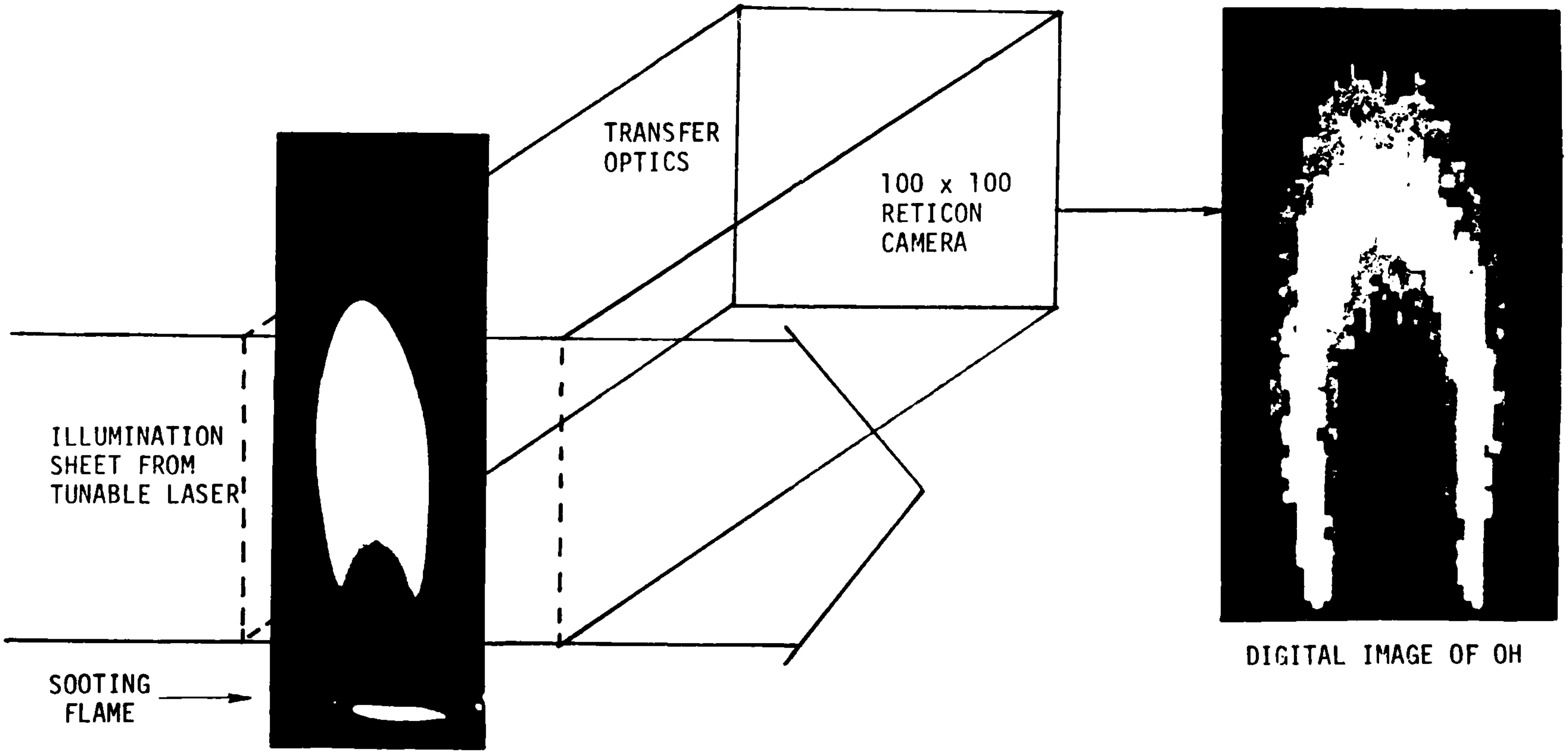
Distinguishing features of the Stanford activity are: (1) use of fluorescence rather than Raman or Mie scattering; (2) emphasis on recording at high repetition rates, thereby allowing studies of the real-time evolution of fluid mechanical structures; (3) use of an intensified photodiode array rather than a vidicon detector; and (4) the goal of measuring multiple quantities, including species concentrations, temperature and velocity.

The advantages of fluorescence are that the gas can be tagged at a molecular level, thereby avoiding lag, and the signal is species specific. The major disadvantage of fluorescence has been that of properly accounting for quenching. We believe this can be handled through calibration or, in some cases, by using variations of LIF in which quenching effects cancel.

The approach and some initial results (in a false-color format) for species concentration and velocity are shown in Figs. 1 and 2 respectively. In both cases the flow is illuminated with a sheet of light from a tunable laser and the laser-induced fluorescence is recorded with an intensified Reticon array (100 x 100) coupled to a laboratory computer. In Fig. 1, instantaneous, single-frame results for OH are shown for a sooting candle flame. Sensitivity of below 100 ppm has been achieved, with submillimeter spatial resolution, in this two-phase combustion flow. Discrimination against scattered light was accomplished by using separate bands of OH for excitation (1, 0) and detection (1, 1). In Fig. 2, velocities in a steady, subsonic jet of N_2 (seeded by 300 ppm of I_2) are inferred (at each flowfield point) from quantitative comparisons of fluorescence intensities obtained using 4 different angles of sheet illumination. A narrow-linewidth cw dye laser source was used, set at a wavelength (547.3301 nm) in the wing of an I_2 line to enhance the effect of small Doppler shifts on the fluorescence intensity. Sensitivity of about 5 m/sec and a recording time of a few seconds has been achieved in these initial experiments.

