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Pasadena, California 91125

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Dimotakis, P. E., Lang, D. B., and Miake-Lye, R. C.

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

The design and technical capabilities of the following systems are described:

(1) Copper Vapor Laser pulsed light source with spatial filter and collimator
(2) Proximity focussed diode intensified linear CCD camera
(3) High speed multiplexed Analog to Digital Conversion system
(4) Monochromator system for point or line imaging of chemiluminescence

This instrumentation has been assembled to exploit several nonintrusive optical techniques to make measurements in a wide range of turbulent flows.

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1.0 Introduction

The equipment purchased under this grant has been chosen to permit a variety of non-intrusive optical measurements to be made in a wide range of turbulent flows. The primary , but not exclusive, measurement technique to be implemented was Rayleigh scattering, imaged along a line as a function of time. A slightly modified version of the same apparatus was to be used in performing scattering measurements or (liquid-phase) laser-induced fluorescence measurements with the same temporal and spatial resolution capabilities. A second technique was to make use of a monochromator to analyze, and possibly image, chemiluminescence in a reacting flow in a wavelength-specific fashion, either at a point or along a line. The light source, the detection systems, and the data acquisition systems assembled under this funding will each be described, ~~in the following.~~

2.0 Copper Vapor Laser (CVL)

A 40 Watt average power copper-vapor laser (Plasma Kinetics model 451) serves as the light source for the Rayleigh scattering system. Its short pulse width (~ 40 ns) and high repetition rate (1kHz to 6kHz) will allow freezing in time for virtually any flow and essentially continuous sampling of the scattered intensity for low Mach number flows. Despite the improvement realized in choosing the unstable resonator optics, the beam quality of the large Fresnel number, moderate gain resonator was quite poor. The far field beam contained significant amounts of power in strongly diverging modes (over 100 times diffraction limited).

This required the design of a spatial filter system (see Figure 1) that could withstand the high peak power density of the focussed beam (albeit at the expense of transmitted power). By using a long focal length telescope objective (antireflection coated achromat) and a high melting point metallic pinhole, the power density and pinhole properties were kept to levels that were technically feasible. The diameter of the beam at the pin hole (focal point) is approximately 1mm. However, the long path lengths involved required folding this optical system with stably mounted, antireflection coated mirrors which placed the spatial filter telescope beneath and parallel to the laser cavity.

The divergence of the final output of the system is slightly greater than 10 times diffraction limited. The output diameter can be chosen to have one of several values between 2 and 10 mm. Using Gaussian beam properties, the collimated beam can be focussed to a pencil of light which has a waist length proportional to the square of the waist size. (For a 10 times diffraction limited beam, a 2 mm beam would remain collimated over almost 60 mm.)

3.0 Intensified CCD Array

The advantages of CCD (charge coupled device) technology made apparent the choice of a linear CCD array for the line-based Rayleigh detector. The high speed (up to 12 - 20 MHz clock rate), the large dynamic range (7500:1), and high sensitivity allow greater flexibility in designing the detection and data aquisition systems compared to competing technology. Additional advantages of the linear detector chosen (Fairchild CCD134) include a blanking capability to reduce noise between laser pulses and enhanced spectral response in the CVL wavelength region.

Even accounting for the sensitivity of the CCD detector, the calculated scattered intensities for the anticipated Rayleigh scattering gases fell below that required for shot noise limited signal-to-noise ratios. Thus an optical intensifier stage was specified to be mated with the CCD detector using fiber-optic coupling. The restrictions imposed on the intensifier by the repetition rate of the CVL light source precluded the use of very high gain microchannel plate (MCP) intensifiers, but proximity focussed diode intensifiers still provide sufficient gain to be advantageous while allowing 6 kHz repetition rates at the expected photon fluxes.

A special order proximity focussed diode intensifier (F4140) was purchased from ITT Electro Optics. This vendor also did the mating of the intensifier to the CCD array. The intensifier stage was optimized in gain and spectral response (at input and output stages) for this particular application. A sensitive-alignment camera was designed and built to house the intensifier, array, and local electronics. With an aspect ratio of 1000:1, it is clear that the angular alignment of the detector to the laser beam must be to sub-milliradian accuracy. A Power Designs (model 1543A) high voltage power supply was purchased to supply very clean high voltage to the intensifier so that noise would not be introduced at the most sensitive stage.

