OVERVIEW OF DIODE LASER MEASUREMENTS IN LARGE-SCALE TEST FACILITIES

M.G. Allen*, B.L. Upschulte†, D.M. Sonnenfroh†, W.J. Kessler†, and P.A. Mulhall‡

Physical Sciences Inc.
Andover, MA 01810

Abstract

Near-IR diode laser sensors and associated fiber-optic networks are finding applications to a variety of aerospace test applications - from large scale ground test facilities to flight testing. The sensors have been used to measure species concentration, temperature, and velocity in a range of flows. Recent applications to scramjet, oxygen-enriched combustion, and flight testing are described.

Introduction

Near room-temperature diode lasers have received considerable attention in recent years for their potential role as real-time sensors in a variety of combustion, aerodynamic, environmental, and propulsion applications. Compact lasers operating a wavelengths between 630 and 2000 nm have been applied to absorption-based measurements of species such as a CO, CO₂, NO, NO₂, H₂O, O₂, and CH₄, among others, all of which are relevant to aerospace development and testing. Well developed spectroscopic techniques for gasdynamic measurements of velocity, temperature, pressure, and mass flux have also been demonstrated in both laboratory flames, supersonic test facilities, and industrial furnaces, as summarized in the recent review of Reference 1.

As the understanding of the sensor architecture and the near-IR spectroscopy of the target molecules matures, these sensors are finding application to large-scale test facilities. A fiber-coupled sensor operating near 763 nm developed for simultaneous measurements of air density and velocity was applied to a Pratt & Whitney F-100 engine in ground tests nearly 3 years ago.² The success of this test has resulted in a flight test program scheduled to apply an environmentally qualified, fully-autonomous sensor aboard an F-18 aircraft in late 2000.³

Many issues remain to be resolved, however, before the full potential of these devices for general purpose test facility application is realized. These range from persistent inadequacies in the basic spectroscopic database of the weak near-IR transitions, particularly at high temperature, to engineering issues associated with reliable optical access, long-term stability of the autonomous sensor platforms, and environmental certification for flight applications.

In this paper, we describe progress in our laboratory toward addressing these issues. We focus on two specific sensor configurations and several application scenarios representative of the most mature target measurements: water vapor and CO (representative of a combustion product species), and oxygen (representative of general unseeded air sensing). In these cases, the basic spectroscopy is reasonably well understood and applications to gasdynamic measurements are well established (cf., Reference 1 and the references therein).

Overview of Measurement Approaches and Sensor Requirements for Aeroengines

The diode laser sensors derive their measurements of the gasdynamic properties through resonant absorption by target molecules in the flow. Details of the methods for density, temperature, velocity, and mass flux are described in Reference 1. To briefly summarize, the absorption is described by the Beer-Lambert relation:

\[
I_\nu = I_{\nu,o} \exp \left[ -S(T) g(\nu - \nu_0)N/ \right] 
\]  

(1)

where \(I_\nu\) is the monochromatic laser intensity at frequency \(\nu\), measured after propagating a pathlength \(l\) through a medium with an absorbing species number density \(N\). The strength of the absorption is determined
by the temperature-dependent linestrength, S(T), and the lineshape function, g(ν-ν0). The lineshape function describes the temperature- and pressure-dependent broadening mechanisms of the fundamental linestrength. If the medium is invariant over the absorption pathlength, then straightforward inversion of Eq. (1) yields a quantity proportional to a number of gas dynamic properties.

The linestrength of the absorption transition is a fundamental spectroscopic property of the absorbing species, although usually it is expressed in relationship to tabulated values available in one of a number of databases. The most commonly used and extensive database for IR transitions of small molecules is the U.S. Air Force HITRAN database, originally developed for atmospheric transmission applications. The linestrength at any temperature S(T) can be calculated from the known linestrength at temperature S(T0) using:

\[
S(T) = S(T_0) \frac{Q(T_0)}{Q(T)} \exp \left[ -\frac{hcE}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \times \frac{1 - \exp(-hcE/kT)}{1 - \exp(-hcE/kT_0)}
\]

(2)

where Q is the total molecular internal partition function, E is the energy of the lower transition state, h is Planck's constant, k is Boltzmann's constant, and c is the speed of light. The last term accounts for stimulated emission and is negligible at wavelengths below 2.5 µm and temperatures below 2500 K.