QUANTITATIVE FLOW VISUALIZATION

PLANAR LASER-INDUCED FLUORESCENCE (PLIF) YIELDS
2-D CONCENTRATIONS IN SOOTING FLAMES

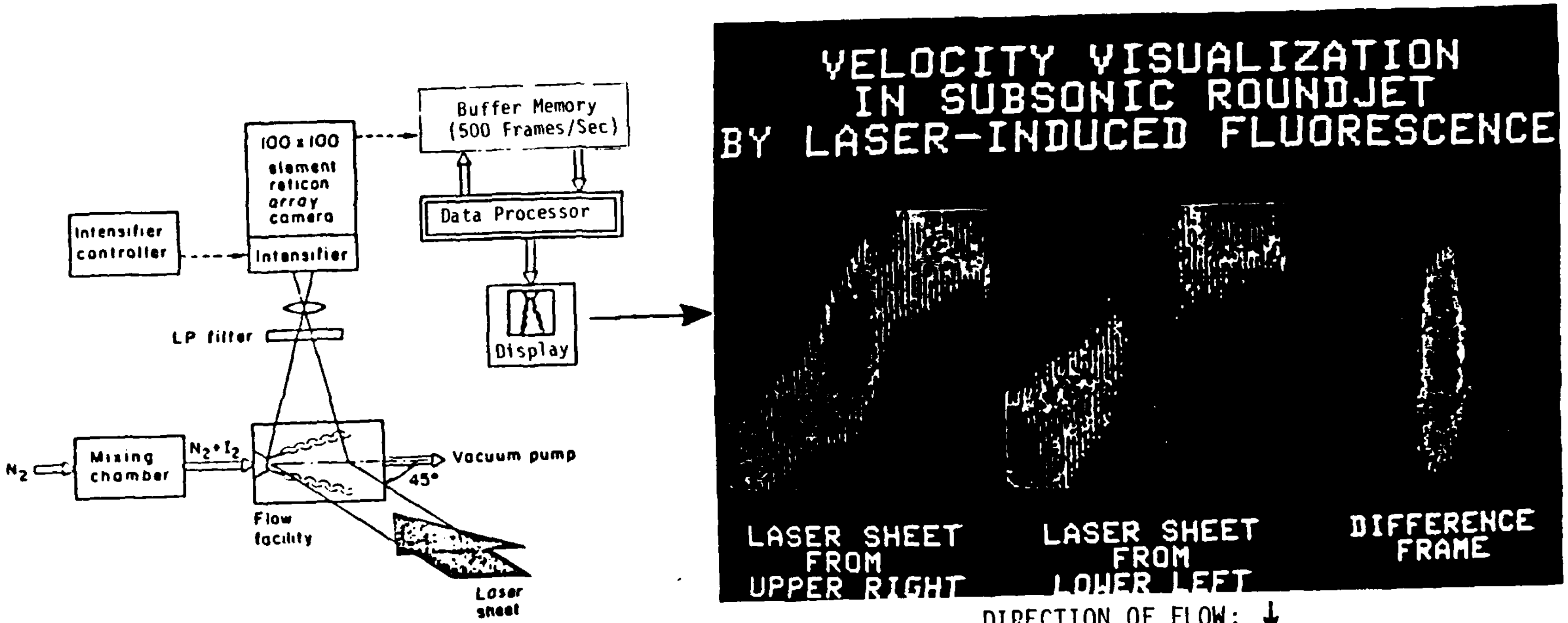


- FIRST INSTANTANEOUS MULTIPLE-POINT SPECIES MEASUREMENTS IN A SOOTING FLAME (10^4 POINTS)
- HIGH SPATIAL (0.4 · 0.4 · 0.2 MM) AND TEMPORAL (5 NSEC) RESOLUTION
- POTENTIAL MAJOR IMPACT ON COMBUSTION MODELLING
- SCATTERED LIGHT PROBLEM SOLVED BY USING SEPARATE BANDS OF OH FOR EXCITATION AND DETECTION

Fig. 1. Approach and results for planar laser-induced fluorescence (PLIF) method of quantitative flow visualization.

VELOCITY VISUALIZATION

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



DIRECTION OF FLOW: ↓

- FIRST QUANTITATIVE MULTIPLE-POINT VELOCITY MEASUREMENTS IN AN UNSEEDED GAS FLOW
- NO PARTICLE SEEDING REQUIRED
- NO TEMPERATURE PERTURBATION (AS WITH SODIUM SEEDING)
- PROSPECTIVE TECHNIQUE FOR REAL-TIME VELOCITY MONITOR
- SENSITIVITY DEMONSTRATED TO 5 M/SEC
- RELATIVE ACCURACY IMPROVES WITH INCREASING VELOCITY

Fig. 2. Approach and results for multi-point velocity technique.

QUANTITATIVE THREE-DIMENSIONAL FLOW VISUALIZATION

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Research Objective: Turbulent combustion requires molecular mixing, a complicated three-dimensional process. Improved knowledge about the topology of the fluid elements which are fully mixed will greatly enhance our understanding of combusting flows. Presently no satisfactory three-dimensional spatially and temperally resolved technique exists for making such measurements. The objective of the research is to devise such a method. The focus of the effort is directed towards new approaches in data processing and data display with full 3-D parallax.

Explanation of the approach: The approach involves acquiring quantitative flow data in cross sectional planes at regular intervals throughout the three-dimensional flow field. The volumetric data are processed in a digital computer for feature extraction and image enhancement. The processed data associated with the stack of planes are synthesized into a continuous volumetric object using interpolation techniques or a video stereo pair display.

Uniqueness of the approach: i) Any quantitative data obtained in a stack of planes can be analyzed and displayed with the new technique, including velocity, temperature, pressure, density and species concentration. ii) Either coherent (laser) or incoherent (e.g. fluorescence) radiation can be used to probe the flowfield, in contrast to holography which requires coherent light for data acquisition. iii) Digital data processing provides a solution for the cloud-within-a-cloud problem; opaque elements at the perimeter of the volume can be digitally removed or artificially made transparent to expose details in the interior. iv) Feature extraction such as determination of the interphase between fuel and oxidant or the topology of the reaction product can be performed digitally as well as optically.

RESULTS: To investigate the capabilities of the new technique the three-dimensional wake behind a circular cylinder has been visualized by illuminating a cross-section of the particle laden flow. *Smoke is injected into the flow from two slots* parallel to the cylinder axis and located at 45 degrees with respect to the front stagnation line, as indicated in Figure 1. The scattered radiation is recorded sequentially on film with a high speed motion camera. Sequential frames in the movie thus represent planar cross sections of the three-dimensional streak line pattern made visible by smoke tracers. In a similar fashion species concentration has been measured in a laminar premixed methane-air flame seeded with sodium. The laser light is tuned to the sodium-D line and high resolution images of the fluorescent radiation are stored on motion picture film. The intensity on the film represents the number density of the tracer gas, and provides information about the topology of the combusting process. A multiplexed hologram of the 3-D wake pattern has been obtained, as well as a 3-D video stereo display.

Important issues of optimal feature extraction such as edge detection in smoothly varying data bases have been investigated. We have found that sophisticated panel techniques are needed to discern 3-D contours in these smoothly varying flows, in particular when strong background noise is present. Image processing techniques developed for other applications, such as aerial photography and medicine cannot be directly applied but new software is needed for processing combustion data.

In addition to the holography techniques we have investigated video based methods for *interactive* processing and display of flow data. As shown in Figure 2 stereo projections of the stack of planes are numerically evaluated and displayed on a black and white monitor under computer control. The object can be manipulated, such as rotated and dissected interactively, and displayed in real-time. Topics such as optimal data representation and methods for comparing two 3-D data bases are being investigated.