4.0 Computer Data Acquisition System

The analog-to-digital conversion (ADC) system will allow the retrieval and storage of the CCD output. The CCD has two channels of output which must be clocked out at rates exceeding 6 MHz (net data rate) to make full use of the CVL source. To encode these two streams of output values with 8-bit resolution requires a multiplexed ADC capable of at least 3 MBytes/s per channel. Even so, only the constraints of the CVL are limiting thus far, since the CCD can be clocked at rates exceeding 12 MHz (net).

Thus a 4-channel multiplexed ADC system is currently under development (see Figure 2) around four parallel 8-bit flash converters. The multiplexing will be done digitally after conversion, assembling 32-bit words from a selection of the flash converters which will then be written to 32 MBytes of high speed memory for storage. The communication between the ADC board and the high speed memory (and also a computer controlling the entire experiment) will be through a VME bus, an industry standard high speed computer architecture.

An interface controlling the CVL and the CCD detector system will also reside on the VME bus, integrating the timing of laser pulses and data acquisition. The CVL pulses must be maintained both between data collection to control the CVL temperature and during data collection to synchronize pulses and detector integration times. This interface will supply the several clock signals required to sensitize the CCD array and clock out the two channels of data. An interim upgrade of the existing ADC system has also been completed, permitting data rates up to 3.5 MBytes/s, for a total of ~ 4 MBytes.

5.0 Monochromator

A versatile monochromator system was purchased (Instruments SA model HR 320) to allow several spectrally sensitive techniques to be implemented. Gratings were chosen to permit visible and near infrared wavelengths to be chosen. The optical features of this monochromator include a low f-number (4.4) for good light throughput, variable entrance and exit slits to allow selection of resolution and range, and two output windows. One of the output windows (selectable with the placement of a mirror) sends the monochromatized beam to a low dark current, broad flat response photomultiplier tube (RCA 31043) to measure the radiation emitted from the imaged region as a function of time. If the spatial distribution of the emitted radiation is of interest, the second output window can be selected.

The second window, originally intended by ISA to be a spectrograph port, will be used in different fashion here. Instead of aligning a linear detector along the spectrum as a spectrograph, the CCD detector will be aligned vertically to permit spectrally sensitive linear imaging. The detector will then be parallel to the input slit, the image of which will fall on the detector. Thus spatially resolved imaging of reaction luminosity or scattering can be performed where the spectral region is defined by the grating and slit combination.