If the gas temperature, line-strength, and absorption path are known, the measured transmission may be directly related to the absorbing species number density. It is usually possible to select a particular absorption transition such that the temperature variation of the linestrength over some limited range (typically several hundred K) can be neglected. Separate measurements of temperature can be used to correct for variations, if necessary.

Alternatively, two absorption transitions may be probed (using one or two lasers, depending on the target transition separation and the laser tuning range). The ratio of the integrated absorbance of each transition is a pure function of temperature:

\[
R = \frac{S_1}{S_2} = \frac{Q(T_0)}{Q(T)} \exp \left[ -\frac{hc\Delta E}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]
\]

(3)

where S1 and S2 are the linestrength values at some reference temperature, T0, and ΔE is the energy separation of the absorbing state. The temperature sensitivity depends on the values of the reference linestrengths and the energy separation. With the temperature so determined, either or both absorbances can be used to determine the number density.

If the laser beam propagates across a flow with a bulk velocity V, the molecules in the moving reference frame of the gas observe a laser frequency that is Doppler-shifted according to

\[
\Delta \omega_{\text{Doppler}} = \frac{V}{c} \cdot \omega_0 \cos \theta
\]

(4)

where \( \theta \) is the angle between the laser propagation and bulk flow directions. Since the absorption measurement itself gives the density of the gas, measuring the Doppler-shift allows determination of the density-velocity product or the mass flux.

The sensor configurations developed at Physical Sciences Inc. (PSI) for large-scale testing consist of inlet air mass flux (based on simultaneous oxygen density and velocity measurements); combustor temperature and product mass flux (based on simultaneous water vapor density, velocity, and temperature measurements); and CO/O2 monitoring in industrial furnaces.

Inlet air mass flux measurements are desired for improved control of variable geometry inlets in supersonic aircraft, power optimization during maneuvering, and engine health monitoring. In these scenarios, the overall bandwidth of the control system is less than 1 Hz, so a sensor response time on the order of 1 s is sufficient. Here and throughout this paper, response time is meant to indicate the time for the sensor to report a new value of the measurand (density, velocity, mass flux, etc.) after a step change in the operating condition and is inclusive of all data acquisition, averaging, reduction, and recording time delays.

Accurate measurements of inlet mass flux (precision better than 2%) suggest that subtle, transient fluctuations in the average inlet mass flux might be used to indicate incipient compressor surge or stall phenomena. Specific response times for sensors used this way depend on the control and actuators employed, although our work is focused on at least 0.1 s (10 Hz) with a desired goal of 0.01 s (100 Hz). The laser wavelength is typically swept across the absorption
lineshape, whose area is then integrated to yield the total absorber number density. This could be accomplished more rapidly, if necessary, although the total sensor throughput is presently limited by the 1 MHz A/D converters used on the PCI backplanes.

Typical performance specifications for inlet mass flux sensors are dictated by the perceived precision of the pitot-static measurements used to calibrate present engine control systems. This is generally specified as ± 2% over the range of about 10 to 300 lb/s. For typical military aeroengines, this range corresponds to an air density and velocity range (at the inlet guide vane station) of about 0.1 to 2 kg/m$^3$ and 10 to 200 m/s.

Measurements at the combustor exit or high-pressure turbine inlet station are the most severe for any optical sensor. In real-time sensor or testing applications, the response time is governed by the overall engine or facility control system and is again typically on the order of 1 s. For gas turbine engines, the temperature range should span 1500 to 2100 K at pressures from at least 10 atm on current engines to up to 50 atm for advanced engines. The combination of high temperature and pressure place extreme demands on the design of optical windows and mounts. The high pressures tend to collisionally broadened the target absorption lines, reducing the visibility of the signal itself and rendering interpretation of the often overlapped line features problematic.

