OCT 10 1991

DIAGNOSTIC INSTRUMENTATION AND ANALYSIS LABORATORY

**DIAGNOSTIC DEVELOPMENT AND SUPPORT
OF MHD TEST FACILITIES**

**Technical Progress Report
for the period
April, May, June 1990**

**Prepared for the United States
Department of Energy
Under Contract No. DE-AC02-80ET-15601**

FE-15601-41
Dist. Category UC-90g

DOE/ET/15601--41

DE92 000633

DIAGNOSTIC DEVELOPMENT AND SUPPORT
OF MHD TEST FACILITIES

Technical Progress Report
for the period
April, May, June 1990

W. S. Shepard, Director
R. L. Cook, Deputy Director

Diagnostic Instrumentation and Analysis Laboratory
Mississippi State University
Mississippi State, Mississippi 39762

Prepared for the United States
Department of Energy
Under Contract No. DE-AC02-80ET-15601

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

TABLE OF CONTENTS

List of Figures	iv
List of Tables	vi
Abstract.	1
Project Objectives.	2
Project Description	5
Description of Facilities	30
Technical Progress.	31
Task 1. Instrumentation Development	32
A. <i>Coherent Anti-Stokes Raman Spectroscopy</i> <i>System (CARS)</i>	32
B. <i>Particle Size Distribution System (PSD)</i>	41
C. <i>Potassium Emission/Absorption System (PE/AS).</i>	42
D. <i>Intrusive Multi-Probe System (IMPS)</i>	62
E. <i>Faraday Rotation System (FRS)</i>	66
F. <i>Multi-Purpose Imaging System (MPIS)</i>	68
G. <i>Differential Absorption Laser</i> <i>Spectroscopy System (DALAS)</i>	71
H. <i>Laser Optogalvanic Spectroscopy</i> <i>System (LOGS)</i>	74
I. <i>Cross Correlation System (CCS).</i>	75
Task 2. Test Stand Operations.	76
A. <i>Test Stand Modifications.</i>	76
B. <i>Test Stand Runs</i>	76
Task 3. Technical Support for National MHD Program	78
A. <i>Field Measurements.</i>	78
B. <i>Field Tests/Instrument Modifications.</i>	82
C. <i>Field Operation/Developing Systems.</i>	94
Task 4. Project Management	95
Task 5. Technology Transfer.	96

LIST OF FIGURES

1.A.1.	Temperature profile of DIAL test stand with folded BOXCARS phase matching geometry.	.33
1.A.2.	N ₂ CARS spectrum taken 4 in. from the gas stream center at DOE/CFFF during the LMF4-T test (T=2673K)	.36
1.A.3.	Temperature profile at DOE/CFFF diffuser with folded BOXCARS phase matching geometry	.37
1.A.4.	Temperature measurements at DOE/CFFF diffuser on three different nights.	.38
1.C.1.	Potassium Emission Absorption System (PEAS) measurement of gas temperature versus time for the CDIF CFC-15 test of 10-Aug-89	.43
1.C.2.	Potassium Emission Absorption System (PEAS) measurement of potassium number density versus time for the CDIF CFC-15 Test of 10-Aug-89.	.43
1.C.3.	Bias in the Planck blackbody ratio as a function of lamp- and detector-side window transmissivities for both the single wavelength and two wavelength methods.	50
1.C.4.	Bias in the Planck ratio as a function of combined window transmissivity for both the single wavelength and two wavelength methods assuming equal transmission losses for the windows.	50
1.C.5.	Plot of the lamp collection efficiency factor and optical depth bias versus misalignment between the centers of the lamp image and the tip of the light collection fiber.	.53
1.C.6.	Time averages and standard deviations for the lamp collection efficiency factor and the optical depth bias versus vibration amplitude for misalignment between the centers of the lamp image and the tip of the optical fiber.	.53
1.C.7.	Optical depth and statistical sample size for the averaged two wavelength temperature versus time for the CDIF CFC-15 test.	.56
1.C.8.	Measured averaged temperatures, single wavelength and two wavelength calculations, versus time for the CDIF CFC-15	56
1.C.9.	Measured averaged temperatures, single wavelength and two wavelength methods, versus the on-line optical depth for the MHD portion of the test.	57
1.C.10	Plot of the average measured temperatures, single wavelength and two wavelength calculations, versus the on-line optical depth for the first portion of the test.	57

1.C.11.	Average measured potassium number density, single wavelength and two wavelength calculation methods, versus time for the CDIF CFC-15 test.	60
1.D.1.	Deposit surface temperature measured during sootblowing	63
1.D.2.	Composite plot of deposit surface temperatures measured during insertions 33, 34, and 35.	64
1.F.1.	Laser-induced fluorescence image of K-seeded into a Bunsen burner (left) and the corresponding off resonance line background (right)	69
1.G.1.	Two-wavelength dye laser for Differential Absorption Laser Spectroscopy System (DALAS)	72
3.A.1.	Effect of the purge on mean axial velocity profile at second level in CFFF radiant furnace	79
3.A.2.	Effect of the purge on data rate.	81
3.B.1.	N ₂ CARS spectrum taken 4 in. from the gas stream center at DOE/CFFF diffuser during the LMF4-T test	84
3.B.2.	N ₂ CARS spectra taken at various points of the gas stream at DOE/CFFF diffuser during the LMF4-T test.	85
3.B.3.	Deposit surface temperature measured during sootblowing	92
3.B.4.	Composite plot of deposit surface temperatures measured during insertions 33, 34, and 35	93

LIST OF TABLES

1.C.1.	Notes for the 10-Aug-89 CDIF CFC-15 Test.	44
2.B.1.	Test stand runs, April - June, 1990	77
3.B.1.	ADP Surface Temperatures, June 2, 1990, Inserts 4-7	87
3.B.2.	ADP Surface Temperatures, June 2, 1990, Inserts 9-14.	87
3.B.3.	Insertions made on June 3, 1990	89
3.B.4.	Insertions made on June 9, 1990	90

ABSTRACT

The Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University (MSU) is developing diagnostic instruments for MHD power train data acquisition and for support of MHD component development test facilities. Microprocessor-controlled optical instruments, initially developed for Heat Recovery/Seed Recovery support, are being refined, and new systems to measure temperatures and gas-seed-slag stream characteristics are being developed. To further data acquisition and analysis capabilities, the diagnostic systems are being interfaced with DIAL's computers. Technical support for the diagnostic needs of the national MHD research effort is being provided. DIAL personnel will also cooperate with government agencies and private industries to improve the transformation of research and development results into processes, products and services applicable to their needs.

PROJECT OBJECTIVES

Diagnostic and special instrumentation beyond that which is normally required for appropriate control and operation of an electrical power production facility is required for a magnetohydrodynamic (MHD) power system. The DOE coal-fired MHD proof-of-concept program will serve as the precursor to larger scale demonstration facilities and commercially-implemented plants. In order that the transition to commercially feasible plant designs be made as quickly and as effectively as possible, it is essential to determine as much as possible about the detailed component operation of the MHD power train and the Heat Recovery/Seed Recovery system.

Conventional diagnostic sensors are of limited use in characterizing the MHD gas stream and special diagnostic instrumentation systems are needed to provide the means to monitor and collect engineering data to determine specific parameters, both baseline values and fluctuations, and to provide background information for continuing MHD development, solutions to technological barriers, and a basis for future plant designs. The accurate characterization of the thermal, chemical and flow properties is essential for future design optimization.

The scale-up process is a nonlinear extrapolation because many of the physical processes are nonlinear. To decrease the uncertainties in this nonlinear extrapolation to a new, larger design, it is necessary to rely not only on engineering experience with smaller systems, but also on mathematical models which describe the physical processes and the manner in which they behave as design variables are changed. Mathematical models require the input of detailed data; the greater the quantity and quality of data, the more accurate the model and the smaller the uncertainty in the extrapolation to larger designs.

The baseline data obtained by diagnostic measurements at the Component Development and Integration Facility (CDIF) and Coal-Fired Flow Facility (CFFF) are providing important engineering experience and data for developing appropriate analytical models. Tests of these models, as well as information to further develop these design models, will be provided by diagnostic measurements on these facilities. These measurements are essential to minimize the technological risks associated with the ultimate construction of a retrofit MHD facility or a commercial MHD power plant.

Moreover, measurements of selected parameters coupled with empirical correlations or an accurate model can contribute significantly to improved control strategies and the selection of control instrumentation. The direct measurement of a particularly useful parameter for system control may be very difficult, if not impossible. However, another parameter which can be correlated to the parameter of interest may be much easier to measure. The application of advanced instrumentation promises to produce fundamental advances in this area. This type of information will be very important in the selection of control instrumentation for a commercial MHD power plant.

MHD flows represent possibly the most severe environment encountered by gasdynamic diagnostics, and special state-of-the-art techniques and instrumentation systems are required to monitor and collect data for MHD component systems. In addition, these systems are operating under severe environmental and magnetic field conditions. The Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University is developing and applying advanced optical diagnostic techniques and instrumentation systems which provide nonintrusive, remote, real-time measurements and are designed to operate successfully in the industrial-like environment of large-scale facilities. Such diagnostic instrumentation can provide the information required to more clearly characterize the various processes involved in the ash/seed-laden gas stream of the coal-fired MHD flow. Moreover, these systems will provide performance monitors giving real-time indications of

- water leaks,
- nonuniformity in the K-seed,
- flow train discontinuities in the channel,
- flow distributions and turbulence levels,
- combustor performance, stoichiometry,
- proper operating conditions to optimize efficiency and component lifetime,
- the extent of ash rejection by the combustor,
- conductivity, generator performance,
- hot spots (e.g., in the radiant boiler),
- baghouse and/or electrostatic precipitator performance,
- heat transfer characteristics at critical locations,
- the particle loading and size distribution entering the boiler or other system components, and

- stack emissions, pollutant levels,

and will, therefore, further reduce the technical and financial risks associated with scale-up to the retrofit size integrated MHD/steam plant or to a commercial size plant.

Direct instrumentation support and measurements will be provided to the various DOE MHD test facilities. The amount of direct diagnostic support to the MHD engineering development test facilities will be as directed by the Department of Energy.

A number of the diagnostic systems which are fully developed will be used for field measurements at the HRSR and MHD power train facilities. Additional diagnostic systems previously developed are being constructed/modified to provide field-use instruments particularly for the MHD power train. Field tests for system refinements of these instruments will be conducted on the DIAL test stand and the various DOE MHD test facilities before proceeding with field measurements.

DIAL has constructed a test stand that can simulate the gas-slag-seed stream composition, temperature, and metal/fireside environmental conditions for the radiant furnace, superheater, and other MHD system components. The computer-controlled diagnostic instruments being developed are being evaluated and tested on the test stand. Measurements conducted on the test stand also provide useful data for the national MHD program.

PROJECT DESCRIPTION

In order to meet the overall contract objectives, the scope of work to be performed is outlined by the following tasks.

Task 1. Diagnostic Instrument Development

The following computer-controlled, optical diagnostic instrumentation is being developed for support of the MHD component engineering development. Objectives for the specific instrumentation systems follow.

1.A. Coherent Anti-Stokes Raman Spectroscopy System (local gas temperature and species concentration, temperature and concentration profiles)

The CARS system is a laser-based, nonlinear, optical technique being developed to provide temperature and species concentration measurements with spatial and temporal resolution. Of the many laser-based techniques, CARS is the best suited for thermometry in high-interference environments because of its coherent, laser-like signal character and high signal conversion efficiency. To obtain a CARS spectrum, two narrow band lasers at pump frequency ω_1 derived from the pump laser and one broadband dye laser at Stokes frequency ω_2 , are phase matched and focused in the gas stream thereby generating, through the third-order susceptibility of the medium, a spectrum at anti-Stokes frequency $\omega_3 = 2\omega_1 - \omega_2$. The CARS spectrum of a species (e.g. nitrogen) can be sensitive to both gas temperature and species concentration.

The mobile CARS instrument is ready for field tests. Based on these tests, a few minor modifications may be required. Field measurements are planned throughout the contract period at both CFFF and CDIF. Initially, point temperatures and temperature profiles from N_2 CARS spectra will be measured. Work on improving the capabilities of the present CARS system will also continue. This will include automation of the mobile CARS system. In particular, the CARS signal is focused to a 200- μ m core diameter, 0.12 numerical aperture optical fiber with an achromatic lens and is piped to the instrumentation trailer from the test environment. This coupling is very critical and needs to be remotely-controlled. In addition to temperature measurements, field measurements of species concentration

will also be made. For example, temperature and CO concentration can be measured simultaneously using the multiplexed CARS spectra of N₂ and CO. The combined N₂-CO CARS spectrum is then fit to a computer-simulated CARS model to extract the temperature and CO concentration. Work will continue on simultaneous N₂-CO CARS to determine the detection limits of this technique for CO concentration measurement in a particle-loaded gas stream.

Likewise, simultaneous CO₂, H₂ and O₂ concentration measurements in an MHD gas stream can supply the stoichiometry every 1-2 minutes which will enable one to monitor the performance of the combustor in real time. The Raman resonant frequencies of CO₂, H₂ and O₂ differ less than 200 cm⁻¹ and can be assessed simultaneously with a single dye laser. Therefore, temperature and the CO₂, H₂ and O₂ concentrations can be extracted from the simultaneous CO₂, H₂, and O₂ CARS spectrum. A computer model will be developed and tested to enable the determination of the simultaneous temperature and CO₂, H₂ and O₂ concentrations.

Particle-induced laser breakdown is known to produce a nonresonant CARS component which can affect the CARS measurement in a coal-fired flow. One way to alleviate this problem is to employ a two-wavelength dye laser CARS configuration to extract the temperature. Moreover, this technique produces a signal which is 20 times stronger than that of broadband CARS at the same laser power. This and other ways to reduce the effects of particles will be studied.

1.B. Particle Size Distribution System (particle size distribution)

The Particle Size Distribution System uses optical, in-situ, scattering methods for measurement of particle size distribution. The three-beam, two-color particle size measurement system is designed to measure particles at slow velocity using a single-particle counting method, while an ensemble averaging technique is used for high velocity flows. The system employs the output (green and blue) from an argon ion laser. The green beam is focused on the central axis and the blue beam is divided into two equal intensity beams which are focused and crossed inside the green measurement volume producing an interference fringe pattern. The light scattered from these beams by a particle is processed to extract the particle size.