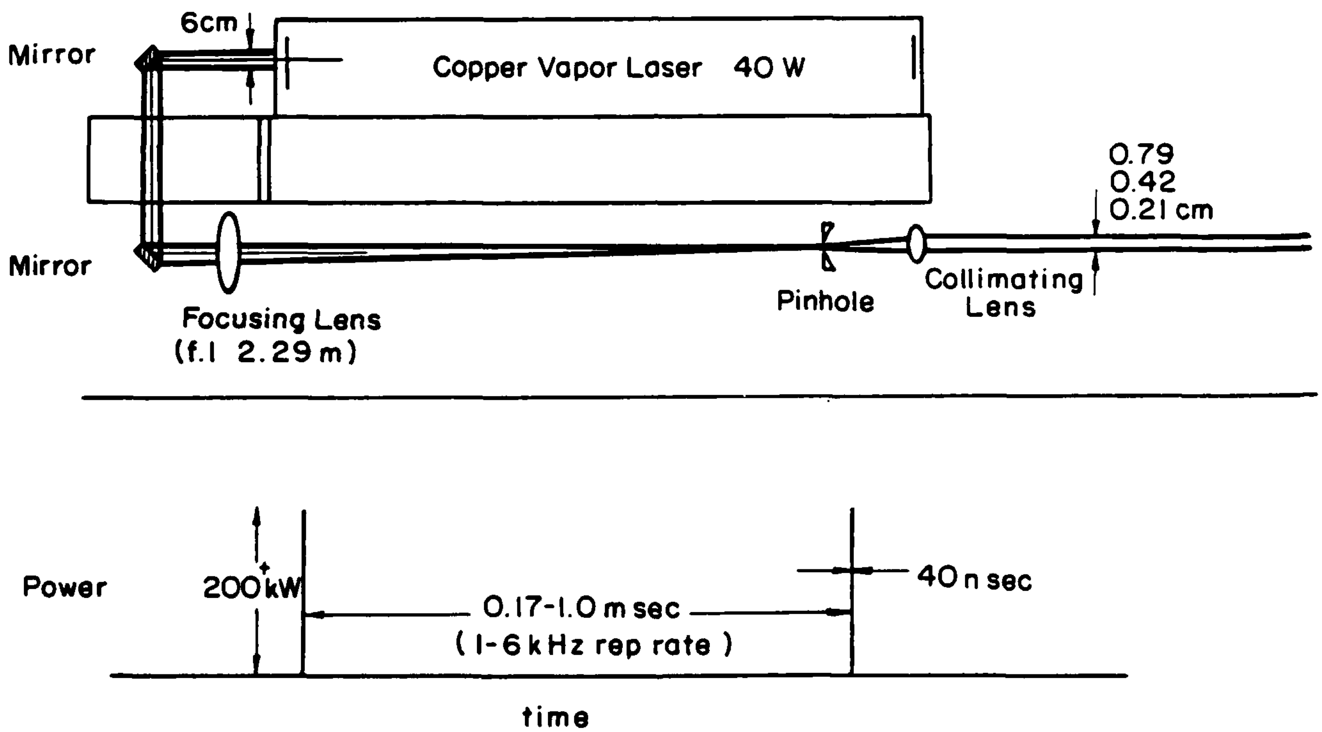

Figure 1. Copper Vapor Laser with folded Spatial Filter System

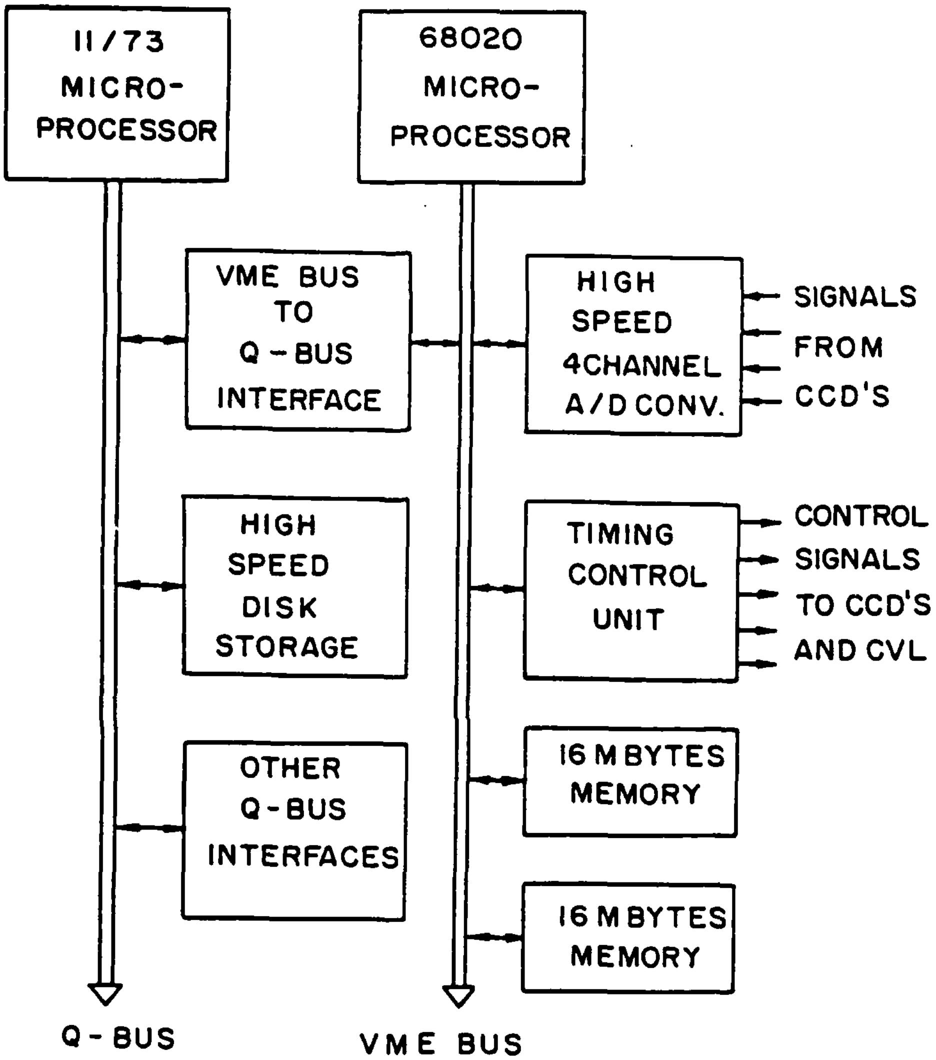

Figure 2. High Speed 4-Channel Multiplexed Analog-to-Digital Conversion System

APPENDIX

The following personnel were involved in designing, procuring, and implementing the various systems described in this report:

Dr. P. E. Dimotakis - Professor of Aeronautics and Applied Physics

Dr. D. B. Lang - Engineer, Aeronautics

Dr. R. C. Miake-Lye - Senior Research Fellow, Aeronautics

The curricula vitae of these researchers are appended on the following pages.

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Full name & title: 24-Sep-87

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Paul Emmanuel DIMOTAKIS [redacted]
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Honors/distinctions:

date	description	Institution
Jun 64	Delta prize	Athens College
Jun 68	George Green Memorial award	Caltech
Nov 80	Elected Fellow	Am. Phys. Society
Apr 87	Survey Paper Citation (Ref. #31)	AIAA

Educational Experience:

date	degree	Institution
Jun 64	Gymnasium diploma	Athens College
Jun 68	B.Sc. Physics (honors),	Caltech
Jun 69	M.Sc. Nuclear Engineering,	Caltech
Jan 73	Ph.D. Applied Physics,	Caltech

Professional Experience:

dates	position	Institution
Jan 73 Jul 75	Research Fellow, dept. of Aeronautics	Caltech
Jul 75 Jun 81	Assistant Professor, Aeronautics and Applied Physics	Caltech