Presently research is also underway investigating the fundamental properties of nonlinear optical materials to be used for real-time holography and data acquisition/processing. This effort was started this summer and we have formulated the most desirable properties of these materials. A very promising class of materials have been located and these materials are presently being investigated in holographic configurations.

Data Recording

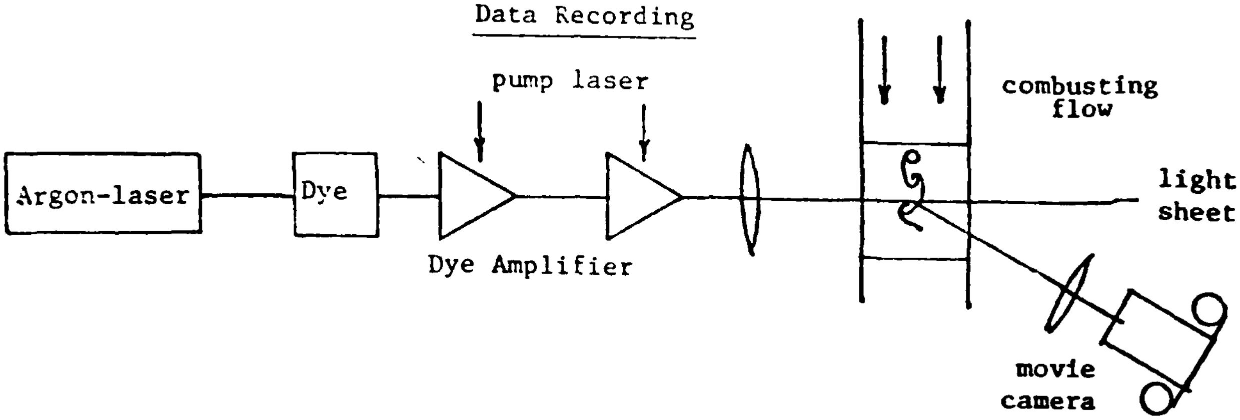
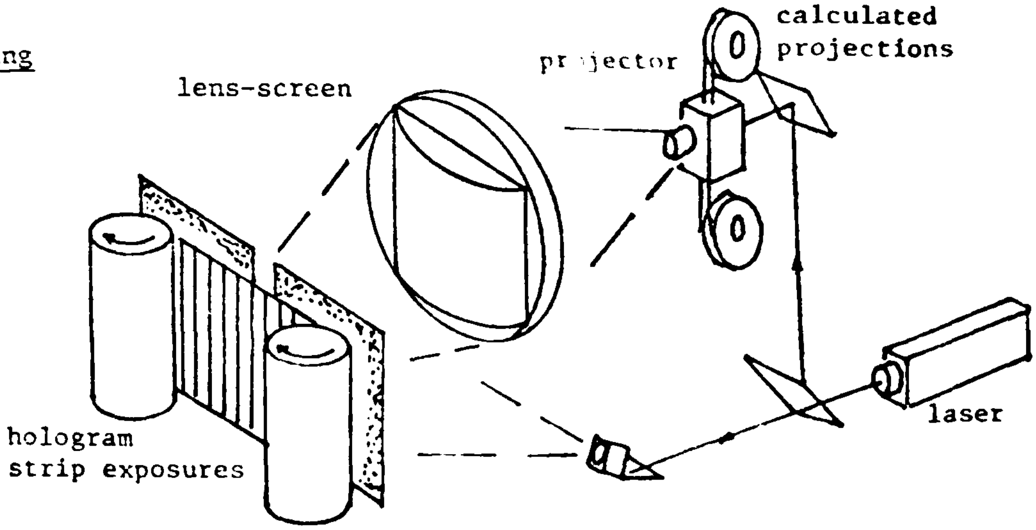


Image frames are digitized and processed for feature extraction, such as edge detection and a three-dimensional computer representation of the flow field is synthesized. Subsequently, stereo projections of the object onto a cylinder surrounding the object (as seen by an imaginary human observer) are calculated. These projections are used to synthesize a multiplexed hologram.

Synthesizing



Viewing

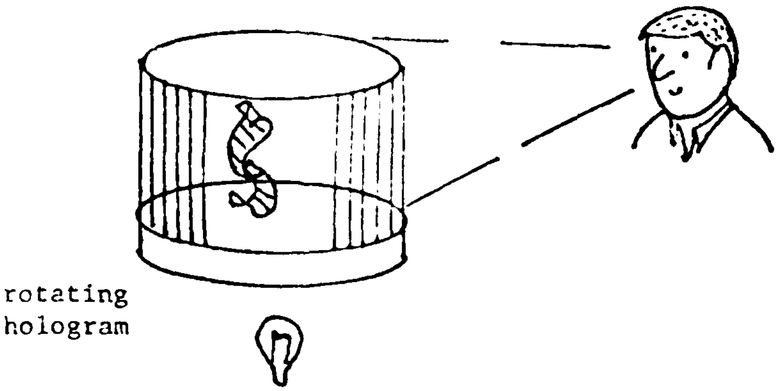
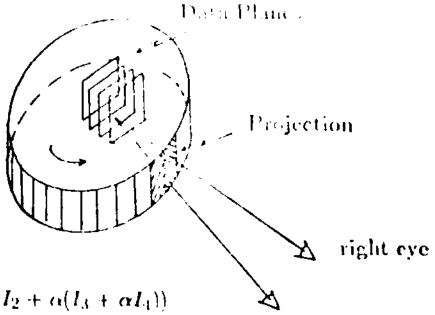


Fig. 1. Principle of the Approach

COMPUTER COMPUTATION OF PROJECTIONS



$$\begin{aligned} I &= I_1 + \alpha(I_2 + \alpha(I_3 + \alpha I_4)) \\ &= I_1 + \alpha I_2 + \alpha^2 I_3 + \alpha^3 I_4 \end{aligned}$$

- Source attenuation

First calculate projections, then perform feature extraction and subsequently use video stereo display

Video stereo pair of 3-D wake data

- FIRST QUANTITATIVE 3-D DISPLAY OF CONCENTRATION DATA FOR A GAS FLOW
- MULTIPLE VIEWING DIRECTIONS UNDER COMPUTER CONTROL
- SOFTWARE OPTIMIZED FOR FEATURE EXTRACTION AND INTERACTIVE 3-D DISPLAY OF FLOW DATA

Figure 2. Processing and video based display of 3-D flow data

TEMPORAL EVOLUTION OF INSTANTANEOUSLY DETECTED TWO-DIMENSIONAL IMAGE OF GAS CONCENTRATION IN A JET FLOW*

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To fully characterize turbulent flows requires simultaneous information on velocity, pressure, temperature and species concentration at each point within the flow as a function of time. As yet, current measurement techniques are unable to provide this type of complete data and new methods of studying these flows are needed. Of particular value are techniques which can provide simultaneous multipoint spatial profile data as a function of time as a result of the increasing realization that the large-scale structures in the flow play a significant role in fluid mechanics and combustion.