A particle passing through a focused laser beam sample volume generates a Gaussian-shaped scattering signal. The peak amplitude, detected at small angles in the near forward scatter direction, is essentially a monotonic function of particle size and virtually independent of the particle refractive index and shape. The scattering signature is, however, dependent on the local sample volume intensity and, hence, the particle trajectory through the sample volume. Two techniques are presently being used to measure particle size -- the single particle counter (SPC) for low velocity flows and the ensemble averaging method (EAM) for high velocity flows. In the latter instrument the small-angle, near-forward scatter (SANFS) signals of the green beam are measured. To eliminate the nonuniformity of response within the sample volume, the measurement volume intensity variation is measured. With this response function, a mathematical inversion technique (termed deconvolution) is employed to extract the particle size distribution from the distribution of SANFS signal amplitudes.

In the case of the SPC instrument, two modes of operation are available, namely, the ripple-validated small-angle, near-forward scatter (RVSANFS) and the ripple deconvolution method (RDM). To reduce the trajectory ambiguity in the RVSANFS method, the single particle scattering signal from the central green beam is used to measure large particles (2-15 μm) with the ripple signal from the crossed blue beams used to validate the trajectory of the large particles and, hence, discriminate particles not near the central region of the green measurement volume.

On the other hand, for the RDM the amplitude of the ripple signal from the crossed blue beams is used to size particles smaller than 2 μm . In particular, the visibility parameter, obtained from the ripple and pedestal signal, is used to reject data from large particles, and the deconvolution method is applied to the scattering signals from the blue beams to remove the ambiguity caused by the trajectory dependence.

Expected activities include laboratory experimentation, operation on the MSU test stand, and operation in the field. Laboratory experimentation will be related to development of the EAM instrument and continual upgrading of the SPC instrument. It will also include development of calibration techniques and the production and evaluation of aerosols. Operation on the MSU test stand will primarily be done for development of the EAM instrument and development of techniques for use of physical sampling probes. Operation in the field will involve the SPC instrument until the EAM instrument is refined for field operation.

The overall objective is to improve the capability for measurement of particle size distributions by providing several alternate approaches that are feasible in various situations. Realization of this objective requires continual efforts to establish credibility that instruments are accurate and measurements are meaningful. This can only be achieved by continual attention to calibration methods and uses of alternate measurements, where possible, to supply corroborative data.

The particular objectives for the SPC are to finish construction of the system, to prove operation of the system in the field, and to refine the system for convenience in use and performance. Receiving fibers will be added to reduce the susceptibility to noise. Data will also be gathered for comparison of different modes of operation in the field environment; and, field measurements, to characterize the downstream components at the CFFF, will be conducted.

The specific objectives for the EAM are to prove the feasibility of the concept through experimental tests and incorporate this method into the field instrument. This will require continued theoretical and computational efforts to evaluate the parameters for the data reduction model; preliminary work on this is finished. Refinements will be needed as soon as the work is far enough along to justify them; these include the effects of lens aberrations, which will also require some experimental investigation.

Efforts will also begin on development of an experimental configuration for particle generation and laboratory measurements. Experiments will be conducted as soon as feasible on the test stand and, concurrently, field tests of the method will be made to define a suitable instrument package.

1.C. Potassium Emission / Absorption System (time - resolved temperature, K - atom density, electron density)

The Potassium Emission/Absorption System will rapidly measure (order of milliseconds) the average channel temperature by the line reversal technique, provide the average neutral potassium number density from lineshape information, and provide the average channel electron number density using the Saha equation assuming thermodynamic equilibrium.

This system has been field tested and is presently being used to provide time-resolved temperature and potassium number density measurements in support of the national MHD effort. Some software enhancement of the instrument is planned; however, the major issue to be resolved is the over estimation of the potassium number density. This is particularly important for wide gas streams and is believed to be caused by the line profile deviating from a Voigt shape in the far wings. Work to resolve this problem will continue.

1.D. Intrusive Multi-Probe System (optical temperature probes -- wall and gas temperature)

An Intrusive Multi-Probe System has been developed to position various sensors at a precise location in a combustion gas stream for precise increments of time. It is completely computer-controlled and may be operated to both position the probe and acquire the data. Optical sensors, as well as conventional sensors, can be used with this probe insertion system; however, its main use is with techniques where the probe will spend a very short period of time in the gas stream. Such a system interfaced with an optical technique can provide measurement capabilities in regions where, because of path length, optical measurements would not be possible.

Development and field testing of one viable intrusive sensor has been completed for the measurement of MHD interior wall surface temperatures. This sensor is capable of measuring surface temperatures in the range of 500°C to 2000°C. Field tests have been conducted at

the DOE/CFFF by measuring the front surface temperatures of the superheater tubes during several test runs; the interior wall surface temperature of the furnace has also been measured.

The development of an intrusive sodium line reversal (SLR) sensor, to be used with the multi-probe systems for measuring local gas stream temperatures, is about 60 percent complete. This system uses an intrusive miniature optics system and the SLR principle to make spatially-resolved gas stream temperature measurements. The SLR sensor will provide gas stream temperature measurements from 1700 to approximately 2500 K.

Because surface temperature measurements would usually be required at distances greater than five feet in the MHD power system, an optic system is being developed to add to the existing lightpipe sensor to provide greater intrusive distances. In general, intrusive distances much greater than five feet are not possible with this sensor when accessing surfaces through the standard four-inch ports. This optics/lightpipe sensor system will provide added flexibility and a useful monitor for the larger-scale MHD development systems.

With the equipment on hand the possibility of developing an intrusive, two-sensor system for measuring gas stream temperatures and wall surface temperatures appears to be very viable. This system would provide measurements of gas stream and wall surface temperatures in the range of 500°C to 2000°C and would be especially important for surface and gas temperatures measurements in the region of the superheater tubes in large-scale MHD development systems.

1.E. Faraday Rotation System (electron density to infer conductivity)

The Faraday Rotation System will provide real-time electron density measurements averaged across an MHD channel. The electrical conductivity scales very nearly linearly with the electron density. The technique is based on the Faraday effect. Linearly polarized light may be decomposed into right (+) and left (-) circularly polarized waves. Since the absorption coefficients and refractive index are different for right and left polarization, the amplitude and relative phase of the polarized waves are affected on passing through a plasma along a uniform magnetic field. Measurement of the rotation of the polarization of a beam of linearly polarized light after passing through a medium (plasma) in the direction of an applied magnetic

field determines the electron number density. The system employs radiation in the far infrared derived from a CO₂-pumped far infrared laser.

The Faraday Rotation System will provide, directly, the electron density and conductivity of the MHD channel which is essential to the characterization of the power train performance. Most of the major equipment for the system has been obtained. The system assembly for electron density and conductivity measurements on a laboratory plasma are basically complete. Electron mobility modeling and measurements will be addressed and system refinements, such as waveguides and detector vibration isolation for field tests, will follow. Field measurements will take place as soon as possible at CDIF; optical access through the channel side walls is necessary and would require new construction at the CDIF.

1.F. Multi-Purpose Imaging System (K-atom density, pressure profile)

The Multi-Purpose Imaging System is a laser-excited imaging system suitable for spatially-resolved optical diagnostics. The system is based on the phenomena of laser-induced fluorescence. Here an atomic or molecular species is raised to an excited electronic state by absorption of laser radiation. The emitted radiation when the species returns to the ground state is termed fluorescence. The instrument consists of a laser whose beam is expanded with cylindrical optics into a wide, thin sheet that is directed through the region of interest. A camera lens is then used to focus light emitted by this region onto a charge injection detector, the signal from which is processed by a computer to produce a two dimensional image of the probed region. The versatility of the system comes from the ability to select both the excitation and observation wavelengths to determine various parameters of interest, such as the concentration mapping of selected atomic and molecular species.

The Multi-Purpose Imaging System (MPIS) is an instrument currently in development which will allow measurements of species (K, Na, OH) concentration profiles in harsh combustion environments. The excitation intensity must be tuned to a resonance absorption with sufficient power that the fluorescence intensity is proportional to species concentration. In addition, measurements of number density and pressure profiles are possible, as well as temperature profiles using two-wavelength, excited-state fluorescence measurements. In

the case of pressure determinations, the excitation intensity must be above that required for level saturation; then the fluorescence intensity is proportional to the pressure.

Previous work has involved the construction of a laboratory-scale system and subsequent measurements of Na concentration images and K laser-induced fluorescence (LIF). The latter measurements have been complicated by collisional quenching, a process whereby the excited states decay non-radiatively. For example, K LIF at 404.5 nm has been observed but at a significantly reduced quantum efficiency as compared to Na. Saturation of the 404.5-nm K line is not possible without increasing the intensity level of the incident excitation wavelength. Addition of a wavelength extension unit (WEX) to the current optical train is planned since this will drastically increase the incident laser power by mixing the 1.06- μ m fundamental of the Nd:YAG laser with the low efficiency output of the dye laser in an appropriate crystal. Concentration measurements on K can then proceed. The determination of pressure profiles will begin with the construction of a variable pressure burner which will permit measurements as a function of known pressure. LIF measurements will then be performed to determine the limitations of the technique as applied to harsh environments.

Determination of the fluorescence at two wavelengths will allow the measurement of the populations of the excited species which, in turn, can be used to determine spatial temperature profiles of a region. In order to accomplish this task, an additional detector (camera) will be incorporated with an extended blue wavelength response. This detector will also permit the evaluation of OH fluorescence. Measurements on the MHD power train will require optical access. Access can be expected to be a problem, especially for image capture; therefore, a flexible, image transmitting fiber bundle will be added allowing the fluorescent or scattered laser light image to be routed to the camera which will be located away from the measurement penetration and clear of the upstream plumbing and structure.

The limitations and attributes of the system with respect to species concentration, pressure gradients, two wavelength temperature and number density measurements will be established and concurrently field tests with the system will be conducted. Results from these initial tests will be used to construct a stable, reliable field version of the instrument.

1.G. Differential Absorption Laser Spectroscopy System (species concentration, SO₂, NO₂, NO, H₂O, OH)

The Differential Absorption Laser Spectroscopy System is a general purpose, nonintrusive instrument for measuring time-resolved, line-of-sight average concentrations of atomic and molecular species. The system employs a two-wavelength dye laser and measures the extinction of the two wavelengths through the gas stream. One wavelength is on, and the other off resonance of the species of interest thereby eliminating particle absorption and scattering effects.

A general purpose system for measuring average concentrations of individual species (e.g. H₂O, SO₂, NO₂, NO, and OH) is desirable to complement the CARS system, which does not measure the concentrations of these species. Differential Absorption Laser Spectroscopy (DALAS) is a general purpose technique which can, in principle, be applied to any atomic or molecular species; and can be brought on-line by additions to the existing mobile CARS instrumentation. DALAS can also provide time-resolved concentration measurements when concentration fluctuations are of interest. DALAS uses methodology and technology developed over the past decade for Differential Absorption Lidar, a mobile, laser-based remote sensing technique for measuring the concentrations of pollutants in the atmosphere. To implement the technique, frequency doubling crystals, a detector, two boxcar averagers, and a control computer are required.

A DALAS experiment is performed by comparing the transmission of two wavelengths through the sample. One wavelength corresponds to a strong absorption of the species of interest. The other wavelength is a nearby wavelength that the species does not (or only weakly) absorb. Taking the ratio of the transmitted intensities of the two wavelengths "cancels out" background effects, such as light scattering

due to particulates, that are not associated with absorption by the species. If the absorption coefficient of the species is accurately known, or appropriate calibration experiments have been made, then the absolute concentration of the species can be determined.

The DALAS apparatus will use a single laser system to generate both wavelengths. An alternating two-wavelength dye laser pumped by the CARS Nd:YAG laser (10 Hz) will generate on alternate laser pulses the on-resonance wavelength (5 Hz) and the off-resonance wavelength (5 Hz). In particular, a rotating, rectangular optical block is used to refract the dye laser beam to independent, wavelength-selection systems, thereby generating two closely spaced wavelengths. The successful operation of this dye laser is not sensitive to the alignment of the dye laser beam and the block; this "ruggedness" is important for field measurements. The visible dye laser beams can be frequency doubled into the ultraviolet by sending them through two frequency doubling crystals -- one crystal for each wavelength. Both wavelengths follow the same path through the plasma onto a single photodiode. The output of the photodiode for on-resonance laser pulses is fed to one boxcar averager; and the output of the photodiode for off-resonance pulses is fed to a second boxcar averager. The ratio of the intensity outputs of the boxcar averagers enables calculation of the concentration of the species.

DALAS can, in principle, be applied to any atomic or molecular species. The focus will be on measuring the concentrations of H_2O , SO_2 , NO_2 , NO and OH , because the concentrations of these species, though important, are not measured by the CARS system. OH and H_2O are of interest because they decrease flame conductivity, and hence, adversely effect the performance of the MHD power train system. SO_2 , NO_2 and NO are of interest because they are pollutants and thus their environmental impact is important.

The methodology for observing and recording DALAS signals will be validated. We will optimize the instrumental operating parameters for H_2O , SO_2 , NO_2 , OH and NO in bench-top flames and the MSU MHD test stand. The system will be field tested prior to field measurements.

1.H. Laser Optogalvanic Spectroscopy System (average gas temperature, qualitative species identification)

The Laser Optogalvanic Spectroscopy System is a general purpose instrument for measuring line-of-sight average temperatures and will provide qualitative identification of various atomic and molecular species. The system employs a tungsten electrode which is inserted into the gas stream and used to monitor changes in conductivity as a dye laser is tuned into resonance with a particular species.

A general purpose system for measuring average temperature is desirable, especially one capable of working even when high particulate flow severely limits transmission of optical beams across the MHD flow. Laser Optogalvanic Spectroscopy (LOGS) is such a general purpose technique and can be brought on-line by additions to existing instrumentation. Essentially, a frequency doubling unit with automatic scanning capability is all that is required. Because LOGS uses electrical rather than optical detection, the technique alleviates problems associated with monitoring small absorptions or weak fluorescence in the presence of a strong optical background signal or large path lengths. Hence, LOGS can identify species present and characterize their temperature under conditions where techniques employing optical detection fail. Moreover, only optical access on one side of the gas stream is required for this system.

