DIAGNOSTIC INSTRUMENTATION AND ANALYSIS LABORATORY

INTRUSIVE MULTI-PROBE SYSTEM

TOPICAL REPORT

**Robert A. Green
Leslie R. Hester
Charles W. Bouchillon**

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

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Diagnostic Instrumentation and Analysis Laboratory
Mississippi State University

MASTER

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Professor Hester served as mentor to many of us young engineers and assisted us in our work on the Intrusive Multi-Probe System. While we all contributed to the project, its success is due in large part to the efforts of Professor Hester in the early days.

A great deal of appreciation must also be expressed to the technicians who assisted in the construction of the various prototypes and who offered invaluable advice on construction methods and material choices. They willingly reviewed drawings for manufacturability and often worked from rough sketches. The quality product we developed is due to their skill and craftsmanship.

INTRODUCTION

The Diagnostic Instrumentation and Analysis Laboratory (DIAL) in the College of Engineering at Mississippi State University is the result of the efforts of several faculty members in the Aerospace and Chemical Engineering Departments obtaining funding in 1976. At that time, an initial research project was begun which was funded by the U.S. Department of Energy as part of the national magnetohydrodynamic (MHD) program.

Initial research efforts concentrated on heat recovery and seed recovery (HRSR) from the MHD combustion process as well as some materials investigations. Over the years, efforts at DIAL were shifted from HRSR studies to the development of optical based, microprocessor controlled instrumentation for use in the harsh MHD environment.

By 1980 the project had grown to such a scale that the MHD Energy Center (later renamed DIAL) was given departmental status in the MSU college of engineering. DIAL employs both full time research engineers and scientists as well as teaching faculty within the University who divide their time between DIAL and their academic departments. DIAL is a truly interdisciplinary organization employing scientists and engineers who not only cover the various engineering disciplines but crosses college boundaries and employs faculty from the College of Arts and Sciences as well. The interdisciplinary nature of DIAL is part of the reason for its continued success.

In addition to the researchers and academic faculty, DIAL also employs research assistants, support staff, and technicians. DIAL's support staff includes a technical editor, project coordinator, procurement coordinator, and several technical typists. To carry out its instrumentation development mission, DIAL also employs several technicians who specialize in various fields such as electronics, welding, carpentry, and machining. DIAL also has a very capable machine shop containing various lathes and milling machines among other equipment.

One important aspect of DIAL's mission is support of the national MHD project. One of the ways that DIAL fulfills this commitment is by transporting its instruments to the various facilities for operational testing and support. DIAL developed instruments have been utilized at facilities

across the nation including the University of Tennessee Space Institute (Tullahoma, TN), Mountain States Energy Corporation (Butte, MT), Argonne National Laboratory (Chicago, IL), and Avco Everette (Boston, MA). Many of the DIAL developed instruments have also been used at various industrial facilities as part of DIAL's technology transfer mission.

The development of instruments at DIAL go through several stages. Once an idea is conceived and developed, a laboratory based instrument is constructed. This stage allows fundamental concepts to be investigated and capabilities and limitations of the instrument to be determined. Because this is a laboratory-based instrument, changes can easily be made to the system configuration and various parts of the instrument optimized.

Once the laboratory phase is completed the instrument undergoes field trials. This involves some modification to the laboratory instrument to allow for the harsh environments encountered in the field. The modifications are made and tested on the DIAL test stand which simulates field conditions. Once these modifications have been made and tested the instrument is taken to a DOE operated facility where the true field test begins. During this phase, modifications are made to optimize the instrument to work under real conditions.

When the field test phase is complete and the needed modifications are made, the instrument is said to be field ready. This typically means that the instrument operation has been automated to an extent that a technician can operate it with minimal intervention. The instrument development does not stop, however. As new technology evolves or test conditions change, the researchers modify the instruments.

DIAL has developed several instruments in the manner described above. This report details the evolution of just one of these instruments known as the Intrusive Multi-Probe System or the IMPS.

NEED FOR INSTRUMENT

Measurements of systems must be made in order to obtain the needed information. Unfortunately, once a sensor is added to the system to obtain the needed data, the system changes due to the addition of the sensor. It is for this reason that nonintrusive or noninvasive techniques are in such high demand. In fact, development of nonintrusive optical techniques has been DIAL's forte for many years.