For the past several years, work has been done at Yale to develop instantaneous and quantitative two-dimensional techniques for simultaneously mapping gas concentration profiles in turbulent flows. Different light scattering mechanisms, including Lorenz/Mie, Rayleigh, fluorescence and Raman scattering, have been used to measure instantaneously concentrations in two dimensions. These data obtained thus far can yield considerable information on the spatial character of structures within the flow.

One limitation of the techniques developed thus far is their inability to obtain a time history of the flow due to the limited speed of the computer-controlled imaging system used ($\sim$60 frames/s). New work has been done to modify the existing techniques to yield information on the temporal evolution of structures in the flow.

Figure 1 shows an experimental configuration used to make a series of time resolved measurements in a turbulent jet. In this approach, a rotating mirror is used to displace the elastically scattered image of the jet to different regions of the existing two-dimensional detector. The laser is gated with a short duty cycle so that during the illumination pulse it can be assumed that the mirror does not move appreciably and the flow patterns do not change.

Figure 2 shows four two-dimensional realizations recorded during different times. The effective frame rate for this case is 2220/s and can be increased if the flow being studied requires it. For the existing slow detector, this approach of displacing the scattered image allows several sequences of events to be recorded. However, as new detectors with higher framing rates (· 1000 frames/s) become available, it should be possible to obtain a continuous time history of the flow being observed. The limitations of both the slow detector-rotating mirror approach and the future fast detectors will be discussed.

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*This work is partially supported by the Department of Energy.

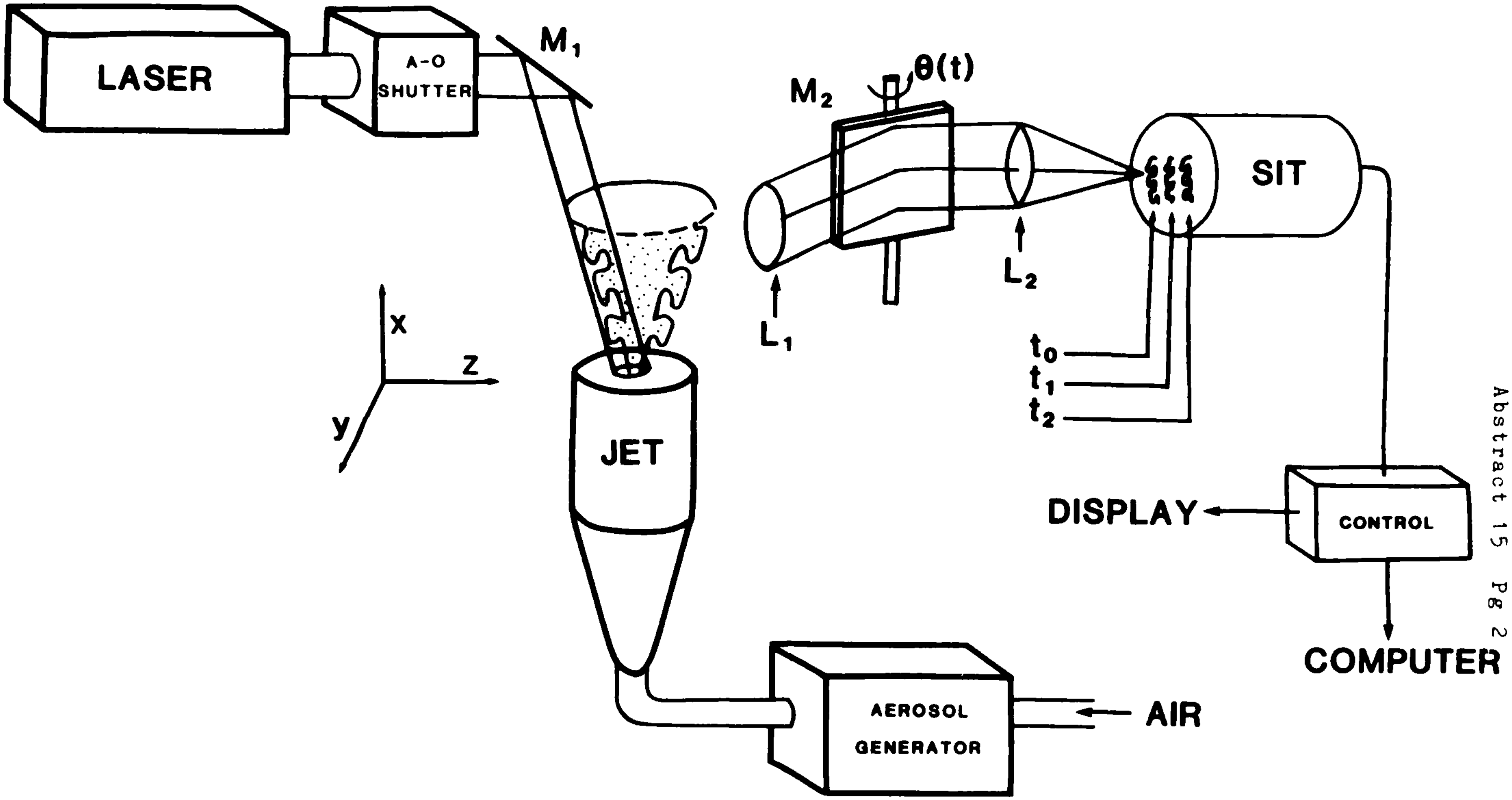

Figure 1. Experimental schematic for detecting the time evolution of instantaneous two-dimensional gas concentration profile with a slow television camera. The rotating mirror M_2 displaces the elastically scattered light image onto different portions of the camera.