In LOGS a pulsed dye laser is tuned into resonance with a transition of a species in a plasma; the excited state concentration of that species then temporarily increases. Because the energy necessary for ionization is less for an excited electronic state than for the ground state, the rate of ionization temporarily increases. This process can be monitored as a transient (10⁻⁵ sec) voltage change (in lab flames, typically hundredths of a volt) if a high voltage (typically +400 V) electrode (e.g. tungsten, MP 3410°C) is inserted into the plasma. Although most of the research on LOGS has concentrated on atomic species, twenty-five molecular species (such as NO₂, HCO, N₂, CO, CO₂ and H₂) have been studied to date. Efforts will concentrate on molecular species present in combustion environments, in particular, on OH, C₂, NO and CO. By scanning the wavelength of a tunable dye laser and recording the optogalvanic signal as a function of laser wavelength, the optogalvanic spectrum (which is analogous to an

absorption spectrum) is obtained. The temperature of the species can be ascertained by the standard technique of ratioing the intensities of different transitions and taking into account their different transition probabilities.

The methodology for observing and recording LOGS signals of atomic and molecular species will be validated in bench-top flames and the MSU MHD test stand and the instrumental operating parameters will be optimized. Effects of electrode "aging," of electrode size, and of particles on the LOGS signal intensity will be studied in benchtop tests in DIAL test stand experiments. The precision of the temperature measurements in MHD environments will be established by comparing temperatures determined by LOGS with that obtained from CARS. Field tests and subsequently field measurements will be carried out during this work period.

1.1. Cross Correlation System (flow velocity)

The Cross Correlation Velocity System will measure the flow velocity nonintrusively with only limited optical access. The technique involves measuring the fluctuations in gas luminosity, e.g., at two spatially separated locations. The cross-correlation function of these signals gives the time interval between which the signal and a time-displaced version of itself correlates.

A simple, rugged, accurate and nonintrusive system to measure the gas flow velocity would be a particularly valuable device to help monitor the MHD power train. The cross correlation technique can provide such an instrument and can be used to find the mean velocity of the gas flow. The method can find application where only limited access to the gas stream is available. The technique is based on the naturally occurring fluctuations in, e.g., species concentration, temperature, and particle concentration in a turbulent combustion environment. If a fluctuating variable is measured at two known locations -- one upstream and the other downstream -- then the time required for the fluctuations to travel from one location to another provides the flow velocity.

Preliminary work performed by DIAL indicates that the cross correlation method can be implemented using gas luminosity as the fluctuating variable. We also believe that the correlation of signals obtained by measuring the extinction of laser light at two or more locations can provide the flow velocity. This method would allow velocity measurements where gas luminosity is weak. Other extensions of this basic concept, employing intersecting beams, have the potential for measuring spatially-resolved velocity profiles.

A cross correlation experiment performed by using two identical optical systems for data collection, with one located upstream and the other downstream. Each optical system consists of a focusing lens, a small monochromator, and a photomultiplier tube. The monochromators allow any wavelength of light from 200 nm to 800 nm to be selected. This spans the range from the ultraviolet to visible to the near infrared. The electrical signals from the photomultiplier tubes are amplified, low pass filtered, and sampled (both signals simultaneously) by an analog to a digital converter connected to a computer.

The data analysis consists of computing the cross correlation function of the two digitized signals. If the signals are correlated, i.e., only shifted in time by an amount τ , then the cross correlation function will show a peak at τ . In this way, by computing the cross-correlation function of the two photomultiplier signals, the time delay required for intensity fluctuations to propagate downstream can be found and thus the flow velocity can be determined.

To implement the system for measurements on MHD channels with large flow velocities will require a fast A/D converter and continuous operation will require large storage capacity and a fast processor to reduce the data as fast as possible.

Task 2. Test Stand Operations

DIAL has a computer-controlled, combustion test stand to simulate the combustion and thermal parameters present at various locations in a fossil-fueled MHD combustion system. Its versatility allows it to be used to simulate any type of combustion condition and effluent gas stream.

The existing DIAL/MHD/HRSR simulation test stand will be used for support of diagnostic instrumentation development, shake-down and evaluation. The test stand has recently been modified to better simulate the MHD gas stream environment. This will further aid in the evaluation of the instruments before they are taken to DOE's MHD engineering development test facilities. In particular, the test stand has been modified to burn a fuel oil/coal slurry which will more accurately simulate a coal fuel MHD combustor. Provisions for an increased flow rate of fuel-air mixture of approximately 700 lb/hr have been made. The test stand control and data acquisition computer has also been replaced with a new system to enhance data collection and control as well as provide much needed memory and disk space.

As the need arises the test stand may also be used to gather data systematically, under controlled conditions, to provide validation data for analytical models.

Task 3. Technical Support for the National MHD Program

The primary objective of this task is to provide diagnostic measurements and support to the national MHD program. The task will include attendance at contractor review meetings and contributions to technical progress reports. It will also include the preparation of a Topical Report for each diagnostic system at the time when it is available for field measurements. Objectives for this task are:

3.A. Field Measurements

3.A.1. Sodium Line Reversal System (SLR) (average gas temperature)

The Sodium D-Line Reversal System essentially measures the temperature of the central region of the gas stream. The technique employs a calibrated light source and is based on making a series of intensity measurements on the wing of one of the sodium D-lines.

This system is field ready and has been used at various MHD facilities in support of the national program. No additional modifications are planned except to maintain the system field ready.

3.A.2. Multi-Color Pyrometer System (MCP) (wall temperature and emissivity)

The Multi-Color Pyrometer measures the wall temperature and emissivity of the wall surface. The technique is based on Planck's radiation law and requires measurement of the radiation intensity from the wall surface at two or more wavelengths, assuming the presence of a graybody radiator.

The system is field ready and has been used at various MHD facilities in support of the National program. No additional modifications are planned except to maintain the system field ready.

3.A.3. Two-Color Laser Transmissometer (TCLT) (average particle size and particle number density)

The Two-Color Transmissometer measures the average particle size and particle loading in the gas stream. The technique is based on measurement of the extinction of laser light at two wavelengths (e.g., the IR and V regions) and knowledge of the refraction index of the particles.

This system is field ready and the TCLT units will continue the determination of average particle diameters and loadings at various DOE MHD facilities. Previous work has concerned the study of K_2SO_4 nucleation and real time evaluation of the performance of the CFFF electrostatic precipitator and baghouse. During this work period characterization of the particle size at upstream locations will be carried out. These measurements will concern particulate behavior and ash carry-over in the upstream portions of the facility and have implications on slag/seed interactions and thus seed recovery. In addition, ongoing measurements concerning the CFFF particulate retention components will continue to evaluate the effects of the ESP operating characteristics on particulate properties.

Initial TCLT measurements at the CFFF diffuser exit and at various levels of the radiant furnace have indicated that the average particle diameters at some locations exceed the current measurement range (0.3-4 μm) of the instrument. Somewhat larger diameters are expected

at upstream locations when compared to the cooler sections of the steam bottoming plant. In regions of high turbulence such as channels, slag can become re-entrained; in addition, fly ash (not K_2SO_4) will nucleate at high temperatures. Knowledge of the average particle diameters and loadings would be expected to aid in calculations of heat transfer, erosion and generator performance. Extension of the particle size range would increase the accuracy of the system and allow direct measurements at upstream locations.

In order to increase the upper particle size limit of the TCLT, an isotopic CO_2 laser and accessories will be added. The use of an isotopic lasing medium such as $C^{12}O_2^{18}$ will permit operation at $> 9 \mu m$ and will effectively avoid attenuation of the beam by the natural $C^{12}O_2^{16}$ present as a combustion byproduct. Incorporation of the isotopic CO_2 laser into the TCLT optical configuration will increase the particle diameter measurement range from $(0.3-4 \mu m)$ to $(0.3 - \sim 9 \mu m)$.

The current size of the TCLT optical breadboard is approximately 29" x 80" and weighs about 100 lbs. It should be possible by incorporating fiber optics to route the laser beams from one breadboard unit to multiple port locations using both visible and infrared fibers along with appropriate connectors and optics. In this way, measurements of average particle size and loadings could be made at different locations from the centrally located breadboard. At present, the optical breadboard must remain in close proximity to the penetration position and each measurement location must have one breadboard. The incorporation of fiber optics would result in increased flexibility and moreover, the lasers, etc. can be conveniently removed from the magnetic field regions present at CDIF.

3.A.4. Laser Doppler Velocimeter System (LDV) (local velocity, velocity profile and turbulence level)

The Laser Doppler Velocimeter measures the gas velocity and turbulence level at a given point in the gas stream. The technique is based on measurement of the modulation frequency of the scattered light from a particle traversing a measurement volume which is formed by intersection of two focused laser beams. A one-color and a two-color

system are available which measure one and two components of the velocity, respectively. A velocity profile can be obtained and both forward and back scatter measurements can be made.

The LDV system is field ready and has provided a number of useful velocity flow measurements in support of the national MHD program. To improve the operation and information derivable from the system, a second pair of transmitting and receiving optical fibers will be incorporated in the LDV optical train. This will allow two colors (green and blue) of incident laser light to be simultaneously transmitted to the measurement site and thus, two components (axial and radial) of particle velocity can be determined. The use of optical fibers is absolutely mandatory for field measurements, especially for difficult measurement sites such as the combustor exit at CDIF.

To complete the two-color optical fiber LDV system, a second signal processor (burst spectrum analyzer) is required. Two signal processors are required for simultaneous measurement of two velocity components of a particle. During prior field measurements at CFFF and TRW, two-component (nonsimultaneous) velocity measurements were made; but it was possible to do so only because physical access to the measurement site was allowed during the test. Protocol at the CDIF facility strictly forbids such access during a test, so a second signal processor will be mandatory for two-component measurements.

Plans also include incorporating smaller stepper motors in both the forward and backscatter traverses so only one power supply will be required to drive both. A remote controlled focusing device for the forward scatter detection system will also be added. This will allow optical alignment to be maintained during traverse of the forward optics for velocity profile measurements.

Recent experience at CDIF proved that Doppler frequencies in the range 50-70 MHz are to be expected for such flows. The only way to be confident that a proper LDV signal is being processed is to capture the transient Doppler burst using a storage oscilloscope. It is desirable, therefore, to add a high speed digital storage oscilloscope to use in such applications.

3.A.5. Potassium Emission/Absorption System (PE/AS) (time-resolved temperature)

The Potassium Emission/Absorption System rapidly measures (order of milliseconds) the average channel temperature by the line reversal technique.

This system has been field tested and is presently being used to provide time-resolved temperature measurements in support of the national MHD effort. Some software enhancement of the instrument is planned.

3.A.6. Gas Analysis System (GAS) (gas composition, e.g., CO, CO₂, NO, etc.)

The Gas Analysis System is capable of analyzing gases from fossil fuel combustion processes including NO_x, CO_x, SO₂, O₂ and combustibles. The system requires continuous extraction of a gas sample for analysis. The Gas Chromatograph (GC) can detect CO, CO₂, N₂ and O₂ using a thermal conductivity detector. Other gases of interest can also be monitored with the GC by selection of the appropriate column. Samples to be analyzed by the Gas Chromatograph are collected and stored in glass sample bulbs for later analysis.

This system is field ready and no additional modifications are planned except to maintain the system field ready.

3.B. Field Tests/Instrument Modifications

3.B.1. Coherent Anti-Stokes Raman Spectroscopy System (CARS) (local gas temperature and species concentration, temperature and concentration profiles)

The CARS system is a laser-based nonlinear optical technique being developed to provide temperature and species concentration measurements with spatial and temporal resolution. Of the many laser-based techniques, CARS is the best suited for thermometry in high-interference environments because of its coherent, laser-like signal character and high signal conversion efficiency. To obtain a CARS spectrum, two narrow band lasers at pump frequency ω_1 derived from the pump laser and one broadband dye laser at Stokes frequency ω_2 , are phase matched and focused in the gas stream thereby generating through the third-order susceptibility of the medium a spectrum at anti-Stokes frequency $\omega_3 = 2\omega_1 - \omega_2$. The CARS spectrum of a species (e.g., nitrogen) can be sensitive to both gas temperature and species concentration.

The mobile CARS instrument is ready for field tests. Based on these tests, a few minor modifications may be required. Field measurements are planned throughout the contract period at both CFFF and CDIF. Initially, point temperatures and temperature profiles from N₂ CARS spectra will be measured. Work on improving the capabilities of the present CARS system will also continue. This will include automation of the mobile CARS system. In particular, the CARS signal is focused to a 200 μm core diameter, 0.12 numerical aperture optical fiber with an achromatic lens and is piped to the instrumentation trailer from the test environment. This coupling is very critical and needs to be remotely controlled. In addition to temperature measurements, field measurements of species concentration will also be made.

3.B.2. Particle Size Distribution System (PSD) (particle size distribution)

The Particle Size Distribution System uses optical, in-situ, scattering methods for measurement of particle size distribution. The three-beam, two-color particle size measurement system is designed to measure particles at slow velocity using a single-particle counting method, while an ensemble averaging technique is used for high velocity flows. The system employs the output (green and blue) from an argon ion laser. The green beam is focused on the central axis and the blue beam is divided into two equal intensity beams which are focused and crossed inside the green measurement volume producing an interference fringe pattern. The light scattered from these beams by a particle are processed to extract the particle size.

Operation in the field will involve the single particle counter (SPC) instrument until the ensemble averaging method (EAM) instrument is refined for field operation. The particular objectives for the Single Particle Counter Instrument are to finish construction of the system, prove operation of the system in the field, and refine the system for convenience in use and performance. We anticipate adding receiving fibers to reduce susceptibility to noise. Data will also be gathered for comparison of different modes of operation in the field environment and field measurements to characterize the downstream components at UTSI will be conducted.

The specific objectives for the Ensemble Averaging Method Instrument are to prove the feasibility of the concept through experimental tests and incorporate this method into the field instrument. This will require continued theoretical and computational efforts to evaluate the parameters for the data reduction model. Preliminary work on this is finished. Refinements will be needed as soon as the work is far enough along to justify them; these include the effects of lens aberrations, which will also require some experimental investigation.

Efforts will also begin to develop an experimental configuration for particle generation and laboratory measurements. Experiments will be conducted on the test stand (as soon as feasible) and concurrently, field tests of the method will be employed to define a suitable instrument package.

3.B.3. Intrusive Multi-Probe System (IMPS) (wall and gas temperature)

An Intrusive Multi-Probe System has been developed to position various sensors at a precise location in a combustion gas stream for precise increments of time. It is completely computer-controlled and may be operated to both position the probe and acquire the data. Optical sensors as well as conventional sensors can be used with this probe insertion system; however, its main use is with techniques where the probe will spend a very short period of time in the gas stream. Such a system interfaced with an optical technique can provide measurement capabilities in regions where, because of path length, optical measurements would not be possible.