Oct 75 Jan 76	Visiting Research Scientist (on leave from Caltech)	Democritos Res. Center (Greece)
Sep 76 Nov 81	Member, Advisory Committee on Science and Technology	Greek government
Jul 81 Dec 85	Associate Professor, Aeronautics & Applied Physics	Caltech
Jan 86 present	Professor, Aeronautics & Applied Physics	Caltech

Courses taught:

dates	description	Institution
Nov 75	Infra-Red Engineering	Office Naval R&D Greece
Jan 76 Jun 78	Experimental methods (graduate lecture/lab course on modern experimental methods)	Caltech - Ae104
Sep 78 Jun 80	Quantum Physics (Quantum Mechanics & applications)	Caltech - APh50
Sep 80 Dec 83	Case Studies in Engineering	Caltech - Ae107
Apr 84 Jun 84	Turbulent Shear Flows	Caltech - Ae239
Sep 84 Jun 86	Fluid Mechanics	Caltech - Ae/APh101
Sep 86 present	Experimental Methods	Caltech - Ae/Aph104

Research interests/experience:

1. Turbulent mixing, chemically reacting flows and combustion.
2. Compressible/incompressible turbulent shear flows.
3. Cryogenic fluid mechanics, heat transfer and instrumentation.
4. High energy/chemical lasers.
5. Aero/hydrodynamic noise.
6. Adaptive feedback control of turbulent shear flows
7. Advanced diagnostic techniques in fluid flow, including:
   a. Laser Doppler Velocimetry
   b. Ultrasonic velocimetry
   c. Particle streak velocity field measurement
   d. Rayleigh scattering
   e. Laser induced fluorescence
   f. Digital image acquisition and processing
8. Computer aided Engineering, Design & Manufacture.