In ram/scramjet propulsion system development, peak combustor exit temperatures can approach 3000 K, although the pressure is usually limited to a few atm. Here, the thermal management of the optical interfaces is even more challenging. The basic spectroscopy becomes increasingly uncertain, as well, particularly with regard to water vapor, which possess numerous transitions throughout the near- and mid-IR. The lack of detailed information on high temperature water vapor makes quantitative interpretation of sensors targeting water vapor absorption difficult and spectral interferences with other target species becomes increasingly difficult to predict.

For industrial furnace measurements, the response time requirements are again driven by overall control systems to between 0.1 and 1 s. In the case of oxygen-enriched combustion, where much of our work is concentrated, exhaust temperatures can be as high as 2500 K. Total gas pressure is usually about 1 atm.

Simultaneous Water Vapor Mass Flux and Thermometry

A dual laser sensor based on water vapor absorption measurements near 1.31 μm has been installed on a scramjet propulsion test facility at Wright Patterson AFB. The sensor is used for simultaneous measurements of water vapor density, velocity, and temperature at various locations within model combustors. The measurements are based on the methods outlined in the section above and are all determined autonomously from an integrated laser/computer/electronics module housed in a half-height, 19-in. rack. The rack is located in a separate control room with only fiber-optic and electrical connections to the test facility. The dual wavelengths are combined on a single fiber-optic line using a time-domain multiplexing technique, previously described and demonstrated for up to three different wavelengths, although much higher density multiplexing is also feasible.

Since the test facility is itself driven by the vitiated output of a combustor, water vapor is present in at levels of several percent or higher through the combustor. The eventual application of the sensor is to measure the temperature increase and increased water vapor flux between the test model inlet and exhaust to aid in determination of the combustor efficiency.

Lasers near 1.31 μm were selected for this sensor because this wavelength corresponds to a telecommunication wavelength standard, thus ensuring a ready supply of high quality devices for the foreseeable future. Reliable supply of custom wavelength diode lasers for other sensor applications remains a critical barrier to widespread commercialization. Although the HITRAN database tabulates water transitions at these wavelengths, earlier work showed that significant errors appeared in the high temperature spectra, even at relatively modest exhaust gas temperatures near 1000 K.

Fundamental measurements of the linestrengths, positions, and broadening behavior of target transitions in this wavelength region were recently completed and compared to new high temperature computational databases. These results show that individual isolated transitions are not necessarily available, so our strategy has been to empirically calibrate the temperature-dependent behavior of absorption features that consist of multiple transitions, some of which are not assigned at this time. Measurements from room temperature to...
1000 K were made in a heated cells and measurements from 1200 to 2100 K were made in a laboratory flat flame burner.

Figure 1 is an example of the dual wavelength sensor’s performance during a continuous sequence of measurements in an atmospheric pressure, H₂-air laboratory flat flame burner. The measurements were acquired with a 0.3 Hz bandwidth and a total hot-gas pathlength of 70 cm. The figure shows a sequence of flame stoichiometries obtained by adjusting the inlet fuel/air ratio, thereby spanning gas temperature from 1200 to 2100 K and water vapor number densities from $6 \times 10^{17}$ to $1.1 \times 10^{18}$ cm$^{-3}$. The optical sensor data are compared to simultaneous thermocouple gas temperatures (solid line) and calculated equilibrium water vapor concentrations at the measured stoichiometry and gas temperature (dashed line). The precision of the temperature measurements over this large range is ±15 K (corresponding to less than 1% of full-scale) and the absolute difference between the optical and thermocouple measurements never exceeds 50 K (about 2% of full-scale), well within the absolute uncertainty of the thermocouple measurement. The precision of the density measurement is better than $2 \times 10^{16}$ cm$^{-3}$ (less than 2% of full-scale). Comparisons between the sensor and calculated equilibrium concentrations differ by as much as $1.5 \times 10^{17}$ cm$^{-3}$ (about 15% of the nominal value), although at least part of this may be attributable to non-equilibrium conditions in the flame.