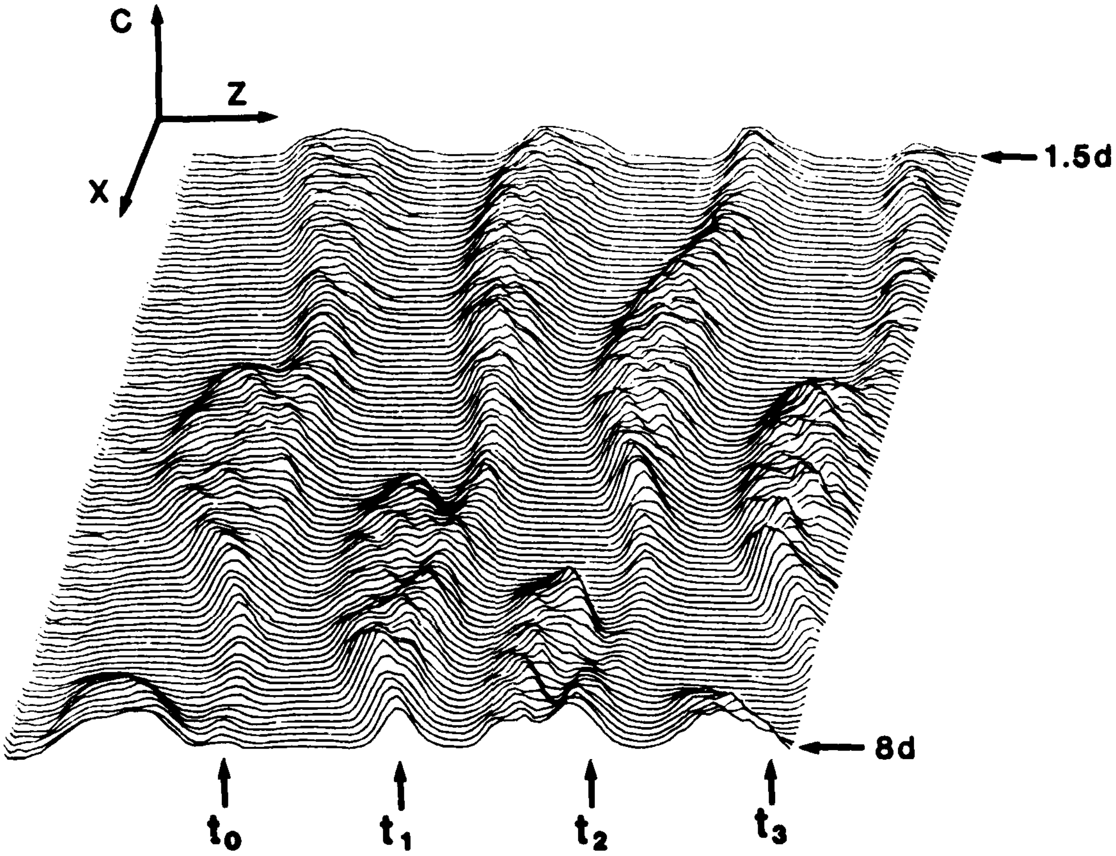

Figure 2. Experimental data of the time evolution of four instantaneous Lorenz/Mie scattered images from a sheet of laser radiation intersecting the flow along the streamwise direction. The large scale turbulent structures are noted to evolve in time. The Reynolds number is 2228 and the effective frame rate is 2220/s.

COMBUSTION DIAGNOSTICS RESEARCH SPONSORED BY APL

BISH GANGULY, SIG KIZIRNIS AND MEL ROQUEMORE

AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AERO PROPULSION LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

The Aero Propulsion Laboratory (APL) is sponsoring both in-house and contracted research in which diagnostic techniques are being developed and utilized as tools for gaining a better understanding of the turbulent mixing processes in reacting and non-reacting flows. The following paragraphs give a brief overview of these different programs:

a. Flame Luminosity Conditional Sampling of CARS and LDA - A centerbody research combustor is being used at APL to evaluate and improve combustion models. Figure 1 depicts the experiments in which laser techniques and conventional probes are used to study the turbulent combustion processes in the centerbody combustor. High speed cine pictures of the flame show that large, discrete flame structures, called flame turbules, are formed downstream of the recirculating zone. One of our objectives has been the investigation of the temperature and velocity characteristics of the flame turbules. In these investigations, a relatively simple technique of using flame luminosity to conditionally sample CARS and LDA data has proven very useful. Probability distribution functions (pdf's) of the conditionally sampled CARS measurements made by Switzer, et al., are shown in Fig. 2 and the LDA measurement made by Magill, et al., are shown in Fig. 3. The bimodal temperature distribution is indicative of the discrete flame structures. The velocity histogram in Fig. 3 shows that the most probable velocity of the flame turbules (luminous histogram) is about 18% larger than the most probable velocity of the nonluminous regions. For this histogram, the luminosity was recorded for each LDA realization. From the number of realizations, one would conclude that the nonluminous regions are occurring more often than the luminous regions. However, from the temperature pdf's in Fig. 2, one would conclude that the nonluminous and luminous regions occur about an equal amount of time. This discrepancy suggests that in combusting flows with large temperature fluctuations, there can be significant seed biasing errors in the LDA data due to the large density gradients.

b. Unbiased LDA Data - On an APL contract with Purdue University, Stevenson and Thompson proposed and verified a constant time interval sampling approach for providing unbiased LDA data. One difficulty with this approach is that high seeding rates are required to insure that seed particles pass through the measurement volume at regular time intervals. Recently, Craig, et al. at APL demonstrated a solution to this problem by using a chemical seeder in which $TiCl_4$ and moisture are reacted to produce micron sized TiO_2 seed particles at very high data rates (20,000/s) and long operating times (hours). To illustrate this approach, Fig. 4 shows the integrated mass/flux at different axial locations in a nonreacting axisymmetric dump combustor where the LDA data were collected randomly. Note that the mass is not conserved, whereas in Fig. 5 where the chemical seeder and the constant time interval sampling rate are used mass is conserved.

c. Multi-Point Fluorescence - Two-dimensional (2-D) concentration profile of OH radical has been measured by laser induced fluorescence in an atmospheric pressure CH_4/air flame. The OH fluorescence shown in Fig. 6 was obtained by exciting (1,8) band and emission was observed in the (0,0) and (1,1) bands of A-X system. The sensitivity of this measurement was 500 counts, per mm^3 of flame volume, per J/cm^2 of photon flux, per ppm of OH. The 2-D spatial and temporal resolution of the measurements were 0.35 mm x 1.75 mm and 10 nsec, respectively. This work was performed at SRI by Dyer and Crosley (see References).

d. Photo Acoustic Spectroscopy (PAS) - The Photo Acoustic Spectroscopy, whose signal generation depends upon quenching rate, has been successfully used at the University of Arkansas to measure concentration of NO_2 (Tennel et al.) and OH (Rose et al.) in a CH_4/air flame. The detectivity of this technique was found to be 3×10^{13} OH molecules/cm^3 and 4×10^{13} NO_2 molecules/cm^3 using 300 μJ per pulse laser energy. The single photon PAS measurement provides good temporal resolution but it has poor spatial resolution.

e. Photothermal Effects - A variant of PAS technique, namely photothermal effect, has been exploited by Brecka et al. to measure relative OH concentration profile in a propane/air flame and temperature in methane/air flame. Figure 7 shows the OH concentration profile as measured by Photothermal laser beam deflection technique, are in good agreement with laser induced fluorescence measurement. The photothermal laser beam deflection technique provides measurements with good temporal and spatial resolution, as required for turbulent combustion studies.