Development and field testing of one viable intrusive sensor has been completed for the measurement of MHD interior wall surface measurements. This sensor is capable of measuring surface temperatures in the range of 500°C to 2000°C. Field tests have been conducted at the DOE/CFFF by measuring the front surface temperatures of the superheater tubes during several runs of the facility; the interior wall surface temperature of the furnace has also been measured.

3.B.4. Potassium Emission/Absorption System (PE/AS) (K-number density)

The Potassium Emission/Absorption System will provide the average neutral potassium number density from lineshape information and provide the average channel electron number density using the Saha equation assuming thermodynamic equilibrium.

This system is presently being employed to provide potassium number density measurements in support of the national MHD effort. Some software enhancement of the instrument is planned; however, the major issue to be resolved is the over estimation of the potassium number density. This is particularly important for wide gas streams and is believed to be caused by the line profile deviating from a Voigt shape in the far wings. Work to resolve this problem will continue.

3.B.5. Faraday Rotation System (FRS) (electron density to infer conductivity)

The Faraday Rotation System will provide real-time electron density measurements averaged across an MHD channel. The electrical conductivity scales almost linearly with the electron density. The technique is based on the Faraday effect. Linearly polarized light may be decomposed into right (+) and left (-) circularly polarized waves. Since the absorption coefficients and refractive index are different for right and left polarization, the amplitude and relative phase of the polarized waves are affected on passing through a plasma along a uniform magnetic field. Measurement of the rotation of the polarization of a beam of linearly polarized light after passing through a medium (plasma) in the direction of an applied magnetic field determines the electron number density. The system employs radiation in the far infrared derived from a CO₂-pumped far infrared laser.

The Faraday Rotation System will provide directly the electron density and conductivity of the MHD channel, which is essential to the characterization of the power train performance. Most of the major equipment for the system has been obtained. The system assembly for electron density and density measurements on a laboratory plasma are basically complete. Electron mobility modeling and measurements will be addressed. System refinements for field tests (such as waveguides and vibration isolation for detectors) will follow. Field

measurements will take place as soon as possible at CDIF. Optical access at CDIF through the channel sidewalls is required and may necessitate new construction at the CDIF.

3.C. Field Operation/Developing Systems

3.C.1. General Purpose Spectral Scanning System (GPSS) (emission spectra from UV to near-IR)

The Spectral Scanning System will detect emission from atomic and molecular species in the gas stream, and provide an intensity versus wavelength record covering the ultraviolet to the near infrared. The system employs receiving optics and a computer - controlled monochromator equipped with a wideband detector.

Initial spectral emission measurements in the visible region at CDIF indicate it would be valuable to have a spectral scanning system covering the wavelength region from the ultraviolet to the near infrared. Building on existing equipment, construction of a general purpose spectral scanning system is planned. This system will provide a direct qualitative indication of many of the atomic and molecular species present in the gas stream. It would be particularly convenient for studying the MHD channel flow since only a very small optical fiber access hole would be needed. For instance, atomic lines (N, S, C, O, etc.) or diatomic lines (CO, OH, O, NO) could probably be detected at very high temperatures. These measurements would provide useful information for comparison with equilibrium calculations and possibly useful correlations on the operation of the MHD power train.

3.C.2. Visible IR Emission Spectroscopy (VIES) (emission spectra from ultraviolet through near infrared)

The Visible/Infrared Emission Spectroscopy System will detect wavelength-resolved emission from the ultraviolet through the near infrared. Comparison of the resulting emission spectrum with the spectrum of an available, commercial blackbody radiation source will enable estimation of relative emissivity values. The system employs receiving optics and a computer-controlled monochromator equipped with broadband detectors.

In order to evaluate the HTAH ceramic for possible use in its combustor, CFFF would benefit from knowledge of its relative emissivity values in CFFF's gas stream. Construction of a visible/infrared emission spectroscopy system built mostly from available equipment

is planned. This system will record the wavelength-resolved emission spectrum of the ceramic in the CFFF gas stream. Estimates of the relative emissivity values would be obtained from comparison of the emission spectrum with the spectrum of an available, commercial blackbody radiation source. In addition, this general purpose system could be utilized to obtain the relative emissivity values of other substances, or to study the emission of atomic and molecular species present in high temperature MHD gas streams.

3.C.3. IR Water Detector (IWD)

Water absorbs infrared radiation at a number of wavelengths, but those located near 1.4, 1.9 and 2.7 microns hold the greatest potential for diagnostic purposes in a combustion stream. The radiation emitted from the walls of a combustion facility provide sufficient intensities of infrared light in these regions to allow simple absorption measurements to be made at a single viewing port. The selection of the optimum region for making the necessary measurements depends upon factors such as the amount of water normally in the combustion stream, the minimum amount of excess water which must be detected, and the inherent absorption strengths of water at the wavelengths under consideration.

Experiments will be conducted to determine the feasibility of developing an infrared water detector instrument.

DIAL will supply a Mobile Instrument Laboratory (MIL) with computer controlled diagnostic instrumentation for on-site measurements and trained diagnostic operators. Field measurements will be made at the national MHD facilities on an as-needed basis. The Mobile Instrument Laboratory will be used to house the diagnostic equipment for transportation to, and for use at, a particular facility. The Airstream MIL has its own electric power source. Recently an 18-wheeler type trailer has been modified to provide an Advanced Mobile Instrument Laboratory (AMIL) to supplement the Airstream MIL which has been operational for a number of years. This field laboratory is used for the advanced diagnostic systems, such as CARS, FRS, etc., and for simultaneous operation of a large number of DIAL instruments.

Both field laboratories have on-board computers for on-line data acquisition and control of the diagnostic equipment. The existing data analysis system, however, lacks the speed and capabilities necessary to provide quick, report quality, feedback to the facility. To this end, modifications and additions will be made to the on-line data analysis system. The particular goals are:

- speeding up analysis and display so as to provide quick feedback to the facility;
- providing on-line data display using 2D/3D techniques to help visualize and interpret the data and facility behavior;
- producing presentation quality reports for each instrument by the end of the day of measurement; and
- validating data -- which is done manually at present -- automatically by the analysis system.

DIAL has started evaluation of the required advanced instrumentation to control a complete MHD system. As part of the support of the national MHD program, this effort will include evaluation of diagnostic systems for monitoring/control as well as an evaluation of the dynamic characteristics of the complete MHD system when the bottoming cycle is integrated with the topping cycle. Instrumentation will hence be selected to control the MHD power system under all perturbations.

Task 4. Project Management

The objective of this task is to provide the required management for accomplishment of the Statement of Work with the proposed resources management reporting as required by DOE Order 1332.1A. Contract Reporting Requirements will be part of this task.

Task 5. Technology Transfer

Technology transfer is a congressionally mandated objective of the Federal Government. To ensure the maximum benefits to PETC's and subsequently DIAL's investment in research and development, DIAL's personnel will cooperate with regional industries to demonstrate the technology for intrusive and nonintrusive diagnostic instrumentation developed for the characterization of MHD systems. Organizations which have already benefited from this actively are Dow Chemical,

USA, Dantec Electronics, NASA and the Stennis Space Center. However important, this task shall in no way interfere with the mainstream efforts of the MHD program.

DESCRIPTION OF FACILITIES

The combustion test stand is a computer-controlled simulation test facility available for the combustion of fuel oil at up to 800 lbm/hour of fuel and air. A system for using a coal slurry for fuel is presently under development. The air can be preheated to temperatures up to 1100 K (1520°F) by electrical resistance heaters. Downstream of the combustor are refractory-lined sections containing access ports on both sides and the top of each section.

The DIAL test facility has a Hewlett-Packard measurement and control system (HP-1000/A400 minicomputer-based system) with real-time software, graphics, and extensive input-output (I/O) capability.

The microprocessor development laboratory has six PC's, two IBM PS/2-80's, and two Diversified Technology development systems for developing software and firmware for special purpose microcomputers to be used in controlling diagnostic instruments, signal processing, and signal and data analysis. A variety of other PC's and microcomputers (at least twelve) are part of the field instruments and those under development.

Complete laser facilities are available, including YAG and dye lasers, spectrometers and photometers, fiber optics, and other equipment. Discharge lamps, power supplies, vacuum systems, UV optics, monochromators, detectors and processing electronics are also available. In addition, the laboratory has several benchtop laboratory burners controlled by precision gas handling systems.

The department of Electrical Engineering at MSU has the facilities and staff for the design, development and construction of hybrid integrated circuits and printed circuit boards.

The following support facilities are available in DIAL: (1) Electronics Shop, (2) Machine Shop, (3) Instrument Shop, and (4) Gas Sampling and Analysis System.

Modeling and data analysis are done on the newer, more powerful PC's (e.g. PS/2 and 386 PC's) and the VAX 11/780 and VAXstation 3200.

Large scale analysis and modeling is required for various instruments including CARS, LDV, and PE/AS. Other instrument development and refinement projects also require continued modeling support in the areas of general combustion/heat transfer and gas flow modeling.

technical
progress

Task 1. Instrumentation Development: R. L. Cook

A. *Coherent Anti-Stokes Raman Spectroscopy System (CARS)*

J. P. Singh and F. Y. Yueh

Work Performed

CARS measurements were made on the DIAL test stand to test the folded BOXCARS phase matching technique and study the new feature observed in the CARS spectra taken at DOE's Coal-Fired Flow Facility (CFFF) diffuser during the LMF4-S test. The folded BOXCARS phase matching geometry crosses the input beams only at the focal region. This geometry produces a low signal level but excellent spatial resolution and therefore is preferable for the temperature profile measurement in a medium with a large temperature gradient. To evaluate the feasibility of this technique to perform a temperature profile measurement in the DOE/CFFF diffuser during the LMF4-T test, four test stand runs were completed. The CARS system was operated from the mobile laboratory parked adjacent to the test stand building. In order to successfully operate the system which is 60 ft away from the test medium, the laser beams were first manipulated the same distance inside the mobile laboratory with prisms attached at four corners in the ceiling. The laser beams were then aligned in the test stand. Initial tests were not very successful in getting a good CARS signal. The CARS signal was improved by realigning the laser beams and using a fresh dye solution. In order to obtain a better signal-to-noise ratio, the entrance slit of the spectrograph was modified and a mount was designed to couple the optical fiber directly to the spectrograph. The new optical fiber coupling system has enhanced the sensitivity of the detection system about six times. After successfully obtaining the temperature profile using this phase matching geometry, the test stand was then modified. A 24-in. diameter test section was installed next to the combustor to provide a 16-in. diameter gas stream which was used to further evaluate the folded BOXCARS technique and also to study the new feature observed in the CARS spectra taken in the CFFF diffuser with collinear CARS. A temperature profile measurement was successfully performed in this modified test stand section using folded BOXCARS phase matching geometry. The results of these measurement are shown in Figure 1.A.1.

Figure 1.A.1. Temperature profile of DIAL test stand with folded BOXCARS phase matching geometry.

The optical ports were purged either with nitrogen or argon during these measurements. There was no significant difference found between data taken when the ports were purged with argon and purged with nitrogen. A slightly lower gas temperature was observed near the edge of the gas stream when the nitrogen purge was applied. None of the CARS spectra taken in the test stand using folded BOXCARS phase matching geometry has the new feature observed during the LMF4-S test. The CARS spectra were then taken using collinear CARS phase matching to study the feature. Different fly ash injection rates were tested in those measurements. Unfortunately, no spectra in these measurements have the feature observed in the CFFF diffuser. However, the spatial resolution of these measurements was improved by properly expanding the pump and Stokes laser beams. The mobile CARS instrument was transported to the University of Tennessee Space Institute for field testing during the LMF4-T test at the CFFF.

The mobile CARS instrument was aligned at the CFFF during the LMF4-T test at penetrations 1542 and 1541 to continue the CARS performance evaluation and perform a preliminary temperature profile measurement. To obtain good spatial resolution, folded BOXCARS phase matching geometry was used to align the laser beams. The laser beams were manipulated up to 35 ft inside the mobile instrument laboratory with prisms attached at the corners of the ceiling for fine adjustment. After the crossing of the laser beams at the focal point was checked, the laser beams were then directed to the diffuser via a hole in the back of the trailer. A 43.5-in. focusing lens was mounted on a 36-in. traverse which was used to focus the laser beams into the diffuser. A 234-in. focal length lens was used to collimate the laser beams and the CARS signal on the receiver side. The CARS signal was separated from the high intensity laser beams with low wave pass (LWP) filters and beam blocks and then coupled to a 200- μm (NA = 0.12) optical fiber mounted on a computer-controlled x-y-z translator. The other end of the fiber was directly coupled with the SPEX 500M monochromator. The emission from the laser-induced breakdown produced a strong background on the CARS spectra. A reduced gate pulse width of the OSMA (optical spectrometric multichannel analyzer) detector and proper aperture in front of the fiber reduced this background effectively.

The N₂ CARS spectra were recorded at various points of the gas stream by moving the focusing lens. All the spectra observed have the new feature observed during the LMF4-S run. The feature appeared on the N₂ CARS hot band and was more pronounced near the center of the gas stream. To eliminate the cold CARS signal generated near the wall, argon purge was used for the measurements near the boundary of the gas stream. The quality of the spectra was quite good. However, a small amount of cold CARS signal was still found on the spectra taken near the boundary of the gas stream due to cold nitrogen leaking from the slag buster during its operation. The CARS data were fit with DIAL's theoretical model to extract the temperature information. A typical fit from these measurements is shown in Figure 1.A.2. Part of the CARS spectrum containing the unknown feature was ignored in the fit.

The result of the profile measurement made between June 6 and June 7, 1990 are shown in Figure 1.A.3. The data were taken from the center of the gas stream up to 18 in. toward the west side of gas stream and 11 in. toward the east side of the gas stream. The temperature gradients are small near the center of the gas stream and increase rapidly near the edge of the gas stream. N₂ CARS spectra taken during this test run were also consistent and reproducible at the same place from one day to the next. The results of CARS measurements performed on three different nights are shown in Figure 1.A.4. The inferred temperatures near the center of the gas stream were found to be 2600 ± 100 K.