A time does come when nonintrusive methods simply will not work and it is at this time that intrusive techniques must be used. There are many reasons why nonintrusive techniques will not work. Some reasons encountered by DIAL over the years involve characteristics of both the process and the facility. A frequent problem involving the facility was not having adequate view ports available for the instruments to work. Several instruments involve transmitting light through a gas stream and receiving the light on the other side. This requires that two opposing ports be available with an unobstructed path between the two. Oftentimes there are not two opposing ports available and, when there are, they frequently not do have an unobstructed path. Another factor precluding the use of nonintrusive techniques is the optical depth or thickness of the gas stream. At times the gas contains too many particles to allow light to pass through it to the other side. The gas simply absorbs or scatters all of the incident light, leaving none for detection. To overcome these problems, intrusive techniques must be used.

Optical techniques developed or implemented by DIAL have numerous benefits. The fact that physical characteristics of a particular facility or process prevents them from being used in their nonintrusive form does not lessen their desirability. The IMPS resulted from this philosophy. DIAL wanted to marry the nonintrusive optical techniques to an intrusive vehicle thereby obtaining the benefits of the optical techniques while overcoming the physical limitations imposed by particular facilities or processes.

TECHNICAL APPROACH

Initial work on the probe system began in 1982 under the direction of Professor Leslie R. Hester. This work consisted of the design and construction of a probe insertion, retrieval, and positioning system (PIRP) that would deliver various probes into a gas stream, position them for data collection, and finally retrieve the probe from the gas stream.

Probes Considered

The primary goal behind the design of the probe system was to have a flexible instrument system that could be used to make many different types of measurements in a harsh combustion environment such as that encountered in magnetohydrodynamics.

Consideration was initially given to probes capable of delivering sensors which could measure parameters which were of prime interest at the time. These parameters included total pressure in the gas stream, electrical conductivity of the gas, and gas temperature. Although each of these sensors would be investigated, initial emphasis was placed on the design of a Sodium Line Reversal (SLR) probe which would measure the gas temperature.

Probe Insertion, Retrieval and Positioning System (PIRP)

The Probe Insertion, Retrieval and Positioning System (PIRP) was to be the primary vehicle used to deliver sensors to the gas stream. Equally important was the ability of the PIRP to deliver signals from the sensors in the gas stream to the data collection equipment. Due to the unique characteristics required of the PIRP, its design was necessarily difficult and tedious.

To be completely operational not only did the PIRP have to be designed but a control system had to be developed as well. While the PIRP was being designed, work on the sensors was also being conducted. Problems in obtaining needed parts and equipment were responsible for several delays in the initial phases of the project.

Intrusive Multi-Probe System (IMPS)

Once the PIRP was operational, operating parameters were changed and longer insertion lengths were required. A new sensor, the Accufiber Lightpipe also came on the market and met many of DIAL's needs. Effort then concentrated on the development of a new probe system which would handle the Accufiber Lightpipe Sensor and the longer insertion distances. The development of the new system however tried to maintain many of the PIRP design considerations, namely flexibility in the use of various probes.

The IMPS was to be designed as a lightweight, transportable system capable of supporting probes of various types, and ultimately being placed under computer control. To speed up field availability of the IMPS several of these design factors, such as computer control and flexibility, were initially ignored.

SYSTEM DESCRIPTION AND DEVELOPMENT

PIRP

The PIRP was to be designed as a flexible system which would allow sensors of various types to be placed on its end, inserted into a gas stream, and finally retrieved. The design philosophy was to maintain flexibility for future enhancements while allowing rapid changing of sensors in the field. Operation in the field was to consist of making a measurement with one sensor, then quickly changing sensors to measure another parameter.

Design constraints consisted of:

- Signal leads fixed at one end and able to translate 18 inches (457 mm) at the other;
- Handle high accelerations (on the order of 200 g);
- Interface to several types of sensors;
- Accommodate signal leads consisting of electrical wires, fiber optics, hoses, tubes, etc.;
- Accurately place the probe within a 16 inch (406 mm) range;
- Maintain exposure to the gas stream for a minimum of 250 milliseconds.

A major difficulty to be overcome in this system was the design of a signal lead handling system. Not only did the signal leads have to be flexible, they had to be sealed at the point they passed through the gas tight shell. Both of these problems were solved by using a self-coiling nylon tube. This tube entered the shell through a bulkhead fitting which allowed for a gas-tight seal and then coiled around the probe. As the probe was extended the coil allowed for the signal leads to extend as well. The nylon tube also prevented the fiber optic cables from exceeding their minimum bend radius.¹ This arrangement is shown in Figure 1. Once completed, numerous tests were conducted to determine if the stress induced in the fiber optic cables due to their stretching resulted in any signal attenuation. None was found.

A schematic of the PIRP system is shown in Figure 2 below. The main components of the PIRP were the probe, the insertion and retraction pneumatic cylinder, positioning stepper motor and encoder, pneumatic

isolation valve, and a pneumatic cylinder used to insert and retract the probe.