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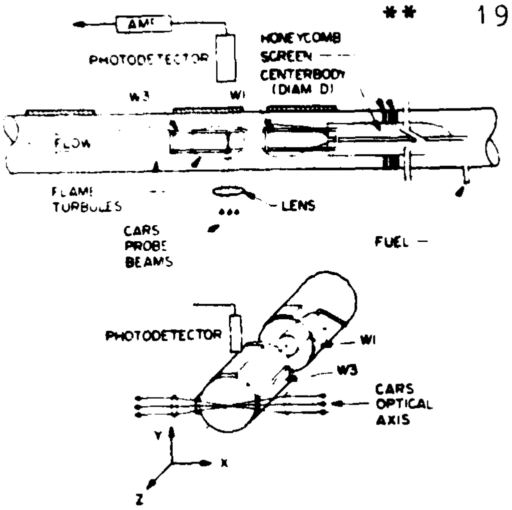

Figure 1. Schematic Diagram of the Combustor and the Optical Configuration Used to Make Simultaneous Flame-Luminosity and CARS-Temperature Measurements.

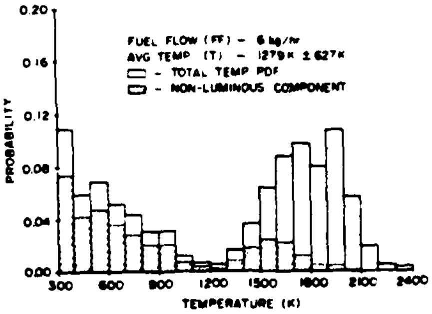

Figure 2. Conditionally Sampled Temperature PDF's at a Radial Location of 0.0 cm and Axial Location of 40 cm (2.86D) for an Annulus-Air Velocity of 23.3 m/s and Fuel-Exit Velocity of 69.6 m/s.

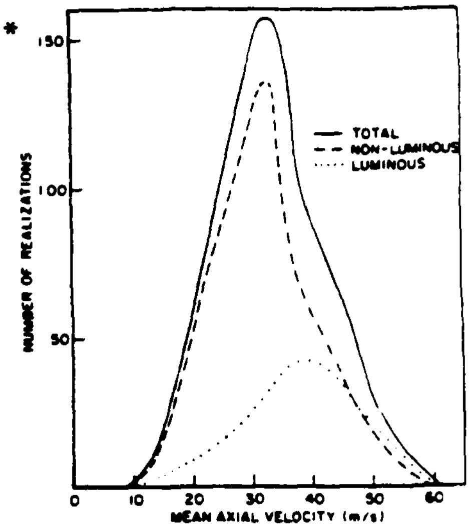

Figure 3. Distribution of the axial velocity measurements. The two distributions obtained by conditional sampling are shown with the total (unconditional) sampling distribution.

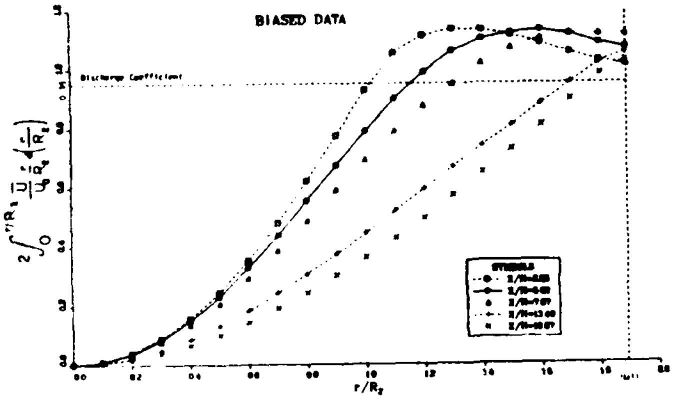

Figure 4. Integrated Mass Flux Profiles.

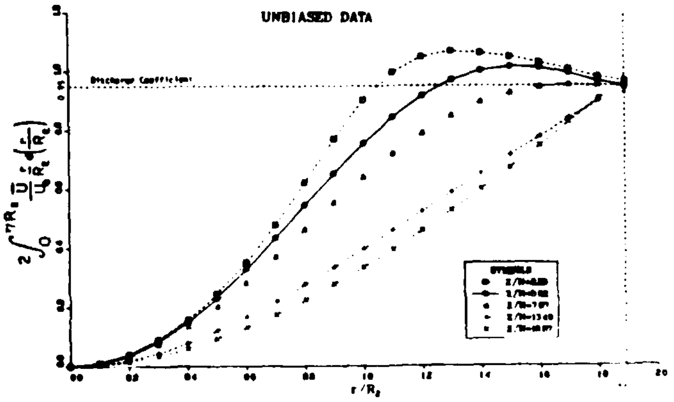

Figure 5. Integrated Mass Flux Profiles.

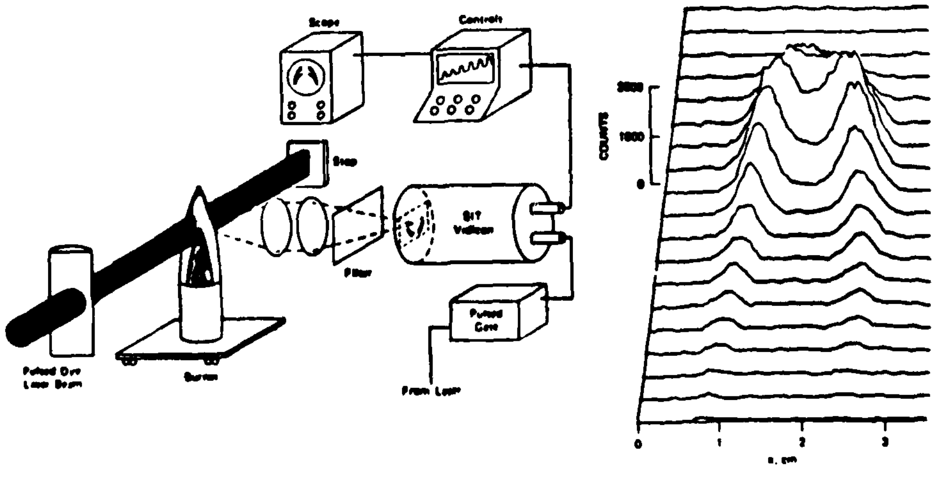

Figure 6. 2-D Measurements of Temperature and Concentration in a Flame.