The N₂ CARS temperature measurements were also performed at several locations near the center of the gas stream with collinear CARS phase matching on June 8, 1990 to compare with the measurements with folded BOXCARs phase matching. The signal-to-noise ratio of these collinear CARS measurements was better than with folded BOXCARs due to its longer interaction length. The fit of those data are also quite good. The inferred temperature from the data taken at the west side of the gas stream (toward the transmitter) was close to the measurements with folded BOXCARs geometry. However, the inferred temperature is 150 - 300 K higher at locations toward the east side of the gas stream (i.e. away from the transmitter). This higher inferred temperature may be due to the slightly different run conditions between the measurements. The poor spatial resolution has been considered as the main reason for the higher inferred

Figure 1.A.2. N₂ CARS spectrum taken 4 in. from the gas stream center at DOE/CFFF diffuser during the LMF4-T test (T=2673K).

Figure 1.A.3. Temperature profile at DOE/CFFF diffuser with folded BOXCARS phase matching geometry.

Figure 1.A.4. Temperature measurements at DOE/CFFF diffuser on three different nights.

temperature toward the east side of the gas stream. Since the laser powers were attenuated more toward the east side of the gas stream, the averaging effect will be more significant for the measurement taken at the east side of the gas stream. According to the results of these measurements, the collinear CARS is only suitable for a facility which has short penetration or low signal attenuation.

Several experiments were conducted during the test run to study the origin of the feature on the N₂ hot band. CARS spectra were recorded with different dye solutions, monochromator settings, alignments of the laser beams, and purge rates at the optics ports with nitrogen or argon. A strong molecular band was observed at ~ 4847.6A by using the dye laser whose center wavelength is ~ 6020A. Similar to the CARS signal, this molecular band is generated where the pump and Stokes beams overlap. It could be either a CARS process, other nonlinear process, or two or multiphoton process. These data will be examined carefully. Although no conclusion can be made at present, the spectral line position of H₂ pure rotational line S(10) matched with part of the feature on the N₂ hot band. However, the theoretical study shows there must be at least 20% H₂ in the gas stream to match the intensity shown on the CARS data. More measurements will be made with various gas samples to continue this study.

Conclusions

Six test stand runs were conducted during this quarter to test the folded BOXCARs and collinear CARS phase matching geometries for the LMF4-T field test at DOE/CFFF. The temperature measurements were successfully performed with folded BOXCARs. A reasonable temperature profile can be obtained with collinear CARS by properly expanding the laser beams. These two phase matching geometries were further tested in the CFFF diffuser during the LMF4-T test. The temperature profile measurements were successfully performed at the CFFF diffuser with the folded BOXCARs technique. The feature observed during the LMF4-S run was found on all the data taken during the LMF4-T test. A strong molecular band was observed by using a dye laser with a center wavelength ~ 6020A.

Work Forecast

A series of experiments will be conducted in the CARS laboratory to study the new feature observed during the LMF4-S and LMF4-T test runs at the CFFF. Modification of the existing CARS data analysis software began to make accessing the data files more efficient.

B. Particle Size Distribution System (PSD)

J. D. Gassaway and W. Okhuysen

Work Performed

See Section 3.B, *Particle Size Distribution Test, CFFF LMF4-T Test Run*, of this report.

C. Potassium Emission/Absorption System (PE/AS)

L. E. Bauman

Work Performed

Component Development and Integration Facility's CFC-15 Test, 10-Aug-89: Figures 1.C.1 and 1.C.2 show, respectively, the measured gas temperature and potassium atom number density for the CFC-15 test of August 10, 1989. Measurements were made at the middle ports of the triple port, diffuser test section -- downstream from the MHD channel. Relevant test log notes are shown in Table 1.C.1. The second half of the recorded data, during which time the magnetic field was energized, appears typical for PE/AS measurements; prior to channel operation the temperature results are anomalous. The potassium number density results appear typical throughout the measurement period. The test continued for several hours after fouling of the optical windows became too severe to continue diagnostic measurements.

Two questions arise from this test. What is the cause of the extreme temperature fluctuations in the first half of the test, and why do the number density results not show similar large uncertainties? Secondly, are the variations in potassium density real? The results reveal a generally higher value during magnet operation and also a sudden drop that occurs at the same time as the window fouling about 14:42. An analysis of the effect of loss of window transmission given below implies that the seed atom density drop is real. This drop does occur before the test log indicates problems with the seed flow system.

The anomalous temperature measurement uncertainty on the CDIF which disappears with extraction of power from the MHD channel is puzzling. A look at the raw data reveals that the transmitted lamp signal has very large uncertainties that drop with power extraction, but the emission-only signal has a relatively constant signal-to-noise ratio for the span of measurements. This disparity cannot then be explained by a change in temperature or number density fluctuations in the gas flow so the source of the uncertainty would seem to be due to a rapidly fluctuating misalignment of the reference lamp beam. This misalignment could arise from vibrations of the optical mounts which are fixed on rails to the diffuser. The change in aerodynamic noise from

Figure 1.C.1. Potassium Emission Absorption System (PEAS) measurement of gas temperature versus time for the CDIF CFC-15 Test of 10-Aug-89.

Figure 1.C.2. Potassium Emission Absorption System (PEAS) measurement of potassium number density versus time for the CDIF CFC-15 Test of 10-Aug-89.

Table 1.C.1. Notes for the 10-Aug-89 CDIF CFC-15 Test.

13:14:29	Coal-Fired Combustor (CFC) ignition
13:18:29	Seed flow initiated
13:58:00	Inverter on-line
14:00:02	Starting magnet, gradual power up
14:15:25	Magnet at 4000 Amps
14:16:50	Begin increasing magnet and inverter
14:26:54	Magnet at full power (2.92 Tesla)
15:54:00	Seed system in manual
15:10:00	Seed flow steadily dropping, trying to restore
15:15:00	Seed system in auto

the channel when power is extracted could explain the reduction in vibrations. However, we have not experienced such problems with operation of the PE/AS previously. A more likely cause is beam steering in the flow. Velocity measurements for the same test indicate that before power is extracted there are large recirculation regions in the diffuser that rapidly shift from one wall to the other. Beam steering caused by pressure gradients in the flow could very well explain the anomalous results and presented here is an analysis of the effect of a harmonic optical misalignment on emission absorption measurements that is consistent with the test results. Presented first is a review of the measurement technique and an analysis of the affect of window fouling on these measurements. The bias due to a misalignment of the lamp image is analogous to fouling of the lamp-size window.

Consider a parallel, axisymmetric source light passing through an emitting, absorbing, and scattering medium that is a hot gas at a temperature, T_g , containing particles at temperature, T_p . The assumptions are made of local thermodynamic equilibrium and constant properties across the flow such that

$$I_\lambda(L) = \frac{\alpha_\lambda + z\eta}{\alpha_\lambda + \eta E} B_\lambda(T_g) [1 - e^{-\tau_\lambda}] + I_\lambda(O) e^{-\tau_\lambda} + J_\lambda \quad (1)$$

$$\text{and } \tau_\lambda = (\alpha_\lambda + \eta E)L,$$

where $I_\lambda(L)$ is the intensity exiting the flow of path length L , $I_\lambda(O)$ is the incident lamp intensity, α_λ is the absorption coefficient of the gas, and the Planck spectral blackbody function at the temperature, T , is denoted by $B_\lambda(T)$. The term, J_λ , represents the in-scattered radiation exiting the out-going boundary of the medium. Here the extinction-to-absorption ratio for the particles has been introduced as $E = (\eta + \sigma)/\eta$, where η is the absorption coefficient of the particles, σ is the scattering coefficient of the particles, and the explicit dependence on the particle temperature has been removed by using the ratio $z = B_\lambda(T_p)/B_\lambda(T_g)$. The wavelength subscripts on the particle parameters have been omitted here since they vary relatively slowly compared to the atomic absorption coefficient.

Although Eq. (1) was derived for isothermal flows, it is a useful approximation for the wings of atomic lines in a boundary layer flow where the parameters are those of the core region of the flow. The narrower absorption linewidths of the cooler boundary layer effect significantly only the center region of the line.

The classical, i.e. single wavelength, emission absorption calculation of gas temperature can be made from measurements of the signals of lamp-plus-flame, flame only, and preflame lamp, with parameters subscripted for wavelength, λ_1 :

$$M_1 = K_1 \left[\frac{\alpha_1 + z\eta}{\alpha_1 + \eta E} B_1(Tg) [1 - e^{-\tau_1}] + J_1 + I_1(O) e^{-\tau_1} \right] \quad (2a)$$

$$M_2 = K_1 \left[\frac{\alpha_1 + z\eta}{\alpha_1 + \eta E} B_1(Tg) [1 - e^{-\tau_1}] + J_1 \right] \quad (2b)$$

$$M_3 = K_1 I_1(O). \quad (2c)$$

Here K_1 is the collection efficiency of the optical system which need not be known since only ratios of signals at a single wavelength are used in the calculations. The optical depth is found from these measurements as

$$\tau_1 = \ln \frac{M_3}{M_1 - M_2}. \quad (3a, b)$$

Then the ratio of Planck functions at the gas and effective lamp temperature is given by

$$\Phi_1 = \frac{M_2}{M_3 - M_1 + M_2} \approx \frac{B_1(Tg)}{I_1(O)}, \quad (4)$$

and the measured gas temperature is

$$\frac{1}{Tg} = \frac{1}{T_1} - \frac{\lambda_1}{C_2} \ln \Phi_1. \quad (5)$$

Similarly, Φ_2 and τ_2 can be found for a second independent wavelength on the resonance line and an approximate expression can be written for the blackbody ratio that accounts for particle out-scatter and cancels much of the particle in-scatter as well:

$$\Phi_{1,2} \approx \frac{\tau_1 \Phi_1 - \tau_2 \Phi_2}{\tau_1 - \tau_2}. \quad (6)$$

This equation is the so-called two wavelength calculation used for the PE/AS measurements. If necessary, a recursive form can also be written to account for differing Planck ratios for widely separated wavelengths.

A particularly simple expression can be used for determining the emitter atom number density if the line wings can be modeled by a Voigt profile.¹ The optical depth, considering only resonance line absorption, is then

$$\tau_\lambda = \alpha_\lambda L \approx n_K a_2 \alpha_\lambda L / T g^{0.5}, \quad (7)$$

where n_K is the seed atom number density labeled here for potassium (K). The constant, a_2 , depends upon the constituents of the flow through collision effects:

$$a_2 = \frac{e^2}{2m_e c^3} \left[\frac{8k}{\pi} \left(\frac{1}{m_K} + \frac{1}{m_f} \right) \right]^{0.5} n_s T_s, \quad (8)$$

where e is the electron charge, m_e is the electron mass, c is the speed of light, k is the Boltzmann constant, m_K is the seed atom mass, m_f is the foreign atom mass, n_s is the number density at standard temperature and pressure, and T_s is the standard temperature. The parameter, α_λ , contains the wavelength dependence as follows for a doublet line

$$\alpha_\lambda = \sum_{i=1}^2 \frac{f_i \sigma_i^2}{(\lambda - \lambda_i)^2} \lambda_i^2, \quad (9)$$

where f_i are the oscillator strengths subscripted for the two lines of the doublet, σ_i^2 are the collision cross sections, and λ_i are the line center wavelengths. Rearrangement of Eq.(7) gives the emitter atom number density.

Using the previous expressions, taking the difference in optical depths at two wavelengths eliminates broadband contributions. Then number density of the seed atom, here labeled for potassium, can be found as

$$n_K = \frac{\tau_1 - \tau_2}{\alpha_2(\alpha_{\lambda_1} - \alpha_{\lambda_2})L} Tg^{0.5}. \quad (10)$$

This is the so-called two wavelength method for density determinations.

The worst source of bias in emission absorption measurements on large-scale combustion flows is the fouling of the optical windows. Depending upon the optical port design and the flow patterns, the fouling could occur on one or both windows. Introducing t_d and t_l as the detector and lamp-side window transmissivities, respectively, Eqs. (2a), (b), and (c) become

$$M = K_1 t_d \left[\frac{\alpha_1 + \gamma \eta}{\alpha_1 + \eta E} B_1(Tg) [1 - e^{-\tau_1}] + J_1 \right] + K_1 t_l t_d I_1(O)^{-\tau_1} \quad (11a)$$

$$M_2 = K_1 t_d \left[\frac{\alpha_1 + \gamma \eta}{\alpha_1 + \eta E} B_1(Tg) [1 - e^{-\tau_1}] + J_1 \right] \quad (11b)$$

$$M_3 = K_1 I_1(O). \quad (11c)$$

The transmission losses will not be a function of wavelength except perhaps for the most unusual case of deposition of a selectively absorbing material on the window, so no wavelength subscript is indicated for t_d and t_l . Solving for the measured blackbody ratios and optical depths allows for inspection of the introduced error:

$$\Phi_1^m = \Phi_1 t_d (1 - e^{-\tau_1}) / (1 - t_l t_d e^{-\tau_1}), \quad (12)$$

$$\tau_1^m = t \alpha_1 - \ln(t_l t_d), \quad (13)$$

and

$$\Phi_{1,2}^m = (\tau_1^m \Phi_1^m - \tau_2^m \Phi_2^m) / (\tau_1^m - \tau_2^m). \quad (14)$$

The window transmissivities, t_d and t_l , will vary individually from one down to zero as the window fouls becoming opaque; so, as one or both of the windows foul, the optical depth will increase and the single wavelength blackbody ratio will decrease. Fouling of the detector-side and lamp-side windows will

each cause cumulative errors in the same direction for the single wavelength measurement of temperature. The error is greater for a transmission loss in the detector-side window but either undervalues the true gas temperature as shown in Figure 1.C.3 for $\tau_1 = 0.8$ and $\tau_2 = 0.2$.

In contrast, the errors are in opposite directions for the two wavelength method; the two wavelength blackbody ratio will overvalue the gas temperature if the lamp-side window fouls and undervalue the temperature with fouling of the detector-side window. If both windows are fouled, the error for the two wavelength technique lies somewhere between the two extremes shown in Figure 1.C.3. The theoretical case for both windows fouling equally is shown in Figure 1.C.4. The two wavelength technique remains reasonably well-behaved down to 20% transmission, i.e. only 45% transmission through each window. In contrast, the single wavelength technique shows significant error even at small transmission losses. However, the specific results depend upon the optical depth at the two chosen wavelengths.

Figures 1.C.3 and 1.C.4 illustrate the effect of window fouling for the optical depths that are typically of measurements made in the laboratory or on the 20-cm diameter DIAL test facility. Measurements at the CDIF with heavy ash carryover and on the CFFF with a longer path length give significantly larger continuum optical depths so that error from a fouled lamp window is reduced for the single wavelength method. However, it is such particle-laden conditions that cause considerable error in the single wavelength temperature and number density methods and make the two wavelength methods preferable.