The mounting cylinder was designed to mate with a 3 inch pipe flange. To prevent exposing the probe and PIRP to excessive heat while retracted, a DeZurik knife gate valve (shutter valve) is used. This valve mounts on the 3 inch pipe flange and the PIRP then mounts to the shutter valve. The DeZurik valve operates on 10-100 psig air and the control solenoids require electricity at 60 Hz and 120 volts AC. The valve consumes 10.5 watts.

Two Parker pneumatic valves are used to control the insertion and retraction of the probe. These valves require 120 VAC, 60 Hz electricity and 10-50 psig air. The valves consume 14 watts of power. For insertion, one of the valves is supplied power which allows the air to force the probe into the gas stream. When ready for retraction, the insertion valve is de-energized and opened while power is supplied to the other valve which allows air to force the probe out of the gas stream. At the end of the probe retraction, the DeZurik shutter valve is closed, sealing the gas stream and protecting the PIRP from heat.

To achieve the precise positioning requirements of the PIRP a lead screw, DC stepper motor, and an encoder are used. The lead screw is attached to the probe so that when rotated it positions the probe platform. The motor can also be used in single step or jog mode for extra precise positioning. The position of the probe is determined by counting the pulses generated by an encoder. The encoder is a wheel which has 200 slots cut along its circumference. An infrared source on one side of the wheel shines light on the wheel while a detector on the other side of the wheel receives the light when it passes through a slot on the wheel. The detector generates a 5 volt pulse every time the infrared beam is broken. By counting these pulses the position of the probe can be determined. Each infrared pulse translated into a 0.01 mm movement of the probe.

One of the problems to be overcome in the design of the positioning system was the tendency for the probe to continue to move due to inertia once the stepper motor had been turned off. This was overcome by continuing to count pulses from the encoder after the motor had been turned off. Use of the single step or jog mode then allowed precise positioning of the probe.

IMPS

Accufiber System. The foundation of the IMPS system is the Accufiber Model 310 system manufactured by Accufiber, Inc. of Beaverton, Oregon. This system consists of a sapphire lightpipe sensor and detector unit. The detector unit receives radiation from the lightpipe via a fiber optic cable and then splits the radiation to two photo detector diodes. One detector is optimized for light at a wavelength of 800 nm and the other is optimized for 950 nm.

Detector signals are then sent through amplifiers to the signal processor where the signal is digitized and formatted. This processed signal is then sent via the General Purpose Interface Bus (GPIB) to a personal computer. The computer serves two functions; it converts the processed signal into temperature data, and it controls the entire system.

Additional information on the function of this system can be found in the Accufiber Model 310 Operator Manual.²

Gas Temperature Sensor. The gas temperature sensor consists of a sapphire rod with Iridium sputtered on its end. The rod is then placed in a protective sapphire sheath and inserted into the gas stream where its temperature rapidly approaches that of the gas. The Iridium serves as a blackbody cavity on the end of the sensor allowing the Accufiber system to measure the gas temperature. This system, while inherently extremely accurate, is faced with the same radiation problems as thermocouples. Once the appropriate corrections are applied the end result is no better than that obtained with thermocouples.

Some preliminary testing of this sensor was conducted in the DIAL combustion test stand but, due to the required radiation corrections, it was never taken into the field.

Wall Temperature Sensor. The Accufiber wall temperature sensor is similar to the gas temperature sensor, the only difference being the lack of Iridium sputtered on the end of the sapphire rod. The wall or surface temperature sensor, often referred to as the lightpipe sensor, consists of a sapphire rod which is surrounded by either a sapphire or quartz protective sheath. One end of the sapphire rod is attached to a fiber cable which transmits received light to the detector.

Surface temperatures are measured using the lightpipe sensor simply by placing the sensor in the vicinity of the surface to be measured. Radiation emitted by the surface is transmitted through the protective sheath to the sapphire rod which then transmits the radiation to the detector through a fiber optic cable. While the sapphire rod can be used without the protective sheath in certain applications, the sheath is normally required to protect the sapphire rod from surface contamination which degrades its total internal reflection characteristics.

Initial field testing of the lightpipe sensor began with inserting the lightpipe in a protective sapphire sheath into the gas stream. It was quickly realized that the sensor was fragile and any contact with the surface or large particles in the gas stream would break the sensor. To obtain accurate measurements, the sensor also had to be placed fairly close to the surface of interest to ensure cooler surrounding areas were not in the sensor's field of view.