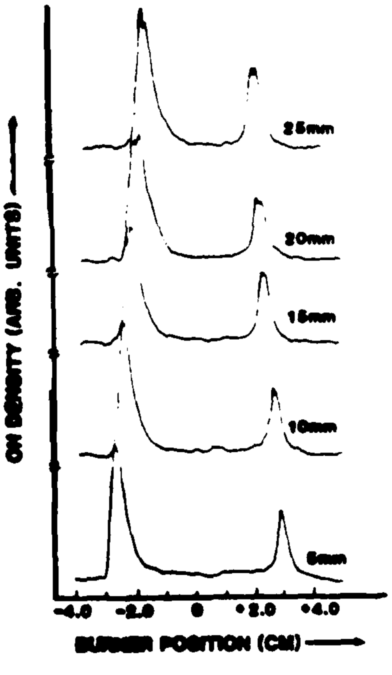

Figure 7. OH Concentration Profile.

TIME AND SPACE RESOLVED LASER DOPPLER VELOCIMETRY

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The use of Laser Doppler Velocimetry (LDV) systems to measure flow velocities has been well established. Current systems can accurately measure flow velocities in very small measurement control volumes. However they can provide only limited information about the nature of the measured flow. This is because the data collected in each set of measurements is for only one specific control volume and yields no information about neighboring points.

In the study of turbulent flows it would be desirable to measure velocity profiles. The one-dimensional LDV (1-D LDV) system is specifically designed to make measurements in turbulent flows and allows many successive scans of a cylindrical measurement control volume, which is 50 mm long and approximately 0.2 mm in diameter. The scan time is 1 ms with a spatial resolution of 0.4 mm. This system provides information in the form of nearly instantaneous velocity profiles with the ability to process many successive profiles. The final result is a finely resolved time history of velocity profiles.

The system itself is an expansion of the basic one point LDV system. A single color from an argon-ion laser is split into two parallel beams, one of which is then frequency shifted using a Bragg Cell. The beams are then spread into two 50 mm wide parallel sheets using cylindrical lenses. Another cylindrical lens is used to intersect the two beams. At the intersection of the two beams a cylindrical measurement control volume is formed (see Fig. 1). The scattered light from this control volume passes through six spherical lenses where it is focused down into a half size image. In the focal plane of this image is a rotating slotted disc, which rotates at a speed such that the scan time for a slot to pass through the control volume is 1 ms. The slot width is 0.2 mm which determines the spatial resolution. The light, which passes through the slot and contains the velocity information, is then focused into the aperture of a photo multiplier by a pair of spherical lenses.

There are two separate data acquisition systems currently under development. The first system uses acousto-optic techniques to demodulate and display the velocity information from the photo multiplier (see Fig. 2). This work is based in part on earlier work done at CMU by Sommer, Hemmerle and Mosula [1], and by Schnettler [2]. The photo multiplier output runs into a Radio Frequency (RF) amplifier which drives a Bragg Cell. The beam from a low power He-Ne laser is passed through this cell at the Bragg angle. The output of the cell is two beams, an undeflected one which serves as a reference and a deflected beam whose degree of deflection is proportional to the frequency input of the Bragg Cell and consequently to the velocity of the measured flow. A second Bragg Cell driven by a voltage controlled oscillator (VCO) produces the horizontal deflection. The VCO is controlled by a sawtooth voltage wave which is synchronized to the sweeps of the slotted disc. The deflected beam is then focused on a screen where it sweeps much like the time based of an oscilloscope. The data is then recorded either photographically or with a digital camera.

The second system takes the photo multiplier output and uses a custom designed phase locked loop (PLL) to demodulate the signal. The PLL puts out a voltage which is proportional to the frequency input and thus velocity. This output is recorded using a digital oscilloscope and stored on a floppy disc for later analysis.

System design is completed, transmitting and receiving optic systems and the acousto-optic demodulation data analysis systems have been individually tested. The digital output data acquisition system has been preliminarily tested and is being debugged. The rotating disc, permanent lens mounts, and optic bench are now being fabricated. Computer programs to record and store the data are being written, and a computer program to determine optimum particle seed and material is under development.

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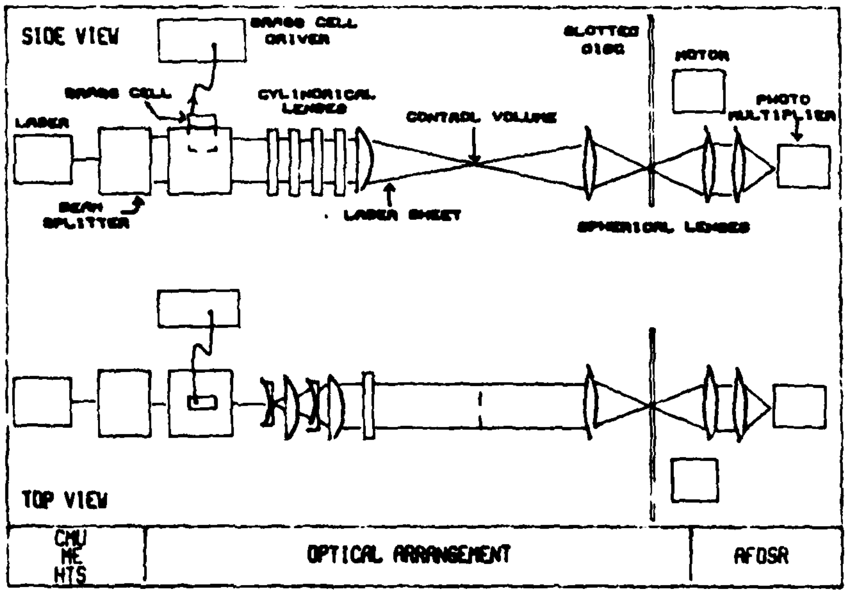