Observations by this author over several years are that the most severe window fouling occurs during the combustor ignition. If the optical ports can be shuttered during these time periods, the fouling of windows is minimal. If the windows cannot be shuttered and the fouling occurs during the ignition, then recording post-test the effective blackbody lamp temperature through the fouled lamp-side window and the lamp signal through both fouled windows and using these in the calculations will essentially eliminate the error in either measurement method. This presumes that transmission is not reduced so as to seriously reduce the signal-to-noise ratio. The advantage of the two wavelength method arises if the fouling occurs throughout the test. In this case the

Figure 1.C.3. Bias in the Planck blackbody ratio as a function of lamp- and detector-side window transmissivities for both the single wavelength and two wavelength methods.

Figure 1.C.4. Bias in the Planck ratio as a function of combined window transmissivity for both the single wavelength and two wavelength methods assuming equal transmission losses for the windows.

systematic error from the indeterminate transmission losses is reduced by using the two wavelength method. One can put a limit on the error by measuring the window transmissivities after the test.

The increase in the measured optical depth with window fouling will directly introduce error in the single wavelength measurement of emitter number density; this technique requires an absolute measure of optical depth at a particular wavelength on the resonance line. In contrast, the two-wavelength method will cancel the error in the optical depth, leaving only the error that arises in the temperature measurement and even this bias is reduced by the square root relationship. As long as there is some lamp light transmitted across the flow, window fouling will not introduce significant bias into the two wavelength measurement of emitter atom number density.

Emission absorption measurements require collection of a transmitted lamp signal eliminating light collection from any section of the flame that has not been transilluminated by the lamp. Problems in maintaining an optical alignment over long path lengths and on sometimes severely vibrating facilities can be considerable. On large-scale combustion facilities slowly varying shifts in alignment will have an insignificant effect on the emission signal but potentially will cause a loss of transmitted lamp signal affecting the emission absorption measurements in just the same way as lamp-side window fouling does. Careful selection of the optical elements and mounts can reduce this problem and, if access to the optics is available during testing, such shifts can be corrected for as they occur. For this author such problems have been minimal. However, the problem of rapidly fluctuating misalignment of the lamp image seems to have arisen in the CDIF CFC-15 Test and presented here is an analysis of how a harmonic alignment problem effects bias and uncertainty in emission absorption measurements. If lamp misalignment occurs through beam steering caused by rapid pressure fluctuations in the flow or by vibration of the optical mounts, then a harmonic oscillator treatment would be an appropriate model for analysis of the problem.

The analysis here is specific for the optical elements of the PE/AS instrument, but the treatment could be generalized to other optical geometries. A tungsten lamp with a 2-mm wide strip filament is used as the reference lamp. On the opposite side of the hot flow, a 1-mm core diameter fiber is used for

light collection and transmission back to a monochromator and detector, in this case a vidicon detector. The fiber tip is carefully centered on the lamp image, leaving 0.5 mm of the lamp image on either side of the fiber tip for 'grace'. This optical arrangement has been used successfully for many tests. Figure 1.C.5 shows how the effective lamp signal collection efficiency is reduced by displacement of the lamp image and also how the measured optical depth would increase due to the loss of lamp signal.

Using the results of Figure 1.C.5 and time-averaging over the harmonic displacement cycle reveals how the misalignment will affect measurements. Figure 1.C.6 shows how the time averaged lamp collection efficiency factor changes with vibration amplitude along with the standard deviation for averaging time-resolved measurements. Also shown is the average and standard deviation for the bias in the measured optical depth due to the vibration-induced misalignment.

The PE/AS has a time resolution for illumination of the lamp and emission signals of about 0.5 ms with a separation of 1.5 ms so that knowledge of the misalignment frequency would be required to determine whether the results would be described as time averaged or resolved. All of the spectral information is collected for the same time intervals. If the detection system time-resolves the vibration, which seems to be indicated, then a large population of individual measurements of collection efficiency and optical depth bias would yield averages and standard deviations as shown in Figure 1.C.6.

For time averaged intensity measurements, writing the lamp collection efficiency factor as F , the time averaged transmitted lamp signal can be written in terms of the time average of F and its standard deviation (averages with overbars and standard deviations with δ)

$$\overline{M}_1 = K_1 \left[\frac{\alpha_1 + z\eta}{\alpha_1 + \eta E} B_1(Tg) [1 - e^{-\tau_1}] + J_1 + (\overline{F} \pm \delta F) I_1(O) e^{-\tau_1} \right] \quad (15)$$

and one can write the expressions for measured optical depth and blackbody ratio as

$$\tau_1^m = \tau_1 - \ln(\overline{F} \pm \delta F) \approx \tau_1 - \ln(\overline{F}) \pm \delta F / \overline{F} \quad (If \delta F / \overline{F} \ll 1) \quad (16)$$

Figure 1.C.5. Plot of the lamp collection efficiency factor and optical depth bias versus misalignment between the centers of the lamp image and the tip of the light collection fiber.

Figure 1.C.6. Time averages and standard deviations for the lamp collection efficiency factor and the optical depth bias versus vibration amplitude for misalignment between the centers of the lamp image and the tip of the optical fiber.

and

$$\Phi_1^m = \Phi_1(1 - e^{-\tau_1}) / [1 - (\bar{F} \pm \delta F)e^{-\tau_1}]. \quad (17)$$

One can then write $\Phi_{1,2}^m$ in terms of these expressions as in Eq. (17) and inspect for bias caused by the fluctuating misalignment. The optical depths are overestimated and Φ_1 and Φ_2 are underestimated with greater error at smaller optical depths. The two wavelength method overestimates the gas temperature as occurs with fouling of the lamp-side window.

The optical depth difference used in the number density calculation is

$$\tau_1^m - \tau_2^m = \tau_1 - \ln(\bar{F} \pm \delta F)_1 - \tau_2 + \ln(\bar{F} \pm \delta F)_2 \quad (18)$$

and will be reasonably accurate in spite of the oscillating misalignment if the transmitted lamp signals for the two wavelengths are collected over the same time interval.

If, instead, one averages the results found from time-resolved intensities, then the measured optical depth and blackbody ratios are as follows:

$$\tau_1^m = \tau_1 - \overline{\ln(F)} \pm \delta[\ln(F)] \quad (19)$$

and

$$\Phi_1^m = \Phi_1(1 - e^{-\tau_1}) \left\{ \overline{[1/(1 - Fe^{-\tau_1})]} \pm \delta[1/(1 - Fe^{-\tau_1})] \right\}. \quad (20)$$

These expressions also predict that the optical depths are overestimated and Φ_1 and Φ_2 are underestimated with greater error at smaller optical depths. Single wavelength measurements, then, would underestimate the gas temperature and overestimate the emitter atom number density. In contrast, the two wavelength $\Phi_{1,2}^m$ will measure high as shown earlier for fouling of the lamp-side window.

The optical depth difference used in the two wavelength number density calculation is then

$$\tau_1^m - \tau_2^m = \tau_1 - \tau_2 \pm \delta[\ln(F)]_1 \pm \delta[\ln(F)]_2 \approx \tau_1 - \tau_2. \quad (21)$$

The PE/AS instrument collects the transmitted lamp signals for the two wavelengths from the same time interval so that the number density calculation will be accurate in spite of the oscillating misalignment and with no appreciable increase in uncertainty. Indeed, there is no noticeable change in the number density measurement uncertainty over time for the CFC-15 Test as shown in Figure 1.C.2.

Now, having laid out the appropriate equations, sense can be made of the experimental data. Figure 1.C.7 plots, as a function of time, the optical depth at the on-line wavelength and the number of valid temperature calculations from a set of 50. At about 14:09 the optical depth decreases by about 0.6 and the number of valid measurements increases to typical numbers of 47-49. Both of these trends are consistent with a harmonic misalignment of the lamp beam that disappears with MHD operation of the channel. The preceding harmonic vibration analysis revealed that the uncertainty in optical depth bias is nearly the same as the average bias. So if the bias is about 0.6 then the uncertainty is on the same order and many of the data sets would be invalid since the typical optical depth difference used for selection of wavelengths for the Potassium Emission/Absorption System is 0.5. Three values in the data set just before 13:40, however, do show a low optical depth and large sample size indicating perhaps no misalignment problem and a good measure of the gas temperature prior to energizing the magnet. Figure 1.C.8 shows the measurements of gas temperature versus time for the CDIF CFC-15 test on 10-Aug-89. The measured temperature at 13:40 is 2361 ± 73 K and, after power extraction begins, the temperature drops to around ± 30 K.

The optical depth after energizing the magnet is nearly as low as that observed at the beginning of the test, which suggests that there has been little fouling of the windows. The gradual climb in optical depth during MHD operation appears to be associated with an increase in potassium number density as argued below. At the end of the measurement span, the sudden increase in optical depth associated with a drop in samples indicates windows fouling.

Figure 1.C.9 shows the temperatures versus measured optical depth for the power extraction portion of the test. Looking first at optical depths below 3.0, temperatures calculated with the one wavelength method show a 50 K drop as the optical depth varies from 3.0 to 2.3. This trend is consistent with

Figure 1.C.7. Optical depth and statistical sample size for the averaged two wavelength temperature versus time for the CDIF CFC-15 Test.

Figure 1.C.8. Measured averaged temperatures, single wavelength and two wavelength calculations, versus time for the CDIF CFC-15.

Figure 1.C.9. Measured averaged temperatures, single wavelength and two wavelength methods, versus the on-line optical depth for the MHD portion of the test.

Figure 1.C.10. Plot of the average measured temperatures, single wavelength and two wavelength calculations, versus the on-line optical depth for the first portion of the test.

error introduced by the particle emission, absorption, and scattering effects that cause the one wavelength method to underestimate the gas temperature with greater error at lower optical depth. This underestimation is the reason for using the two wavelength method on particle laden flows. The two wavelength results show greater spread corresponding to the almost double measurement uncertainty but are independent of optical depth as expected. From this plot one can conclude that window fouling has not occurred before the last five data sets and that the trends observed with the two wavelength temperature and number density measurements reflect true changes in the flow (within error bounds of course). While the trends in the single wavelength results also include particle bias and so are more difficult to interpret, the emitter number density increase during this time span causes the one wavelength method to over predict the temperature rise.

Measured optical depths greater than 3.0 all occur at the end of the measurement span and are consistent with the window fouling analysis presented here. At the greatest optical depth, which is for the last recorded measurement, the one wavelength temperature has dropped by over 200 K while the two wavelength temperature has dropped by only 60 K. This is consistent with fouling of both windows giving additional bias in the one wavelength method compared to the two wavelength method.

Now to address the anomalous temperature fluctuations before power extraction. Figure 1.C.10 plots the temperature measurements as a function of optical depth for the first half of the measurements. The data sets for optical depths of 2.0 and below are measurements at the start of the test and appear unaffected by lamp misalignment as shown in Figure 1.C.7. For the remaining sets, the single wavelength temperature results show a decrease of about 80 K in temperature with an increase in optical depth of about 1.3. The measured two wavelength temperatures show an increased uncertainty with the higher optical depths and a trend toward higher temperatures. The temperature increase is at least 100 K; however, the sets with high measured optical depths correspond to small sample sizes, so the trend in temperature is difficult to quantify. These general trends are consistent though with a fluctuating lamp misalignment, a consequent bias in the measured optical depths and temperatures, and would indicate a fairly large vibration amplitude.

Figure 1.C.11 shows the calculated potassium atom mole fraction for the single and two wavelength methods. The offset between the two results is the bias introduced into the single wavelength measurements by particle cloud absorption, leading to an overestimation of about 300%. For the period before energizing the magnet, the single wavelength results are predicted by the harmonic misalignment analysis to be biased even higher because of the bias in the optical depth and, indeed, this is reflected in the results with a drop as the magnet is energized. The single wavelength results will also be biased by window fouling and this is seen in the rise at the end of the measurements while a decrease is seen in the two wavelength results.

In contrast, and based upon the analysis presented here, the trends in the two wavelength calculations should be real since the method is unaffected by either problem and differences in optical depth cancel out window transmissivity and misalignment-induced bias in optical depth. The results show a near steady value at a mole fraction of 0.01 that gradually doubles during channel operation before dropping. The drop begins at about 14:42, in advance of the log note at 14:54 stating that the seed flow was in manual mode and the note at 15:10 that the seed flow was steadily dropping. It is not inconceivable that changes in control of the facility that led to manual seed control were what caused the fouling of the windows. There is no significant indication of window fouling until the precipitous onset at about 14:46.

On the basis of this analysis the observed drop in potassium number density at the end of the measurement period is believed to be real. The misalignment fluctuations did not affect the two wavelength measurement of number density and the measured variations in number density for the test are presumably valid.

Conclusions

The very large temperature uncertainty in the two wavelength method arises because of the form of the equation that depends upon the difference in optical depths at two wavelengths. The one wavelength method suffers bias but not the dramatically increased uncertainty. One could argue that the one wavelength method is preferable to the two wavelength method because of smaller uncertainty, but using such a method one would have had no indication of the misalignment

Figure 1.C.11. Average measured potassium number density, single wavelength and two wavelength calculation methods, versus time for the CDIF CFC-15 Test.

problem -- the observed lower temperatures and higher densities would have been presumed to be real. Beyond the misalignment and window fouling, the test results also show that the particle bias in the one wavelength measured temperatures is over 100 K and in the measured atomic density is over 300%.

On particle-laden combustion where window fouling is a problem or on large-scale systems where vibrations and long path lengths exacerbate alignment problems, the two wavelength emission absorption technique is preferable to a single wavelength technique and does provide accurate diagnostic measurements. Such line-of-sight measurements can provide robust monitoring that is complementary to more complex spatially-resolved, laser-based techniques.

References

1. Onda, K.; Kaga, Y.; and Kato, K. 1981. *J. Quant. Spectrosc. Radiat. Transfer* 26: 147.

D. Intrusive Multi-Probe System (IMPS)

L. R. Hester

Work Performed

Investigations into various methods for extending the calibration and temperature measuring range of the intrusive lightpipe sensor continued. Several tests were conducted with the intrusive lightpipe sensor, the wall-embedded thermocouple, and the Multi-Color Pyrometer System (MCP) on the special test section of the DIAL test stand. No satisfactory conclusions resulted from the data obtained. Modifications to the test procedures are being made with additional tests to be conducted. A new scheme for faster data acquisition and analysis for the intrusive lightpipe sensor was devised. Preliminary tests of this scheme indicate a better accuracy at a higher speed can be achieved.