Consultant to:

dates	Company/Institution	Location
Mar 70	Meteorological Res. Institute (RPV auto pilot)	Altadena California
Jan 73 Dec 80	TRW Systems Group (High Energy Lasers)	Redondo Beach California
Apr 75 Jun 75	Tech Mate (Laser instrumentation)	Torrance California
Jun 77 Aug 77	Naval Construction Battln. Center (Low Reynolds number drag measurements)	Port Hueneme California
May 78 Apr 79	Thermo-Electron (Advanced projects, Comptng. Equip.)	Boston Mass.

Consultant to

Mar 79 Mar 80	Science Applications, Inc. (Laser instrumentation)	La Jolla California
Oct 79 Jul 80	Lockheed (Advanced Instrumentation)	Burbank California
May 80 Jul 80	Jet Propulsion Laboratory (transonic flow, upper wing surface pressure loading)	Pasadena California
Jun 80 Oct 80	Tandon (computer disk aerodynamics)	Los Angeles California
Jun 80 Dec 80	Poseidon Research (Instr. for oceanographic meas.)	Los Angeles California
Nov 80 May 81	Science Applications (Drag reduction in turbulent boundary layers)	La Jolla California
Jun 81 Dec 81	Jet Propulsion Laboratory (hydraulic noise)	Pasadena California
Jun 82 Apr 83	WED (Disney) enterprises (Laminar jets)	Glendale, Calif. EPCOT, Florida
Oct 83 present	Garrett Pneumatic (Analysis of advanced technology combustor)	Phoenix Arizona
Mar 84	Taylor Instruments (Capacitance calculations for pressure transducer)	Los Angeles California

Publications:

1. P. E. DIMOTAKIS [Oct 1968] "OGO-C Orientation Study", Space Radiation Laboratory Internal Report, California Institute of Technology.

2. P. E. DIMOTAKIS [Oct 1972] Supercritical Heat Flow in Helium II, Ph. D. thesis, California Institute of Technology.

3. P. E. DIMOTAKIS and J. E. BROADWELL [Nov 1973] "Local Temperature Measurements in supercritical Counterflow in Liquid Helium II", Phys. Fluids 16(11), 1787.

4. P. E. DIMOTAKIS [Dec 1973] "Rate Equation Analysis of Flowing Lasing Systems. Part I : Uniform Pumping", TRW Report 99994-6255-RU-00.

5. P. E. DIMOTAKIS [Nov 1974] "Gorter-Mellink Scale and Critical Velocities in Liquid Helium II Counterflow", Phys. Rev. A 10(5), 1721.

6. P. E. DIMOTAKIS, J. JIMENEZ-SENDIN [Nov 1974] "Velocity Measurements in the Transition Region of a Two-Dimensional Shear Layer", Bull. Am. Phys. Soc. II, 19, 1151.

7. P. E. DIMOTAKIS and G. L. BROWN [Dec 1976] "The Mixing Layer at High Reynolds Number : Large Structure Dynamics and Entrainment", J. Fluid Mech. 78(3), 535 (+ 2 plates).

8. P. E. DIMOTAKIS [May 1976] "Single Scattering Particle Laser Doppler Measurements of Turbulence.", Application of Non-Intrusive Instrumentation in Fluid Flow Research, AGARD-CP-193, 10.1-14 .

9. P. E. DIMOTAKIS and G. A. LAGUNA [Jun 1977] "Investigations of Turbulence in a Liquid Helium II Counterflow Jet." Phys. Rev. B. 15(11), 5240.

10. B. CANTWELL, D. COLES and P. DIMOTAKIS [Oct 1977] "Anatomy of a turbulent spot", Phys. Fluids 20(10.II), S291.

11. B. CANTWELL, D. COLES and P. DIMOTAKIS [Dec 1978] "Structure and Entrainment in the Plane of Symmetry of a Turbulent Spot." J. Fluid Mech., 87(4), 641.