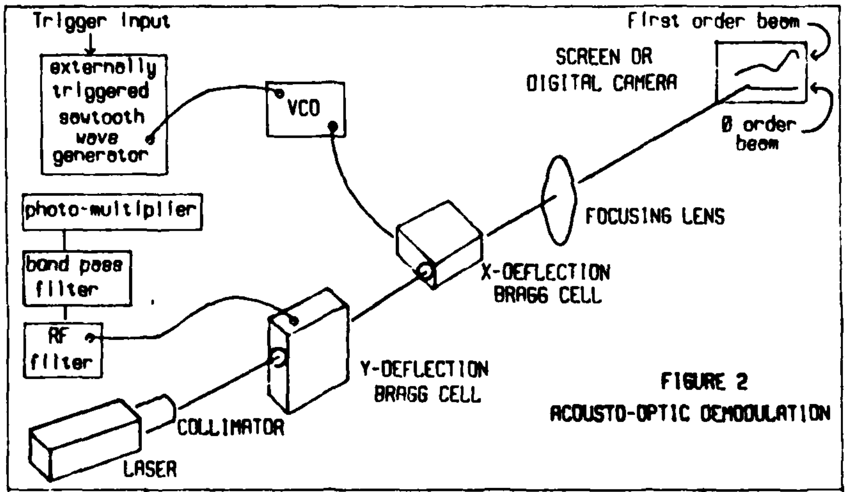
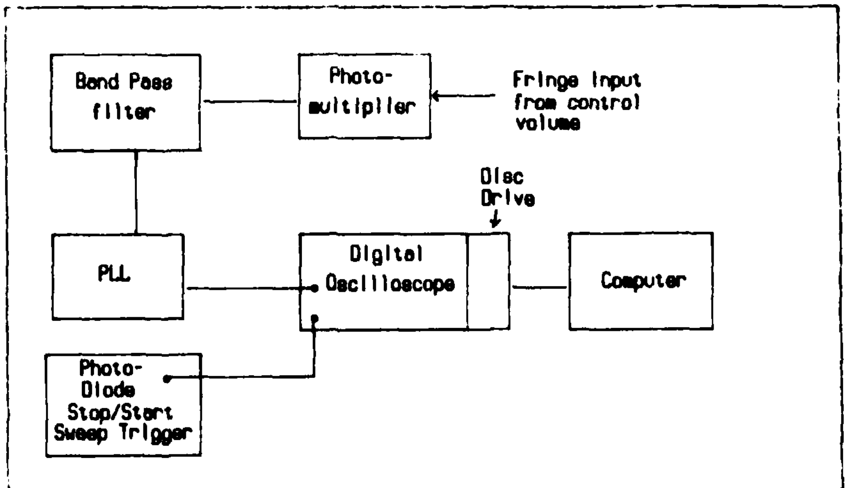


FIGURE 2
ACOUSTO-OPTIC DEMODULATION

C-MU ME HTS	ACOUSTO-OPTIC DEMODULATION	AFOSR 82-256 14



C-MU ME HTS	FIGURE 3: ELECTRONIC DATA AQUISITION	AFOSR 82-266 15

OVERVIEW: AFOSR INTERESTS IN DIAGNOSTICS OF REACTING FLOW

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The Air Force sponsored basic research program which provides new diagnostic techniques for the advancement and understanding of reacting flows (now in its fourth year) is being assessed. The national attention on laser-based techniques is rapidly achieving many "first-ever" measurements, for both laboratory and bench-test conditions. Research on these techniques has momentum and effective advocates; the successes will continue with the increasing capability (and availability) of lasers, detectors, digital electronics, fiber optics, etc. Indeed, technique advancements are integral goals of several of the AFOSR sponsored combustion research programs.

To insure major advancements, the investigators are being asked to consider the new research which will enable the diagnostics and sensing techniques of the 1990's. The funds supporting the research (summarized in this meeting) are only for techniques research not for research applications of the techniques; thus, we must identify and pursue the next set of diagnostics and sensing challenges.

The emphasis of the first two years was on combustion processes; recent programs are addressing plasma and laser flows.

Present and future propulsion, power, and laser systems present critical challenges not addressed adequately by present technologies. Ample opportunities exist for new approaches, e.g.,

--High performance systems often frustrate attempts to gain optical access. Non-optical, non-intrusive approaches are needed.

--The advent of quantitative flow visualization for turbulent reacting flows has not been accompanied by corresponding theoretical treatments to fully exploit array data, capable of revealing rapid evolution of flow structure, flame fronts, and instabilities.

--The anticipated requirements for adaptive control and for autonomous operation require major advances in sensing strategies, sensors, and diagnostics. For example, approaches suitable of probing laboratory burners are unlikely to be applicable to operational engines. Configurational constraints tend to limit options to global (or to limited spatial resolution) observations. Data acquisition and processing must be consistent with real-time strategies for seeking optimal performance under changing operational conditions, for sensing malfunctions, etc.

--Optical diagnostics should lead to new approaches for investigating plasma flows which must be understood and controlled under magnetoplasmadynamic and beamed energy thruster conditions. The research on life limiting processes which occur at the surfaces of electrodes, electrical insulators, and refractories will benefit from advances in remote sensing of surface temperatures, composition, and structure.

We welcome discussion on these and other topics pertinent to the Air Force basic research program.

DIAGNOSTICS OF REACTING FLOW RESEARCH GOALS

GENERAL GOALS: Research in support of energy conversion is directed at providing a fundamental basis for a new generation of concepts and improving the scientific understanding of the associated phenomena. Research is needed from molecular to macroscopic scales in areas which include plasma acceleration, dynamics of combustion, the behavior and synthesis of advanced energetic materials, characteristics of exhaust plume formation and radiation, and the dynamics of advanced propulsion and power concepts. Every aspect of energy conversion research will benefit from advancements in diagnostic techniques.

SPECIFIC GOALS:

The following topics summarize many of the current goals which are being addressed by the ongoing research programs.

Noninterfering Diagnostic Techniques To make major advancements in noninterfering diagnostic techniques for measuring the gas and gas/particle flow properties representative of rocket systems including plumes. To improve understanding of the factors involved in sensing and detecting the chemical and physical properties related to rocket flow systems. To quantify characlersitics of candidate techniques and to define their respective zones of applicability for propulsion combustion systems.

Kinetics of Multicomponent Condensation To achieve methods of performing quantitative measurements for polydispersed gas/particle systems so that the influence of composition and flow environment on particle formation and growth characteristics and particle size distribution can be investigated.

Energy Exchange Rates To achieve a methodology for remotely measuring transient species concentrations in exhaust plumes so that emission and absorption contributions associated with nonequilibrium processes can be isolated.

Chemical Kinetics for Reacting Flows To quantify candidate approaches for determining the spatial and temporal distribution of important species so that rate processes can be measured. Attention is to be given to multi-dimensional turbulent flows.

Combustion To explore methods for obtaining rate data for solid and liquid energetic materials being heated at rates in excess of 10^5K/sec.

Combustion Instability To investigate methodologies for measuring the acoustic level excitations of velocity, pressure, and temperature components in multi-dimensional, unsteady reacting flows. To quantitatively visualize multi-phase flow and condensed phase breakup for the purpose of understanding the role of transient processes on acoustic energy gains or losses.

1984 AFOSR RESEARCH MEETING ON DIAGNOSTICS OF REACTING FLOWS
AUTHORS - ABSTRACTS & PRESENTATIONS

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