The design and engineering of the optical interface to the supersonic combustor is critical for high temperature applications. Because the steady state wall temperature of the combustor can exceed 400 K, it was necessary to cool the optics to protect the fiber optic collimators and InGaAs photo detectors. To achieve high absorbance sensitivity, the windows required anti-reflection coatings at the laser wavelength and these coatings were limited to 500 K. In addition, particulate deposition on the windows was a concern. These considerations required the use of both water cooling and gaseous nitrogen film cooling to protect the optics. Because the flow field was supersonic, minimizing flow perturbations due to the film cooling was critical for the design.

A schematic of the gaseous film cooling system is shown in Figure 2. The IR-grade fused silica windows are 1.9 cm diameter with a 2.54 cm diameter shoulder. The windows are AR-coated at 1.31 µm for an incidence angle of 15 deg. Nitrogen was fed through machined passages in the window mount and limited by a choked, 2.0 mm orifice. Mass flow for film cooling corresponded to about 5 scfm per window or 25 scfm total which was less than 0.5% of the main combustor flow.
tunnel test section schematic is from left to right and the tunnel test section is immediately downstream of the expansion nozzle. The test section includes a variable expansion plate in the top. The side wall panels were positioned in the center corresponding to expanded conditions of Mach 2.1 at the sensor location. These panels included connections for water cooling, nitrogen gas film cooling, and a variety of locations for pressure taps to monitor potential flow disturbances. Water cooling to stabilize the panel for the optical windows required the removal of 200 W of thermal power and corresponded to an 11 K temperature rise for a nominal water flow rate of 8 gallons per minute with a pressure drop of 10 psi for each panel.

The detector holders for the sensor were purposely positioned after a turning mirror to reduce light collection by the detector from the heated walls and hot particles in the flowing gas stream. The mirrors possess a narrow band coating for maximum reflectivity only at the laser wavelength, further reducing the radiative load on the photodetectors. The collimating optics consisted of a 5 mm diameter anti-reflection coated asphere mounted directly onto the end of the fiber by the manufacturer. Typical collimated beam diameters from single-mode near-IR fibers are about 2 mm. No attempt was made in this setup to further expand this beam, although it is well known that increasing the beam diameter will reduce the angular deflection of a collimated light beam in the presence of a given density distortion. The beams impinged directly onto the largest area InGaAs photodetectors presently available with a 5 mm diameter active area.

Several spectrally resolved lineshapes were obtained during the startup sequence and initial pump-down of the tunnel. Figure 4(a) shows the atmospheric water absorption on the 7612 cm\(^{-1}\) doublet prior to pump down. The minimum tunnel pump down pressure is 3 psia, and the observed water absorption at the 7612 cm\(^{-1}\) doublet under these conditions is shown in Figure 4(b). The narrow line widths due to reduced collisional broadening are consistent with the low pressure condition. At this low signal level, some optical interference fringe effects are evident in the baseline.

Simultaneous density, temperature, and velocity measurements were recorded at 1 Hz throughout the sequence of increasing stagnation temperatures at an expanded pressure of 13 psia. Figure 5 shows the measured water density during the sequence of changing stagnation temperatures. Figure 6 shows the simultaneous free stream static temperature measurement, and Figure 7 the simultaneous velocity measurement.

The data exhibits the best signal to noise in the density measurement with decreasing signal to noise in the temperature measurement and large excursions in the velocity measurement. This behavior is nominally
understood by recognizing that four different absorption lines are monitored, integrated, and averaged to determine density. The temperature measurement requires at least one line of sight in the high speed flow to provide good signal to noise data so that the ratio of integrated absorption can be measured to determine the temperature. The temperature measurement exhibits the combined noise from both integrated lineshapes. The most demanding is the velocity measurement which requires high signal to noise in the line shape to determine position shift, i.e., not an integrated area, and requires that high signal to noise lineshapes be present on both lines of sight simultaneously. Further, the algorithms used to determine velocity are more sensitive to noise than either the density or temperature.