12. P. E. DIMOTAKIS [Aug 1978] "Laser-Doppler Velocimetry, Momentum Defect Measurements of Cable Drag at Low to Moderate Reynolds Numbers", NCBC Report, Contract no. N62583/77-M-R541.

13. P. E. DIMOTAKIS and D. B. LANG [Sep 1977] "Signal Responsive Burst Period Timer and Counter for Laser Doppler Velocimetry and the Like", U. S. Patent No. 4,051,433.

14. P. E. DIMOTAKIS, D. J. COLLINS and D. B. LANG [Jul 1978] "Laser Doppler Velocity Measurements in Subsonic, Transonic and Supersonic Turbulent Boundary Layers", Third International Workshop on Laser Velocimetry, Purdue University, published in: H. D. THOMPSON, W. H. STEVENSON (eds.), Laser Velocimetry and Particle Sizing (Hemisphere Publishing Corporation, 1979).

15. K. KOENIG, A. ROSHKO and P. E. DIMOTAKIS [Nov 1978] "An Axisymmetric Cavity Flow", Bull. Am. Phys. Soc., 23(8), 995.

16. P. E. DIMOTAKIS, D. J. COLLINS and D. B. LANG [Jul 1979] "Measurements in the Turbulent Boundary Layer at Constant Pressure in Subsonic and Supersonic flow. Part II. Laser-Doppler Velocity Measurements", AEDC-TR-79-49.

17. M. M. KOOCHESFAHANI, C. J. CATHERASOO, P. E. DIMOTAKIS, M. GHARIB, and D. B. LANG [Dec 1979] "Two-point LDV Measurements in a Two-dimensional Mixing Layer." AIAA J. 17(12), 1347.

18. P. E. DIMOTAKIS, F. D. DEBUSSY and M. M. KOOCHESFAHANI [Jun 1981] "Particle Streak Velocity Field Measurements in a Two-Dimensional Mixing Layer." Phys. Fluids, 24(6), 995.

19. L. BERNAL and P. E. DIMOTAKIS [Sep 1981] "Streamwise Vortex Structure in a Plane Mixing Layer." 3rd Symposium of Turbulent Shear Flow (U. C. Davis), 9-11 Sep 1981.

20. E. DIMOTAKIS, R. MIAKE-LYE and D. A. PAPANTONIOU [Sep 1981] "Structure and Dynamics of Round Turbulent Jets", XV International Symposium of Fluid Dynamics, 7-12 Sep 1981 (Jachranka Poland), documented in Fluid Dynamics Transactions 11, 47-76 (1983), and (revised) in Phys. Fluids 26(11), 3185-3192 (1983).

21. D. B. LANG and P. E. DIMOTAKIS [Nov 1982] "Measuring Vorticity Using the Laser Doppler Velocimeter", Bull. Am. Phys. Soc. 27(9), 1166.

22. M. G. MUNGAL, P. E. DIMOTAKIS and J. E. BROADWELL [Jan 1983] "Turbulent Mixing in a Reacting Shear Layer.", AIAA 21st Aerospace Sciences Meeting, 10-13 Jan 1983, Paper AIAA 83-0473, published in AIAA J. 22(6), 797-800.

23. P. E. DIMOTAKIS, J. E. BROADWELL and R. D. HOWARD [Jan 1983] "Chemically Reacting Turbulent Jets.", AIAA 21st Aerospace Sciences meeting, 10-13 Jan 1983 (paper AIAA-83-0474).

24. P. E. DIMOTAKIS [Nov 1983] "Simultaneous Multi-Point Laser Measurements in Turbulent Flow", Bull. Am. Phys. Soc. 28(9), 1401.

25. DAHM, W. J. A., DIMOTAKIS, P. E. and BROADWELL, J. E. [1984] "Non-premixed turbulent jet flames", AIAA 22nd Aerospace Sciences Meeting (Reno, Nevada), AIAA Paper No. 84-0369.

26. MUNGAL, M. G. and DIMOTAKIS, P. E. [1984] "Mixing and combustion with low heat release in a turbulent mixing layer", J. Fluid Mech. 148, 349-382.