As effort shifted toward measuring the temperature of the Ash Deposition Tube (ADP) in the Superheater Test Module (SHTM) section of the CFFF, sensor position became even more critical since the diameter of the ADP necessitated that the sensor be placed within approximately one-half inch of the tube surface. Any further than half an inch from the ADP, the lightpipe would also see the cooler walls of the SHTM. To obtain this precise a position, the lightpipe was positioned before the CFFF test began and marks were made on the probe system so that the insertion could be repeated. During CFFF test LMF4-K, several measurements of the ADP tube were made. It was then noted that the ADP, which was supported only at one end, had moved downstream approximately one inch which required that the lightpipe be repositioned. During this repositioning, the sensor was broken and the need for a better protection system became obvious.

Several sensor protection alternatives were developed and constructed for field evaluation. The common feature of all designs was a metal sheath which surrounded the lightpipe sensor and protruded over the end of the sensor approximately half an inch. One of the designs consisted of an open sheath which was a series of three concentric rings connected by four rods running longitudinally along the outer diameter of the rings. Other designs were simple stainless steel tubes which fit over the tube.

Testing of the various protective sheaths revealed several interesting features. First, it was necessary for the sheath to protrude approximately half an inch from the end of the lightpipe sensor to protect the sensor from ash deposits on the tube should contact be made. Second, the concentric ring sheath (or open sheath) proved unsatisfactory due to deposit buildup on the sapphire sheath. As the ash deposits would accumulate they would begin to radiate and this radiation was detected by the Accufiber sensor. Since the sensor was in the gas stream, the accumulated ash would approach a temperature near that of the gas, significantly higher than the ADP.

Continued testing of the closed sheath indicated that reasonable temperature measurements were made during the first few seconds of insertion but then the temperature started a gradual increase. This increase, shown below in Figure 3 was found to be caused by heating of the sheath as reported by Hester.³ As the sheath remained in the gas stream it became hot and started to glow. Since the sheath had to protrude past the end of the sensor, it was within the sensor's field of view. As long as the sheath remained cool it had negligible effect on the temperature measurement, but when it became hot it approached the gas temperature causing the ADP temperature to appear to be higher than it actually was. After some extensive testing the solution to this problem was found to be the insertion of a ceramic liner inside the tip of the closed sheath. The ceramic served as an insulator and allowed insertion times upwards of one to two minutes before the inner surface of the ceramic began to interfere with the measurement.

To allow probe position checks to be made during test runs when visual sighting was not possible, a closed-ended sheath was constructed. This sheath was similar in design to the closed sheath except that it had a closed end. By constructing this sheath to be a particular length, it could be placed over the lightpipe sensor and the probe then inserted until contact with the ADP (or other surface) was made. The probe position was then marked and retracted. When the open-ended sheath was placed over the sensor, the probe could be reinserted to the marked position ensuring that the sensor was the proper distance from the surface.

Sodium Line Reversal (SLR) Probe. Another important parameter to be measured in combustion systems is the gas temperature. Many techniques exist to accomplish this measurement but they have certain drawbacks which must be overcome. High velocity thermocouples

(HVT's) have typically been used for the measurement of gas temperatures but since these thermocouples also radiate to the furnace walls which are cooler than the gas, radiation corrections must be applied to the temperature. These corrections involve several factors, many of which are only estimates, leading to a relatively high degree of uncertainty in the final corrected temperature.

While infrared radiation techniques appear to have merit, they too have their problems. While looking at the gas stream with a pyrometer the operator will often have some of the surrounding furnace walls in the field of view. This will skew the temperature measurement made. Another infrared technique uses the Accufiber blackbody sensor which is described below.

A method that has been in use for many years DIAL is Sodium Line Reversal (SLR). This method detects the emissions from sodium atoms which can be found in sufficient quantities in most all fuel sources. Should adequate sodium not be present then the fuel can be seeded. This technique, described by Bauman⁴, is a line-of-sight technique requiring two opposing view ports. A light source is transmitted from one side of the gas stream to the other and absorption/emission of the light is measured. This absorption/emission is then related to the temperature. While great care has been taken to consider cooler boundary layers and their effects on the measured temperature, the measurement is still an estimate of the core temperature.

Given the accuracy of the SLR system and the insertion capabilities of the IMPS system, it was decided to pursue the development of a SLR sensor. This sensor would be designed to contain the necessary optics in a small sensor which would be fitted to the end of the IMPS water-cooled probe. All fiber optic cables would then be water cooled. The sensor would be inserted into the gas stream for a relatively short time and collect data. Initially the sensor was anticipated to operate with the existing SLR system thereby simplifying the instrument design phase.