Although large excursions in the sensor output were observed, the optical sensor tracks both the water density and temperature changes. The sensor density and temperature measurements both suggest that the static conditions in the supersonic test section are not stable, but drift upwards in density and temperature during these periods. At present, this effect is not well understood, but is tentatively attributed to instability in the facility operation. The measured water density shows a discrepancy with predictions ranging from 17 to 56%, but has a precision of better than 10%. The present flow models used to predict the in-stream values should be considered as estimates at the present time and more detailed model/experimental data comparisons are required before any concrete conclusions can be drawn regarding the absolute validity of either measurement or model. At this stage of the sensor development, we are more concerned with the precision of the sensor since that is an independent assessment of the stability of measurement condition. The measured temperatures show the best accuracy relative to predictions, 7 to 11%, but the low signal to noise results in a typical temperature precision of only ± 100 K. The velocity measurement is the most distorted. The poor signal to noise in the velocity measurement is attributed to beam steering effects in the flow. Additional details of this sensor can be found in Reference 6.

**Flight Testing of Inlet Mass Flux Sensor**

For aerospace systems, the final and most important testing occurs during flight. We have been developing air mass flux sensing technology based on simultaneous density and velocity measurements of $O_2$ for a number of years and successfully completed a number of ground tests in compressor test facilities, calibrated supersonic flow tunnels, and full-scale aero-engine in ground tests. A fully autonomous, flight-qualified sensor package is now being installed on a NASA Dryden F-18 Scientific Research Aircraft and will undergo a first series of tests in late summer, 2000.
Figure 8 shows a schematic of the F-18 with the engine inlet duct cutout and the location of the two lines of sight for the sensor installation in the left side inlet. The main Sensor Processor Module (SPM), which houses the laser, computer controller, and associated detection electronics, is mounted in a small chamber immediately behind and below the pilot cockpit. In conjunction with Boeing, we have designed optical mounting hardware to fit within the F-18 structural frame and penetrate the inlet duct wall. Two mounting points are located in the main landing gear bay on the underside of the inlet duct approximately 0.9 m forward of the front face of the engine.

![Figure 8 Schematic of F-18 engine inlet showing mass flux sensor mounting locations.](image)

To achieve fully autonomous operation, including health monitoring, control, data acquisition, data reduction, data archiving, careful attention must be paid to the overall software environment. A flowchart describing the sensor operation in the context of a flight test is shown in Figure 9. Prior to powering the SPM, the pilot switches and external panel switches need to be reset. The computer power should be turned on first. After a short pause (30 seconds), the analog systems can be powered. The computer operating system, Microsoft Windows NT®, is then loaded. During this process, the system clock is synchronized with the IRIG B time code retrieved from the aircraft by the time and frequency processor card (Datum BC620AT). Two applications will be resident when the sensor is operating: 1) Norton PC-Anywhere® which allows the system to be controlled by a remote computer via the ethernet port, and 2) a custom application to control the sensor operation. The latter is written in the C programming language under the National Instruments Lab Windows® programming environment.

The first operation of the sensor is to initialize the data acquisition system and stabilize the laser temperature. During this process the sensor signals the aircraft via the RS-232 serial port that it is initializing. The stabilization of the laser temperature takes several minutes. The sensor then monitors the status of the laser enable switch on the outside of the SPM. Turning on the laser enable switch signals the SPM to execute a

approximately 40 deg and 45 deg. This sensor geometry is similar to that used during ground testing and is expected to achieve +/- 2% rms mass flux precision.

A unique attribute of flight testing is the requirement to interface with vehicle power and data communications protocols. For the flight sensor, the interface with the aircraft consists of four connections: 1) +28 VDC power in, 2) RS-232 serial port communications output, 3) IRIG B time input, and 4) pilot reset signal input. Additionally, there are two switches on the external panel of the SPM for powering the computer and analog systems, respectively, and a third switch to enable/disable the laser. Finally, an ethernet connection is provided for pre- and post-flight operations, such as instrument reconfiguration and data archiving. During flight tests, the pilot can affect the sensor’s operation through two switches: 1) a power switch which will interrupt the +28 VDC to the SPM, and 2) a pilot reset switch which will signal the SPM to start/stop the logging of measurements to its internal hard drive.