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28. KOOCHESFAHANI, M. M. and DIMOTAKIS, P. E. [1985] "Laser Induced Fluorescence Measurements of Mixed Fluid Concentration in a Liquid Plane Shear Layer", AIAA 22nd Aerospace Sciences Meeting (Reno, Nevada), AIAA J. 23(11), 1700-1707 (AIAA Paper 84-0198).

29. MUNGAL, M. G, HERMANSON, J. C. and DIMOTAKIS, P. E. [1985] "Reynolds Number Effects on Mixing and Combustion in a Reacting Shear Layer", AIAA J. 23(9), 1418-1423.

30. BROADWELL, J. E. and DIMOTAKIS, P. E. [1986] "Implications of Recent Experimental Results for Modeling Reactions in Turbulent Flows", AIAA J. 24(6), 885-889. (AIAA Survey Paper Citation).

31. KOOCHESFAHANI, M. M. and DIMOTAKIS, P. E. [1986] "Mixing and chemical reactions in a turbulent liquid mixing layer", J. Fluid Mech. 170, 83-112.

32. DIMOTAKIS, P. E. [1986] "Two-Dimensional Shear-Layer Entrainment", AIAA J. 24(11), 1791-1796.

33. HERMANSON, J. C., MUNGAL, M. G. and DIMOTAKIS, P. E. [1987] "Heat Release Effects on Shear Layer Growth and Entrainment", AIAA 23rd Aerospace Sciences Meeting 14-17 January 1985 (Reno, Nevada), AIAA J. 25(4), 578-583 (AIAA Paper 85-0142).

34. GONGXIN, S., MIAKE-LYE, R. and DIMOTAKIS, P. E. [1987] "A preliminary experimental investigation of turbulent jet mixing flow in high Sc number", Acta Aero. Sinica 5(1), 47-54.

35. DIMOTAKIS, P. E. and HALL, J. L. [1987] "A simple model for finite chemical kinetics analysis of supersonic turbulent shear layer combustion", AIAA/SAE/ASME/ASEE Joint Propulsion Conference Colloquium on Supersonic Combustion, 29 June - 2 July 1987 (San Diego, California), AIAA Paper 87-1879.

36. DAHM, W. J. A. and DIMOTAKIS, P. E. [1987] "Measurements of Entrainment and Mixing in Turbulent Jets", AIAA J. 25(9), 1216-1223.

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Education:

degree	date	Institution
B.S. Applied Physics (honors)	Jun 76	Caltech
M.S. Applied Physics	Jun 77	Caltech
Ph.D. Applied Physics	Nov 84	Caltech

Positions held:

Staff engineer, Aeronautics, Caltech, and System Specialist, CADRE (Computer Aided Design in Research and Education), Caltech	Jan 1985 - present
Research Assistant, Applied Physics, Caltech	1981-1984
Fannie and John Hertz Fellow, Applied Physics, Caltech	1976-1980
Physicist, O Group, Lawrence Livermore Laboratory	Summer 1976
Undergraduate Employee (part time), Caltech	1973-1976
Summer Employee, Onan Corp., Minneapolis, Mn.	Summer 1972,1973

Honors and awards:

Oral Deaf Adults Section Scholarship, Alexander Graham Bell Association for the Deaf	1972
Elected to Tau Beta Pi, Caltech Chapter	1976
The George W. Green Memorial Prize, Caltech	1976
The Fannie and John Hertz Fellowship	1976
William F. Ballhaus Prize, Caltech	1985

Research interests

1. Laser Doppler Velocimetry including vorticity in turbulent shear flows.
2. High speed computer data acquistion.
3. Low noise optical detector/amplifier subsystems.
4. Computer systems hardware design and development.
5. Computer software including plotting and text processing packages.
6. Maintaining computer systems including diagnostics and repair.

Patents:

1. Dimotakis, P.E. and Lang, D.B. 1977 Signal Responsive Burst Period Timer and Counter for Laser Doppler Velocimetry and the Like. U.S. Pat. No. 4,051,433 issued 27 September 1977.