The overall design of the SLR sensor seemed simple. The optical layout, depicted below in Figure 4, consisted of attaching a fiber optic cable to the end of the sensor which would deliver the light source. Optics inside the sensor would receive this light and focus it to a point in the center of the one-inch sample volume. On the opposite side of the sample volume additional optics would receive this light and collimate it. The

collimated light would then enter a dove prism fixed at the far end of the sensor which would turn the light 180 degrees where it would enter a fiber optic cable butted to the face of the prism. This cable then ran inside the sensor to the water-cooled probe.

Initially, the SLR sensor was designed so that the optics were placed inside a ceramic housing. This housing, manufactured from machinable ceramic, was split lengthwise to allow access to the interior optics. Since the ceramic required curing at elevated temperatures after machining, and since this curing resulted in dimensional changes, Teflon spacers were constructed to hold the optics in place within the ceramic. The two halves of the ceramic were then held together by a stainless steel housing and the entire assembly was placed inside a ceramic tube. Sapphire windows were added on each side of the sample volume to protect the interior optics from particles.

This assembly was tested in the laboratory and appeared to work properly. Field testing occurred at the Coal Fired Flow Facility (CFFF) in Tullahoma, Tennessee during test LMF4-O. This test revealed problems with the seals around the fiber optic cables and prevented any insertions from being made. A new seal design was developed and implemented on the SLR sensor and probe allowing testing to occur during LMF4-P, three months later.

During CFFF test LMF4-P, the SLR sensor and IMPS were set up to make insertions into the radiant furnace. The conventional SLR system was used to collect the data. The first insertion lasted for 12 seconds during which time some data were collected. Upon retraction of the sensor it was noted that the windows were dirty, a fact which would have impacted the temperature measurement. It was also reported that the conventional SLR system had obtained some data but the insertion time was too short to allow all of the needed data to be collected. The windows were cleaned and the probe inserted again. This time the sensor remained in the gas stream for approximately 60 seconds. When retracted, serious damage was noted. After cooling, the sensor was disassembled and it was discovered that the Teflon spacers had melted, some of the optics had melted, and the fiber optic cable had broken. CFFF instrumentation indicated that at the time of insertion, the gas temperature was approximately 3300°F (1815°C) which was much higher than anticipated.

Armed with data from the sensor failure, new design concepts and corrective measures were discussed. It was obvious that Teflon spacers would not work necessitating another method of anchoring the optics inside the sensor. The fiber optic cable running inside the sensor was also susceptible to damage requiring that it be moved outside the sensor. To prevent the windows from fouling they needed to be recessed from the gas stream, and it was ultimately decided that if the optics were recessed far enough to prevent fouling, then windows would be unnecessary.

A new machinable ceramic was found that did not require post-machining curing. This material allowed the sensor to be machined to precise dimensions eliminating the need to use spacers. This material could also be machined so that optics could be inserted without having to split the sensor lengthwise. This greatly improved the accuracy of positioning the optics. The only difficulty encountered was in developing a method to hold the optics in place and to connect the sensor to the fiber optic cables. This was a problem due to the different thermal expansion characteristics of the materials used. A firm fit had to be provided at room temperature while still allowing the optics to remain in alignment as the sensor heated during an insertion. The final design of this sensor is shown below in Figure 5.

The revised sensor was taken to the CFFF for testing during test LMF4-Q. During this test significant vibrations were present at the furnace and the sensor optics could not maintain alignment. Modifications in the SLR software had also been made to allow faster data collection. Although the optical alignment problem prevented the collection of valid temperature data, insertions were made to determine if data could be collected fast enough and to investigate thermal effects on the sensor. Results were promising. The SLR system appeared to be able collect the data in a short period of time (approximately 20 seconds) and no adverse effects of heat were observed on the probe.

The design of the SLR probe was continued as an ongoing project although no additional tests were conducted at the CFFF. Revised designs were developed and a water-cooled sensor was even developed.⁵ The SLR probe holds great promise for being able to make spatially resolved gas temperature measurements.

Positioning System. A central part of the IMPS was the positioning system. The positioning system was the element common to all probes

and sensors and would deliver the various sensors to their targets. Ultimately the positioning system was to be computer controlled and remotely operated.

Once it was noted that longer insertion lengths were required than could be obtained with the PIRP, new designs were considered. Since time was of the essence, a completely manual system was devised which could be immediately implemented in upcoming tests at the CFFF. This initial design consisted of a "L" bracket which could be attached to the 3-inch gate valves used by DIAL as shutters. This gate valve was then attached to the 3-inch flanges on the CFFF view ports. The vertical portion of the bracket had a hole drilled through it into which a Delrin ring was inserted. The Delrin ring had a hole drilled through it which was just slightly larger than the diameter of the probe. This hole was also drilled off center to allow additional positioning of the probe by rotation of the Delrin ring.