Two additional mounting points are located immediately upstream of the inlet face on the upper side of the inlet duct. Because a multitude of equipment is located adjacent to the inlet duct and because many other areas are not accessible, these mounting locations represent a compromise between utilizing space available and optimizing the sensor geometry. The absorption pathlengths are slightly greater than 1 m, and the crossing angles of the two beams are
Figure 9. Flow chart for sensor operation.
calibration sequence. This is part of the pre-flight ground operations with the aircraft engines off. The density of the air in the inlet is calculated from measurements of the static pressure and temperature. It is assumed that the velocity of the air inside the inlet is zero. The sensor acquires signals as in normal operation and use these measurements to determine the parameters necessary to convert the raw absorption signals to air density, velocity and mass flux. A summary of the calibration results is communicated to the aircraft so that the proper operation of the sensor can be verified prior to a flight test. If the laser enable switch is already on when the sensor initializes, it uses the previous calibration parameters in the data reduction process. This logic is programmed into the sensor to allow the pilot to power down the sensor during flight, and return it to operation without executing a calibration sequence when power is restored.

After the calibration sequence, the sensor begins to report mass flux measurements via the serial port. Data is logged to disk only during certain periods of the flight test. Thus, if the pilot reset switch is turned on, the sensor logs the results to the internal hard drive. In either case, data will be continually reported to the serial port. For the initial flight tests, the data reporting rate will be 1 Hz. Included in serial port data will be a 4-byte sensor status indicator and a 4-byte counter. The status indicator is used to report the operating mode of the sensor as well as any detected faults (e.g., low laser power, laser temperature out of range). The counter is continually incremented and acts as a heartbeat signal for the sensor so that interruptions in normal operation can be detected quickly.

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After the test sequence is completed and the engines are shut down, a final sequence of mass flux measurements are recorded to verify the static flow condition results. This is used as a post-flight verification of the initial sensor calibration. Subsequently, the laser is disabled, which signals the sensor to stop reporting massflux measurements. The sensor can then be safely powered off.

To retrieve data from the sensor after a flight test, a remote computer, such as a laptop, is connected to the SPM via the ethernet port. The SPM computer can then be powered up to access the data files on the hard drive via the PC-Anywhere interface.

Another unique attribute of flight testing is the thermo-environmental requirements imposed. These have been discussed previously. Here, we show recent data from a thermal testing of the SPM over a 50 C temperature excursion. From previous tests, we expected that the actual laser operating temperature might drift slightly during the external temperature ramp, therefore we modified our basic sensor control/data reduction software to include automatic centering of the O2 absorption feature. The line center of each sweep is determined by interpolating from the two Full-Width, Half Maximum (FWHM) points of the lineshape. The starting value of the injection current ramp is adjusted with a 1 s time-constant to account for small drifts in the laser wavelength that result from the temperature drift.

Figure 10 is a plot of the average injection current value and the laser baseplate temperature as the environmental chamber temperature is changed from 50 C to 0 C (at 9:20). It takes approximately 30 min for the baseplate temperature to equilibrate at the setpoint. Throughout this cycle, the laser thermistor temperature read a constant value of 14.0 C and the average output maintained a constant value of 3.3 mW. In order to center the lineshape, the average laser injection current was automatically adjusted downward by about 10 mA. From the DC injection current tuning rate measurements provided by the manufacturer, this suggests that the laser wavelength changed by about 26 GHz, or 0.866 cm⁻¹.

![Figure 10. Plot of baseplate temperature and average laser injection current as a function of time during a – 50 C change in environmental chamber temperature.](image-url)
Figure 11 is a plot of the measured absolute O₂ concentration during the temperature cycle. The effect of the automatic line-centering software is evident in the decreased stability of the measured O₂ concentration beginning just before 9:20. The amplitude of these fluctuations is approximately 25% of the average value is clearly unacceptable for the eventual sensor performance, thus illustrating the need for improving thermal packaging of the lasers themselves as well as higher fidelity line-centering software routines. These are presently under development.

![Figure 11. Plot of the absolute O₂ concentration measured in a 50 cm external path during the temperature cycle shown in Figure 10.](image)

CO and O₂ Sensing in Pilot-Scale Industrial Furnaces

Although not strictly an aerospace application, monitoring combustion species in large scale industrial furnaces shares many of the same practical integration and engineering issues. In collaboration with American AirLiquide (AAL) Corporation, we have been developing and testing diode laser sensors for simultaneous measurements of CO and O₂ in oxygen-enriched combustors.