Publications:

1. Marling, J.B. and Lang, D.B. 1977 Vacuum Ultraviolet Lasing from Highly Ionized Noble Gases. App. Phys. Lett. 31(3) 181-184.

2. Dimotakis, P.E., Collins, D.J. and Lang, D.B. 1979 Measurements in the Turbulent Boundary Layer at Constant Pressure in Subsonic and Supersonic Flow. AEDC-TR-79-49.

3. Koochesfahani, M.M., Catherasoo, C.J., Dimotakis, P.E., Gharib, M. and Lang, D.B. 1979 Two-Point LDV Measurements in a Plane Mixing Layer. AIAA J. 17(12), 1347-1351.

4. Lang, D.B., and Dimotakis, P.E. 1982 Measuring Vorticity Using the Laser Doppler Velocimeter. Bull. Am. Phys. Soc. 27(9), 1166, AD5.

5. Lang, D.B., and Dimotakis, P.E. 1984 Vorticity Measurements in a Two-dimensional Shear Layer. Bull. Am. Phys. Soc. 29(9), 1556, DH5.

6. Lang, D.B. 1985 Laser Doppler Velocity and Vorticity Measurements in Turbulent Shear Layers. Ph.D. Thesis, Caltech.

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1978-1984	Applied Physics Department
	Advisor: Sebastian Doniach
	Co-advisor: Keith O. Hodgson; Chemistry
	'Anomalous X-ray Scattering as a Probe of Biological Structure'
B.Sc.	California Institute of Technology
1974-1978	Physics Department
	Advisor: James E. Mercereau
	Senior Thesis Advisor: Paul E. Dimotakis
	'Laser Induced Fluorescence Measurements of the Turbulent Jet'

Honors

1978	Graduation with Honors
1978	Caltech nomination for the Apker Award (American Institute of Physics undergraduate research award)
1977-1978	Caltech Prize (Merit) Scholarship
1975-1977	Honor Standing at Caltech
1974-1978	Martin Marietta Corporation Scholarship
1974	Lancers Boys' Club Scholarship

Professional Affiliations

American Association for the Advancement of Science
American Physical Society
Sigma Xi

30 April 1987

Professional Experience

1987-present	Senior Research Fellow; Aeronautics, California Institute of Technology; Pasadena, California
1984-1986	Research Fellow; Aeronautics, California Institute of Technology; Pasadena, California
Spring 1983	Instructor, Introductory Physics; Physics Department, San Jose State University; San Jose, California
1978-1984	Research Assistant; Applied Physics Department, Stanford University; Stanford, California

Publications

1. R.C. Miake-Lye and S.J. Toner (1987) 'Laser soot-scattering imaging of a large buoyant diffusion flame' *Combust. Flame*, *67*, 9-26.

2. G.-X. Shen, R. Miake-Lye, and P.E. Dimotakis (1987) 'A preliminary experimental investigation of turbulent jet mixing flow in high Sc number' *Acta Aerodynamica Sinica*, *5*, 46-54.

3. R.H. Fairclough, R.C. Miake-Lye, R.M. Stroud, K.O. Hodgson, and S. Doniach (1986) 'Location of terbium binding sites on acetylcholine receptor-enriched membranes' *J. Molec. Biol.*, *189*, 673-680.

4. R.C. Miake-Lye (1984) 'Anomalous x-ray scattering as a probe of biological structure' Ph.D. thesis, Applied Physics, Stanford University.

5. P.E. Dimotakis, R.C. Miake-Lye, and D.A. Papantoniou (1983) 'Structure and dynamics of round turbulent jets' *Phys. Fluids*, *26*, 3185-3192.

6. R.C. Miake-Lye, S. Doniach, and K.O. Hodgson (1983) 'Anomalous x-ray scattering from terbium-labeled parvalbumin in solution' *Biophys. J.*, *41*, 287-292.

7. R.C. Lye, J.C. Phillips, D. Kaplan, S. Doniach, and K.O. Hodgson (1980) 'White lines in L-edge x-ray absorption spectra and their implications for anomalous diffraction studies of biological materials' *Proc. Natl. Acad. Sci. U.S.A.*, *77*, 5884-5888.

30 April 1987