The intrusive probe support system and the intrusive lightpipe sensor were transported to the Coal-Fired Flow Facility (CFFF) and installed at penetration 3015 of the superheater test module (SHTM) in support of test LMF4-T. The lightpipe sensor was positioned to measure the surface temperature of the ash deposition probe (ADP) during sootblowing. During test LMF4-T, a total of 38 insertions were made on three separate days. A typical ADP temperature profile during a sootblowing experiment is shown in Figure 1.D.1. A composite of ADP temperature profiles before, during and after the sootblowing action is shown in Figure 1.D.2. The "before" data were taken 15 minutes prior to the "during" data. The "during" data coincides with the "before" data until sootblowing starts. Sootblowing took place for five seconds. The "after" data was taken 12 minutes following the "during" data. This data was taken late into test LMF4-T after significant deposits had accumulated on the ADP.

Conclusions

The intrusive probe support system with the intrusive lightpipe sensor proved to be very useful in support of the LMF4-T test at the CFFF in determining the effects of surface temperature changes with ash deposition and sootblowing. There are still a few problems that need to be solved to improve the accuracy and to simplify the overall measurement procedures.

Figure 1.D.1. Deposit surface temperature measured during sootblowing.

Figure 1.D.2. Composite plot of deposit surface temperatures measured during insertions 33, 34, and 35.

Work Forecast

Plans are underway to complete the new scheme for improving the accuracy of the intrusive lightpipe sensor and increasing the data acquisition rate. Also, the intrusive support system with the intrusive lightpipe sensor will be installed at the same penetration of the CFFF during test LMF4-U. For this test, an attempt will be made to determine a time history of the ash build-up on the ADP through the total run.

Effort will also continue on the construction of the intrusive SLR sensor along with the development of the faster data acquisition software.

E. Faraday Rotation System (FRS)

L. E. Bauman

Work Performed

During this period, laser characterizations at the 496- μm and 118- μm lines were completed which reveal that the wave guide does depolarize the laser beam. At the place where the flame is located, the ellipticity (with the wave guide) for the 118- μm line is twice as much as the ellipticity of the 496- μm line. The transfer process from the LSI-11/23 computer to an IBM-compatible 386 computer was basically completed for single experiments.

Laser Characterization: The FIR output is linearly polarized with a degree of polarization expected to be greater than 98 percent. The polarizer used in this system has a degree of polarization greater than 93 percent. The size of the laser ellipticity without the wave guide and the amount of ellipticity the wave guide introduces into the system are factors that play a big role in the interpretation of the results. They need to be characterized numerically.

Two polarizers were used in four different configurations to estimate the laser ellipticity and the polarizer parameters. Without the wave guide, the laser ellipticity is not measurable with the polarizers in this system. However, with the ellipticity introduced by the wave guide, the laser ellipticity at the place where the flame is located is detectable. For the 496- μm line, this ellipticity is found to be 6.8°. The 118- μm line is much more depolarized by the wave guide and the ellipticity is twice as much. The two polarizers were found very much consistent with the manufacturer's specifications.

Computer System Change: Until now, all experimental data were collected with an LSI-11/23 computer and analyzed on another IBM-compatible 286 computer in the Physics Department. The LSI-11/23 computer is unreliable and due to its extremely slow speed and other problems, no effort has been made to set an integrated program on the LSI-11/23 for this system. An IBM-compatible 386 computer was obtained from the Physics Department for the development of the Faraday Rotation System.

On the LSI-11/23 computer, the data acquisition was done through a GT360 interface board and the control program was written in Fortran using RT-11 functions. The program was built up while configuring the Faraday Rotation System setting, so it is not structurally designed. The configuration of the system was basically completed before this period of time. The program on the IBM compatible computer was designed, coded, and tested with some application of software engineering principles. A Lab-PC interface board (from National Instruments) is used to serve as the hardware of data acquisition, digital I/O, and timing. Functions of LabWindows (also from National Instruments) are called to program the interface board. The program itself is written in Microsoft C.

This new program has a graphics user interface which provides the operator graphics and text information to update experiment parameters, select experiment methods (rotating polarizer or beam splitting), and control instruments individually. Data acquired are displayed numerically and graphically while the acquisition process is proceeding which gives the operator some idea of the experiment situation. Raw data and analyzed results are saved automatically with systematic file names which reflect the order and date of the experiments. The program is quite user friendly and requires no specific computer operator knowledge.

Conclusions

At the end of this period, an integrated system was basically established. More theoretical work needs to be done on the analysis of the raw data. Configuration of a compact detecting block is necessary before taking to a field test.

F. Multi-Purpose Imaging System (MPIS)

R. Lengel and J. S. Lindner

Work Performed

Papers were presented at the 21st AIAA Fluid Dynamics, Plasma Dynamics and Laser Conference¹ and at the 28th SEAM.² These papers reported previous efforts on the laser-induced fluorescence (LIF) of rubidium (Rb). In summary, the Rb atoms, which arise primarily from the technical grade potassium (K) salts used for seeding the MHD generator, can be used as a suitable surrogate for K in imaging experiments. Relative temperature profiles of the laboratory flame can be obtained by spectrally resolving the Rb $5P_{1/2}$ and $5P_{3/2}$ resonance lines and using the Boltzman equation. Determination of the absolute flame temperature revealed that quenching destroys the $5P_{3/2}$ line faster than the $5P_{1/2}$ line leading to undercalculated temperatures. It is possible to correct the intensity observed to the proper temperature through knowledge of the quenching term. Further experiments are planned to investigate the intensities of the two levels at different flame temperatures.

Previous efforts to image K directly were limited by collisional transfer and low incident laser powers at the $5S - 5P$ (404.7 nm) resonance transition.³ Although Rb will serve as a replacement atom in imaging experiments, the assumption of a completely directed proportionality between Rb and K may not be entirely correct if, for example, the Rb atoms preferentially deposit in the slag and ash. Consequently, it is important to be able to image K as well as Rb and other species of interest.

Figure 1.F.1 shows the on resonance (404.7) LIF of K (left image) and the corresponding background. In order to obtain increased laser power at 404.7, the recently purchased wavelength extension unit (WEX) was installed into the optical train and used to frequency mix the output from the dye laser (DCM dye, 651 nm) and the residual 1064 nm radiation from the Nd:YAG laser. In this way a 10 X increase in laser beam power at 404.7 nm resulted when compared to the use of the LDS 821 near IR dye and doubling. In both images the burner head is clearly visible and the images correspond to the use of the cylindrical

Figure 1.F.1. Laser-induced fluorescence image of K-seeded into a Bunsen burner (left) and the corresponding off resonance line background (right). The more intense portion of the on-resonance image corresponds roughly to the height of the incident beam.

optics to expand the laser beam into a two dimensional sheet of light. The increase in laser power has therefore allowed K imaging. Further studies are in progress.

Conclusions

Potassium imaging is now possible at the 5S - 5P (404.7 nm) resonance transition.

Work Forecast

Further studies on K and Rb are in progress. Determination of the response behavior of the intensified CID camera, as well as the associate modulation transfer function, will be the first step in the quantitative analysis of images gathered with the system.

References

1. Lindner, J. S. and Lengel, R. K. 1990. Proceedings of the 21st AIAA Fluid Dynamics, Plasma Dynamics and Lasers Conference, Paper No. 90-1547.
2. Lindner, J. S. and Lengel, R. K. 1990. Proceedings of the 28th Symposium on Engineering Aspects of MHD, XII.3-1.
3. Lindner, J. S. and Lengel, R. K. 1990. Proceedings of the 28th AIAA Aerospace Sciences Meeting, Paper No. 90-0348.

G. Differential Absorption Laser Spectroscopy System (DALAS)

David L. Monts

Work Performed

During the second quarter of 1990, work progressed more slowly than anticipated on the Differential Absorption Laser Spectroscopy (DALAS) system for measurement of line-of-sight-average species concentration. Progress toward achieving lasing with the homemade, alternating two-wavelength dye laser was halted by low pump laser power from the old CARS Nd:YAG laser, which is also shared by the LOGS system. Routine maintenance (replacement of flashlamps, etc.) improved the laser power somewhat, but failed to bring the Nd:YAG laser up to its specified power rating. Systematic sleuthing revealed that the Nd:YAG laser's Q-switch was damaged. A laser service representative replaced the Q-switch and realigned the Nd:YAG laser in May. We are now getting higher 532-nm laser power than ever obtained from this Nd:YAG laser.

In the two-wavelength dye laser's oscillator section, the dye laser beam from the oscillator dye cell, after passing through a pinhole aperture, is reflected by a diffraction grating at grazing incidence onto the end mirror, which reflects the laser beam back onto a slightly different region of the same diffraction grating (see Figure 1.G.1.). The laser beam is then reflected through the same pinhole aperture through which it entered, and again through the oscillator dye cell and finally through the output mirror. As in the design of Hung and Brechignac (1988), rotation of a glass block by 90° between laser pulses diverts the dye laser beam onto a second, independently-positionable end mirror on alternate laser pulses.¹ The wavelength generated by the dye laser is a sensitive function of the position and angle of the end mirror with respect to the diffraction grating. Because of the complicated alignment requirements, great care is required in aligning the optical components. To aid this process, a computer spreadsheet utilizing the analytical relationships of Hung and Brechignac (1985) for a narrow bandwidth, grazing incidence dye laser is employed to calculate the positions of the end mirrors for a given grazing incidence angle and for wavelengths in a chosen spectral region.² In June, an error (the use of degrees rather than radians) in the spreadsheet was

Figure 1.G.1.1. Two-wavelength dye laser for Differential Absorption Laser Spectroscopy System (DALAS).

discovered and corrected. Using the corrected spreadsheet, a variety of configurations for the optics have been examined and new parameters selected: e.g., a grazing incidence of 87° will be used with a 0.042-in. diameter pinhole aperture. The optical train is being aligned with a HeNe laser, for which an alignment mount has been built. After all the optical components have been aligned with the HeNe laser (632.8 nm), the end mirrors will be moved to their position for lasing in the Rhodamine 590 lasing region (552 - 580 nm).

Conclusions

Progress on this project, while satisfactory, is less than anticipated.

Work Forecast

During the next quarter, we expect to obtain lasing from the dye laser oscillator section, and to begin characterizing and optimizing its output. The stepper motor system for alternating the wavelength of the dye laser will be designed and constructed. Once lasing has been achieved at a single wavelength and dye laser operation optimized, testing of the alternating wavelength mode of operation will begin. When all of the remaining computer components have been received, the computer system and the BOXCAR averager system will be thoroughly tested. Design and construction of the detection system will begin during the next quarter.

References

1. Hung, N. D. and Brechignac, P. 1988. Tunable alternate double-wavelength single grating dye laser for DIAL systems. *App. Opt.* 27:1906-1908.
2. Hung, N. D. and Brechignac, P. 1985. A single-mode single-grazing incidence pulsed dye laser. *Opt. Commun.* 54:151-154.

H. Laser Optogalvanic Spectroscopy System (LOGS)

David L. Monts

Work Performed

During the second quarter of 1990, work on the Laser Optogalvanic Spectroscopy (LOGS) system progressed slowly, but satisfactorily. As described in detail in the DALAS section (1.G), progress was slowed by the time required to diagnose and repair the old CARS Nd:YAG laser. We are now obtaining higher 532-nm laser power than ever before from this Nd:YAG laser. In addition, further delay occurred in May when the sprayer nozzle, used to atomize aqueous solutions of potassium and sodium salts into the homemade burner flame, broke and had to be replaced. Preliminary, qualitative experiments on the effect of electrode aging by reaction with a methane/air flame have been performed by tuning the dye laser to a potassium transition (583.2 nm) and monitoring the intensity of the LOGS signal as a function of time. Standard operating conditions are being chosen to facilitate comparison of results. Work on normalizing the LOGS signal for laser power changes has begun.

The electronics and optics, but not the frequency doubling crystal of the frequency doubling system have been received.

Conclusions

Due to time lost in diagnosing and repairing the Nd:YAG laser, work on this project progressed more slowly than anticipated.

Work Forecast

The LOGS system will use a new computer system (shared with the DALAS system) for data acquisition. When a data acquisition computer program has been completed by a DIAL computer software technician, quantitative measurements of the effects of the electrode aging, diameter, material, voltage, etc., will begin. Modification of the new data acquisition program will enable use of the new computer system to scan the dye laser. Enhancement of the signal-to-noise ratio will continue. Documentation of the response of the photodetector circuit for normalizing the LOGS signal for changes in laser power will be completed. The frequency doubling system and the entire LOGS apparatus will be tested thoroughly when the doubling crystal is received.

I. Cross Correlation System (CCS)

O. P. Norton

Work Performed

The acquisition of the necessary equipment for the Cross Correlation System was begun. Preliminary data were taken on the DIAL combustion test stand using borrowed equipment, and the analysis of these data was begun.

An abstract, based on these preliminary results, was submitted to the AIAA 29th Aerospace Sciences Meeting.

Conclusions

Excellent agreement was found between cross correlation velocity measurements and LDV velocity measurements.

Work Forecast

Most of the equipment should be ordered and received during the next quarter. Analysis of the preliminary test stand data will continue, with more data taken as required.

Task 2. Test Stand Operations: J. A. Etheridge

Work Performed

A. Test Stand Modifications

No modifications were made to the test stand.

B. Test Stand Runs

Thirteen test runs were completed during this quarter for a total run time of approximately 102 hours. The table below is a summary of these tests. The CARS runs were all made with the CARS instrument in the Advanced Mobile Instrument Laboratory. The CARS laser was shot through a hole in the rear door of the test stand room into the test stand and back to the mobile laboratory. The TCLT tests were for support of a potassium carbonate seed study. The MCP tests were for testing the effect of CO on MCP measurements.

Table 2.B.1. Test stand runs, April - June, 1990.

RUN #	DATE	INSTRUMENTS	CONDITIONS	RUNTIME
1	4/3	CARS	Argon Purge on Ports	9 hrs.
2	4/5	CCS	Seed Injection	9 hrs.
3	4/19	CARS	Seed Injection	8 hrs.
4	4/25	IMPS MCP		9 hrs.
5	5/1	CARS	Seed Injection	10 hrs.
6	5/8	CARS	Seed Injection	7 hrs.
7	5/10	MCP		6 hrs.
8	5/11	CARS	Seed Injection	7 hrs.
9	5/16	CARS	Seed Injection	78 hrs.
10	5/17	MCP	CO, Seed Injection	8 hrs.
11	5/23	IMPS MCP	Seed Injection	7 hrs.
12	6/12	TCLT	Potassium Carbonate Injection	7 hrs.
13	6/26	TCLT	Potassium Carbonate Injection	7 hrs.