Figure 12 shows an example raw data signal from a prototype O₂ sensor obtained at AAL's pilot-scale oxy-fueled test furnace at our Chicago Research Center (CRC). The pilot furnace dimensions are 1 × 1 × 4 m and can operate at a maximum heat input of 750 kW with wall temperature up to 1900 K. Natural gas fuel is typically used with oxygen; however, air and oxygen-enriched air can also be used. The furnace is fully instrumented with thermocouples, heat flux meters, and continuous flue gas composition and temperature monitoring using conventional analyzers. For the diode laser measurements, the beam is positioned in the exhaust flue with a 30 × 30 cm cross sectional area. At this location, homogeneous concentration and temperature profiles are obtained allowing direct comparison with the conventional analyzers.

The data are compared to an ideal Voigt lineshape function and show excellent visibility of the oxygen signal in the furnace at this condition. The area under the lineshape is directly proportional to the O₂ density, as described above. By integrating this signal, the sensor's sensitivity to noise in the transmitted power is reduced. Further, the absolute intensity transmitted effects only the magnitude of the signal, not the differential absorbance across the line. Therefore, the sensor is inherently robust with respect to broadband absorption or scattering from flow particulates or changing window transmission.

In the present work, the sensor is tested with a pulsed fuel injection scheme for control of low-NOx oxy-fueled furnaces. The fuel is pulsed at 0.5 to 1 Hz rates in order to vary the instantaneous stoichiometry at a fixed average fuel flow (or firing) rate. This approach leads to a reduced level of total NOx emissions. In this case, conventional analyzers are not fast enough to monitor the dynamic combustor conditions.

Figure 13(a-c) compare the initial pilot scale furnace data for three candidate sensor strategies where we now show the continuous data stream from the integrated computer controlled sensor prototype produced by PSI. The data illustrate several important aspects of the development required to complete the transition of near-IR diode laser sensors from the laboratory to the industrial combustion environment. The noise level in Figure 13(a) is much higher than equivalent tests performed in our laboratory burners and was determined to arise from fluctuations in the
radiative emissions from the high temperature refractory and particulates embedded in the exhaust flow. The fluctuations in the radiative loading on the photodetector contributed to the overall noise in the raw data which was not completely suppressed through the data filtering. It is further exacerbated in the case of O\textsubscript{2} monitoring due to the relatively low levels of laser power available at this wavelength in the initial prototype design.

The CO data shown in 13(b) was acquired in a second test entry where the optical collection system design was improved so as to reduce the transmitted furnace radiation and shows a substantially reduced noise level. Furthermore, the laser available at 1.56 µm for the CO overtone transition was about an order of magnitude more powerful than the O\textsubscript{2} laser, thereby further reducing the magnitude of the fluctuations compared to the incident laser power. Even though the concentration of CO is more than two orders of magnitude below the O\textsubscript{2} values, the visibility of the pulsed operation is higher with this sensor than with the O\textsubscript{2} sensor. Since the noise on this pulsed waveform will impact the controller dynamics, we seek to improve the fidelity of the sensor further.

In a recent pilot scale test, the laser used to monitor the CO absorption signal was tuned to nearby water vapor transition and the pulsed mode combustion sequence was repeated. The results of this experiment are shown in 13(c). Although it was not possible to absolutely quantify the water vapor concentration in this case since the linestrength of the H\textsubscript{2}O transition used was not known, it is obvious that this signal represents a much higher fidelity representation of the pulsed combustion wavefront in the furnace exhaust. In our next series of tests, we plan to incorporate two-line thermometry using a set of H\textsubscript{2}O transitions in this spectral region.

**Summary and Conclusions**

This paper illustrates three demanding applications for tunable diode laser sensors in large scale facilities - both ground based and flight. Engineering solutions for the unique challenges of autonomy, long-term stability, and harsh environmental survivability have been developed and applied. Although further work is required to meet eventual target sensitivity and stability, the initial results are encouraging and demonstrate clearly that near-IR diode laser sensor technology can meet the needs of next generation gasdynamic testing.
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References