The horizontal section of the bracket had an assembly which supported the sensor end of the probe when it was not inserted through the Delrin ring. This was a clamp assembly which also secured the probe when not in use.

A bipod was constructed to support the rear of the probe and consisted of a clamp assembly on the top of a shaft which secured the probe to the bipod. The bipod was capable of being adjusted vertically to ensure the probe was level once the Delrin ring was positioned properly. Insertion was effected by swinging the probe away from the side of the SHTM at the CFFF to a predetermined position and then manually walking the rear bipod forward to another predetermined position. Done properly, at the end of this operation the sensor would be located at the proper distance from the sensor.

Several problems were encountered with the system. First, it was very difficult to position the probe properly when swinging it away from the SHTM and then maintain this relative position as the probe was inserted. This procedure had very poor repeatability and limited positioning accuracy. Second, the Delrin ring hole was a close fit to minimize air infiltration into the SHTM. This required that the probe be maintained level during the insertion, otherwise it would bind. While the probe's level could be established before insertion, the uneven decking surrounding the SHTM prohibited maintaining this level during insertion. Third, considerable time was spent positioning the sensor and probe once the

insertion was made. Since this fine adjusting was occurring while the probe was inserted and being heated by the gas stream, the actual time for data collection was limited.

The second generation insertion mechanism was designed to overcome the problems with the first design and to allow for the eventual implementation of computer control. The main elements of this new design were a precision grooved shaft and a linear bearing in a pillow block. This allowed a probe support/clamp to be attached to the top of the linear bearing and a drive cable attached to the bottom. The drive cable (aircraft cable) passed over a pulley at the rear of the probe and then wrapped around a drive drum several times at the front of the probe. The drive drum had a shaft extending from the side which allowed for the attachment of an optical encoder and a drive motor.

The linear bearing selected had a row of bearings which could be adjusted radially. This allowed the bearing to be placed on the grooved shaft and positioned so the adjustable row of bearings would be aligned with the groove. The adjustment screw could then be turned forcing the bearings into the groove. This feature prevented rotation of the bearing around the shaft requiring only one shaft to be used. Without this feature two shafts and bearings would have to be used to prevent rotation and larger supports would be required. A two-shaft design would weigh more than twice as much as the single shaft design.

On the front of the insertion mechanism a loose fitting clamp assembly was installed to support and guide the probe. During field tests it was found that this guide frequently caused the probe to bind so it was modified to include several roller bearings which eliminated the binding. Several adjustments were included on the front of the insertion mechanism to allow horizontal and vertical movement to align the probe with the Delrin ring and the target. The rear of the probe was supported by a bipod similar in design to that used with the first generation design. This bipod however had finer height adjustments which could be used since the bipod did not move during insertion.

Insertion occurred by moving the probe along the grooved shaft. A clamp placed at a specific location on the probe served as a positive stop for the probe. This was invaluable for manual insertions and would serve as a safety feature for computer controlled insertions.

Computer control of the insertion mechanism was a goal to allow operation of the system by one person from a remote location. It was decided that the system should be pneumatically operated since the gate valve was pneumatically operated and compressed air was available at all sites visited by the IMPS. The gate valve operation could be easily controlled from a computer. To control an air motor, which was to drive the probe, a subsystem had to be designed. This subsystem consisted of a series of solenoid valves which could be computer controlled and would direct the flow of air to the air motor. Switching these valves allowed the direction of rotation of the motor to be controlled and allowed for the motor to be stopped.

Probe position was able to be determined by using an optical encoder on the drive drum shaft of the insertion mechanism. By counting the number of revolutions made by the shaft, and by knowing the drum diameter and initial position, the final position of the probe could be determined. This system was field tested and found to work although the results were not as well as been hoped for.⁶

A study of the system indicated that the biggest problem with the system was in stopping the probe's translation. Initial efforts consisted of designing the software such that when the probe approached its desired position, compressed air would be simultaneously applied to the inlet and outlet of the air motor. In theory this would stop the air motor from turning. Since the position obtained by this method was crude, short pulses of air would then be applied to the air motor to make fine adjustments to the probe's position. However, applying these pulses could not be done quickly enough to obtain the desired positioning accuracy. Further investigation seemed to indicate that the problem could be an oversized air motor.