Task 3. Technical Support for National MHD Program: R. D. Benton

A. Field Measurements

Work Performed

The Laser Doppler Velocimeter (LDV) System was used to make measurements at DOE's CFFF during the LMF4-T test May 29 - June 12, 1990. The results of these measurements are summarized below. The slag rams and the PE/AS were taken to DOE's CDIF for testing June 25-28, 1990 but the tests were postponed.

Laser Doppler Velocimeter Test, CFFF LMF4-T Test Run, (D. V. Srikantaiah and W. W. Wilson): The LDV apparatus was positioned at ports 2122 (north) and 2126 (south) at the grating level of the second floor of the CFFF radiant furnace. LDV measurements had been obtained at these ports during the LMF4-S test and the results showed an unusual shape to the particle velocity profile near both the north and south walls that was inconsistent with the flow modeling studies performed by UTSI personnel. Our purpose during the LMF4-T test was to remeasure the particle velocity profile across the radiant furnace in order to confirm the unusual shape to the profile and determine if external experimental factors were influencing the profile shape.

A plot of the mean axial velocity profile is shown in Figure 3.A.1. The data given by the squares represents the major (upward) component of particle velocity at different spatial locations within the radiant furnace. Note that the profile is skewed towards the south wall of the furnace, which is consistent with modeling predictions. The shape of the profile towards the south wall was essentially the same as that obtained during the LMF4-S test. The unusual feature of the profile is that it displays a recirculation zone (positive to negative velocities) as the south wall is approached, which is not consistent with modeling predictions.

Since this effect occurred within several inches of the south wall, it was thought that the port and window purge may be affecting the flow in this region. The purge was intermittently turned off (5-10 sec) and the LDV data was acquired. The results of this experiment are represented by the crosses in Figure 3.A.1. Note that there is a dramatic effect on the shape of the profile. The profile assumes a more normal shape and shows no evidence of recirculation. The purge effect seems to extend into the gas stream about 6-7

IMF4 1 RUN 05 JUNE 1990

Figure 3.A.1.1. Effect of the purge on mean axial velocity profile at second level in CFFF radiant furnace.

in. from the furnace wall, at least for this port. Farther into the gas stream, the data with and without purge begins to overlap. A similar but not as large an effect was found for the profile near the north wall. The purge effect, of course, depends on the purge rate and port geometry. For some ports, especially east-west ports in the furnace where low purge rates are sufficient to maintain clean windows, the effect of purge on LDV data is minimal. However, for south wall ports where the flow is highly directed, larger purge flow rates are necessary and the effect on LDV data near the wall is quite severe.

The purge also affected the data rate. This effect as a function of the penetration distance is shown in Figure 3.A.2.

Figure 3.A.2. Effect of the purge on data rate.

B. Field Tests/Instrument Modifications

Work Performed

The Coherent Anti-Stokes Raman Spectroscopy (CARS) System, the Particle Size Distribution (PSD) System and the Intrusive Multi-Probe System (IMPS) were field tested during the LMF4-T test at CFFF. The results are summarized below.

Coherent Anti-Stokes Raman Spectroscopy Test, CFFF LMF4-T Test Run, (J. P. Singh and F. Y. Yueh): The mobile CARS instrument was aligned at the CFFF during the LMF4-T test at penetrations 1542 and 1541 to continue CARS performance evaluation and perform a preliminary temperature profile measurement. To obtain good spatial resolution, folded BOXCARS phase matching geometry was used in aligning the laser beams. The laser beams were manipulated up to 35 ft inside the Mobile Instrument Laboratory with prisms attached at the corners of the ceiling for fine adjustment. After tweaking the laser beams to peak the signal, the laser beams were then directed to the diffuser via a hole in the back of the trailer. A 43.5-in. focusing lens was mounted on a 36-in. traverse which was used to focus the laser beams into the diffuser. A 24-in. focal length lens was used to collimate the laser beams and the CARS signal on the receiver side. The CARS signal was separated from the high intensity laser beams with low wave pass (LWP) filters and beam blocks and then coupled to a 200- μm , (NA = 0.12) optical fiber mounted on a computer controlled x-y-z translator. The other end of the fiber was directly coupled with the SPEX 500 M monochromator. This direct coupling method enhanced the CARS detection about six times.

The N₂ CARS spectra were recorded at various points of the gas stream by moving the focus lens. All the spectra observed have the new feature observed during the LMF4-S run. The feature appeared on the N₂ CARS hot band and were more pronounced near the center of the gas stream. To eliminate the cold CARS signal generated near the wall, argon purge was used for the measurements near the boundary of the gas stream. A small amount of cold CARS signal was still found on the spectra taken near the boundary of the gas stream due to cold nitrogen leaking from the slag buster during its operation. N₂ CARS spectra taken during this test run were consistent and reproducible at the same place from one day to the other. The quality of the spectra were also quite good.

The CARS data were fit with DIAL's theoretical model to extract the temperature information. A typical fit from these measurements is shown in Figure 3.B.1. Part of the CARS spectrum containing the unknown feature was ignored in the fit. The results of the preliminary profile analysis are shown in Figure 3.B.2. The spectra were taken at -18, -16, -12, -4 and 0 in. from the center of the gas stream. The inferred temperatures are uniform near the center of the gas stream and drop rapidly near the edge of the gas stream.

Particle Size Distribution Test, CFFF LMF4-T Test Run, (W. P. Okhuysen):
The Particle Size Distribution instrument was installed at the exit duct of the ESP, (diagnostic penetrations 4904 and 4901). On the morning of May 29, the assembly of the optics was completed and tentatively aligned while the signal cables and optical fibers were routed from the platform measurement location to the sampling shelter below. The adjustment of the illumination beam focus and crossing was performed during the night of May 29 since the bright sunlight during the day obscured the projected image of the beam crossing. The receiver pinhole which determines the field of view for the collection optics was aligned using the illuminating beams as a guide. When the duct flow was initiated the following morning, the ripple signals were not present and it was concluded that the receive optics were inadequately aligned. Readjustment of the receive optics pinhole onto the external crossing of the illuminating beams resulted in good Doppler burst signals which were centered on the small-angle, near-forward scattering (SANFS) pulse when observed on a dual trace oscilloscope. No further alignment difficulties were encountered and the instrument remained in alignment until the end of the test.

Some difficulties were encountered with the prototype signal processor. For the ripple deconvolution unit, a broken wire in the beam power/chopper synch circuit was repaired. Problems with the ripple validated SANFS unit were judged to be of a much more difficult nature and repair efforts were discontinued. These problems, combined with some minor difficulties with the pulse height acquisition software, prevented measurements until 2220 hours on June 4. A total of 38 measurements were obtained using the ripple deconvolution mode of operation from June 4-8 and June 10-11. Most of these were accumulated over periods of 15 to 30 minutes and contain a total particle count of 50,000 to 100,000. Although the signal processor data rate was moderate at around 5,000

UTSI DIFFUSER CARS DATA: P=4", T= 2673K
DATE: JUNE 6, 1990

Figure 3.B.1. N₂ CARS spectrum taken 4 in. from the gas stream center at DOE/CFFF diffuser during the LMF4-T test.

Figure 3.B.2. N₂ CARS spectra taken at various points of the gas stream at DOE/CFFF diffuser during the LMF4-T test.

counts/sec, the pulse height histogramming software was not optimized for rapid execution and thus consumed most of the time during counting. This resulted in measurement times which were much longer than the minimum time period which is dictated by the maximum speed of the peak detectors in the signal processor. Optical access could not be maintained after 2200 hours on June 11 and measurement efforts were discontinued.

Analysis of the test data has been postponed until the field signal processor is complete and the acquisition software has been modified to speed the histogramming of pulse height data. The large quantity of data obtained will require some improvements to the present data reduction procedure.

Intrusive Multi-Probe System Test, CFFF LMF4-T Test Run (L. R. Hester and R. A. Green): The Intrusive Multi-Probe System (IMPS) with its light pipe sensor (LPS) was installed at penetration 3015 of the superheater test module (SHTM) in support of test LMF4-T. The LPS was positioned to measure the surface temperature of the ash deposition probe (ADP) during sootblowing. During the test a total of 38 insertions were made on three separate days.

On June 2, 1990, 13 insertions were made of which two coincided with sootblowing. At 1128 hrs an insertion was made while there was no sootblowing and the ADP was covered with a fine white ash. The tube surface temperature measured by the LPS was found to be 1658°F (1176 K) while the tube metal temperature, as measured by a CFFF installed thermocouple, was approximately 1200°F (922 K). This measurement indicates that even a thin layer of deposit on a tube can result in a pronounced difference between metal temperature and surface temperature. Measurements made later in the test indicated the surface temperature increased as the test progressed. These temperatures are given in Table 3.B.1.

At 1201 hrs a measurement of the ADP surface temperature was made during a sootblowing cycle. The surface temperature measured just prior to sootblowing was 1674°F (1185 K) and dropped 38°F (21 K) during the 5.5 seconds of sootblowing. Immediately after sootblowing the temperature was 1634°F (1163 K). A measurement made at 2200 hrs during sootblowing indicated the ADP surface temperature just before sootblowing was approximately 1689°F (1194 K). During sootblowing, the ADP surface temperature actually increased approximately 17°F (9 K) and then

Table 3.B.1.

ADP Surface Temperatures, June 2, 1990, Inserts 4-7.

ADP was covered with a thin layer of fine ash-like substance.

Insertion ID	Time	Temperature	
		°F	K
4	1128	1658	1176
5	1138	1703	1201
6	1148	1712	1206
7	1155	1673	1185

Table 3.B.2.

ADP Surface Temperatures, June 2, 1990, Inserts 9-14.

Insertion ID	Time	Temperature	
		°F	K
9	2130	1701	1200
10	2150	1689	1194
12	2230	1698	1199
13	2249	1706	1203
14	2330	1682	1189

returned to 1687°F (1193 K) after sootblowing. The reason for the temperature increase during sootblowing may be due to a temporary fuel rich condition resulting in secondary combustion at the sootblower. This is the only occurrence of this phenomenon observed during the test.

Average ADP surface temperatures measured when no sootblowing was in progress are tabulated in Table 3.B.2.

On June 3, 1990, a total of 14 insertions were made of which 12 provided useful data. An attempt was made to make measurements 10 minutes before sootblowing, during sootblowing, and 10 minutes after sootblowing. ADP surface temperatures and sootblowing temperature drops are given in Table 3.B.3. Due to changes in the sootblowing cycle and minor IMPS operating problems, only one insertion during sootblowing yielded valid data. Insertion 16 indicated that the deposit surface temperature dropped 44°F (24 K) during sootblowing.

Data collected on June 3, 1990, indicates that the surface temperature dropped rapidly during insertions. The reason for this effect is not known but is believed to be due to minimal deposits on the ADP resulting in a pronounced cooling effect caused by the IMPS or by ash deposits forming on the IMPS LPS reducing transmission of the radiation to the sensor. This effect was not observed during insertions of June 9, 1990. Several experiments are under consideration to be performed both in the laboratory and during the next CFFF test to investigate this phenomenon.

On June 9, 1990, additional insertions were made with the IMPS LPS to measure the surface temperature of the ADP deposits after they had reached equilibrium thickness. Eight insertions were made before a diffuser water leak caused a delay in the test.

Three insertions were made during sootblowing. These insertions were conducted by inserting the IMPS LPS to the proper position and making five seconds of measurements. Sootblowing was then conducted for five seconds as the surface temperature of the deposits was measured. An additional 5-10 seconds of data were collected after the sootblower was secured. Results from all eight insertions are given in Table 3.B.4.

Table 3.B.3.
Insertions Made on June 3, 1990.

Insertion ID	Time	During Sootblowing?	Deposit Surface Temperature	
			°F	K
17	0030	NO	1659	1177
18	0050	NO	1665	1180
19	0129	NO	1583	1135
20	0150	BEFORE	1645	1169
22	0217	AFTER	1603	1146
23	0935	NO	1703	1201
24	0949	BEFORE	1701	1200
26	1014	AFTER	1635	1164
27	1034	NO	1882	1301
28	1044	NO	1881	1300
29	1057	NO	1704	1202

Table 3.B.4. Insertions made on June 9, 1990.

Insertion ID	Time	Deposit Surface Temperature							
		No Sootblowing		5 Sec. Before Sootblowing		Drop During Sootblowing		5 Sec. After Sootblowing	
		°F	K	°F	K	°F	K	°F	K
30	0935	----	----	2003	1368	109	61	----	----
31	1017	----	----	1958	1343	94	52	1868	1293
32	1038	1971	1350	----	----	----	----	----	----
33	1053	1972	1351	----	----	----	----	----	----
34	1108	----	----	1992	1362	105	58	1881	1300
35	1120	1930	1328	----	----	----	----	----	----
36	1134	1965	1347	----	----	----	----	----	----
38	1225	1912	1318	----	----	----	----	----	----

A plot of a typical data set collected during a sootblowing cycle is given in Figure 3.B.3. This insertion, insertion 31, indicates a surface temperature of 1958°F (1343 K) before sootblowing. During the 5.5 seconds of sootblowing the temperature dropped 94°F (52 K) and then rose slightly after sootblowing to 1868°F (1293 K). Figure 3.B.4 is a composite plot of three insertions conducted 15 minutes before sootblowing, during sootblowing, and 12 minutes after sootblowing. Insertion 33 showed the temperature to be 1972°F (1351 K) which agrees well with the temperature measured during insertion 34 immediately prior to sootblowing. The sootblowing caused a temperature drop of 105°F (58 K) and a gradual temperature increase occurred after sootblowing. Insertion 35, made 12 minutes after sootblowing, indicated the deposit surface temperature was 1965°F (1347 K) which is 84°F (47 K) higher than the temperature measured immediately after sootblowing.

Figure 3.B.3. Deposit surface temperature measured during sootblowing.

Figure 3.B.4. Composite plot of deposit surface temperatures measured during insertions 33, 34, and 35.

C. Field Operation/Developing Systems

There is nothing to report for this quarter.

Task 4. Project Management

This is an ongoing task considered up to date with the submission of this report.

Task 5. Technology Transfer

While mindful of the mission of this task, there is nothing to report for this quarter.

END

**DATE
FILMED**

12/05/91