Several alternatives were discussed to overcome this problem. One option was to try a smaller air motor, but the concern was that oftentimes the air motor would overshoot the target distance running the risk of damaging the probe sensor. Another option was to add a clutch and brake assembly to stop the probe. This was given serious consideration but ultimately decided against implementation due to weight considerations. The third option which was investigated was the use of an electric motor. Chosen properly, an electric motor could supply the power needed for probe insertion and retraction while offering the needed resistance to stop the probe's translation. This design looked promising but was not im-

plemented due to termination of the program. Details of the control strategy and dynamic modeling can be found in *The Design and Simulation of a Positional Servo System Using Digital Control of a Continuous Time DC Motor.*⁷

Figure 1. Fiber optics signal transfer system.

Figure 2. Intrusive Multi-Probe System with SLR sensor and fiber optics signal transfer system.

Figure 3. Temperature variation measured by lightpipe sensor on DIAL test stand.

Figure 4. Sodium line reversal sensor system.

Figure 5. Schematic of SLR probe optics.

SYSTEM TESTING

PIRP

Testing of the probe insertion retrieval and positioning system (PIRP) was conducted on the DIAL combustion stand. The purpose of these tests were to determine the capabilities of the system and to test the control software. The PIRP was found to operate satisfactorily.

Initial testing of the PIRP was conducted using the original SLR probe. The sensor was inserted into the gas stream which was at a temperature of 3454 °C for 9, 5 and 4 seconds. No SLR signal loss was observed during these tests however, the SLR system could not respond fast enough to obtain useful temperature data. A visual inspection of the sensor and the PIRP revealed no physical damage occurred during the insertion.⁸

IMPS

Gas Sampling Chamber. To assist in the development of the Optical Nitric Oxide (ONO) system, a gas sampling chamber was developed for the IMPS. Difficulty in measuring the NO concentration on the gas stream was found to be the inability of light to pass through the thick gas streams encountered in MHD flows. To overcome this problem, a stainless steel vessel was designed which had opposing windows. Gas would be withdrawn from the test stand through the sample vessel and the ONO system would be set up to look through the sample vessel.

Testing was conducted and ONO data were found to be repetitive. Further data analysis however revealed that the ONO data indicated a NO concentration of roughly half that measured by the conventional NO system.⁹ The cause of this discrepancy is believed to be due to cooling of the gas sample during extraction and the resulting condensing of NO.

Gas Temperature Sensor. One sensor purchased with the Accufiber system was a gas temperature or blackbody sensor. This sensor consisted of a sapphire rod with a layer of Iridium sputtered on the end. This rod was then inserted into a sapphire sheath for protection. In theory, when the sensor was inserted into a gas stream, the sapphire rod would heat up to the gas temperature and the Iridium would act as a blackbody cavity. The

Accufiber system could then detect the emitted radiation inside the Iridium cavity and determine the gas temperature.

Bench top tests of this sensor were conducted on various types of flames and compared to the flame temperatures as measured by a platinum-rhodium thermocouple. These tests indicated that the blackbody sensor repeatedly yielded temperatures approximately 250°C lower than that obtained by the thermocouple. These results indicated that further testing on the combustion test stand should be conducted using the blackbody sensor and the SLR system.¹⁰

Testing on the test stand of the blackbody sensor showed that the temperatures measured were on the order of 350 K lower than those measured by the SLR system. Both the blackbody sensor and the SLR system were operating on the test stand in a region where the gas temperature was 1800-1900 K.¹¹ Further analysis and modeling revealed that the temperature difference was due to the cooler walls of the test stand. This being the case, several corrections had to be applied to the temperature obtained with the blackbody sensor rendering its accuracy to be no better than that obtained with other temperature measurements such as thermocouples.

Lightpipe Sensor. After testing of the blackbody sensor was completed, effort shifted to testing the Accufiber lightpipe. As discussed above, the lightpipe sensor is a rod of sapphire enclosed in a sapphire sheath. The rod receives radiation from a source such as a furnace wall and transmits the radiation to the detector. The lightpipe is designed for surface temperature measurements vice gas temperature measurements.

Initial testing on the MSU combustion test stand was conducted using the SLR and Multi-Color Pyrometer (MCP) systems for data verification. To avoid having to insert the sensor into the gas stream an attempt was made to conduct measurements using the lightpipe outside the gas stream. Initial results looked good but further analysis indicated the temperatures measured by each particular detector were vastly different. This resulted in erroneous emissivity calculations and prompted further testing using a blackbody temperature source. The blackbody testing showed that to obtain the proper emissivity, the lightpipe needed to be placed roughly one inch from the surface being measured.

Field testing of the lightpipe sensor began at the CFFF, Tullahoma, Tennessee by measuring the surface temperature of the superheater tubes in the superheater test module (SHTM). Of particular interest in the SHTM was a tube being used to study the deposition of ash during a test run. This tube, known as the ash deposition tube or ADP, simulated a superheater tube in that it had water and steam flowing inside, but differed in its ability to be retracted thereby removing ash deposits. The ADP was also positioned so that various types of sootblowers could be tested.

The performance of the lightpipe sensor on the SHTM was outstanding. Numerous measurements were made over a series of CFFF runs beginning with LMF4-K. A typical test began by positioning the IMPS and the lightpipe before the test began ensuring that the proper tube was being looked at by the sensor. During the test, insertions would be made placing the lightpipe within one inch of the tube and collecting data for up to a minute. The probe would then be retracted and allowed to cool before another insertion was made. During these tests several modifications were made to the IMPS as described above. These modifications allowed for more reliable operation and data collection. Ultimately a system was obtained that could be set up during a test run eliminating the need to have a cool facility for installation. This feature makes the IMPS a truly field-operable instrument requiring minimal support from the facility where the tests are being conducted.

Several tests were conducted on a row of superheater tubes in the CFFF SHTM. These tests were performed to see the variation in tube temperature as a function of tube position. Limitations on which tubes could be measured were caused by the physical location of the tubes and the view port through which the IMPS was operating.

Interesting data were collected during sootblowing of the ADP. Working closely with the CFFF engineers, measurements of the ADP were made just prior to sootblowing. At this time ash deposits had accumulated on the surface of the ADP causing it to have a surface temperature significantly higher than that of the underlying metal tube temperature. These measurements typically occurred 2 minutes prior to sootblowing. Another insertion was made while sootblowing with air was actually being conducted. These measurements revealed a sudden drop in tube temperature as the deposits were removed. The lightpipe was then retracted and reinserted for additional measurements two minutes after

sootblowing was secured. These measurements showed that the tube temperature had risen slightly after sootblowing but not up to the pre-sootblowing values. A plot of the before, during, and after sootblowing tube temperatures for test LMF4-P are shown in Figure 6.

As an indication of the versatility of the IMPS lightpipe sensor, measurements of the furnace wall temperature at the CFFF were made during test LMF4-Q. Since the gas temperatures were higher in the radiant furnace than in the SHTM, initial measurements were conducted at the fourth level of the furnace (penetration 2231). After making eight insertions at this location it was decided that the IMPS could withstand the higher temperatures and the system was relocated to the third level of the furnace at penetration 2225. Gas and wall temperatures were expected to be higher at this location. Nine data sets were collected from this location indicating the wall temperature was approximately 100 to 150 K higher than at penetration 2231.

The series of tests conducted at the CFFF were invaluable in providing information for system modifications. It was from the CFFF tests that the sensor protection and radiation shielding designs described above evolved. These modifications to the IMPS make it a highly reliable instrument for making accurate temperature measurements under harsh conditions.

Sodium Line Reversal System. Testing of the Sodium Line Reversal (SLR) System began with lab testing using a burner. These tests indicated that the SLR probe design was workable and ready to proceed to additional testing.

Results of field tests of the SLR probe revealed several design obstacles to be overcome before a fully functional design could be developed. The primary effects include that of vibration. The difference in thermal expansion properties of the ceramic optics housing, the optics spacers, and the optics themselves present a design challenge. As the probe is heated each of these materials expands at a different rate and to different sizes. To prevent over-stressing the material while at operating temperatures, the design must include a certain amount of loose fit in the components at ambient temperatures.

It was observed that during CFFF testing the vibration of the test facility resulted in excessive shifting of the optics within the housing. This

then added misalignment errors to the system which had to be overcome. The ultimate solution to this problem lies in further optimization of the thermal properties of the materials used.

Figure 6. Superheater tube surface temperature, DOE/CFFF.

CURRENT STATUS

Performance

The Intrusive Multi-Probe System has proven itself time and again to be a highly reliable method of temperature measurement. Numerous field applications have resulted in overcoming the initial difficulties with the lightpipe sensor and the system is now optimized and ready for additional field application.

Availability

As with most field ready equipment at DIAL, the IMPS is field ready and available for field application with minimal notification. The small size of the heart of the system makes for easy transportation to most any facility. The only potential transportation problem is the ten foot long probe however, a shorter probe could be easily constructed for shorter insertion depths.

Future Development

Currently no additional development is anticipated for the IMPS unless new applications arise. The manufacturer of the lightpipe system is no longer making this particular model for retail sale but has a multi-channel model available for industrial control use. This older model however still finds application at DIAL and in the manufacturer's lab.

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